DEVELOPMENT OF HIGH ENERGY PULSED PLASMA SIMULATOR
FOR PLASMA-LITHIUM TRENCH EXPERIMENT

BY
SOONWOOK JUNG

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Doctoral Committee:
Professor David N. Ruzic, Chair
Professor George H. Miley
Professor J. Gary Eden
Professor Clair J. Sullivan
Abstract

To simulate detrimental events in a tokamak and provide a test-stand for a liquid - lithium infused trench (LiMIT) device [1], a pulsed plasma source utilizing a theta pinch in conjunction with a coaxial plasma accelerator has been developed. An overall objective of the project is to develop a compact device that can produce 100 MW/m$^2$ to 1 GW/m$^2$ of plasma heat flux (a typical heat flux level in a major fusion device) in $\sim 100$ µs ($\leq 0.1$ MJ/m$^2$) for a liquid lithium plasma facing component research.

The existing theta pinch device, DEVeX, was built and operated for study on lithium vapor shielding effect. However, a typical plasma energy of 3 - 4 kJ/m$^2$ is too low to study an interaction of plasma and plasma facing components in fusion devices. No or little preionized plasma, ringing of magnetic field, collisions of high energy particles with background gas have been reported as the main issues. Therefore, DEVeX is reconfigured to mitigate these issues. The new device is mainly composed of a plasma gun for a preionization source, a theta pinch for heating, and guiding magnets for a better plasma transportation. Each component will be driven by capacitor banks and controlled by high voltage / current switches. Several diagnostics including triple Langmuir probe, calorimeter, optical emission measurement, Rogowski coil, flux loop, and fast ionization gauge are used to characterize the new device.

A coaxial plasma gun is manufactured and installed in the previous theta pinch chamber. The plasma gun is equipped with 500 µF capacitor and a gas puff valve. Plasma produced in the chamber by the plasma gun has $n_e \sim 10^{21}$ m$^{-3}$, $T_e \sim 10$ - 20 eV that lasts for 150 µs. The velocity of the plasma ranges from $2.5 \times 10^4$ to $4 \times 10^4$ m/s. The increase of the plasma velocity with the plasma gun capacitor voltage is consistent with the theoretical predictions and the velocity is located between the snowplow model and the weak - coupling limit. Plasma energies measured with the calorimeter ranges from 0.02 - 0.065 MJ/m$^2$ and increases with the voltage at the capacitor bank. A cross - check between the plasma energy measured with the calorimeter and the triple probe / optics shows that the plasma energies are in agreement with each other.

The effect of theta pinch on preionized plasma has been investigated when operated in conjunction with the coaxial plasma gun. The previous theta coil (1 turn, 40 nH) is connected with 72 µF capacitor bank to
handle more energy. The theta coil is reconfigured as a two-turn coil (160 nH) to facilitate the operation of a crowbar. The two-turn coil achieves a maximum current of 300 kA (= 1.2 T) at 20 kV of the main capacitor bank voltage and the operation of the crowbar allows for a monotonically decreasing current. With the 2-turn theta coil, a maximum plasma energy of \( \sim 0.08 \text{ MJ/m}^2 \) is achieved with 6 kV at the plasma gun and 20 kV at the theta pinch. Plasma velocities of 34 - 74 km/s are observed at the first few peaks of theta pinch current. A problem of plasma transport with short delay times is observed.

The effects of guiding magnetic field and crowbar on plasma transport has been studied. Guiding magnets (0.3 T and 0.15 T, respectively) are equipped with SCR switches and driver circuits, capacitor banks (8 mF and 4 mF, respectively), and a magnetic flux excluder. Optical emission and calorimeter measurements for plasma gun and guiding magnet experiments show that the guiding magnetic field form a magnetic pressure that impedes plasma from transport to the target chamber. Two effects are observed in the theta pinch and the guiding magnetic field experiment. 1) A less delay time results in a less decrease in plasma energy. 2) When theta pinch magnetic field is reversed, the plasma produces a less emission. A crowbar experiment with the guiding magnetic field shows that a long lasting unipolar magnetic field at the theta pinch and the guiding magnet field give an enhanced plasma transport and a plasma heat flux of 0.42 GW/m².

Ideal MHD simulations are carried out to verify the experimental results on plasma transport. Ideal MHD and Athena MHD simulation code are found to be reasonable approximations to simulate behaviors of the plasma in the experimental condition. Simulation results for the effect of guiding magnetic field on plasma gun show that plasma is accumulated at the guiding magnetic field due to magnetic pressure and it is in agreement with the experimental results. Simulations also show the divergence of plasma when the magnetic field from the guiding magnets is in the opposite direction to the theta pinch magnetic field.

Lithium vapor shielding phenomenon is studied in the newly developed machine. A theoretical model for plasma energy absorbed in lithium vapor cloud is derived based on corona equilibrium. Experiments in a prototype theta pinch device shows a reduction in plasma energy on a target of 2.7 ± 1.7 J (29 ± 19 %) at 1.6 mTorr and approximately 0 J at 9.5 mTorr. The energy reduction is in agreement with a prediction the theoretical model. Experiments conducted in a new plasma gun do not show much of visible difference in terms of target temperature. The experiments with the plasma gun with the theta pinch, guiding magnetic fields, and the crowbar shows approximately 40 ± 23 J (26 ± 15 %) of energy reduction. The model predicts a similar energy level for the cases and finds that the main differences of plasma parameters in the theta pinch device and in the plasma gun is a larger sputtering with crowbar due to faster plasma velocity and presumably hotter ions / electrons.

Finally, the dissertation concludes with a few ways to further improve the device and increase the plasma
heat flux. A change in the system design as well as a compact toroid generation are proposed and preliminary results are presented. The dissertation also suggests hardware upgrades which include an increase in the energy at the plasma gun / the theta pinch capacitor banks. At the same time, additional diagnostics will allow to further investigate the effect of pinching on the plasma from the plasma gun as well as determine the overall effect of the guiding magnetic field.
To my family
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6.7 Density plots calculated with Athena MHD code at various times for two different conditions (a) the guiding magnetic field in the same direction as the theta pinch magnetic field (b) the guiding magnetic field in the opposite direction to the theta pinch magnetic field. Data at eight different times are shown: 0, 0.25, 0.5, 0.75, 1, 1.5, 2, 3 µs.
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7.15 (a) The equivalent thermal circuit for the molybdenum target. It is originally developed in [8] (b) The surface temperature estimated by the thermal model in [8] implies that the calibration factor for the thin molybdenum target is approximately 1.3 [17].

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7.17 Incident energy on the target estimated by triple Langmuir probe data with $\gamma_{heat} = 6.5$ (solid squares) and $\gamma_{heat} = 4.8$ (empty squares) shows the similar behavior as the actual temperature increase measured by thermocouple (triangle) [17].

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7.21 (a) Triple Langmuir probe measurement at 6 kV plasma gun shot. Average plasma densities, electron temperatures, and plasma velocities are plotted in (b), (c), and (d). (b) Average plasma densities for the first 30 µs (c) Average electron temperatures for the first 30 µs (d) plasma velocities measured using time of flight technique.

7.22 Triple Langmuir probe measurement at 6 kV plasma gun and 15 kV theta pinch shot. Guiding magnetic fields are on and the crowbar switch is triggered. (a) Plasma gun current signal (b) Plasma density and electron temperature as a function of time.

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8.1 A difference between field reversed configuration and spheromak [27]

8.2 Formation of a compact toroid in two ways. (a) Field reversed configuration formed in a field reversed theta pinch device [3, 28]. Four stages are specified: preionization, field reversal, reconnection, and contraction to an equilibrium. (b) Spheromak formation using a coaxial plasma gun [29]. The formation consists of three stages: elongation of the initial magnetic field, expansion into a flux conserver, and relaxation.

8.3 The relation between gun current and the required magnetic field to satisfy $\lambda_{\text{gun}} = \lambda_{\text{geom}}$.

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9.3 A cad drawing of the retarding field energy analyzer.

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A.3 A plot of the plasma conductivity (a) for weakly - ionized plasmas and (b) for fully - ionized plasmas.

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A.5 (a) A schematic of a double probe and its measurement circuit [32] (b) A schematic of a triple Langmuir probe and its measurement circuit [33].

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A.7 An I - V curve of a double Langmuir probe [32] and load lines of the probe for two different measuring resistors at the same bias voltages. The red solid line is a load line with a lower resistor than the resistor for the blue dotted line on the graph. When the resistor is low, the obtained voltage - current pair is at the point A. However, as the resistor increases, the the pair moves to the point B where the current is no more saturated.
Chapter 1

Introduction

1.1 Fusion Energy and Tokamak

Energy is essential for human life. The standard of living is highly related with energy consumption [34]. For the last few tens of years, however, people have encountered an unprecedented energy crisis as exemplified by high oil price. Therefore, a lot of efforts are currently being made on the development of alternative energy sources such as solar panels, wind power, bioenergy and fusion energy. Among them, fusion energy has been considered a very attractive energy source due to no carbon emission and abundance of fuel. Deuterium, one of the fuels for the fusion reactor, is expected to able to supply the world’s energy needs for millions of years [35].

In order for a fusion reactor to generate a net energy output, Lawson criterion or triple product $n_e T \tau_E$ criterion should be satisfied. Here, $n_e$ is the plasma density, $T$ is the plasma temperature, and $\tau_E$ is the energy confinement time. For deuterium - tritium reaction, the physical value is about

$$n_e T \tau_E \geq 10^{21} \text{ keV s/m}^3$$ (1.1)

Basically what Fig. 1.1 tells us is that the plasma pressure ($= n_e T$) has to be confined long enough to achieve the net energy gain. At the same time, Fig. 1.1 also shows that the condition is a strong function of the plasma temperature, and normally 100 million K or higher temperature is required for the maximum fusion reaction. While this value is normally beyond imagination for most of materials, the triple product criterion again tells us that only very low density and thereby very little mass of the fuel are necessary for the breakeven condition. The triple product criterion, therefore, still allows for a scientific and engineering feasibility of the fusion reactor.

In order to suppress the plasma pressure in a fusion reactor in a timescale determined by the triple product, two major approaches have been proposed. The first one is inertial confinement concept, where a

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1Tritium, another sour of fuel for D - T fusion, is very rare in the world and has to be obtained by tritium breeding process $\text{Li}(n, T) \text{^4He}$. Abundance of lithium is estimated approximately 22 million tons [36].
pulse of radiation such as a laser rapidly heats the surface of a fuel capsule to compress it and to achieve ignition condition. The other approach is magnetic confinement fusion, where plasma is confined by an external magnetic field. While inertial confinement fusion is characterized by very high pressure but a much lower confinement time, magnetic confinement fusion normally achieves much lower plasma pressure but a long energy confinement time. For example, the National Ignition Facility for inertial confinement fusion is targeting a plasma pressure of $10^{11}$ atmospheres in billionth of a second pulse \cite{37, 38} while in International Thermonuclear Experimental Reactor (ITER), a tokamak device under an international collaborative research and engineering project, aims at a plasma pressure of approximately 7 atmospheres with an energy confinement of 3 - 400 seconds. Fig. 1.2 shows a cross sectional diagram of the ITER \cite{5}. Plasma energy in a current tokamak varies from 1 to 10 MJ, and typical plasma parameters for various tokamaks are listed in Table 1.1 \cite{2}.

While the initial estimate on the plasma diffusion across a magnetic field based on MHD seemed well within the range of technical feasibility, enhanced diffusion rate across a magnetic field by particle collisions made difficult the realization of a magnetic fusion reactor. Especially, Bohm found in 1940s a threatening semi-empirical formula

$$D_{\perp}B = \frac{kT}{16eB} \quad (1.2)$$

where $e$ is the electric charge and $B$ is the magnetic field. The discovery of the Bohm diffusion was a
disastrous news for fusion researchers \cite{39}. While the plasma particle loss rates measured experimentally were much smaller than the Bohm diffusion, they were much larger than the rates calculated from the neoclassical theory \cite{39, 40}. Therefore, for a long time researchers have tried to understand the transport physics and to increase plasma energy with auxiliary heating methods for better energy content \cite{40}.

The initial experimental data with additional heatings showed very disappointing results. It was observed that there was a clear deterioration of energy confinement time with external heatings. For example, an

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|}
\hline
Machine & Stored Energy (MJ) & Pulse Length (sec) & Plasma Volume (m$^3$) \\
\hline
DIII-D & 3.5 & 6 & 21 \\
TFTR & 7 & 5 & 30 \\
JT - 60U & 10.9 & 20 – 60 & 90 \\
JET & 10 & 10 – 30 & 95 \\
Tore Supra & 0.3 – 1 & \leq 400 & 20 \\
ITER & 500 & \geq 300 & 840 \\
DEMO & 600 & steady-state & 500 – 1500 \\
\hline
\end{tabular}
\caption{A summary of plasma parameters for various tokamaks \cite{2}}
\end{table}
experiment at the Oak Ridge National Laboratory showed that energy confinement time decreased by a factor of 2 with 2.5 MW neutral beam heating [41]. The result was quite serious: one cannot just increase the triple product by external heatings since the increase in the temperature occurs simultaneously with the decrease in the energy confinement time.

However, there were still some more progress in the plasma confinement. During neutral beam heating experiments on ASDEX in Germany, it was observed that there was an transition to high confinement, which is about a factor of two higher confinement time than low confinement mode [6]. Fig. 1.3 shows the first observation of the H-mode from the ASDEX results [6]. The enhancement of the confinement is caused by a steeper pressure gradient at the edge of the plasma. While for the transition to H-mode an external heating power above a certain threshold is required [40] and the underlying physics for the H-mode are not fully understood, the discovery of the H-mode definitely has drawn a huge interest from fusion researchers.

Figure 1.3: Global energy confinement time vs average line density for toroidal limiter (triangles) and divertor discharges (other symbols) shown in Ref. [6]
1.2 Detrimental Effects of Edge Localized Modes and Disruptions in Tokamaks

However, the H-mode has a few negative sides [40]. One of them is edge localized modes, or ELMs, where relaxation of the transport barriers is followed by a disruptive instability with short bursts of plasma ejection. Even though the removal of about 1 GJ of energy over long timescales has been demonstrated [2], the discovery of off-normal events in tokamaks, such as edge-localized mode and disruption, has dramatically changed the perspective of stability of wall components in tokamaks. These violent events where the plasma confinement is severely degraded or even destroyed, occur in a very short timescale, typically milliseconds, resulting in a huge amount of power bombarding on the target. 500 MJ of energy for ITER is equivalent to 100 kg of TNT so that the wall material will experience serious damage if the plasma energy is released in much faster timescales than radiative/convective cooling timescale. A recent report says that ITER will not be able to tolerate damage to its plasma facing components unless ELMs can be eliminated or reduced in magnitude by 95 % [42] and the peak energy density must be smaller than 0.5 MJ/m$^2$ to have a lifetime of $10^7$ thermal pulses of 500 $\mu$s duration [43]. Fig. 1.4 shows what results from these extreme events. Therefore, a major part of the tokamak research is aiming toward the development of physics and technologies to cope with these extreme events including mitigation of ELM events such as resonance magnetic perturbation [44] and study on plasma-wall interaction at a high level of heat flux. For more details on plasma - wall material researches, one may refer to Ref. [45].

![Figure 1.4: (a) A picture of a tungsten upper divertor tile at the ASDEX-Upgrade [7] (b) A picture of a localized melt damage in the Alcator-C Mod, most likely due to runaway electrons during an ELM [2]](image-url)
1.3 Lithium-Metal Infused Trenches for Heat Removal

Lithium has been considered one of candidates for a liquid metal fusion facing component, not only because it has much less radiation loss than carbon and tungsten and is a good getter for carbon and oxygen, but it also has a very low recycling coefficient [46, 47]. While fusion researchers have struggled with lithium’s high vapor pressure and its magneto - hydrodynamic (MHD) behaviors, a recent research at University of Illinois showed that liquid lithium in metal trench flows by a thermoelectric MHD force in such a way that it removes the heat flux and refresh the surface with pure lithium [1]. This configuration shown in Fig. 1.5(b) with an slit-shaped electron beam source implemented to create a heat gradient in the trench, removes a peak heat flux of 3 MW/m$^2$ and with the potential possibly to remove up to 20 MW/m$^2$. This trench concept is very attractive as a candidate for a plasma facing component in a fusion reactor since the force generated in the liquid by J x B force drives the liquid in such a way it circulates, removes heat, and refreshes the surface.

![Figure 1.5: (a) Concept for removing heat using thermo-electric MHD [1] (b) Lithium-Metal Infused Trenches are metal tiles with radial trenches containing lithium. The trenches run in the radial (poloidal) direction such that they lie primarily perpendicular to the toroidal magnetic field and the divertor heat stripe [1].](image)

An unexplored part of work related with the Lithium-Metal Infused Trenches is how the trench will behave with a larger amount of heat flux at shorter time scale. In order to investigate more in detail the feasibility of the lithium-trench for a plasma facing component, a new project titled Thermoelectric-driven Liquid Metal Plasma Facing Structures (TELS) has started. For this project, we are mainly in focusing on two subtasks: 1) we develop and refine the geometry of new thermo-electric driven structures to handle higher heat flux and 2) to develop a laboratory-scale experiment to simulate off-normal events in tokamak devices and to test the trench in those environments. Therefore, this thesis presents mainly the development of a small-size pulsed plasma heat load simulator to investigate a short-pulse effect on the liquid lithium.
1.4 Review of Previous Experimental Work

1.4.1 Laboratory - scale Plasma Simulators

There are numerous works that aim toward the development of laboratory - scale energetic plasma generators to simulate and study an interaction of plasma and plasma facing components. A summary of specifications of the facilities is listed in Table 1.2. In the table, FRX-L is added to the list due to its similar setup to the current existing plasma-wall interaction facility at University of Illinois (DEVeX) although the device is not a plasma-wall interaction simulator but focuses on magneto-inertial fusion. In Table 1.2, efficiency is estimated in such a way that a diameter of plasma is used to calculate the size of plasma and the total energy is compared with the main power stored in a main capacitor bank or supplied by a power supply. Therefore, the energy used for magnets is not counted and the efficiency may be overestimated for the facilities using additional energy for magnets and other components. Still, a few noticeable features of the existing device are found in Table 1.2: 1) The plasma is normally produced in a Penning Ionization source or an arc source and 2) confined and translated with a magnetic field, either in the form of external field or self-confined magnetic structure.

1.4.2 DEVeX - Divertor Erosion Vapor - shielding eXperiment

The University of Illinois currently has a theta pinch machine called Divertor Erosion Vapor-shielding eXperiment (DEVeX) which has been used as a laboratory test facility for lithium vapor shielding effect. The device was built by a former graduate student and it is approximately 2 meter long. The DEVeX

<table>
<thead>
<tr>
<th>Machine</th>
<th>( n_e (\text{m}^{-3}) )</th>
<th>( T_{i,e} ) (keV)</th>
<th>( t_p ) (µs)</th>
<th>( Q ) (MJ/m²)</th>
<th>Eff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-200 [50]</td>
<td>( 10^{22} )</td>
<td>( T_i + T_e = 0.8 ) keV</td>
<td>10</td>
<td>3 - 4</td>
<td>N/A</td>
</tr>
<tr>
<td>MK-200UG [51, 52]</td>
<td>( \leq 2 \times 10^{20} )</td>
<td>( E_i = 2-3 ) keV</td>
<td>50</td>
<td>0.05 - 1</td>
<td>~ 8</td>
</tr>
<tr>
<td>QSPA [52]</td>
<td>( 10^{21} )</td>
<td>( E_i = 0.6 ) keV, ( T_e \leq 7 ) eV</td>
<td>300</td>
<td>25</td>
<td>~ 2 - 10</td>
</tr>
<tr>
<td>MCPG [53]</td>
<td>( 1 - 4 \times 10^{21} )</td>
<td>( E_i = 15 ) eV</td>
<td>500</td>
<td>0.9</td>
<td>~ 3</td>
</tr>
<tr>
<td>Pilot-PSI [54]</td>
<td>( \leq 2 \times 10^{21} )</td>
<td>( \leq 2 ) eV</td>
<td>SS</td>
<td>1</td>
<td>~ 6</td>
</tr>
<tr>
<td>Magnum-PSI [55, 56]</td>
<td>( 10^{19} - 10^{21} )</td>
<td>( 0.1 - 10 ) eV</td>
<td>SS ( ^2 )</td>
<td>\geq 10</td>
<td>N/A</td>
</tr>
<tr>
<td>PISCES-B [49]</td>
<td>( 10^{17} - 10^{19} )</td>
<td>( 3 - 50 ) eV</td>
<td>SS</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>MPEX [57]</td>
<td>( \sim 10^{19} )</td>
<td>( 1 ) eV at target</td>
<td>SS</td>
<td>10 - 40</td>
<td>N/A</td>
</tr>
<tr>
<td>FRX-L [28]</td>
<td>( 1 - 8 \times 10^{23} )</td>
<td>( T_i + T_e \leq 0.4 ) keV</td>
<td>10 µs ( ^3 )</td>
<td>N/A</td>
<td>0.1 - 1</td>
</tr>
<tr>
<td>DEVeX (2011) [5]</td>
<td>( 10^{19} - 10^{20} )</td>
<td>( T_e \leq 0.1 ) keV</td>
<td>80 - 300</td>
<td>~ 3 \times 10^{-3}</td>
<td>~ 0.1</td>
</tr>
</tbody>
</table>

Table 1.2: A summary of plasma parameters for various plasma simulators

\( ^2 \text{Steady-state} \)
\( ^3 \text{Projected parameters} \)
\( ^4 \text{Lifetime of compact toroid} \)
\( ^5 \text{See [10, 17, 11, 58] for further references.} \)
Figure 1.6: (a) The data shows that the absorbed energy to a stainless steel target with a lithium film is lower than that without a lithium film [8]. (b) A screenshot of a movie recorded with a fast-framing camera (143 kfps) and a neutral lithium filter shows a neutral lithium emission on a molybdenum target with plasma energy as low as 1 ± 0.5 kJ/m².

revealed a possible evidence of vapor shielding of lithium for a lithiated stainless steel target [8] and a similar effect was observed for a lithiated molybdenum target [17].

The limitation of this device is that a typical plasma energy of the device stays around 3 - 4 kJ/m², which is too low compared to other devices. For the disruptions, the heat loads to the ITER divertor components are anticipated to be about \( Q = 10 - 100 \text{ MJ/m}^2 \) at the load duration \( t_p = 1 - 10 \text{ ms} \). The ITER ELMs are estimated to be \( Q = 1 - 3 \text{ MJ/m}^2 \) at \( t = 0.1 - 1 \text{ ms} \) with the repetition frequency of about 1 Hz (400 ELMs per ITER pulse) [59, 60]. Therefore, an order of GW/m² of heat flux (or MJ/m²) and ~ keV of \( T_e \) and \( T_i \) are required.

Several factors are addressed as the main issues that prevent from obtaining a high plasma energy. No or little preionized plasma, ringing of magnetic field, collisions of high energy particles with background gas have been reported. For the last few years, many experimental attempts have been made to solve the issues. Fig 1.7 shows the results of the experimental efforts. First, Fig 1.7(a) shows an increase in plasma energy by a factor of 2.5 with a preionized plasma produced by 1 \( \mu \text{F} \) capacitor charged at 9 kV [10, 17]. Fig 1.7(b) shows an increase of plasma energy with the use of a PV-10 puff gas valve by a factor of 2 or more [58]. As shown in Fig 1.7(c) a monotonically decreasing magnetic field has been achieved by changing the number of turns of the coil from 1 turn to 4 turn.
Figure 1.7: (a) Temperature increase on a molybdenum foil (55 mm x 52 mm x 0.075 mm) at various operating scenarios (b) Increase of plasma energy with the use of a gas puff (c) The current from the theta coil when the coil is reconfigured to a 4-turn coil. The plot in black is when the crowbar is not fired while the plot in red is with the crowbar in operation.
Figure 1.8: Schematic of a possible schematic of the theta pinch pulsed plasma source for the Lithium-Metal Infused Trenches experiment

1.5 Objective Statement

As shown in Table 1.2, the current status of DEVeX, compared to the facilities, is far below the requirement for the ELM simulator in terms of the plasma energy output. However, it is shown in chapter 1.4.2 that the plasma energy can be increased with the use of preionized plasma, gas puff valve, and so on. Moreover, theta pinch is believed to be a possible way to control temperatures of charged particles [61], the unique characteristic of plasma heating by theta pinch is interesting in terms of a ELM simulator over other devices. It is because many other facilities have electron temperature in a few or few tens of eV and ion temperature normally lower than electron temperature, while theta pinch may preferentially heat ions and produce high temperature ions. As shown in Table 1.2, the thermal temperature is \(\leq\) a few tens of eV except MK-200UG. While there are several techniques available to increase ion or electron temperature such as ion cyclotron heating and electron berstein wave heating [57], they are not suitable for a small pulsed device due to the difficulty in energy coupling and impedance matching. On the other hand, plasma heating through adiabatic compression by magnetic pinching may still be useful in two ways: 1) the adiabatic compression and shock wave heating is not as complex as the wave-resonance heating so that one may avoid the problem of wave coupling and 2) since the device is inherently in a pulsed mode, one can deliver much more power to the plasma through capacitor discharge and pinching. For example, 10 kJ of capacitor energy discharged in 100 \(\mu\)s is the same as 1 GW of power while external heating systems for ITER are planned and developed to deliver a power of a few tens of MW.

However, it is questionable how the theta pinch will interact with high density, fast - moving plasma and
how efficiently the pinched plasma may be transported to the target region. Moreover, the strong magnetic field from the theta pinch or the axial magnetic fields for LiMIT can act as a magnetic hill and prevent the plasma from transport to the chamber.

The objective of the proposed work, therefore, is to build a test facility for liquid lithium trench experiment using a new plasma gun and the existing theta pinch facility. This device will provide magnetic fields to drive the liquid lithium and produce a similar pulsed-plasma heat load to simulate the extreme events in the tokamaks. Not only that, the use of the theta pinch can manipulate the ion / electron thermal temperature which has not been attempted by other devices. This new setup, therefore, will allow for the energetic plasma to impinge upon the surface of the thermo-electric driven structure. The performance of the device will be tested in various operation scenarios so that we may characterize the interaction of the plasma with the theta pinch and the magnets.

For these purposes, the device will be reconfigured to allow for the lithium trench experiment and the existing DEVeX device will be upgraded and tested to create an energetic plasma flow in the following manners:

- Plasma creation and acceleration: coaxial pulsed plasma gun will be installed to the DEVeX to produce high density preionized plasma. Gas-puff experiment, discharge characteristic study and plasma parameter diagnostics are carried out.

- Plasma heating: the existing theta pinch device will be operated in conjunction with the coaxial pulsed plasma gun to see if the theta pinch may deliver more energy to the plasma and to the energy incident on the target chamber.

- Plasma transport: two magnet sets, which provide an axial magnetic field for LiMIT, will be added to the existing facility. Estimate on plasma diffusion, magnetic field simulation, plasma MHD simulation are carried out. And the flux conservers are designed to minimize the magnetic field perturbation.

- Plasma parameter measurements: plasma from the theta pinch is diagnosed with a triple Langmuir probe and its energy on the target will be measured with a calorimeter. Time of flight diagnostics will allow for plasma flow velocity measurement.

In sum, an overall objective of the dissertation is to develop a compact device that can produce 100 MW/m² to 1 GW/m² of plasma heat flux in ~ 100 µs for a liquid lithium plasma facing component research. As shown in the graph ?? and ??, a condition similar to the ELM will be achieved in the TELS. Table 1.3 shows the comparison of plasma parameters for major magnetic fusion devices. Typical energy of
Figure 1.9: (b) The projected plasma energy from the new device in comparison with the energy from the DEVeX and other energy levels in tokamaks [9].

Table 1.3: A summary of plasma parameters for ELMs of major devices

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ITER [8]</th>
<th>NSTX [63]</th>
<th>DIII-D [64]</th>
<th>JET [65] [66]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_e$ (m$^{-3}$)</td>
<td>$10^{21} - 10^{22}$</td>
<td>$\sim 10^{19}$</td>
<td>$3 - 5 \times 10^{19}$</td>
<td>$5 \times 10^{19}$</td>
</tr>
<tr>
<td>$T_e$ (keV)</td>
<td>$\sim 1$</td>
<td>0.1</td>
<td>$\sim 0.5$</td>
<td>1-3</td>
</tr>
<tr>
<td>Flow velocity (m/s)</td>
<td>$\geq 1 \times 10^5$</td>
<td>0.1 - 1</td>
<td>$\sim 1$</td>
<td>$0.2 - 0.3$</td>
</tr>
<tr>
<td>$t_p$ (ms)</td>
<td>0.1 - 1</td>
<td>$\sim 1$</td>
<td>$\sim 0.2$</td>
<td>0.1 - 0.5</td>
</tr>
<tr>
<td>Plasma Energy (MJ/m$^2$)</td>
<td>1-3</td>
<td>$\sim 0.1 - 1$</td>
<td>$\sim 0.2$</td>
<td>0.1 - 0.5</td>
</tr>
<tr>
<td>Heat Flux (GW/m$^2$)</td>
<td>$\leq 10$</td>
<td>$\leq 1$</td>
<td>$\sim 0.1$</td>
<td>1</td>
</tr>
</tbody>
</table>

ELMs is about 0.01 - 0.05 MJ/m$^2$ for ASDEX - upgrade, 0.1 - 0.5 MJ/m$^2$ for JET and is expected to be 1 - 5 MJ/m$^2$ for ITER [62]. TELS aims at simulating the ELMs on the level of JET.
Chapter 2
Overview of the Project and Diagnostics

2.1 Estimate of Plasma Heat Flux on a Target

A plasma heat flux delivered on a target is estimated either using Eq. (2.1)\[67\] or Eq. (2.2)\[40\]:

\[
\vec{Q}_\sigma = \frac{1}{2} n_\sigma m_\sigma (\vec{v}_\sigma \cdot \vec{v}_\sigma) \vec{v}_\sigma + \frac{5}{2} p_\sigma \vec{v}_\sigma + \vec{v}_\sigma \cdot \vec{\pi}_\sigma + \vec{q}_\sigma \quad (2.1)
\]

\[
Q = \gamma_s n_e c_s T_e \quad (2.2)
\]

where \(\sigma\) is the species of the charged particles (namely, electrons and ions), \(n\) is the plasma density, \(m\) is the mass of the species, \(\vec{v}\) is the plasma advection velocity, \(p\) is the plasma pressure, \(\vec{\pi}_\sigma\) is the shear stress tensor, \(\vec{q}_\sigma\) is heat conduction term, \(\gamma_s\) is called sheath power transmission coefficient defined as

\[
\left[\frac{2T_i}{T_e} + \frac{2}{1-\delta} + \frac{1}{2} \ln \left(\frac{(1-\delta)^2 m_i/m_e}{2\pi(1+T_i/T_e)}\right)\right],
\]

\(\delta\) is the secondary electron emission coefficient, and \(c_s\) is the Bohm velocity defined as \(\sqrt{k(T_i+T_e)/m_i}\). Eq. (2.2) assumes a formation of sheath in front of a wall and acceleration of ions due to a negative sheath potential by fast electrons while Eq. (2.1) considers a bulk plasma advection and thermal motion. While both expressions are valid for an estimate of a plasma heat flux on a target, Eq. (2.1) is chosen for describing a transient plasma heat flux since Eq. (2.2) is more suitable for steady-state plasma interaction with a wall.

In Eq. (2.1) \(\vec{q}_\sigma\) is heat conduction, which is zero for an isotropic thermal velocity distribution. Since \(\vec{\pi}_\sigma\) is an anisotropic shear term, it becomes zero in case of an isotropic thermal velocity distribution as well. In this case, Eq. (2.1) is reduced to

\[
\vec{Q}_{\sigma,iso} = \frac{1}{2} n_\sigma m_\sigma (\vec{v}_\sigma \cdot \vec{v}_\sigma) \vec{v}_\sigma + \frac{5}{2} p_\sigma \vec{v}_\sigma + \left(\frac{1}{2} n_\sigma m_\sigma v^2_\sigma + \frac{5}{2} n_\sigma k T_\sigma\right) \vec{v}_\sigma \quad (2.3)
\]

Eq. (2.1) can be rewritten in the following form if the plasma flow velocity is assumed to be determined
as a single value $v_0$ for both electrons and ions:

$$Q_{\text{isotropic}} \sim \left\{ \frac{1}{2} n_e (m_i v_0^2 + m_e v_0^2) + \frac{5}{2} n_e (kT_i + kT_e) \right\} \bar{v}_0$$ (2.4)

This assumption is only valid in MHD model. In the MHD model for a fusion plasma, the following inequalities should be satisfied: [34]

- length: $\lambda_{De} \ll r_{Li} \ll L$
- frequency: $\frac{v_{T_i}}{L} \ll \omega_{ci} \ll \omega_{pe}$
- velocity: $v_{T_i} \ll v_{Te} \ll c$ (2.5)

where $\lambda_{De}$ is the Debye length, $r_{Li}$ is ion Larmor radius, $L$ is the characteristic length of change, $\nu_{ci}$ is electron-ion collision frequency, $v_{T_i}$ and $v_{Te}$ are ion and electron thermal velocities, $\omega_{ci}$ is ion gyro-frequency, $\omega_{pe}$ is plasma frequency, and $c$ is the speed of light. Normally the MHD approximation is a reasonable assumption in describing a violent, a large-scale motions of a highly magnetized plasma and valid in collisional plasmas or the perpendicular motions of collisionless plasmas [68]. At 0.1 T, $\omega_{ci}$ is about $10^7$ Hz (≈ 0.1 µs) and the electron-ion collision time ranges from 0.1 - 1 µs while the end loss timescale for a theta pinch is a few tens of µs [69]. In terms of length, the Debye length for $n_e \sim 10^{21}$ m$^{-3}$, $T_e \sim 100$ eV is approximately a few micrometers and the Larmor radius is approximately 1 cm or less. Therefore, the MHD approximation may be acceptable for further analyses.

Fig. 2.1 predicts the amount of plasma heat flux on the target at various plasma density, ion/electron temperature, and plasma flow velocity. From Fig. 2.1, it is found that a considerable amount of energy flux is obtained even when ion and electron temperatures are very low. The initial target for the plasma parameter is $n_e \sim 10^{21}$ m$^{-3}$, $T_{e+i} \geq 100$ eV, $v_0 \sim 5 \times 10^4$ m/s, which gives heat flux around $\geq 1$ GW/m$^2$ and $\geq 0.1$ MJ/m$^2$ with 100 µs pulse.

### 2.2 Overview of the Experimental Setup

Table 2.1 shows a comparison of plasma parameters for the prototype machine DEVeX and the new device TELS. The key changes are plasma density and the plasma flow velocity. Higher ion / electron temperature may be expected as well due to larger energy in the capacitor bank for the theta pinch.

The project for the new device is mainly divided into two phases. At the first phase we develop a theta pinch device with a coaxial plasma gun and test its performance. At the second phase, the device will be
2.2.1 1st Phase

The project is mainly divided into two phases. In the first phase we develop a theta pinch device with a coaxial plasma gun and test its performance. Therefore we aim more at the development of a plasma source rather than lithium experiment and it is the main scope of the dissertation. The coaxial plasma gun is to create high density plasma and provide it with an axial momentum through Lorentz force. Oxygen free copper has been chosen as an electrode material for initial testing. 500 $\mu$F capacitor is charged up to 6 kV (= 9 kJ) and discharged through a spark gap switch.

The plasma from the gun lasts for a very short pulse. It is hard to heat the plasma with resonance type wave heating for various reasons. It includes an expensive and sophisticated setup, a small device dimension, and a difficult coupling and matching. Therefore, considering the experimental setup a theta pinch is a good alternative to heat the plasma. A pyrex tube is surrounded by a theta coil which is connected to a 72 $\mu$F

![Figure 2.1: Estimated heat flux on the target using Eq. (2.4) at (a) $n_c = 10^{20}$ m$^{-3}$ (b) $n_c = 10^{21}$ m$^{-3}$](image)

Table 2.1: A summary of plasma parameters for DEVeX (2011) and TELS (projected)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>DEVeX (2011) [10, 17, 11, 58]</th>
<th>TELS (projected) [70]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_c$ (m$^{-3}$)</td>
<td>$10^{19} - 10^{20}$</td>
<td>$\geq 10^{21}$</td>
</tr>
<tr>
<td>$T_e$ (eV)</td>
<td>10 - 100</td>
<td>$\leq 100$</td>
</tr>
<tr>
<td>Flow velocity (m/s)</td>
<td>$\sim 2 \times 10^4$</td>
<td>$\geq 5 \times 10^4$</td>
</tr>
<tr>
<td>$t_p$ (ms)</td>
<td>$\sim 0.1$</td>
<td>$\sim 0.1$</td>
</tr>
<tr>
<td>Plasma Energy (MJ/m$^2$)</td>
<td>$\leq 3 \times 10^{-3}$</td>
<td>$\leq 0.1$</td>
</tr>
<tr>
<td>Heat Flux (GW/m$^2$)</td>
<td>$\leq 0.04$</td>
<td>$\leq 1$</td>
</tr>
</tbody>
</table>
capacitor bank. While the capacitor bank can be ideally charged up to the maximum of 60 kV, experiments are carried out mostly under 20 kV (14.4 kJ) due to a limitation on a railgap switch and high voltage insulation issues.

We have two magnets at a target chamber. Guiding magnets initially serve to generate an external toroidal magnetic field for the trench. At the same time, it also suppresses expansion of plasma after it is ejected out of the theta coil. The magnets are powered by separate capacitor banks and 0.35 and 0.15 T magnetic fields are generated. A magnetic flux excluder is inserted between the theta coil and the guiding magnetic field to decouple magnetic fields from each other. In sum, the device aims at achieving \( n_e \geq 10^{21} \text{ m}^{-3} \), \( T_{i+e} \sim 100 \text{ eV} \), \( v \sim 50 \text{ km/s} \), and plasma heat flux \( \sim 0.1 \text{ MJ/m}^2 \text{ in 100 to 200 microseconds} \). Some of the initial work is summarized in [70].

A diagram of the experimental setup for the first phase is shown in Fig. 2.2(a). Fig 2.2(c) shows a cad drawing of the device. All dimensions in Fig 2.2(c) are inches.

### 2.2.2 2\textsuperscript{nd} Phase

While the second phase is beyond the scope of the dissertation, the projected setup is briefly described here for a better understanding of the project. In phase 2, we change our focus of the project to plasma lithium interaction experiment. First, the plasma gun electrode will be changed to tungsten for much higher sputtering threshold energy and better material compatibility with lithium. A high voltage feedthrough for the plasma gun is to be changed to a custom-made one that handles much higher current with the maximum capacitance of 1 mF (= 18 kJ). As for the plasma heating part, a liquid lithium readily reacts with glass, quartz, porcelain, and silicate. Therefore, the pyrex tube will be changed to a dielectric material which does not react with lithium such as Yttria-stabilized zirconia (YSZ). Capacitor energy may be increased further, up to the maximum of 30 kV (=32.4 kJ).

The guiding magnets will be operated in a much longer pulse, because we need magnetic field to last at least a few seconds to circulate the liquid lithium. An electron beam to provide a thermal gradient on the surface of the trench is to be installed in the phase 2 as well. The goal of the second phase is to test the lithium trench and investigate its behaviors under a plasma load. A diagram of the experimental setup for the second phase is shown in Fig. 2.2(b).

### 2.2.3 Operation of the Device

The device is controlled by a Maxwell delay generator and all the components will be triggered sequentially, as described in Fig. 2.3. All the timings are carefully determined based on the duration of the pulse of each
Figure 2.2: (a) A diagram of the TELS for (a) the first phase (b) the second phase (c) a cad drawing of the TELS for the first phase. All dimensions are in inches.
component as well as the performance of the device. The plasma gun and the theta pinch are supposed to be fired when magnets reach their peaks.

![Diagram of sequence of triggering in TELS](image)

**Figure 2.3: Diagram of sequence of triggering in TELS**

### 2.3 Diagnostic Tools

#### 2.3.1 Triple Probe

Plasma diagnostic in a plasma where density and temperature changes in a fast timescale, such as $\mu$s range, is extremely challenging for the following reasons: 1) intrusive methods such as single Langmuir probe requires a voltage sweeping much faster than timescale in which plasma changes its parameters, 2) non-intrusive methods such as optical diagnostics require a good time resolution, the detectable amount of signal in a given time resolution, and a signal amplification device such as a photo multiplier tube if the light is not strong enough. In the most cases, these conditions allow for only two possible choices: 1) triple Langmuir probe and 2) interferometer. However, an interferometer gives a line-integrated density rather than a volume density; therefore, the interferometer requires an additional information on the size of the plasma to fully convert the line-integrated density to the volume density.

A triple Langmuir probe, which was studied and discussed in detail in various papers [10, 17, 33, 71, 72, 73], has been reported to be able to measure the parameters of a fast-changing plasma without necessity of voltage sweeping and even current saturation. Triple Langmuir probe is composed of three wires; one is
floating is and the other two are biased with an external voltage source. Therefore, the triple Langmuir probe is a combination of a floating probe and a double probe. On the assumption of Maxwellian distribution for electron, a negligible contribution of magnetic field, and thin and collisionless sheath for current collection, the electron temperature is determined by the relation:

\[
\frac{I_1 - I_2}{I_1 - I_3} = \frac{1 - \exp \left( -\frac{e\phi_{12}}{kT_e} \right)}{1 - \exp \left( -\frac{e\phi_{13}}{kT_e} \right)}
\]

where \( I \) is the current at each probe tip, \( e \) is electric charge, \( A \) is the area of the probe tip, \( \phi_{12} \) is the voltage difference between tip 1 and 2, \( \phi_{13} \) is the voltage difference between tip 1 and 3, and \( T_e \) is electron temperature. When tip 2 is floated, the term in the left side of the Eq. 2.6 becomes 1/2 and \( T_e \) is determined by voltages at the tips. In this case, ion saturation current and plasma density are easily obtained on the assumption of thin and collisionless sheaths at the probe tips from the double probe relation

\[
I = I_{\text{sat}}^{\text{ion}} \tanh \left( \frac{e\phi_{13}}{2kT_e} \right)
\]

\[
n_e = \frac{I_{\text{sat}}^{\text{ion}}}{\epsilon A \exp(-0.5) \sqrt{\frac{kL}{M}}} \]

where \( T_e \) is measured from Eq. 2.6 and \( V_f \) is the voltage at the tip 2. Eq. 2.7 also implies that ion saturation current is not always necessary to obtain the plasma density, although a higher bias voltage (\( \phi_{13} \)) significantly reduces the uncertainty of the measurement. It is explained later in Appendix 4 that the Eq. 2.7a is basically the same equation as the I - V equation for a triple Langmuir probe when the probe tip 2 is floating (\( I_2 = 0 \)):

\[
I_{\text{sat}}^{\text{ion}} = \frac{I_3}{1 - \exp \left( -\frac{e\phi_{23}}{kT_e} \right)}
\]

where \( \phi_{23} \) is the voltage difference between the probe tip 2 and 3 and \( I_3 \) is the current collected at the probe tip 3.

The triple Langmuir probe measurement requires a good and sophisticated experimental setup to reduce parasitic capacitance and to measure voltage difference with maximum common mode rejection. A capacitive loading problem caused by input capacitance of the measurement circuit is mitigated by well-calibrated 10:1 attenuation probes. The high-level of common mode rejection in high frequency is achieved by Tektronix P5200 differential probes (with 50:1 attenuation) and a floating circuit powered by batteries. Total battery voltage is limited to 25 to 65 V to prevent arcing between the tips. In some cases a Pearson coil is used to measure the current than a resistor to reduce the resistor - loading effect (it is further discussed in
Appendix 5). Fig. 2.5 shows an example of a temporal behavior of plasma density and electron temperature at the DEVeX.

2.3.2 Calorimeter

Plasma heat flux is one of the most fundamental quantities in fusion energy \[75\]. It is not sometimes easy to derive from plasma parameters since there is a discrepancy between theoretically predicted and experimentally obtained sheath power transmission coefficients \(\gamma\) \[76, 77\]. There are several techniques to measure the plasma heat flux \[78\]: 1) a fast infrared measurement, 2) using plasma diamagnetics, 3) a target Langmuir probe, and 4) a thermocouple. The IR method requires an expensive setup to compensate IR emissivity and the diamagnetic method is reported to correspond to only 20 - 30 % of the flux. The Langmuir probe measurement is challenging when the plasma parameters changes fast with time and the heat flux is large. The thermocouple method is very slow, with a full response time on the order of seconds for a grounded junction type thermocouple \[79\], but the measurement is very simple and accurate. Therefore, we have also manufactured a calorimeter to estimate the incoming plasma energy.

A button - type calorimeter, similar to those in \[80, 81\], made of copper with a 0.25 inch diameter and with a 5 mm length is used. Copper has been chosen for its high thermal conductivity. The copper is insulated with Macor ceramics on all sides except the front surface. Macor has been chosen as a surrounding material since it has much lower thermal conductivity than alumina. Fig 2.6 shows thermal e - folding times for various materials. Here, the thermal e - folding time is associated with thermal diffusivity, which is the measure of thermal inertia of a material. Macor has a thermal e - folding time 160 times greater than copper, while alumina is 15 times greater than copper.
Figure 2.5: Temporal behavior of density and electron temperature when the 500 \( \mu \text{F} \) preionization capacitor is discharged 45 \( \mu \text{s} \) before the main bank is triggered. Black solid line indicates flux loop voltage, grey solid line theta coil voltage, and the grey dash line the preionization capacitor voltage. These plots start when the main bank is fired. Grey areas indicate regions where magnetic field increases. These correspond to peaks in the electron density and temperature [10].

Thermal resistance and capacitance of the element are represented as [8]

\[
R = \frac{L}{A\kappa} \tag{2.9a}
\]

\[
C = AL\rho C_p \tag{2.9b}
\]

where \( L \) is the conduction length of interest, \( A \) is the cross-sectional area, \( \rho \) is the material density and \( C_p \) is the specific heat of the material. The calorimeter, ignoring the effect of the surrounding material, has approximate thermal resistance and capacitance of 0.4 K/W and 0.5 J/K for the heat conduction from the front to the back surface, according to Eq. (2.9). Since 2 mm diameter thermocouple bead has approximate
thermal resistance and capacitance of 10 K/W and 0.02 J/K, the effect of the heat capacitance of the thermocouple is negligible and the heat conduction in the calorimeter is much faster than the thermocouple. Therefore, the time response is more likely determined by the thermocouple bead itself and the loading effect of the thermocouple on the calorimeter is insignificant.

A K-type thermocouple is attached to the back surface of the copper and the thermocouple is connected to a computer through a U-3 Labjack or U-6 Labjack interface to record the rise in temperature. The calorimeter is located at the target region, mostly 30 inches away from the plasma gun. Fig 2.7(a) shows a picture of the calorimeter and Fig 2.7(b) plots a relation of the temperature increase, the energy increase, and the plasma heat flux for the calorimeter.

Since the temperature measurement with the calorimeter has a finite uncertainty, the temperatures before / after a shot are averaged out. Error propagation is calculated using the uncertainty before / after the shot. The level of uncertainty for each measurement usually ranges from 0.0015 to 0.002 MJ/m².

2.3.3 Optical Diagnostics

In order to measure the plasma velocity, we use a time of flight technique with optical signals. Two high-bandwidth silicon photodiodes (PDA100A, Thorlabs), which is sensitive to wavelengths from 340 nm - 1100 nm, are used to collect the light from the plasma. To maximize the bandwidth, the photodiodes are operated with a small gain (≤ 20 dB) or no gain. The photodiodes allow for the maximum bandwidth of 2.4 MHz at

Figure 2.6: A plot of thermal e-folding times for various materials
Figure 2.7: (a) A picture of the calorimeter (b) A relation of the temperature increase, the energy increase, and the plasma heat flux for the calorimeter.

0 dB gain and 860 kHz at 20 dB gain. According to a general relation relating bandwidth and rise time

$$BW = \frac{0.35}{T_r}$$

where $BW$ is bandwidth and $T_r$ is the rise time of the signal, these bandwidths lead to approximately 0.15 µs (at 0 dB) and 0.4 µs (at 20 dB) rise time.

The light is collected with visible matched achromatic doublet pair (MAP1075150-A and MAP1030100-A, Thorlabs) and their working distances as well as focal lengths are considered. Due to a huge emission of radiation from the plasma source, the lenses are mostly equipped with an additional neutral filter (~ 90 % attenuation) to attenuate the signal further and to avoid saturation of the photodiodes. This setup gives a simple and a non-intrusive way to measure the plasma velocity and estimate the spectral of the plasma emission at specific locations. The diodes are placed at the end of the gun for velocity measurement of the plasma from the plasma gun. For measuring the plasma velocity after the pinch, the diodes are relocated between the theta coil and the guiding magnets.

A 1 x 6 optic cable bundle splits the optic signal from the lens through 6 optic cables to 6 photodiodes. The photodiodes are equipped with several optical filters; 670 nm (Li_I, 670.8 nm), 610 nm (Li_I, 610.3 nm), and 550 nm (Li_II, 548.6 nm) for lithium emission spectra, 650 nm (H_α, 656.3 nm) and 480 nm (H_β, 486.1 nm) for hydrogen spectra. All filters have ± 5 nm full - width at half maximum.
2.3.4 Rogowski Coil and Flux Loop

The measurement of the current from the main capacitor bank to the theta coil cannot be measured directly due to the geometrical constraints and too high an amount of the current (> 100 kA). Therefore, a rogowski coil and a flux loop are added to the device to measure the signal.

A rogowski coil measures alternating current or fast-changing current pulse. A self-made rogowski coil with a RC integrator is calibrated with a commercial rogowski coil and the can crusher device in the lab. The result is shown in Fig. 2.8. The calibration is conducted at three different position of the cable. It is found that the calibration value is fairly consistent when the cable is placed either at the center of the rogowski coil or against the coil. However, asymmetry at the junction of the rogowski coil results in inconsistent calibration values. Therefore, those data measured against the junction are excluded from the analysis. The calibration factor at the positive current is different from that at the negative current; this discrepancy is possibly due to some capacitive coupling between the coil and the cable. Therefore, the calibration factor is averaged out and the mean value is chosen as the calibration factor.

A flux loop measures alternating current or fast-changing magnetic pulse. While we are most interested in the magnetic field at the center of the coil, it is hard to place a flux loop at the center between the theta coil due to a very narrow space available. Therefore, the flux loop is placed 3/8 inch from the end of the coil. Formulas in Ref. [82] are used to calculate magnetic field from the theta coil and the magnetic field is surface-averaged since the flux loop measures the averaged magnetic field. With a RC integrator (R = 100 kΩ and C = 1 nF), it is found that $B_{\text{center}} = 14.14 \times V_{\text{out}}$ (T) and $I_\theta = 0.205 \times V_{\text{out}}$ (kA).

Fig. 2.9 shows the current from the main capacitor to the theta coil measured by the rogowski coil and the flux loops. The main capacitor bank is charged at 15 kV and the chamber is in vacuum to eliminate a coupling with plasma. It is found that the flux loop data and the rogowski coil is in very good agreement with each other. The flux loop 2 shows a little difference from the rogowski coil data and it may result from the fact that the radius of the theta coil close to the flux loop 2 is a little bigger than the other side (due to the conical structure).

Table 2.2: Performance Specifications of PDA100A diode

<table>
<thead>
<tr>
<th>dB</th>
<th>Gain (V/A)</th>
<th>BW (MHz)</th>
<th>Noise (RMS, µV)</th>
<th>NEP (W/√Hz)</th>
<th>Offset (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 dB</td>
<td>$1.51 \times 10^3$</td>
<td>2.4</td>
<td>254</td>
<td>$2.7 \times 10^{-11}$</td>
<td>5</td>
</tr>
<tr>
<td>10 dB</td>
<td>$4.75 \times 10^3$</td>
<td>1.6</td>
<td>261</td>
<td>$1.1 \times 10^{-11}$</td>
<td>6</td>
</tr>
<tr>
<td>20 dB</td>
<td>$1.5 \times 10^4$</td>
<td>0.86</td>
<td>349</td>
<td>$8.91 \times 10^{-12}$</td>
<td>6</td>
</tr>
<tr>
<td>30 dB</td>
<td>$4.75 \times 10^4$</td>
<td>0.48</td>
<td>561</td>
<td>$4.65 \times 10^{-12}$</td>
<td>8</td>
</tr>
</tbody>
</table>
Figure 2.8: A plot of the calibration factor for the rogowski coil.

Figure 2.9: A plot of current from the main bank to the theta coil measured by the rogowski coil and the flux loops. The capacitor is charged at 15 kV and the shot is taken when the chamber is in vacuum.
2.3.5 Fast Ionization Gauge

In order to do achieve the objective, a reliable way to measure the fast-changing gas pressure is indispensable. Hot filament ion gauge is considered one of the best ways to measure the time-varying pressure. However, commercially available fast ionization gauges are usually very expensive; therefore, a small size ionization gauge (355 Micro ion gauge, Brooks Granville-Phillips) is tested for fast response pressure measurement. In order for the ion gauge to be applicable for the fast-response measurements, the gauge needs to have 1) a linear response up to the pressure of interest 2) an open structure to minimize the perturbation of gas flow, and 3) fast rise time with a good signal to noise ratio [83]. As for 1), volume of the gauge should be much smaller than mean free path of the gas to ensure that number of electrons resulting from the ionization process is smaller than electrons emitted from a filament, thereby the collected ions at the collector come from the ionization process by electrons from filament. For 3), amplifier circuits are added very close to the pressure gauge to minimize Miller effect and expand the measurement range down to $10^{-6}$ or even lower [84]. However, the amplifier circuit has a inherent limitation in bandwidth so that fast-response measurement is still troublesome. For 355 Micro ion gauge, its size is smaller than other pressure gauges, ensuring linear measurement up to 50 mTorr. Moreover, since we are interested in at lowest $10^{-4}$ Torr, the complexity of amplifier circuit can be avoided.

In Fig 2.11(a) the ratio of ion and electron current follows a linear response up to 10 mTorr or higher. The sensitivity factor of the calibration is estimated 8.0, which is close to an ideal sensitivity factor of the Bayard-Alpert ionization gauge for hydrogen. The calibration curve is obtained to convert the ion and electron current ratio to pressure. Fig 2.11(b) shows the response time of the ion gauge with 10 $\mu$s 180 V
square voltage pulse applied to the collector at 3 mTorr. The rise time of the ion current is approximately 1 µs, resulting in approximately 350 kHz bandwidth.

Figure 2.11: (a) Pressure calibration with Baratron gauge [11] (b) Bandwidth test result with a square voltage pulse at the collector[11].

Figure 2.12: Pressure measurement using the fast ionization gauge in DEVeX at two different locations. The red lines are pressure at the center of the theta coil and the blue lines are 23 inch away from the center of the coil.

2.3.6 Measurement System Setup

The most of diagnostic tools are measuring signals in an inductive way or in a differential way to minimize a direct electric coupling with pulse circuits. The oscilloscopes and other data acquisition systems including computers are grounded to a faraday shielding room and their power cables are wound around ferrite cores to isolate the systems from the power ground temporarily during the shot and to still feed the device with AC power [12, 13]. This setup helps reducing the ground loop between the measurement system and capacitor
banks. Trigger signals to sequentially trigger the puff gas valve, guiding magnets, the plasma gun are transmitted through optic fibers to decouple the trigger signal generator from the device. Trigger signals for the crowbar switch and the main switch for the theta pinch are transmitted through coaxial cables; the trigger unit, though, has DC blocking capacitors that prevent the igniters from coupling with the DC signals.

2.4 Summary

- \( n_e \sim 10^{21} \text{ m}^{-3}, T_{i+e} \geq 100 \text{ eV}, v_0 \sim 5 \times 10^4 \text{ m/s} \) gives heat flux around \( \sim 1 \text{ GW/m}^2 \) and \( \sim 0.1 \text{ MJ/m}^2 \) with 100 \( \mu \text{s} \) pulse.

- The new device, TELS is projected to produce approximately 20 - 30 times plasma energy produced by the prototype machine. TELS is mainly composed of a plasma gun, a theta pinch, and guiding magnets. Each component will be driven by capacitor banks and controlled by a switch. The device is to be upgraded for better compatibility with liquid lithium.

- Several diagnostics including triple Langmuir probe, calorimeter, optical emission measurement, Rogowski coil, flux loop, and fast ionization gauge will characterize the new device.
Chapter 3

Plasma Gun Experiment

3.1 Theory: Preionization and Plasma Acceleration Using Coaxial Plasma Gun

As discussed later in chapter 4.1, plasma heating with a theta pinch can be achieved through an implosion and an adiabatic process. The snowplow model shown later in Eq. (4.2) in chapter 4.1 assumes that the magnetic field does not penetrate the plasma shell of zero thickness and the field inside the plasma shell is zero. This means that plasma heating by implosion and adiabatic compression is effective only when a sufficient amount of preionized plasma exists in the chamber at pre-implosion stage. Importance of preionized plasma cannot be emphasized too strongly, because the initial implosion is done through strong momentum transfer onto the charged particle by magnetic piston. The effects of preionized plasma on plasma diamagnetism, plasma instability suppression and energy delivery have been experimentally found [85, 86, 10, 17].

Not only that, plasma drift velocity is mainly determined by the axial particle diffusion discussed later in chapter 5.1.2. The characteristic velocity of plasma flow is roughly estimated using Fig. 5.2(b) and plotted in Fig. 3.1. From Fig. A.2 in Appendix, it is found that $D_a$ ranges from $10^3$ to $10^4$ m$^2$/s, resulting in plasma flow velocity $\leq 2 \times 10^4$ m/s. Therefore, plasma flow velocity is too low to simulate the extreme events in tokamaks.

The possible solutions are 1) to reduce the distance between the coil and the target, 2) to increase ion temperature, 3) to electrically bias the target to accelerate ions, and 4) to accelerate charged particles by other means. Among them, 1) is limited by guiding magnets that produces an external magnetic field for a trench, 2) is limited by a performance of the theta pinch, and 3) may not be an ideal solution if the trench setup does not allow for an electric biasing. A plasma gun is one of the best methods to increase the plasma flow velocity without making a modification on an existing experimental setup because plasma is accelerated by the plasma current and self-generated magnetic field, which is the same process as a railgun does. Fig. 3.2 describes how a plasma railgun accelerates plasma.
Figure 3.1: Estimate of plasma flow velocity assuming that ambipolar diffusion is a dominant process for the diffusion. Ion-ion collision frequency is assumed $10^6$ Hz.

Figure 3.2: Representation of a plasma block mode or a slug mode of operation with a rail plasma accelerator.

The railgun-type plasma gun, initially invented by Marshall [87], has been used for several applications such as magneto-inertial fusion [88, 89, 90, 91], plasma thruster [92] and plasma flow switch [93]. Among various geometries, a coaxial plasma gun is believed to be the most efficient of all the pulsed electrode plasma accelerators with efficiencies of up to 50%, possibly due to confinement of the plasma within the device and the uniform axissymmetrical accelerating Lorentz force [94]. As for its performance, a Marshall gun in 1960 achieved $1.5 \times 10^5$ m/s with more than 40% of electrical energy deposited [87], and the recent research at the Hyper V shows that plasma parameters for planar plasma gun achieved injection of 160 µg of argon at 85 km/s with $10^{21}$ m$^{-3}$ plasma density and 4 eV electron temperature [90].

Velocity of plasma flow from the coaxial plasma gun is approximated using a slug [95, 96] or snowplow model in circuit theory [15, 97], MHD theory [98, 99], MHD simulation such as MACH2 [99], and magnetic nozzle acceleration model [100].

For an ordinary coaxial plasma gun, $0^{th}$ order approximation on the velocity of the plasma ejected from
a coaxial plasma gun using Rosenbluth-Garwin theory is

\[ V_s = \left( \frac{E^2}{\mu_0 \rho} \right)^{1/4} \]  

(3.1)

where \( E \) is the electric field and \( \rho \) is the initial mass density of the gas in the gun. Assuming 10 kV/m (1 kV voltage across 2.5 inch between a cathode and an anode), the velocity is approximately 100 km/s at 10 mTorr and 50 km/s at 100 mTorr. For magnetized nozzled plasma gun, the converging-diverging nozzle created by external magnetic field accelerates the ions following Bernoulli’s equation and the maximum achievable velocity is

\[ V_{\text{max}} = \sqrt{3} V_0 \]  

(3.2)

where \( V_0 = C_{A0}(1 + \beta)^{1/2}, \beta \sim \beta_i \) is the ratio of ion temperature to magnetic field pressure, and \( C_{A0} = \sqrt{\frac{\mu_0 \rho}{\mu_0 \rho}} \) is the Alfven velocity at \( z = z_0 \), which is the position of the nozzle throat. The Alfven velocity at 0.1 T is 85 km/s at 10 mTorr and 27 km/s so that the maximum achievable velocity is \( \sim 150 \text{ km/s at 10 mTorr and 45 km/s at 100 mTorr.} \) However, the first one is very rough approximation and the second approach requires a magnetic nozzle formed by an external magnetic field. An analytical model developed by \[15\] approximates the velocity using a snowplow and a circuit model in the weak coupling limit (i.e., the gun is fully influenced by the circuit and the effect of the gun is negligible)

\[
z(t) = \Delta (1 + (aQ^2/2\Delta^2) \exp^{-2\nu t}(\nu t)^2 + 2\nu t + \frac{3}{2}) + \nu t - \frac{3}{2})^{1/2} \]  

(3.3a)

\[
\dot{z}(t) = (\nu \Delta)(\Delta/z)(aQ^2/4\Delta^2) \times (1 - \exp^{-2\nu t}[2(\nu t)^2 + 2\nu t + 1]) \]  

(3.3b)

where \( \nu = R_0/2L_0 \), \( Q \) is the initial charge in the capacitor, \( \Delta \) is the thickness of the initial sheath, \( a = (\mu_0/4\pi^2 \rho) \ln (r_0/r_i)/(r_0^2 - r_i^2) \), \( \rho \) is the mass density of the unionized gas, \( R_0 \) is the resistance of the gun circuit (in weakly coupling limit, plasma resistance is assumed zero), and \( L_0 \) is the circuit inductance. Assuming pressure = 100 mTorr, \( r_i = 0.5 \text{ inch, } r_0 = 3 \text{ inch, } C_0 = 500 \mu F, L_0 \leq 1 \mu H, V_0 = 5 \text{ kV, } R_0 = 0.1 \Omega, \nu = 5 \times 10^4. \) The plots are shown in Fig. 3.3. The graph shows that high velocity is achieved with the coaxial plasma gun acceleration. Because the velocity is a weak function of \( \Delta \) but strongly dependent on the electrical parameters such as \( \nu, Q, \) and the geometry, the data on Fig. 3.3 may not be able to be generalized. As shown later, the experimental condition may not satisfy the weak - coupling limit so that a more reasonable modeling may be required.

Plasma acceleration modeling with a slug model and snowplow model takes into account the contribution of the plasma for the plasma gun velocity calculation \[95 \ 96 \ 97\]. In slug model, plasma is assumed to
be all converted into a plasma and accelerated as a discrete mass \[95, 96, 14\]. In snowplow model a thin plasma channel is formed inside an unionized or preionized gas and a shockwave as a result of rapid heating in the channel propagates down the length of the gun and adds mass as it moves down \[14\]. In reality the operation of a plasma gun lies somewhere between the two extreme modes. Because the slug model does not involve phenomena such as shockwave, viscosity, or turbulence, the slug mode has a better energy efficiency than snowplow mode \[14\].

The two different approaches analytically calculate the plasma acceleration with an equivalent circuit model in the following way \[97\]:

\[
(L_0 + L_1 x) \frac{d^2 I}{dt^2} + \left( R_0 + R_1 x + 2 L_1 \frac{dx}{dt} \right) \frac{dI}{dt} + \left( R_1 \frac{dx}{dt} + L_1 \frac{d^2 x}{dt^2} + \frac{1}{C_0} I \right) = 0 \tag{3.4}
\]

where

\[
\frac{d^2 x}{dt^2} = \frac{1}{2m} L_1 I^2 \text{ for a slug model} \tag{3.5a}
\]

\[
= \frac{1}{2} L_1 I^2 - m_1 \left( \frac{dx}{dt} \right)^2 \text{ for a snowplow model} \tag{3.5b}
\]
with initial conditions

\[
x(t = 0) = x_0 \quad \text{(3.6a)}
\]
\[
\left. \frac{dx}{dt} \right|_{t=0} = 0 \quad \text{(3.6b)}
\]
\[
I(t = 0) = 0 \quad \text{(3.6c)}
\]
\[
\left. \frac{dI}{dt} \right|_{t=0} = \frac{V_0}{(L_0 + L_1 x_0)} \quad \text{(3.6d)}
\]

In Eq. (3.4), \(L_0\) is the circuit inductance, \(L_1\) is the inductive gradient of the electrode, \(R_0\) is the circuit resistance, \(R_1\) is the resistive gradient of the electrode, \(C_0\) is the capacitance of the capacitor bank, and \(I\) is the plasma gun current. \(x\) and \(t\) denote the distance and the time, respectively. In Eq. (3.5) and Eq. (3.6), \(m\) is the total mass of the plasma slug, \(m_0\) is the initial mass of the plasma sheath, \(m_1\) is the mass of the gas snowplowed by the sheath per unit length, and \(V_0\) is the initial charging voltage of the capacitor. Since the solutions are very dependent on the electric parameters and mass, following assumptions are made: \(r_o = 3\) inch, \(r_i = 0.5\) inch, length = 12 inch, \(C_0 = 500 \mu\text{F}\), \(L_0 = 700 \text{nH}\), \(L_1 = 350 \text{nH/m}\), \(R_0 = 0.03 \Omega\), \(R_1 \ll R_0\), \(m = \frac{p_r}{kT} \times m_{H_2} \times V \sim 0.60 \mu\text{g/mTorr}\) where \(V\) is the plasma gun volume, and \(m_0 = \frac{1}{1000} m_1\) for the slug model. It will be shown later that the those parameters are similar to experimental results.

Fig. 3.4(a) and Fig. 3.4(a) show that the distance and velocity is greater for the snowplow mode than for slug mode. While the data does not seem reasonable, the results are still reasonable since the accelerated mass for the snowplow mode is much less than that for the slug mode until a considerable mass is accumulated by the plasma sheath. That’s why there is a decrease in the velocity after a few tens of microseconds. It is shown in Fig. 3.4(a) and Fig. 3.4(a) that after a certain amount of acceleration, the velocity of the plasma in the slug mode becomes faster than that in the snowplow mode.

Fig. 3.4(c) shows the terminal velocity of the plasma after the plasma is accelerated to the distance of 0.3 meter, which is the same as the length of the plasma gun electrode used in the experiment. It shows that the velocity in the slug mode is faster than that in the snowplow mode in a wide range of pressure. Therefore, the actual velocity ranges between the two velocities and is 85 - 150 km/s at 10 mTorr and 40 - 75 km/s at 100 mTorr.
Figure 3.4: Plasma velocity at $V_0 = 5$ kV, calculated with Eq. (3.4), Eq. (3.5), and Eq. (3.6) at various gas pressures in two different modes: a slug mode and a snowplow mode. (a) Distance vs. Time (b) Velocity vs. Time (c) Velocity vs. Pressure. The weakly coupling case [15] is included.
3.2 Experimental Setup

3.2.1 Plasma Gun Electrode

As mentioned earlier, plasma heating by implosion and adiabatic compression is effective when a sufficient amount of preionized plasma exists in the chamber at a pre-implosion stage.\textsuperscript{[85, 86, 10, 17]} Not only that, plasma drift velocity by an axial diffusion is too low to simulate the extreme events in tokamaks. While several preionization methods such as inductive coupled plasma generation with a capacitor bank or an RF power supply were tried and showed an increase in plasma energy, the degree of ionization was too low to observe a significant pinch effect. Moreover, the axial diffusion in a theta pinch is too a slow process to be comparable with the drift velocity in off-normal events in tokamaks. A plasma gun, or a plasma accelerator is one of the best methods to produce preionized plasma and accelerate it at the same time.\textsuperscript{[87]} Not only that, the plasma gun is also inherently a pulsed device so that it can create a much larger density of plasma compared to other steady-state type source. Therefore, a coaxial type plasma gun is manufactured and added to the device.

There are a few limitation factors on arc plasma gun. The most serious and important one is ablation\textsuperscript{[14]}, mainly caused by surface heating and arcing. This is detrimental for two reasons:\textsuperscript{[101, 102]} 1) it creates drag force on the accelerating plasma described as ˙\textit{m}v force and 2) it may form a new plasma region called plasma re-strike which steals current from the main plasma. Therefore, the electrodes, especially the cathode on which ions bombard, need to be made of a material with high thermal conductivity and high melting temperature. Physical sputtering yields for several materials at a normal incidence using a formula in Ref.\textsuperscript{[16]} is shown in Fig. 3.5. While tungsten provides the least sputtering yield in a full range of energy up to 10 keV and it has a good compatibility with lithium, it is not used at the first phase due to difficulty in machining. In case of carbon, possible chemical sputtering reactions of hydrogen with carbon causes an additional chemical sputtering. Therefore, an oxygen-free copper has been chosen as the cathode material for its high thermal and electrical conductivities.

A coaxial plasma gun has a finite inductance, which is a function of the diameter and the length of the device. Since the inductance has a significant influence on the acceleration process, the inductance of the gun should be estimated. Unit inductance of a coaxial plasma gun is given by

\[
L_{\text{gun, unit}} = \frac{\mu_0}{2\pi} \ln \left( \frac{r_0}{r_i} \right) \quad (3.7)
\]

where \( L_{\text{gun, unit}} \) is a unit inductance of a coaxial plasma gun, \( r_0 \) is the inner diameter of an outer conductor, and \( r_i \) is the outer diameter of an inner conductor. Fig 3.6 shows total inductance of the coaxial plasma
Figure 3.5: Physical sputtering yields of several electrode materials with an impact of a hydrogen ion as a function of energy. A formula in Ref. [16] is used to estimate the physical sputtering yields.

As for an anode, a 8 inch stainless CF nipple is used. Because it was a part of a prototype device, using the 6 inch nipple minimizes modification of the device. The inner diameter of the chamber is 6 inch. This gives the distance between the electrodes 2.5 inch. According to Paschen curve, for hydrogen $pd$ minimum is approximately at 1 Torr \cdot cm, which is about 150 mTorr of pressure at the minimum breakdown voltage.

### 3.2.2 Plasma Gun Capacitor Bank and Transmission Lines

The oxygen-free copper rod is connected through a medium voltage feed-through to a capacitor bank. A 500 $\mu$F, 40 nH Maxwell capacitor is used to power the coaxial plasma gun. While more than 3 capacitors can be potentially connected in parallel (which results in the total capacitance of 1500 $\mu$F), only one capacitor is used due to limitations on the feedthrough.

The capacitor bank is assembled together and charging/discharging units including high voltage relays, a T - 508 spark gap switch from L - 3 Communications, and a self - made spark gap igniter are assembled
to operate. Actually, a regular spark gap switch is not an ideal choice for high current (≥ 100 kA) and low voltage (≤ 5 kV) for a long pulse due to surface erosion and too low operation voltage. While an ignitron is a much more reliable switch in those voltage and current ranges, it is not used this time due to a budget issue. The gap at the switch is carefully readjusted to be repetitively fired at 5 to 6 kV since the gap switch is designed to operate over 30 kV. The switch has an approximate inductance of 150 nH with the maximum current of 150 kA and the maximum charge transfer of 2 Coulombs. The igniter consists of a self-made 200 V DC power supply, a driving circuit with an internal magnetic isolation and an optical isolation, a high voltage pulse transformer TR 1855, and a 4 µF discharging capacitor. The igniter produces an output pulse with a peak voltage over 20 kV and a rise time less than 5 µs repetitively.

The inductance of the transmission line is reduced by using multiple RG-217 coaxial cables. Each of the cable has a unit inductance of 252 nH/m and the center electrode has a fusing current of approximately 10 kA in 32 milliseconds. Therefore, with 10 RG-217 cables, a total inductance of 25 nH and the maximum current handling up to 100 kA for more than 1 millisecond is expected. The cable is rated at the maximum operating voltage of 5 kV but this value is based on the maximum power capability of the lines rather than the dielectric breakdown. The dielectric strength of the insulator (a solid polyethylene) is at least 20 kV/mm and the thickness of the insulator is 3.35 mm so that the design gives a maximum voltage of 60 kV. Of course, this is a very optimistic assumption: 1) when the frequency increases, the maximum voltage and power for the cable decreases, 2) and if the insulator is interrupted by air it will cause sparks, 3) when the
load is unmatched, the voltage can be as high as twice the input voltage. However, as found later, no fault is found up to the voltage of 7 kV.

The capacitor bank is discharged through a spark-gap switch. High voltage insulation was tested up to 7 kV and no failure of insulation was observed. However, a lower voltage feed-through (rated at 12 kV) had an insulation failure at 7 kV, 500 µF capacitor bank shot. Therefore, a new voltage feed-through rated at 20 kV and 150 A was purchased and installed. The new feed-through was tested up to 6 kV and no fault was found.

3.2.3 Gas Puff System

While the plasma is heated in the theta pinch by the implosion process and the adiabatic heating, the plasma energy is significantly reduced at the transportation region due to 1) decrease in the magnetic field outside the coil which results in a large amount of energy loss in the radial direction and 2) collisions of energetic particles with the neutral gas before they reach the target. The collision will further reduces the plasma diffusion, thereby the plasma flow velocity, and enhances the diffusion across the magnetic field. However, the use of gas puff may mitigate energy loss through collisions because one can control the flow of the gas and trigger the pulse device at a time such that the gas in the plasma generation region is high while the transport region is sub-mTorr.

Considering that the charge-exchange collision ($\sigma_{\text{cx}} \sim 3 \times 10^{-19} \text{ m}^2$) is the most dominant type of collision and the distance from the theta coil to the target chamber is 15.5 inches ($\sim 0.4 \text{ m}$), the mean free path for the charge-exchange is $\lambda_{\text{cx}} \sim 0.1/p$ meter where $p$ is the gas pressure in mTorr. With the design
criterion that the mean free path is at least five times the distance, the pressure required is $p \leq 5 \times 10^{-5}$ Torr.

At the same time, the current configuration requires relatively a high pressure at the plasma gun chamber for gas breakdown ($\geq 100$ mTorr). A fast-opening gas valve is required, because the gas transit time should be smaller than the opening time ($\equiv t_{\text{opening}}$) to allow for the difference in the gas pressure. While the acoustic speed determines the fastest response of the gas in a normal environment, a possible supersonic flow further increases the gas velocity and it can reach as high as 2900 km/s. Therefore, the gas reaches the target as early as 330 $\mu$s ($\equiv t_{\text{transit}}$) after the opening. Therefore, it is advantageous to have a fast-opening valve while in reality we need a valve with a very large throughput to ultimate the benefit of the puff gas valve. (A maximum of the benefit can be obtained when $t_{\text{opening}} < t_{\text{pulse}} < t_{\text{transit}}$ where $t_{\text{pulse}}$ is on-time of the pulse at the puff gas valve.)

Therefore, a gas puff system is introduced to fuel the system. A Series 9 Pulse Valve from Parker is chosen for extreme repeatability and fast response ($\sim 160$ $\mu$s). The orifice size is 0.039 inch diameter and the max flow rate on the assumption of supersonic gas flow is approximately $10^{22}$ s$^{-1}$ at 15 psi (sim 1 atm) plenum pressure, which is $10^{19}$ with 1 ms pulse. This valve is driven by a half-bridge switching circuit and a 27 V DC power supply. The circuit is isolated from the other circuits by an optic cable and an isolated DC power supply, and the half-bridge switching provides a fast closing of the valve. The valve is located at the end of the plasma gun chamber and the gas is fed between the top side of the cathode and the anode.
3.3 Results: Gas Puff and Fast Ionization Gauge Measurement

3.3.1 Gas Puff Results

Fig 3.10 shows the pressure in the chamber after a gas puff. The chamber has a base pressure of $4 \times 10^{-6}$ Torr or lower before the puff. Two different puff valve opening times are tested: 2.9 ms and 5.9 ms. The opening time is adjusted by a variable resistor at the self-made trigger circuit. The gas puff is not conditioned before the first pulse (which means that the puff valve is energized before the first pulse). The turbo pump is closed and a baratron gauge is used during the pulse to measure the pressure. The pressure in the gas puff valve ( = plenum pressure) is assumed to be the same as the pressure in the gas cylinder regulator and the plenum pressures of up to 100 psi were tested.

As shown in Fig 3.10, the gas pressure increases linearly with the plenum pressure. The pressure is very reproducible when the plenum pressure is relatively low ($\leq 60$ psi) while the higher plenum pressure ($\geq 80$ psi) at 5.9 ms gives rise to a large deviation. It is partially due to some conditioning effect at large gas throughput. Two data points at 100 psi, 5.9 ms indicate the chamber pressure at the beginning of the test and at the end of the test. The one with a large deviation is the data at the beginning of the test. As one can see, as the test continues, the deviation tends to reduce. Therefore, for all the experiments shown after this section, the valve is conditioned with 50 - 100 shots to allow for a good reproducibility.

The pressure in the chamber does not increase linearly with the puff valve opening time. For example, with 2.9 ms opening time at 100 psi the pressure reaches approximately 100 mTorr while with 5.9 ms opening
time the pressure increases up to 300 mTorr. This suggests a possible delay time after which the valve opens.

### 3.3.2 Fast Ionization Gauge Measurement

In order to further investigate the performance of the valve, a fast ionization gauge measures the change of the pressure in the chamber at several locations. Here, only one experimental case at the plenum pressure of 100 psi and the opening time of 6 ms is tested. The filament, grid, and the collector at the fast ionization gauge are biased at 2 A, 30 V, and -180 V, respectively. The gauge is placed concentrically with the chamber and its position is moved using a quick-disconnected feedthrough.

Fig. 3.11(b) shows the ratio of ion and electron current collected at the fast ionization gauge. Two shots are taken at one location to estimate the shot-to-shot reproducibility. It is shown in Fig. 3.11(b) that the data has a good reproducibility and the signals measured near the gas puff valve (28, 33, 38, 43 inches from the valve = 6, 11, 16, 21 inches from the target) are very similar to one another at several locations. A little different behavior of the gas far from the gas puff valve (48 inch from the valve = 1 inch from the target) may be attributed to a formation of shock or an interaction of the gas puff with residual gas in the target chamber. The signals from the fast ionization gauge start to increase approximately at 3.8 ms when the gauge is located at 21 inches from the target chamber (= 28 inches from the gas puff valve). The pressure
increase is approximately 66 mTorr/ms and the opening time of 3.5 ms with 2.5 ms delay time (total pulse length of 6 ms) gives around 230 mTorr, which is similar to the chamber pressure after the gas puff.

The ratio of ion and electron current reaches around 0.4 and gets saturated there. It is because linearity of the fast ionization gauge no more holds when the pressure exceeds approximately 50 mTorr. Fig 3.11(c) shows that the response of the fast ionization gauge starts to deviate from linearity when the pressure increases over 50 mTorr or so and the response of the gauge at the pressure over 100 mTorr non-linear and irreproducible. This non-linearity is caused by too much pressure inside the grid of the fast ionization gauge which results in too many collisions between electrons and neutrals and the change of electron energy distribution. In this case, the spread of the electron energy subsequently leads to reduction in ionization and the ratio of ion and electron currents.

Figure 3.11: (a) The position of the fast ionization gauge in the chamber. The gauge is movable by quick-disconnected feedthrough. (b) A plot of the chamber pressure measured by the fast ionization gauge as a function of time after a gas puff. Five different locations are tested to measure the velocity of the gas propagation. Two shots are taken at one experimental case to estimate the shot-to-shot reproducibility. On the right y-axis is pressure in mTorr, which is reliable only up to 50 mTorr. (c) A plot of the ratio of the ion current and the electron current at the fast ionization gauge at various pressures. The ratio follows a linear trend up to 50 mTorr or so and shows a non-linear behavior over the range.

Normally the plasma gun is fired at between 5.5 ms and 6 ms, meaning that the pressure in the target
chamber is approximately 30 - 40 mTorr or so based on Fig 3.11(c) for 100 psi plenum pressure. On the other hand, the total pressure in the chamber is approximately 200 - 300 mTorr as shown in Fig 3.10. A linear approximation of this value to 35 psi plenum pressure shows that the pressure in the target chamber when the plasma gun is triggered is around ∼ 10 - 20 mTorr. These data indicate that the pressure difference between the source and the target chamber is less than an order of magnitude and it is possibly caused by too long an opening time of the valve. It will be shown later that the plasma gun requires a minimum pressure of 100 mTorr to strike plasma. Therefore, just reducing the opening time of the valve is not enough to take advantage of the valve. In order to fully utilize gas puff, throughput of the valve should increase so that the opening time of the valve can be reduced without reducing the total pressure.

3.3.3 Gas Velocity Analysis

Time - of - flight technique is used to calculate the gas velocity. Fig 3.12 plots the velocity of the gas as a function of distance in the device. The velocity is around 600 - 800 m/s, which corresponds to Mach number of 0.45 to 0.61. Based on the theory of exhaust gas velocity, the velocity of hydrogen at a nozzle is determined by

\[ v_e = \sqrt{\frac{TR}{M} \cdot \frac{2\gamma}{\gamma - 1} \left( 1 - \frac{p_e}{p} \right)^{\frac{\gamma - 1}{\gamma}}} \]  

(3.8)

where \( v_e \) is exhaust velocity at the nozzle exit, \( T \) is absolute temperature of inlet gas in kelvin, \( R \) is the universal gas law constant of hydrogen in J/(kmol·K), \( M \) is the gas molecular mass of hydrogen in kg/kmol, \( \gamma \) is isentropic expansion factor, \( p_e \) is the absolute pressure of exhaust gas at the nozzle exit and \( p \) is the absolute pressure of the inlet gas.

According to Eq. (3.8), terminal velocity of hydrogen at room temperature is approximately 2900 m/s when \( p_e \) is much smaller than \( p \) and the sound velocity of hydrogen is 1300 m/s (\( p_e/p \sim 0.46 \)). However, the velocity of the gas measured with the fast ionization gauge is even lower than the sound velocity of hydrogen. It could be possibly because 1) the gas velocity vector is not parallel to the gauge so that we measure only the parallel component of the gas and 2) a possible formation of shock formed inside the chamber. A shock disk may be formed near the nozzle of the gas puff valve since the zone of silence is perturbed by the plasma gun electrode. Actually, formation of a shock disk may be beneficial for this experiment since slower gas velocity allows for a larger difference in neutral gas density between the plasma gun and the target chamber.
3.4 Results: Plasma Gun Experiment

3.4.1 Plasma Gun Breakdown Experiment in static gas

In order to estimate breakdown voltage for the plasma gun, DC breakdown voltage is measured at a static - filled plasma gun chamber. Fig 3.13 shows DC breakdown voltages in the plasma gun at various chamber pressures. The voltage is very low, below 1 kV at the pressure of over 50 mTorr. And at these high pressures, the plasma produced by the plasma gun is localized in the plasma gun. However, as the pressure decreases, the plasma expands all over inside the chamber and becomes unstable. No plasma is produced below the pressure of 40 mTorr with a bias of up to 2 kV. Therefore, at least the pressure of over 50 mTorr is required to produce a stable plasma.

Fig 3.14 shows a picture of the device when the plasma is generated with 500 $\mu$F capacitor bank charged at 5 kV. Here the chamber is filled with 100 - 500 mTorr of hydrogen gas prior to capacitor discharge. It is shown that the plasma is well generated over the pressure range but at 100 mTorr plasma is sometimes produced with a finite delay time (more than milliseconds) after the trigger signal or the plasma is not stricken at 100 mTorr. In all cases, the plasma inside the pyrex tube is well visible as shown in Fig 3.14.

Fig 3.15 shows a picture of an experimental setup for a fast camera measurement and time series images of plasmas propagation from the plasma gun. The chamber is filled with 200 mTorr of hydrogen gas prior to a shot. Fig 3.15(b) shows that the plasma does not stay in one place but it actually moves with time by
Figure 3.13: Breakdown voltage measurement at various pressures. The black dots indicate glow plasma localized in the plasma gun and the red triangles refer to plasma diffused all over inside the chamber.

\[ J \times B \] force. Since the opening of the window is roughly 9 cm and the end of the first plasma moves out in 4 - 5 frames, the velocity is approximately 5 km/s, which is much slower than the theoretical prediction in chapter 3.1. It is possibly due to an interaction of the plasma with the neutral gas (for example, 200 mTorr of the hydrogen gas results in the charge - exchange mean free path of 0.5 mm).

### 3.4.2 Plasma Gun Circuit Analysis in Gas Puff

The current flowing into the plasma gun shows an underdamped behavior; therefore, by fitting the experimental data with a formula for a underdamped current, circuit elements may be extracted. Fig 3.16 shows the circuit resistance, inductance, and the peak current of the plasma gun when the gun is fired at 5 kV. Capacitance is assumed to be 500 \( \mu \)F, which is the same as the capacitance of the cap. It is found that the circuit elements are relatively the same for all plenum pressures, suggesting that the plasma is not a significant contributor to the behavior of the gun circuit. The circuit resistance and inductance are found to be 0.03 \( \Omega \) and 0.8 \( \mu \)H, respectively. The peak current is 65 - 70 kA regardless of the plenum pressure and the delay times. This also suggests that the plasma is relatively weakly coupled to the circuit.
3.4.3 Plasma Velocity Measurement

Fig 3.17 shows the velocity of the plasma when the plasma gun is fired along with the gas puff valve. Here, the theoretical predictions from (3.3b), Eq. (3.4), Eq. (3.5) are added to Fig 3.17 for a comparison with the experimental data. The data are measured with the photodiodes and using the time of flight technique. A various delay times between the gas puff and the plasma gun are tested at 35 psi, 60 psi, and 100 psi of plenum pressures.

Fig 3.17 shows that the velocity is approximately 15 - 30 km/s for the most cases regardless of delay times and the plenum pressure. Moreover, those velocities are faster than the velocities in a static - filled condition. The experimentally measured velocities are, however, located somewhere between the velocities predicted by (3.3b) and by Eq. (3.4) and Eq. (3.5b). This suggests that the plasma generated in the plasma gun chamber is in the snowplow mode as opposed to in the slug mode, and the effect of the plasma in the electric circuit is weakly coupled to the circuit. According to Ref. [15], the weak - coupling limit is given by

\[ L_0 \gg 0.2\alpha Z_g \ln(r_o/r_i) \quad (3.9a) \]
\[ R_0 \gg 7.979 \times 10^{-5} \alpha^{1/2}(V_0^2C)^{1/2} \ln(r_o/r_i)/(\rho Z_g r_i^2[(r_o/r_i)^2 - 1])^{1/2} \quad (3.9b) \]

where \( Z_g \) is the length of the coaxial gun gas compartment, \( L_0 \) is in \( \mu \)H and \( R_0 \) is in m\( \Omega \). Using \( \alpha = 10 \), \( L_0 \geq 1 \) \( \mu \)H and \( R_0 \geq 0.31 \) \( \Omega \). Therefore, comparing these critical values with the circuit values found in the previous section, one can say that the coupling is close to the weakly - coupling limit and that leads to the measured velocity located between two snowplow models.
Figure 3.15: (a) A picture showing the location of the fast-framing camera with respect to the chamber (b) Time series images of plasma propagation from the plasma gun. Each picture has an interval of approximately 22.5 $\mu$s.

Fig 3.18 shows the velocities of the plasma gun at two different plasma gun capacitor voltages. When the voltage increases to 6 kV, the velocity also increases from $24 \pm 7$ km/s to $40 \pm 5$ km/s. The circuit resistance and inductance at 6 kV discharge are found to be $R_0 \sim 0.025\Omega$ and $L_0 \sim 0.7\mu$H. These values are small compared to the circuit values for the weakly coupling limit where $L_0 \geq 1\mu$H and $R_0 \geq 0.38\Omega$. The increase of the plasma velocity with the plasma gun capacitor voltage is consistent with the theoretical predictions and the velocity is located between the snowplow model and the weak-coupling limit.

### 3.4.4 Triple Langmuir Probe Measurement

Fig 3.19 shows a plot of the temporal change of the plasma density and electron temperature produced by the plasma gun at 5 kV. Many different experimental setups for the triple Langmuir probe have been tested to minimize non-saturation of ion current and to avoid an arc between the Langmuir probe tips. Here, a bias voltage of 28 V and P5200 differential probes, 4100 Pearson coil are used to bias the probe and to measure voltage and current from the probe. The density and temperature are measured at the center of the theta coil using a triple Langmuir probe. Typical density measurements are around $10^{21}$ m$^{-3}$ and electron temperature measurements of 10 - 30 eV during 150 $\mu$s pulse.
Figure 3.16: Plots of circuit elements and the peak current from the plasma gun at various delay times: (a) resistance (b) inductance (c) peak current
Figure 3.17: A plot of plasma velocity measured with the photodiodes and using the time of flight technique. Theoretical predictions from Eq. (3.5), Eq. (3.3b), and Eq. (3.4) are added for comparison.

Figure 3.18: A plot of plasma velocity at two different plasma gun capacitor voltages (5 kV and 6 kV) measured with the photodiodes and using the time of flight technique. Theoretical predictions from Eq. (3.5), Eq. (3.3b), and Eq. (3.4) are added for comparison.
3.4.5 Plasma Energy Measurement

Fig 3.20 shows plasma energy measured with the calorimeter at various experimental conditions including magnetic field and delay times. Note that here the delay time does not mean the real delay times since the gun has a large jitter and only relative values matter. Fig 3.20(a) shows that the plasma energy increases linearly with the plasma gun capacitor energy, with an exception of 5 kJ (= 4.5 kV). This increase at the low voltage is not fully understood. However, increase in the plasma energy generally leads to the capacitor energy up to 9 kJ (= 6 kV).

The magnetic field from the grey magnet actually decreases the plasma energy. It is possibly because the magnetic field acts as a magnetic mirror which impedes the plasma flow. The effect of the magnetic field is consistent in all cases and the magnetic field decreases the incoming plasma energy by 20 to 30%.

Fig 3.20(b) shows a plot of the energy measured with the calorimeter at various plenum pressures and various delay times between the gas puff and the plasma gun. Note the delay time does not represent the real delay times since the plasma gun has a large jitter and therefore there is a large error bar on the x-axis. A weak correlation of the plasma energy and the delay times are observed as shown in Fig 3.20(b) and the plasma energy slightly decreases with the delay times. However, since the plasma discharge at shorter delay times (< 4.5 ms) is frequently unsuccessful, the most of the experiments presented in the following sections are conducted with 5 ms delay time.
3.4.6 Validation of the Measurement

Triple Langmuir probe is not an very accurate diagnostic and a possible deviation from ion saturation causes an erroneous measurement, it is important to validate the triple Langmuir probe data with other backup diagnostics. Since the experimental conditions allows for very limited diagnostics, the triple Langmuir probe data is indirectly cross - checked with the calorimeter data.

Fig 3.21 plots plasma energy data measured by the calorimeter as well as the predicted plasma energy using plasma parameters measured by the triple Langmuir probe and the optical methods. Eq. (2.4) is used for the calculation of the predicted plasma energy. Plasma density and the electron temperature are multiplied and integrated with time to calculate the predicted plasma energy. Here, ion temperature is assumed to be very small compared to electron temperature and therefore neglected. Note that the triple Langmuir probe measurement was carried out at the center of the theta coil while the calorimeter was located at the target chamber. Later experiments found that the plasma energy at the end of the theta coil is increased from the energy at the target chamber by approximately 30 %. Therefore, for the purpose of the comparison and validation it is acceptable to use those data. While the predicted plasma energy has a large error bar due to a large uncertainty of the triple Langmuir probe data, Fig 3.21 shows that the plasma energy with the calorimeter is in agreement with the predicted plasma energy.
Figure 3.21: A comparison of the plasma energy measured by the calorimeter and the energy predicted by plasma parameters and Eq. 2.4. Note that some of the measurements are carried out at different locations.

3.5 Summary

- Theoretically, a preionization method using a coaxial plasma gun produces a high density plasma with axial momentum and velocity up to a few $10^4$ m/s.

- A plasma gun is manufactured and installed in the previous DEVeX chamber. The plasma gun is equipped with 500 $\mu$F capacitor, RG - 217 coaxial cables, a spark gap switch and a driver circuit, and a gas puff valve.

- The pressure in the chamber reaches at 100 - 300 mTorr with a 6 ms opening of the gas puff valve at 35 - 100 psi of plenum pressure. The velocity of the gas at 100 psi measured with a fast ionization gauge is estimated around 600 - 800 m/s, which is much slower than the sound speed of hydrogen. This result implies a possible formation of a shock wave.

- Triple Langmuir probe diagnostic shows that only the plasma gun achieves $n_e \sim 10^{21}$ m$^{-3}$, $T_e \sim 10$ - 20 eV for 150 $\mu$s. The velocity of the plasma ranges from $2.5 \times 10^4$ to $4 \times 10^4$ m/s. The increase of the plasma velocity with the plasma gun capacitor voltage is consistent with the theoretical predictions and the velocity is located between the snowplow model and the weak - coupling limit.

- Plasma energies measured with the calorimeter ranges from 0.02 - 0.065 MJ/m$^2$ and increases with the voltage at the capacitor bank. The cross - check between the plasma energy measured with the
calorimeter and the triple probe / optics shows that the plasma energies are in agreement with each other.
Chapter 4

Plasma Gun and Theta Pinch Experiment

4.1 Theory: Plasma Heating in Theta Pinch

In order to achieve the goal initially mentioned, the plasma needs to be heated up to a few hundred eV. The theta pinch device employs mainly two plasma heating techniques: 1) non-adiabatic implosion heating on a microsecond time-scale, and 2) adiabatic compression heating on a much slower time-scale.

Implosion heating is achieved by collisional and collisionless shock heating. Collisional shock heating is mathematically described using \[ T = \left( 1 + \frac{5M^2}{16} \left( 1 - \frac{1}{M^2} \right) \left( 1 + \frac{3}{5M^2} \right) \right)^{1/2} \] (4.1)

where \( M \) is the Mach number, \( T_0 \) the initial temperature and \( T \) the final temperature. However, collisionless shocks cannot be treated by means of a simple fluid model [61]. Shock heating, which is strongly related with implosion velocity, is estimated using the snowplow model [61] and the analytical approach [104].

The snowplow model has been widely used to estimate the shock heating in a theta pinch with finite rise time and with the shock-heating field [61, 105, 106]. The equation of motion for a fully - ionized initial plasma in a cylinder of radius \( r \) is

\[
\frac{d}{dt} \left( m \frac{dx}{dt} \right) = - \left( \frac{B^2}{2\mu_0} - p \right) \frac{2\pi r}{2} \] (4.2)

where \( m \) is the mass of the plasma shell per unit length, \( p \) is the plasma pressure, \( r \) is the size of the plasma, \( a \) is the radius of the tube, and \( \rho_0 \) is the mass density of neutral gas. With some rearrangements and the assumption of an adiabatic change of pressure in three dimensions due to a nanosecond ion - ion collision time at low ion temperatures, the Eq. (4.2) can be rewritten as:

\[
\frac{d^2x}{dt^2} = \left( \frac{2x}{1-x^2} \right) \left( \frac{dx}{dt} \right)^2 + \left( \frac{2(\rho_0 - 2H(x))}{\rho_0 a^2} \right) \left( \frac{x^{-7/3}}{1-x^2} \right) - \left( \frac{B^2}{\mu_0 \rho_0 a^2} \right) \left( \frac{x}{1-x^2} \right) \] (4.3)
where \( x(t) = \frac{r(t)}{a} \). The Heaviside function is included to describe the effect of the tube wall, so that the plasma radius may remain in the tube and we have non-singular solutions. The solutions of Eq. (4.3) are shown in Fig. 4.1 on the assumption of a sinusoidally increasing current and magnetic field in 2 \( \mu \)s or 4.5 \( \mu \)s. Fig. 4.1 shows the temporal behaviors of implosion.

![Graphs showing the solution of Eq. (4.3) for different rise times and pressures.](image)

Figure 4.1: Solution of Eq. (4.3) for 2 \( \mu \)s rise time at (a) 10 mTorr (b) 100 mTorr and for 4.5 \( \mu \)s rise time at (c) 10 mTorr (d) 100 mTorr

The implosion time is also estimated using the relation [104]:

\[
v_s = \left( \frac{E_0^2}{4\mu_0 m_e n_0} \right)^{1/4}
\]

(4.4)

Fig. 4.2 shows that both approaches agree very well with each other and the implosion time of a shock wave is \( \leq 1 \mu \)s for 10 mTorr and \( \sim 1 \mu \)s at 100 mTorr for 2 \( \mu \)s rise time and \( \sim 1 \mu \)s at 10 mTorr and 1 - 2 \( \mu \)s at 100 mTorr for 4.5 \( \mu \)s rise time.
Figure 4.2: Implosion times calculated using Eq. (4.4) are plotted in solid lines and those estimated with Eq. (4.3) and Fig. 4.1 are plotted in dots. (a) 2 µs rise time (a) 4.5 µs rise time

With the implosion velocity, the implosion heating is estimated in the 0th order using \[ kT \sim \frac{1}{2} m v_s^2 = \frac{m \dot{B} a}{4(\mu_0 \rho_0)^{1/2}} \] (4.5)

or \[ kT = \frac{3.5 m_i^{1/2} \left( \frac{B_{sh}}{B_s} \right)^2 (x_{sh})^2 E \theta \times 10^{-10}}{(4\mu_0 P_0)^{1/2}} \] (4.6)

where \( v_s \) is implosion velocity, \( P_0 \) is gas pressure in mTorr, \( B_s \) is the average magnetic field during implosion, \( B_{sh} \) is the magnetic field when the sheath is pushed back to equilibrium, \( x_{sh} \) is the ratio of the size of the plasma to the tube at \( B = B_{sh} \). Since the energy is dependent on mass, theta pinch heats ions preferentially. In Fig. 4.3(a) and Fig. 4.3(b), both models show that higher ion temperatures will be obtained at lower pressures and higher electric fields (or higher changes in magnetic field). From the calculations, it is found that ion temperature may increase up to \( \sim 50 \text{ eV} \) at 100 mTorr with 2 µs rise time and \( \sim 35 \text{ eV} \) at 100 mTorr with 4.5 µs rise time at 200 kA. After the implosion process, the continually increasing magnetic field will further compress the plasma and heat it adiabatically. \( \delta \), the degree of freedom, varies from 1 to 3 depending on the dimension of compression, with its timescale compared to ion-ion collision time and so on. The slow adiabatic compression may increase further ion temperature by a factor of 3 - 5 up to \( \geq 100 \text{ eV} \) at a 2 µs rise time and \( \sim 100 \text{ eV} \) at a 4.5 µs rise time. Since the ion-electron collision time is much slower than ion-ion collision time discussed in Appendix 1, ions get thermalized and remains hot. The ion temperature, however, will be reduced by an adiabatic expansion process without a further compression.
along the transport region.

![Graphs showing ion heating estimates](image)

**Figure 4.3:** Estimates of ion heating in theta pinch by implosion heating at (a) 2 µs rise time (b) 4.5 µs rise time. Solid lines are the implosion heating given by Eq. (4.5) and the dots are ion temperatures by predicted by Eq. (4.6) (c) Further heating by adiabatic compression based on the degree of freedom

### 4.2 Experimental Setup

#### 4.2.1 Theta Coil

Conventional resonance - type wave heating is not an effective way to heat the plasma from the gun since the plasma lasts for a very short time (≤ 150µs) and the temporally changing plasma parameters result in difficulties in coupling and matching. Therefore, the theta pinch is a good alternative to heat the plasma given the current experimental setup. For example, 10 kJ of capacitor energy discharged in 100 µs with an energy transfer efficiency of 10 % results in 10 MW of electric power. Since a couple of research reports claim
that the energy efficiency is 60 - 85 % \[107, 108\], a heating power of greater than 50 MW may be expected.

Fig 4.4(a) shows the target chamber with the theta coil and the guiding magnets. A single-turn, four-segmented theta coil is used to generate and compress the plasma, which is conically tapered to $\sim 1 ^\circ$ to expel the plasma preferentially into the target region, although in reality the plasma goes both directions. The aluminum theta coil is square-shaped, and has a circular hole in the middle to insert a pyrex tube. The tube is planned to be replaced with other types of materials. Mechanical and electrical properties of several materials for the tube are summarized in Table 4.1. The coil has an inner diameter of 0.1 m, an outer length of 0.254 m, and a length of 0.36 m.

The coil can be equipped with additional adapters to change the number of turns in the coil. The main reason for the extension is to allow for the operation of a crowbar. Using the formula in \[109\], the inductance of the theta coil is estimated to be approximately 40 nH for a one-turn, 160 nH for a two-turn, and approximately 500 nH for a four-turn coil.

### 4.2.2 Capacitor Bank and Transmission Lines

In order to produce a very high current through the theta coil, 36 capacitors in parallel with a total capacitance of 72 $\mu$F are connected to the theta coil. It was originally only 18 capacitors (36 $\mu$F), but upgraded to 36 capacitors for two reasons: 1) increase the energy in the capacitors to achieve a higher current at the same voltage while avoiding the problem of high voltage insulation and 2) allow for the crowbar operation. Fig 4.4(b) shows the high voltage side of the 72 $\mu$F main capacitor bank.

While the crowbar is well-operated when the coil inductance is high (i.e., the coil has many turns), too much voltage is applied to the theta pinch, since the voltage is divided mainly by the ratio of inductance. This high voltage loading at the coil causes insulation failure and unexpected arcing. Therefore, the maximum operation voltage for the four-turn coil was 18 kV, while the one-turn coil can operate up to 30 kV.

### Table 4.1: A summary of electrical and mechanical properties of dielectric materials for the tube

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric constant (kV/mm)</th>
<th>Dielectric strength (kV/mm)</th>
<th>Melting point ($^\circ$C)</th>
<th>Young’s modulus (GPa)</th>
<th>Tensile strength (MPa)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plexiglass</td>
<td>2.6 - 3.5</td>
<td>17 - 39</td>
<td>160</td>
<td>1.8 - 3.1</td>
<td>~ 80</td>
<td>~ 110</td>
</tr>
<tr>
<td>Quartz</td>
<td>5</td>
<td>6 - 7.9</td>
<td>1670</td>
<td>71.7</td>
<td>48.3</td>
<td>1100</td>
</tr>
<tr>
<td>Pyrex</td>
<td>3.75</td>
<td>13</td>
<td>800 (softening)</td>
<td>64</td>
<td>28</td>
<td>N/A</td>
</tr>
<tr>
<td>Lexan</td>
<td>2.9</td>
<td>15 - 67</td>
<td>155</td>
<td>2.0 - 2.4</td>
<td>55 - 75</td>
<td>80</td>
</tr>
<tr>
<td>Alumina</td>
<td>9.8 (@ 1 MHz)</td>
<td>16.9</td>
<td>2072</td>
<td>370</td>
<td>170</td>
<td>2600</td>
</tr>
<tr>
<td>YSZ</td>
<td>16 - 18 (@ 1 GHz)</td>
<td>30 - 40</td>
<td>~ 2700</td>
<td>200</td>
<td>200 - 250</td>
<td>2000 - 3000</td>
</tr>
</tbody>
</table>
Moreover, the slower current rise time causes a lower induced electric field and a higher magnetic field diffusion into the plasma.

Therefore, operation of the crowbar switch with a fewer-turn coil is necessary. Two tasks are necessary: 1) lower the inductance of the crowbar switch \[110, 111, 112, 113\] and 2) increase the capacitance of the bank. The critical or overdamping condition for a simple RLC circuit is:

\[
\xi = \frac{R}{2 \sqrt{C/L}} \geq 1
\]  

For the initial discharge, the damping condition should be an under-damping condition to draw electrical current in a fast timescale, while the crowbar triggering decreases the total inductance to the parallel summation of the coil and the crowbar inductances. This change of inductance should satisfy either the critical or over-damping condition for the crowbar operation.

The capacitor bank discharges its energy through 15 LDF5 - 50 A Heliax cables. The inductance and capacitance of each cable is approximately 370 nH and 130 pF, respectively. Therefore, the total inductance and capacitance of the transmission cables are approximately 25 nH and 2 nF. A main railgap switch is used to discharge the main capacitor bank and is controlled by a high-voltage trigger unit that handles more than 300 kA peak current. The crowbar switch has the same design as the main railgap switch and is also triggered by a high-voltage trigger unit. While the railgap switch has a very low inductance, the inductance depends on the design of the switch \[110\] as well as the voltage rise time (\(~ 5 \text{ kV/ns or higher for 20 nH}\)) from the trigger unit \[114\]. Since the trigger units used here in the lab utilize relatively slow
pulse transformers (a few tens of kV /µs \leq 100 V/ns), the railgap normally has only one channel. Not only that, the stand-off voltage for this switch is determined by the gap between the electrodes since it is not pressurized. Therefore, the limitation on the switch results in a relatively high inductance (\sim 100 nH).

4.3 **Plasma Gun and Theta Pinch Combined Experiment: 1 - Turn Coil**

4.3.1 **Initial Test**

Fig 4.5 shows temporal evolutions of the plasma gun current and the theta pinch current at 100 µs and 200 µs delay times. Note that the plasma gun has a large jitter and the actual delays are approximately 20 µs for the 100 µs case and 90 µs for the 200 µs case. Here the plasma gun is charged at 5 kV and the main capacitor bank is charged to 15 kV. 60 kA of the electric current is obtained from the plasma gun and 120 - 150 kA of the electric current is obtained from the theta coil.

![Figure 4.5: A plot of the current from the gun and the current from the theta pinch for two different delay times: (a) 100 µs and (b) 200 µs. Due to the a large jitter at the plasma gun, the set delay time is not the same as the actual delay.](image)

Using a button-type calorimeter, the plasma accelerated using the plasma gun was found to have a peak
energy flux of 0.04 MJ/m² at 100 psi and 6 kV. At 35 psi and 5 kV, the plasma gun delivers a plasma energy of 0.028 MJ/m² at approximately 30 inches from the end of the plasma gun. Testing the theta pinch at two different timings, a maximum of an energy enhancement of a factor of 1.7 compared with the plasma gun is obtained at the same preionization capacitor voltage.

![Figure 4.6: A plot of the energy on the calorimeter for various operating conditions. The black dots indicate the energy only from the plasma gun at 100 psi (solid dots) and at 35 psi (empty dots). The diamond dots refer to the energy when the gun is operated in conjunction with the theta pinch at 15 kV at different timings: 100 µs (solid dot) and 200 µs (empty dot). The star dots indicate the energy onto a molybdenum foil when only the theta pinch is fired at 20 kV in a static - filled chamber. The pink empty dot refers to the experimental case where no preionization is used [8] and the blue solid dots indicates the data when a 1 µF, 10 kV capacitor is used to produce a low density preionized plasma [17].](image)

4.3.2 Delay Time Test

In order to investigate the effect of the delay time, it is important to trigger the theta pinch with a given timing from the plasma gun. However, the fact that the plasma gun has relatively a large jitter (≈ 100 µs) invokes a necessity of having a delay generator that triggers the theta pinch with respect to the plasma gun. Therefore, we manufactured a trigger generator that produces a trigger signal when it receives a current signal from the plasma gun. This circuit diagram for the trigger generator is depicted in Fig 4.7.

Fig 4.8 shows that the plasma energies at various delay times between the plasma gun and the theta pinch. The delay circuit in Fig 4.7 is used to set delays between the plasma gun and the theta pinch. While the trend is not clear, a larger delay between the plasma gun and the theta pinch normally leads to a higher plasma energy. A maximum plasma energy of 0.062 MJ/m² is obtained when the plasma gun is fired at - 6
Figure 4.7: A delay generator to set delay times between the plasma gun and the theta pinch. It uses an IR4427 MOSFET driver as well as a fast recovery diode to convert the signal from the rogowski coil to 10 V square pulse. The actual circuit also includes a DC power supply and a voltage regulator to limit the output voltage within the range of the input voltage signal of the Maxwell delay unit. The signal from the IR4427 triggers the Maxwell delay unit.

This energy enhancement is a large improvement from the previous theta pinch device [8, 17], showing an increase in the energy by a factor of 18 compared to the energy obtained using the same theta pinch, 1 µF capacitor bank (10 kV), and 36 µF capacitor bank (20 kV) [17]. The energy enhancement from the initial theta pinch device is even greater; the initial theta pinch device with just a 36 µF capacitor bank at 20 kV produces approximately 1.5 kJ/m² (= 0.0015 MJ/m²). Therefore, the plasma gun and the theta pinch improves the plasma energy by 41 times compared to those from the initial theta pinch device. Considering that the total energy in the capacitor banks in the new device is 2.4 times as much as those in Ref. [8, 17], the new device gives 17 times greater energy efficiency than Ref. [8].

### 4.4 Plasma Gun and Theta Pinch Combined Experiment: 2 - Turn Coil

#### 4.4.1 Change of the Number of Turns for Crowbar Test

Here, the theta coil is reconfigured to a two-turn coil to allow for a monotonically decreasing current at the theta coil. Fig 4.9(a) shows plots of the electric currents from the theta coil when the crowbar is fired at a 15 kV charge on the main capacitor bank. This graph shows a negative current of 100 - 150 kA. A further investigation of the operation of the crowbar, and further adjustments on the delay times lead to a better behavior for the current, as shown in Fig 4.9(b). However, even in this case, the current still crosses zero.
Figure 4.8: Plasma energies measured by the calorimeter at various delay times between the plasma gun and the theta pinch. Three different plasma gun voltages are tested: -5 kV (black squares), -6 kV (red circles), and +5 kV (blue triangles). The voltage of the capacitor bank for the theta pinch is fixed at 15 kV. PIP stands for plasma gun.

and the crowbar is incomplete.

Therefore, the coil was reconfigured to a two-turn coil. By increasing the inductance of the coil, a few changes are found: 1) the current at the theta coil without the crowbar is much more sinusoidal, 2) the total current of the two-turn coil is similar to that of the one-turn coil, 3) the current rise time gets a little slower with the two-turn coil, from 3.5 \( \mu s \) with the one-turn coil to 4.5 - 5.5 \( \mu s \). The rising times for both cases are much slower than the 36 \( \mu F \) and one-turn coil case, which results in approximately 2 \( \mu s \). The first and the second changes imply that there is a parasitic component, possibly at the main switch, which becomes important when the current from the capacitor increases. The second change is interesting since the higher inductance normally results in a lower total current. The third one indicates that the pinching effect may be reduced with the two-turn coil, as already discussed in chapter 4.1.

Fig 4.10 shows a crowbar test with the reconfigured two-turn theta coil. Great care has been taken in the adjustment of the crowbar gap distance to allow for a breakdown at the theta pinch voltage of as low as 15 kV. The data shows that the delay times of 4 \( \mu s \) or below allows for the operation of the crowbar. When the delay time is 5 \( \mu s \), the crowbar is not triggered, possibly because the voltage at the crowbar is not high enough to lead to a breakdown. When the crowbar switch is fired, the electric current in the theta pinch remains positive over 100 \( \mu s \) with the two-turn coil.
Figure 4.9: (a) A crowbar test at 15 kV of the main capacitor bank. It shows a negative current swing of 100 - 150 kA. This incomplete crowbarring is mostly due to a large inductance at the crowbar switch. (b) A further investigation on the operation of the crowbar leads to an improvement. However, still the current crosses zero.

Figure 4.10: A crowbar test with the reconfigured 2 - turn theta coil. The data show that the electric current remains positive over 100 µs with the two - turn coil.
4.4.2 High Voltage Test for the 2 - Turn Coil

Fig 4.11 shows a plot of peak currents and magnetic fields at various main capacitor voltages. The shots are taken in a vacuum chamber (no pre-fill) to eliminate coupling of the current with plasma. The current at the y-axis is measured with both a flux loop and a rogowski coil in chapter 2.3.4, respectively. The measurements of the current with the two diagnostics are in good agreement with each other. The current going through the two-turn theta coil increases linearly with the capacitor voltage and reaches 300 kA (= 150 kA from the capacitor bank) at 20 kV of the theta pinch voltage. The peak magnetic field in the coil is approximately 1.25 T at 20 kV.

![Graph of peak currents and peak magnetic fields](image)

Figure 4.11: A graph of peak currents and the peak magnetic fields produced at the 2-turn theta coil at various main capacitor voltages. Note that the tests are conducted in a vacuum chamber with no gas. The flux loop and the rogowski coil in chapter 2.3.4 are used to measure the current and the magnetic field.

4.4.3 Circuit Simulation

The plasma is heated in the theta pinch by implosion and adiabatic heating; without crowbarring the current from the theta pinch oscillates due to L-C oscillation and a sudden loss of the magnetic field when \( B = 0 \) may result in a loss of plasma energy to the wall before the second cycle begins. The operation of the crowbar is dependent on the finite inductance of the crowbar switch, and too large of an inductance at the switch may give rise to an incomplete crowbarring. In order to understand the behavior of the theta pinch, a circuit simulation is conducted using PSPICE [58].

Fig 4.12 shows a circuit diagram of TELS. While an actual simulation requires a proper modeling of
the inductive coupling between the theta coil and the plasma (the plasma parameters are functions of time because the plasma density and temperature change significantly with the external magnetic field), it is neglected in the current model for simplicity and only vacuum shots are compared with the simulation. The inductance and capacitance of the transmission lines are obtained from the datasheet of the coaxial cables and the resistance of the theta coil is calculated using \[ R_{hf} = \frac{L}{A} \sqrt{\frac{\mu \omega^2}{2 \sigma}} \quad (4.8) \]

where \( L \) is the length of the coil, \( A \) is the circumference of the conducting area, \( \omega \) is the angular oscillation frequency, and \( \sigma \) is the electrical conductivity of aluminum. Eq. (4.8) gives a resistance of 0.1 m\( \Omega \) for the two-turn coil. The inductance of the theta coil is calculated from and also cross-checked with the data obtained from a Maxwell 2D simulation. The inductance of a railgap switch is hard to theoretically determine; the inductance is roughly estimated using an assumption that the current channel formed at the switch is the same as a straight wire. A straight wire with 1 cm diameter and 10 cm length gives 60 nH of inductance and is similar to the experimentally determined value. Here in the simulation the inductance and the resistance of the switch are approximately 100 nH and 7 m\( \Omega \), respectively.

Figure 4.12: (a) A circuit diagram of TELS. An inductive coupling of the theta coil with the plasma is neglected in the configuration. This assumption is valid for vacuum shots. (b) The circuit schematic tested in the PSPICE. It is assumed that the railgap switch has an inductance of 100 nH and 7 m\( \Omega \) and the theta coil has an inductance of 160 nH.

Fig 4.13(a) plots experimental and PSPICE simulation results of the current in the theta coil without crowbar. The data are in agreement with each other, and the 100 nH at the main switch and the crowbar switch seems a reasonable assumption. Fig 4.13(b) shows an experimental and the PSPICE simulation results of the current in the theta coil with the crowbar in operation. Crowbar is triggered at 4 \( \mu \)s after the main bank triggering. The temporal behaviors of the currents are in good agreement with each other.
Figure 4.13: (a) A comparison of an experimental result (black) and the PSPICE simulation result (red) for two-turn coil with the main capacitor bank charged at 15 kV. (b) A comparison of an experimental result (black) and the PSPICE simulation result (red) for two-turn coil with the main capacitor bank charged at 15 kV and the crowbar fired at 4 µs after the main switch.

4.4.4 Theta Pinch Delay Time Test

Fig 4.14 shows optical emissions from the plasma measured by two photodiodes. As shown in Fig 4.14(a), photodiode #2 is located at the coil and photodiode #1 is located after the coil. The distance between the photodiodes is 85 mm. The plasma gun capacitor bank is charged at -6 kV for this experiment. Fig 4.14(d) shows that the optical signal reaches its first peak approximately 30 µs after ignition and starts to reduce approximately at 60 µs.

Fig 4.15 shows the plasma energy dependence on the delay time between the plasma gun and the theta pinch. Here the theta pinch is charged to 15 kV. While the effect of the theta pinch is unclear at 15 kV, it is found that too early a triggering of the theta pinch forms a strong magnetic pressure in the theta coil region which prevents the plasma from moving into the coil. It is also found that a larger delay typically results in a greater plasma energy until the delay time becomes 70 - 100 µs. This result also implies that when the theta coil is fired too early the magnetic field blocks additional plasma from being transported to the theta coil. Moreover, since the initial plasma reaches the farther end of the theta coil in 30 µs (at 6 kV) after the plasma gun is fired, the reduction or the little change of the plasma energy at 20 - 30 µs of delay time suggests that the pinching takes place too early.

Fig 4.16 shows the plasma energy dependence on the delay time between the plasma gun and the theta pinch when the theta pinch voltage increases to 20 kV. Here, the change of the plasma energy with the theta coil voltage is more visible. A similar trend is observed, namely, a larger delay time results in a larger plasma energy, and the energy has its peak at 50 - 60 µs. The results in Fig 4.15 and 4.16 are contrary
Figure 4.14: (a) The positions of photodiode #1 and #2 (b) Fast camera images of plasma at the target chamber. The voltage at the plasma gun is 6 kV in this case. Note that theta pinch is not used here. (c) The current to the plasma gun at 6 kV (d) Optical emissions measured by photodiode #1 and #2 for (c). Note no filters are used. The numbers on the graph are the delay times between the plasma gun and the theta pinch.
Figure 4.15: A graph of the plasma energy as a function of the delay time at 15 kV of the theta pinch voltage. The voltage at the plasma gun changes from 5 kV to 6 kV.

to the optic emission measurement in Fig 4.14, suggesting 1) when the theta coil is pinched too early the magnetic field from the theta coil prevents additional plasma from moving into the plasma gun and thereby reducing the overall plasma energy to the calorimeter, or 2) there is a possible issue of the plasma transport after the plasma is ejected.

4.4.5 Plasma Energy Measurement in the Plasma Gun and Theta Pinch

Fig 4.17 shows plasma energies at various plasma gun voltages and theta coil voltages. Here, the delay times are set at 50 µs or longer due to the general trend of plasma energy increase with delay time. It is found that a maximum plasma energy of \( \sim 0.08 \text{ MJ/m}^2 \) has been achieved when the plasma gun voltage is at 6 kV (= 9 kJ) and the main capacitor bank for the theta pinch is charged at 20 kV (= 14.4 kJ, \( \sim 1.2 \text{ T peak field, } \sim 300 \text{ kA current} \)). This measurement is directly measured from the calorimeter without a thermal response model [8] or other compensation methods [115, 117, 80] which normally multiply the measured plasma energies by a factor of 3 - 10.

Total pulse length is approximately 200 µs; therefore, a maximum heat flux of 0.4 GW/m\(^2\) has been achieved in this case. This energy increase is approximately 54 times as great as that achieved in [8] which uses only the theta pinch with a 36 µF capacitor bank at 20 kV. This plasma energy is also 23 times greater than in [17] which uses the same 36 µF capacitor bank at 20 kV for pinching and 1 µF capacitor at 9 kV for preionization.
Figure 4.16: Plasma energies as a function of the delay time at 20 kV of the theta pinch voltage. The voltage at the plasma gun is kept at 6 kV.

While an increase of the plasma energy with the theta pinch is not clear when the main capacitor voltage is at 15 kV (= 8.1 kJ, ~ 0.84 T peak field, ~ 200 kA current), the increase becomes more clear when the voltage at the main capacitor bank increases to 20 kV. The enhancement of plasma energy with the theta pinch at 20 kV is estimated 15 - 30 % compared to plasma energy obtained only with the plasma gun. The energy coupling efficiency also increases from 0.18 % \[8\] to 1.2 %.

Fig 4.18 and 4.19 show plasma emissions measured by two photodiodes with only the plasma gun and with the plasma gun and the theta pinch. Note that the position of photodiode #2 has been changed to the target chamber. Plasma emission data for four different delay times are shown in Fig 4.19. It is found that signals from photodiode #1 increase dramatically when the theta pinch is fired and the emission is even stronger at smaller delay times. Not only that, plasma velocities measured using the photodiodes in Fig 4.20 also show that higher velocities are obtained at shorter delays. These data are contrary to the experimentally obtained results, suggesting a possible issue of plasma transport from the theta coil to the target region.

4.5 Summary

- A snowplow model and an analytical model predict an implosion process within ~ 1 \(\mu\)s followed by an adiabatic compression, which possibly heats particles to \(T_{i+e} \sim 100\) eV assuming 100 % ionization.
Figure 4.17: Plasma energies at at various theta coil voltages and plasma gun voltages. Here, delay times are set at 50 µs or longer.

- The previous theta coil (1 turn, 40 nH) is connected now with 72 µF capacitor bank to handle more energy. The theta coil is later reconfigured to a two-turn coil (160 nH) to facilitate the operation of a crowbar. The two-turn coil produces a maximum current of 300 kA (= 1.2 T) at 20 kV of the main capacitor bank and the operation of the crowbar allows for a monotonically decreasing current. The PSPICE simulation results agree with the experimental results.

- A maximum plasma energy of 0.062 MJ/m² is obtained for the 1-turn coil when the plasma gun is fired at -6 kV and the theta pinch is fired at 15 kV. For the 2-turn coil, a maximum plasma energy of ∼ 0.08 MJ/m² is achieved when the plasma gun voltage is at -6 kV and the main capacitor bank for the theta pinch is charged at 20 kV. Plasma velocities of 34 - 74 km/s are observed at the first few peaks of theta pinch current.

- Delay time test shows that a larger delay results in a greater plasma energy. However, energy efficiency measurements and optical measurements show that a smaller delay time creates more plasma. This implies a possible issue with plasma transport.
Figure 4.18: (a) The positions of photodiode #1 and #2 for the plasma emission measurement. Note that the photodiode #2 is moved to the target chamber. (b) Emission signals at the theta coil and at the target chamber only with the plasma gun at 6 kV.
Figure 4.19: Emission signals at the theta coil and at the target chamber when the delay time is (a) 20 µs (b) 29 µs (c) 41 µs (d) 49 µs

Figure 4.20: Plasma velocities measured using the photodiodes at a delay time of (a) 20 µs (b) 49 µs
Chapter 5

Plasma Transport Experiment

5.1 Theory: Particle Diffusion

5.1.1 Radial Diffusion across Magnetic Fields

An important parameter to find is the plasma diffusion characteristic time, since it is one of factors that determines the plasma transport from the theta pinch. Anomalous resistivity, most likely caused by the lower hybrid drift instability, has been experimentally observed and theoretically found as a source of enhanced radial diffusion of the plasma across the magnetic field [118, 119]. However, a report said that this lower hybrid drift instability is stabilized when the condition $v_0/v_i$ (approximately $\sim r_i/a$ where $a$ is the radial density scale length and $r_i$ the ion cyclotron radius) is limited to $\leq 1/16$. Another study also showed that in an 8 meter theta pinch device, plasma diffusion follows classical diffusion time scale, $\frac{a^2}{\eta \beta}$ where $a$ is the plasma radius, $\eta$ is the plasma resistivity, $\beta$ is the plasma beta. However, in this paper, the Bohm diffusion is considered the dominant diffusion process from a conservative perspective.

Bohm diffusion and its characteristic time scale are

$$D_{\perp,Bohm} = \frac{kT}{16eB}$$

$$\tau_{\perp,Bohm} \sim \frac{a^2}{D_{\perp,Bohm}}$$

In Fig. 5.1(a) the plasma diffusion time at 100 eV is approximately 30 $\mu$s at $B = 0.1$ T and 80 $\mu$s at $B = 0.2$ T. Since this approach assumes that the plasma size is very small compared to the size of the tube, the actual diffusion time can be a factor of 2 - 4 shorter than those calculated from Eq. (5.1b). Not only that, cross-field diffusion of the plasma in the radial direction decreases its temperature due to adiabatic expansion. Therefore, if there is no additional field in the transport region, the magnetic field produced at the theta coil decays dramatically from the end of the coil and the plasma is radially diffused by the
ambipolar diffusion process. Ambipolar diffusion is given by

\[ D_i = \frac{kT_i}{m_i \nu_i} \quad \text{(5.2a)} \]

\[ D_a \sim D_i \left(1 + \frac{T_e}{T_i}\right) \quad \text{(5.2b)} \]

where ion collision frequency \( \nu_i = \nu_{ii} + \nu_{ie} \sim \nu_{ii} \) for a fully ionized plasma [120] and \( D_i \) is ion diffusion coefficient. The ambipolar diffusion time-scale in a cylinder is approximated by [121]

\[ \tau_a \sim \left(\frac{a}{\lambda_l}\right)^2 \frac{1}{D_a} \quad \text{(5.3)} \]

where \( D_a \) is the ambipolar diffusion coefficient, \( a \) is the radius of the tube, and \( \lambda_l \) is the \( l^{th} \) root of \( J_0(x) = 0 \). The \( l = 1 \) mode decays the slowest and gives the maximum time-scale for the ambipolar diffusion. Assuming \( \nu \sim 1 \times 10^6 \) Hz in Appendix 1, the diffusion characteristic time is plotted in Fig. 5.1(b). It shows that in the absence of magnetic field plasma diffuses to the wall in \( \tau_a \leq 1 \, \mu s \) for low temperature plasma and \( \tau_a \ll 1 \, \mu s \) for high temperature plasma.

Figure 5.1: Estimate of (a) characteristic plasma diffusion time perpendicular to an external magnetic field and (b) ambipolar diffusion time without an external magnetic field

Therefore, these constraints invoke the necessity of a strong guiding magnetic field. The guiding magnetic field should be strong and straight in the z-direction so that the field suppresses the radial expansion of plasma while it is transported to the target region, and should be unperturbed by the main theta pinch coil when the pinching process takes place. This requirement is further discussed in chapter 5.2.4.
5.1.2 Axial Plasma Loss

For the theta pinch to be used for a hot plasma gun simulator, the time-scale should satisfy the requirement that $\tau_\parallel$, $\tau_{\text{transit}} < \tau_\perp$ and $\tau_\parallel < \tau_{\text{comp}}$ where $\tau_\parallel$ is the characteristic diffusion time parallel to the magnetic field, $\tau_\perp$ is the characteristic diffusion time perpendicular to the magnetic field as discussed in chapter 5.1.1, $\tau_{\text{transit}}$ is the characteristic time for the plasma to transit from the theta pinch to the target chamber, and $\tau_{\text{comp}}$ characteristic time for magnetic pinching. Therefore, the estimate of the parallel plasma diffusion time is important in the design of the device. In the conventional high energy linear device, the characteristic time for particle loss parallel to the magnetic field is approximately $\tau_p \sim L/v_i$ where $L$ is the coil length and $v_i$ is the ion thermal energy $[122]$. Fig. 5.2(a) shows that the plasma axial diffusion time at 10 eV is $\sim 7 \mu s$ and at 100 eV is 2 - 3 $\mu s$. Therefore, $\tau_\perp$ and $\tau_{\text{comp}}$ should be in the range of tens of $\mu s$ to keep the plasma compressed during the axial diffusion process.

Once the plasma is ejected out of the coil, the plasma experiences many collisions with neutrals, which reduces the ambipolar diffusion coefficient and thereby the flow velocity. With the help of a gas-puff valve, however, neutral gas in the transport region can be significantly reduced and plasma will freely diffuse in the axial direction. The gas-puff system is discussed more in detail in chapter 3.2.3. The important part in the transport process is to minimize the radial expansion of the plasma since the expansion results in particle loss to the wall and temperature decrease due to the adiabatic expansion. Using the simple relation $\tau_{\text{transport}} \sim \frac{L_{\text{transport}}^2}{D_a}$ where $L_{\text{transport}}$ is the distance from the end of the theta coil to the target and $D_a$ is the ambipolar diffusion coefficient, the axial diffusion time from the theta pinch to the target is plotted in Fig. 5.2(b) For $n_e = 10^{21}$ m$^{-3}$ and $T_i = 100$ eV, $D_a$ is in the order of $10^4$ m$^2$/s, which results in the axial diffusion time $\sim 20 \mu s$ to travel 0.4 m, which is similar with the previous experiment data. Therefore, the guiding magnetic field must be strong enough to suppress the radial expansion in this timescale.

5.1.3 Magnetic Pressure vs. Plasma Pressure

While the use of guiding magnets reduces radial loss of plasma and facilitates transport of the plasma in the axial direction, a possible issue is that the magnetic pressure from the guiding magnets may dominate the plasma pressure and prevent the plasma from moving into a region where a strong magnetic field is present. This mirror-like effect is particularly important if magnetic lines from the guiding magnets do not diffuse into the plasma. The ideal magnetohydrodynamics condition is one example of this case.

Fig 5.3 shows plasma pressures as a function of plasma density and the sum of electron and ion temperatures, $T_i + e$. Note that magnetic pressures from the theta pinch and the guiding magnet are added to the figure for comparison. One may see that the magnetic pressure is orders of magnitude higher than the
plasma's thermal pressure. This result implies that there may be a possible reduction in the plasma energy with the magnetic field. However, when the plasma is magnetized or when the much stronger magnetic field of the theta coil is connected to the guiding magnetic field, the magnetic fields from the guiding magnets allow for an enhancement of plasma transport and thereby the plasma can move through the guiding magnetic field with reduced radial loss.

Therefore, the pressure of the plasma is more dependent on the convective motion of the plasma. According to plasma fluid theory, the momentum flux due to flux convective motion at a velocity of $\vec{u}$ is given by

$$G = mn\vec{u}\vec{u}$$

(5.4)

where $G$ is the momentum flux. At $n_e = 3 \times 10^{21} \text{ m}^{-3}$ and $\vec{u} = 4 \times 10^4 \text{ m/s}$, the momentum flux is 0.08 atm. Still the plasma pressure is lower than the magnetic pressure when the guiding magnetic field is at 0.2 T (=0.16 atm). Therefore, a reduction in plasma transport to the target chamber may occur until the guiding magnetic field starts to diffuse into the plasma and a higher voltage discharge may allow for a better plasma transport.

### 5.2 Experimental Setup

#### 5.2.1 Two Guiding Magnet Sets

The magnets serve 1) to provide a toroidal magnetic field for the trench and 2) to suppress the plasma from radial expansion. Two guiding magnet sets are constructed. The magnet set located between the theta coil...
and the target chamber is called the "grey" magnet and the magnet set is composed of two grey magnets. Each of the grey magnets has 430 turns, 31.8 mH, and 0.4 Ohm. When combined in parallel, the magnets have a total inductance of 23.2 mH with a coupling coefficient of 0.46. The magnet set is connected to an 8 mF capacitor bank, resulting in a half LC time ($\tau_{1/2}$) of 43 ms. This is similar to the experimentally obtained half LC time of 40 ms.

An additional magnet set is required to extend the magnetic field to the end of the chamber. The magnet set located at the back of the target chamber is called the "copper" magnet and the magnet set is composed of four copper-colored magnets. Each of the copper magnets has approximately 160 turns, 8.6 - 8.7 mH, and 0.5 Ohm. When combined in parallel, the magnets are separated from one another with plastic spacers to avoid arcing and the magnet set has a total inductance of 6.24 mH. The magnet is connected to a 4 mF capacitor bank, resulting in a half LC time ($\tau_{1/2}$) of 16 ms. This is similar to the experimentally obtained half LC time of 15 ms. For more on the details of the setup, one may refer to Fig 4.4(a).

5.2.2 SCR Switches and Drivers for the Guiding Magnets

While the guiding magnets are required to produce a high magnetic field, a steady-state operation of the magnets is not desirable because of a heat dissipation issue; therefore, a semiconductor switch is used to control the current pulse in the magnet. An SCR switch is chosen since the guiding magnets need to generate a magnetic field only in one direction. In order to operate the SCR switch, a switch driver is required. An
additional consideration is required when the switch is operated at high side, where the negative side of the switch is connected to the load, not to the ground. It is because the reference voltage of the switch changes from zero to high voltage during the pulse. Therefore, an adequate voltage isolation between the switch circuit and the power supply is required.

The 50RIA60 SCR switch is selected for its capability to handle a maximum of 1.5 kA non-repetitive surge current at maximum at 600 V maximum off-state voltge. It requires a minimum of 0.1 A peak positive gate current and 2.5 V gate voltage to trigger. The IR4426 is selected as an SCR driver for its maximum output capability of 20 V and 6 A as well as its controllability with a CMOS logic signal. The electric isolation is two-fold: 1) isolation of the signal generator from the main circuit using an optical fiber and 2) isolation of the main circuit from the SCR switch using an isolation transformer.

Fig. 5.4(a) shows the SCR driver circuit for the 50RIA60 SCR switch. IR4426, a DC-DC voltage converter, and an optical fiber receiver are integrated to produce a voltage pulse. It is connected to the SCR switch via an isolation transformer with an inductance at each side around 100 \( \mu \)H. The circuit simulation using PSPICE at Fig. 5.4(b) shows that it produces enough voltage and current to trigger the SCR. Fig. 5.4(c) shows a current waveform when the 4 mF capacitor is discharged at 100 V. Current stops when it becomes zero and \( \tau_{1/2} \) is around 35 ms, which gives 16 Hz.

Fig 5.4(d) and 5.4(e) show the relation of charging voltage, peak current, and peak magnetic field at the center of the guiding magnets. The grey magnet is powered by an 8 mF capacitor bank. Fig 5.4(d) shows that a maximum magnetic field of 0.3 T is obtained with 400 V of charging. Fig 5.4(d) shows that a maximum magnetic field of 0.15 T is achieved with 450 V of charging.

5.2.3 Magnetic Field Simulation

In order to understand the strength and the shape of the magnetic field, an electromagnetic simulation is carried out. The Maxwell 2D code is used to simulate the magnetic field and magnetic flux lines in the target chamber. Maxwell 2D is a two - dimensional electromagnetic field solver, using a finite element method. A magnetostatic solution is used since the magnetic field from the guiding magnets is in a long pulse and this condition can be approximated as a DC current. (If the field changes on a fast timescale, the solution should be "eddy current" or "transient"). The input current conditions for the magnets is adopted from the experimental values in chapter 5.2.1.

Fig 5.5 shows the magnetic field and the flux lines produced by two guiding magnets. Fig 5.5(a) shows that there is a divergence of the magnetic field in the target chamber due to a relatively large length of the device. However, the magnetic Fig 5.5(b) shows that the the magnetic field of around 0.1 T at the target
Figure 5.4: (a) SCR driver circuit in PCB layout (b) SCR output simulation at the secondary side with PSPICE assuming 10 Ohm resistive load. (c) Temporal evolution of current in the magnet with 4 mF capacitor discharged at 100 V (d) The relation of charging voltage, current, and magnetic field at the center of the guiding magnet between the chamber and the theta coil with a 8 mF capacitor bank (e) The relation of charging voltage, current, and magnetic field at the center of the guiding magnet at the end of the chamber with a 4 mF capacitor bank
Figure 5.5: (a) Magnetic flux lines in the target chamber with Maxwell 2D code (b) Magnetic field in the target chamber simulated with Maxwell 2D code

region is obtainable with the current guiding magnets.

5.2.4 Magnetic Flux Excluder for Flux Conservation

Since the operation of the device is in pulsed mode, the magnetic fields produced by the guiding magnets and the theta pinch coil change with time. It is important to consider that the change of the magnetic field at one coil affects the others by magnetic flux-linking. For the theta pinch coil, a magnetic flux of 7 mWb changed in 33 kHz at 200 kA in the coil results in 1.36 kV induced in the tube. Due to a geometrical separation of the theta coil to the guiding magnets, the axial magnetic flux is reduced approximately by a factor of $\sim 10$ at 5 cm away from the end of the coil. This condition can still give about a maximum of 140 V induced at the grey guiding magnet. Therefore, a possible way to further reduce the fast-changing magnetic field while keeping the slow-rising magnetic field is necessary.

A magnetic flux excluder \cite{28}, or flux conserver \cite{123} is normally composed of a sheet of metal with finite inductance and resistance. When the fast-changing magnetic field oscillates at the flux conserver, the field will induce an eddy current in such a direction that reduces the external field. This phenomenon is obviously frequency-dependent and the timescale of the magnetic field exclusion is determined by the L/R time of the excluder.
The inductance of a rectangular cross-sectional cylindrical plate is estimated based on a thick coil approximation using a formula in [109] 

\[
L(\mu H) = 0.001N^2a_{cm}P' 
\]  

(5.5)

where \( P' \) is the product of two factors \( P \) and \( F \), of which the first is the function of \( c/2a \) and applied to a coil of zero axial dimension, while \( F \) takes into account the reduction of inductance due to separating the turns in the axial direction and is a function of two parameters, \( c/2a \) and \( b/c \) (or \( c/b \)) [109]. Here, \( a \) is the mean radius of the disk, \( b \) is the axial dimension of the cross section, and \( c \) is the radial dimension of the cross section. The resistance of the plate is kept constant until the frequency is high enough to make the skin depth of the plate smaller than the thickness of the plate. Above this frequency, the resistance will start to increase and magnetic shielding becomes less effective due to a decrease in the L/R time (i.e., an increase in the critical frequency).

A 12 inch by 12 inch, 1/8 inch thick 316 stainless steel plate was purchased to make a magnetic flux excluder. 316 stainless steel is chosen since it allows for no magnetization as opposed to the widely used 304 stainless steel. Since there is not a well-developed formula to estimate the inductance of a plate, it is approximated as a thick, rectangular cross-sectional and cylindrical disk with a 5 inch inner diameter, 12 inch outer diameter, and 1/8 inch thickness. This geometry results in \( L \sim 0.24 \mu H \), \( R \sim 1.8 \, m\Omega \), and \( \tau_{L/R} \sim 0.14 \, ms \) for 304 stainless steel and \( R \sim 0.1m\Omega \), and \( \tau_{L/R} \sim 3.5 \, ms \) for aluminum. This L/R time gives a 1/4 frequency (\( \tau_{L/R} \)) of 7 kHz for the stainless steel and 285 Hz for the aluminum.

The attenuation factor \( G \) is determined as

\[
G \sim 1 - \exp\left(-\frac{\tau_{1/4}}{\tau_{L/R}}\right) = 1 - \exp\left(-\frac{1}{4f\tau_{L/R}}\right) 
\]

(5.6)

where \( \tau_{1/4} \) is the quarter-time of the oscillation of the perturbing signal, \( f \) is the frequency of the perturbing signal and and the Fig. [5.6(a)] shows the attenuation factor for both the stainless steel and the aluminum. Since the frequency of the magnetic field from the guiding field (\( \equiv f_{guiding} \)) is \( \leq 100 \, Hz \) and the main theta pinch frequency (\( \equiv f_{pinch} \)) is in the tens of kHz (33 kHz for the two-turn coil), the requirement for the flux excluder is \( f_{guiding} \ll 4 \times f_{L/R} \leq f_{pinch} \). Fig. [5.6(a)] shows that stainless steel plate satisfies the requirement, and an additional attenuation by a factor of 10 is expected.

Fig [5.6(b)] shows the voltage of the grey magnet as a function of time when the theta pinch is fired along with the guiding magnet. A perturbation of the voltage at the magnet is apparent from Fig [5.6(b)] however, the maximum of the perturbation is approximately 20 volts, which 80% reduction from the voltage expected
Figure 5.6: (a) An estimate of attenuation factor for a cylindrical disk with 3 inch inner radius, 9 inch outer radius, 1/16 inch thickness using Eq. (5.6). The dashed lines indicate the frequency where the thickness of the plate equals the skin depth for the stainless steel (black) and the aluminum (red). (b) The voltage at the grey magnet measured using a probe when the theta pinch is fired along with the guiding magnets.

without the flux excluder is small compared to the typical voltage at the grey magnet (∼300 - 400 V).

### 5.3 Results: The Effect of the Guiding Magnetic Field on Plasma Gun

Fig 5.7 shows a reduction in the plasma energy measured using the calorimeter. Here the voltages at the magnets are fixed at 300 V and the voltage at the plasma gun capacitor changes from 5 kV to 6 kV. The reduction of the plasma energy is normally 20 - 30 %, and a greater reduction is seen at lower voltages.

In order to further investigate the effect of the magnetic field on the plasma transport, optic emission measurements are carried out. The photodiodes are positioned at the same places as depicted in Fig 4.18(a).

Fig 5.8 shows optical emissions from the plasma at four different operating conditions: 5.5 kV plasma gun without magnetic field, 5.5 kV plasma gun with magnetic field, 6 kV plasma gun without magnetic field, and 6 kV plasma with magnetic field. It is clearly shown that the plasma emissions at the target chamber (measured by photodiode # 2) reduces significantly with the guiding magnetic field within the first 50 - 100 µs. The plasma emissions between the theta coil and the guiding magnet (measured by photodiode # 1) are similar regardless of the guiding magnetic field. This suggests that 1) the guiding magnetic field forms a strong magnetic pressure to prevent the plasma from penetrating, 2) as the magnetic field starts to diffuse into the plasma, the plasma starts to follow the axial magnetic field and to be transported to the target chamber along these lines. Fig 5.9 shows the magnetic diffusion time as a function of plasma conductivity.
and scale length. It is shown that at plasma conductivity of $\sim 1 - 3 \times 10^4$ S/m, the magnetic diffusion time is approximately 30 - 90 $\mu$s and is agreement with the duration of the emission reduction. While the actual physical phenomenon between the plasma and the field is much more complex, it can be concluded that the initial strong magnetic field reduces plasma transport.

5.4 Results: Plasma Transport with Theta Pinch and Guiding Magnets

The previous chapter discussed the issue of plasma transport in the device when the device is operated in conjunction with theta pinch. It is important to know how the external magnetic field alters the plasma transport since the machine will be operated in conjunction with a slowly varying or steady-state magnetic field near the target chamber to drive lithium flow.

In the previous section, it is found that in plasma gun experiments, too high a magnetic pressure from the guiding magnets obstructs the flow of plasma. Therefore, the following questions are 1) whether the plasma transport will be enhanced with the theta pinch owing to a much higher plasma pressure during pinching and 2) whether the reversed magnetic field at the theta coil will deteriorate transport.
Figure 5.8: Emissions from plasma produced by the plasma gun at (a) 5.5 kV without the guiding magnetic field (b) 5.5 kV with the guiding magnetic field (c) 6 kV without the guiding magnetic field (d) 6 kV with the guiding magnetic field. Note that the locations of the photodiodes are identical to Fig 4.18(a).
5.4.1 Plasma Energies with Theta Pinch at Various Delay Times

Fig 5.10 shows plasma energies measured using the calorimeter as a function of voltage at the magnet. Here, the main capacitor bank is charged at 15 kV and the voltages of the grey and copper magnets are the same. For these data, the delay times between the plasma gun and the theta pinch are relatively long, typically 50 - 90 $\mu$s. From Fig 5.10 it is found that plasma energy decreases with the magnetic field in all cases. Since the reduction in emission of light from the plasma is seen within the first few tens of microseconds, too late a pinching of the plasma gives an insignificant effect on the transport.

Fig 5.11 shows the change of plasma energy as the voltage at the main capacitor bank increases to 20 kV. While a reduction in plasma energy is shown in all cases, 20 $\mu$s delay time gives a less reduction than larger delay times ($t_d \geq 50 \, \mu s$). This result suggests that plasma needs to be pinched relatively at a short delay time ($t_d \sim 20 - 30 \, \mu s$) with presence of a guiding magnetic field since the plasma from the plasma gun reaches the first guiding magnet in $t_d \leq 30 \, \mu s$ and the target chamber within 50 $\mu$s after the gun is triggered.

5.4.2 Effect of Magnetic Field Reversal

While a short delay time allows for less reduction in the plasma energy as shown in Fig 5.10, the plasma energy is still reduced with the guiding magnetic field. Fig 5.12 shows emission of light from the plasma at two different timings when the plasma gun is discharged at - 6 kV, theta pinch is triggered at 15 kV, and
Figure 5.10: Plasma energies measured using the calorimeter at various magnetic voltages. The plasma gun voltage is 5 or 6 kV and the theta pinch is 15 kV. The plot shows that a reduction of energy is observed consistently in all tested cases and the higher magnetic field leads to a further reduction.

Figure 5.11: Plasma energies on the calorimeter at various magnetic voltages. The plasma gun voltage is 6 kV and the theta pinch is 20 kV. The plot shows that a reduction of energy is observed consistently in all tested cases and the higher magnetic field leads to a further reduction.
Figure 5.12: Light emissions from plasma when the plasma gun and the theta pinch are fired at two different delay times with the guiding magnetic field. The delay time is 30 µs. (a) Flux loop and plasma gun current signals and (b) emission of light from plasma at 30 µs of delay time. (c) Emission signals with no guiding magnet at 30 µs delay time are included to help readers compare with Fig 5.12(a).
the voltages of the capacitors for the guiding magnets are 300 V. Fig 5.12(a) and Fig 5.12(a) show flux loop, plasma gun signals and emission of light from the plasma at 30 $\mu$s delay time. In Fig 5.12 the emissions collected at photodiode # 1, located between the theta pinch and the plasma gun, show reductions when the guiding magnetic field is reversed with regards to the theta pinch field and increases when the guiding field in in the same direction as the theta pinch field. This result is contrary to the data in Fig 5.12(c) where the emissions at photodiode # 1 produces relatively similar peak values over time. The total compression time is approximately 15 $\mu$s ($=\tau_{1/2}$) and the magnetic field decays rapidly. Therefore, this results suggest that a slow - decaying, unipolar magnetic field is required.

5.5 Result: Plasma Transport with Crowbar

As discussed in the previous chapters, plasma transport with the guiding magnetic field depends on magnetic pressure and plasma pressure. When the plasma is compressed with the theta pinch, however, the magnetic field reversal and the rapidly changing magnetic field may hinder efficient plasma transport. Therefore, crowbarring is attempted to manipulate the magnetic field waveform.

Fig 5.14(a) shows electric signals from the plasma gun and the theta pinch. Here, the delay time between the plasma gun and the theta pinch is set at 30 $\mu$s. It is found that in the flux loop signal in Fig 5.14(b) the peak current and the magnetic field of 190 kA / 2 turn and 0.68 T with duration over 100 $\mu$s are achieved.

Fig 5.14(c) shows emissions from the plasma measured with photodiodes. While the emission signals from the plasma are lower than those in the plasma gun experiment or plasma gun - theta pinch experiment, these emissions are in good agreement with each other. The characteristic diffusion time parallel to the magnetic field $\tau_\parallel$ is a few tens of $\mu$s, the characteristic diffusion across the magnetic field based on Bohm diffusion is around 100 $\mu$s, and the duration of magnetic compression $\tau_{\text{comp}}$ is approximately 100 $\mu$s. Therefore, these results implies that the crowbar transports the plasma well to the target chamber when $\tau_\parallel \sim 10 \mu s < \tau_\perp$ and $\tau_\parallel < \tau_{\text{comp}}$ are achieved. Plasma velocity with the theta pinch and the crowbar, based on Fig 5.14(c) $sim135 \pm 45 \text{ km/s}$ is also observed.

Fig 5.13 shows plasma energies on the calorimeter at various operation scenarios and delay times. Here the plasma gun voltage is - 6 kV and theta pinch voltage is 15 kV. While the measured plasma energy with the crowbar (0.042 MJ/m$^2$ in $t_{\text{pulse}} \sim 100 \mu$s) is only $\sim 75 \%$ of the plasma energy obtained with the plasma gun, theta pinch, and the guiding magnets ($\sim 0.057 \text{ MJ/m}^2$ in $t_{\text{pulse}} \sim 150 - 200 \mu$s), the reduced pulse length of the plasma implies that a greater heat flux is achieved with the crowbar operation ($\sim 0.42 \text{ GW/m}^2$). Note that the signals at photodiode # 2 in Fig 5.14(c) are much smaller compared to those in
Figure 5.13: Plasma energies on the calorimeter at various operation scenarios and delay times. Plasma gun voltage is 6 kV and theta pinch voltage is 15 kV.

Fig 4.18(b) while the plasma heat fluxes are similar. Assuming that $I \propto n_e n_H$ where $I$ is the line intensity, $n_e$ is the electron density, and $n_H$ is hydrogen density, this result implies that the plasma with the crowbar operation results in the change of plasma parameters such as plasma density and electron / ion temperatures.

Fig 5.15 shows the plasma energies at various guiding magnet voltages. It is shown that the plasma energy increases when the voltage increases from 0 V to 50 V ($\sim 0.02$ T at the target chamber and $\sim 0.04$ T at the grey guiding magnet). However, as the voltage goes over 50 V, the plasma energy starts to decrease monotonically. This result suggests that the guiding magnet helps transport the plasma when the field is comparable to the plasma pressure but too strong of a magnetic field suppresses an axial plasma transport.

5.6 Summary

- Various diffusion scalings show that with the aid of a guiding magnetic field, the plasma can be kept compressed from radial expansion and energy loss to the wall may be reduced. However, the guiding magnetic field may form a magnetic wall that prevents plasma from axial transport.

- The guiding magnets are tested and installed on the previous chamber. The guiding magnets (0.35 T and 0.15 T, respectively) are equipped with SCR switches and driver circuits, capacitor banks (8 mF and 4 mF, respectively). A magnetic flux excluder is installed to decouple the magnetic field of the theta coil from the guiding magnets. Maxwell 2D simulations show the magnetic field and flux lines
Figure 5.14: Results of plasma gun, theta pinch, guiding magnets, and crowbar combined operation. Delay time is 30 µs between the plasma gun and the theta pinch and 4 µs between the theta pinch and the crowbar. (a) Signals from plasma gun, theta pinch measured with a flux loop and a rogowski coil (b) Current and the magnetic field produced by the theta pinch (c) Emissions from plasma measured with two photodiodes.
in the chamber with the guiding magnets.

- Optical emission and calorimeter measurements from the plasma for plasma gun and guiding magnet experiments show a reduction in the signal at the target chamber with the magnetic field. The strong magnetic pressure from the guiding magnetic field impedes axial transport of the plasma.

- While the theta pinch increases the plasma pressure by compression, calorimeter measurements still show reduced plasma energies with the guiding magnetic field. Two effects are observed. 1) A further investigation reveals that the reduction depends on the delay time between the plasma gun and the theta pinch and a smaller delay time results in less of a decrease. This suggests that better transport is expected when the device is operated with the pinch before the plasma from the plasma gun reaches the target. 2) When the magnetic field from the theta pinch is reversed, the plasma produces less emission. This suggests that the magnetic field should be in the same direction as the guiding magnetic field during compression.

- A long (∼100 µs), unipolar magnetic field from the theta coil is achieved when the crowbar is operated. Plasma emissions measured at two different locations of the device show within good agreement, implying efficient plasma transport. While the measured plasma energy is lower with the crowbar, a shorter duration of the plasma suggests that a similar / higher heat flux may be obtained with the crowbar.

Figure 5.15: Plasma energies on the calorimeter at various guiding magnet voltages when the device is operated with the plasma gun, the theta pinch, the guiding magnets, and the crowbar.
Chapter 6

Plasma Transport Using an MHD Code

6.1 Introduction

The previous chapters show the effect of the guiding magnetic fields on plasma transport. It was initially assumed that the guiding magnetic field will increase the plasma energy. However, experimental results in chapter 4 and 5 shows that the plasma energy mostly decreases with the guiding magnetic field. Based on the experimental results, the difference in plasma transport for various operating scenarios are attributed to magnetic field line reconnection and plasma / magnetic pressure.

In order to further investigate and verify the effect of the guiding magnet field on the plasma transport, ideal MHD simulations have been carried out. Athena code, an ideal MHD code with a higher Godunov method and a constrained transport, is chosen because of its superiority in shock - capturing and availability in a cylindrical geometry. Two simulation cases, 1) the effect of the magnetic field on the plasma gun, 2) the effect of the magnetic field on the theta pinch with the crowbar, will be simulated using the code and the effect of the field will be presented in this chapter.

6.2 Ideal Magnetohydrodynamics

If a plasma is sufficiently collisional, its behaviors can be macroscopically understood by a simplified form of magnetohydrodynamics [124]. If this is the case, the basic state of a collisional plasma can be described by its mass density $\rho$, its momentum density $\rho \vec{v}$, its pressure $P$, and the magnetic field $\vec{B}$ [124]. There are several conditions where the plasma deviates from ideal MHD [124, 125, 126, 67, 120]:

- Plasma resistivity and Hall effect: ideal MHD implies that the plasma conductivity is so high that there will be no electric field inside the plasma. The magnetic Reynolds number (a ratio of magnetic convection to magnetic diffusion) is defined as

$$R_m = \frac{VL}{\eta} = \mu_0 \sigma VL$$

(6.1)
where \( V \) is a typical velocity scale of the flow, \( L \) is a typical length scale of the flow, \( \sigma \) is the plasma conductivity, and \( \eta \) is the magnetic diffusivity. Therefore, if the magnetic Reynolds number is small, magnetic field diffusion becomes dominant and the flux-freezing condition no longer holds. Therefore, conversion of magnetic energy into joule heating (with a timescale of \( \tau = \mu_0 \sigma L^2 \)) should be taken into account for both the equation of motion and the equation of energy. According to the generalized Ohm's law, the current inside a magnetized plasma is [18]:

\[
\vec{j} = \sigma \parallel \vec{E} \parallel + \sigma \perp \vec{E} \perp + \sigma_H \vec{n} \times \vec{E} \perp
\]

(6.2)

where

\[
\sigma \parallel = \sigma = \frac{n e^2}{m_e \nu_{ei}}
\]

(6.3a)

\[
\sigma \perp = \sigma \frac{1}{1 + (\omega_{ce} \tau_{ei})^2}
\]

(6.3b)

\[
\sigma_H = \sigma \perp (\omega_{ce} \tau_{ei}) = \sigma \frac{\omega_{ce} \tau_{ei}}{1 + (\omega_{ce} \tau_{ei})^2}
\]

(6.3c)

where \( \omega_{ce} \) is the electron cyclotron frequency, \( \tau_{ei} \) is the electron - ion collision time as discussed in Appendix 1. The additional Hall current term, caused by a \( J \times B \) term, is not negligible when a magnetic field is strong enough to result in \( \omega_{ci} \tau_{ei} \gg 1 \) (a much higher gyrofrequency than an electron - ion collision frequency, mostly in the case of a very strong magnetic field or dilute plasma). Therefore, when the magnetic field is strong, the plasma conductivity is no longer isotropic, but is divided into three different components as specified in Eq. 6.3. Fig 6.1 shows the direct and Hall currents in a magnetized plasma. The Hall current, again found in a resistive plasma, may contribute to an additional change in motion and energy loss.

- Thermal conduction: the diffusion of energy depends on the timescale of interest. If the heat conduction is negligible in the time of interest, the plasma can be described in the adiabatic state, since the adiabatic state defines a condition where no heat flow occurs; if the timescale is much more rapid than the characteristic change of the state, it follows that the isothermal equation of state holds. If there is a very strong magnetic field that causes an anisotropic thermal plasma distribution, the heat conduction can be very fast along the magnetic field (mainly from electrons rather than ions, due to a faster thermal velocity), but quite slow across the field (mainly from ions rather than electrons, due
Figure 6.1: The generalized Ohm’s law in a magnetized plasma: the direct ($\mathbf{j}′_\perp$) and ($\mathbf{j}′_\parallel$) and Hall current ($\mathbf{j}′_H$) in a plasma with electric and magnetic fields [18].

to a larger gyroradius) [126]. The thermal conduction for two directions are given by [126] 67

\[ \kappa_\parallel \sim \frac{v_{t,e}^2}{\nu_e} \sim \frac{nT}{m_e\nu_e} \quad (6.4a) \]
\[ \kappa_\perp \sim n\nu_{ii}^2 L_i \sim \frac{nT}{m_i\nu_{ii}} \frac{1}{(\tau_{ii}\omega_{ci})^2} \quad (6.4b) \]

where $n$ is density, $T$ is temperature, $v_{t,e}$ is the electron thermal velocity, $m_i$ and $m_e$ are the ion and electron masses, $\nu_{ii}$, $\nu_e$, $\tau_{ii}$ are the characteristic collision times and frequencies discussed in Appendix, and $\omega_{ci}$ is ion cyclotron frequency.

A heat conduction vector driven by a thermal velocity distribution is given by [67]

\[ q_\sigma = \frac{1}{2} n_\sigma m_\sigma \langle (\vec{w} \cdot \vec{w}) \vec{w} \rangle \quad (6.5) \]

where $\sigma$ is species of particle, $n$ is density, $m$ is mass, and $\vec{w}$ is thermal velocity with respect to the advection velocity. If a plasma has an isotropic velocity distribution, the thermal motion is averaged out and there will be no directional heat conduction term. However, if the plasma has different temperature gradients in different directions, more heat conduction will take place in one direction.
than the other.

- **Viscosity**: a stress tensor due to the thermal motion of particles, defined as $\mathbf{\Pi}$, gives a momentum flux on a surface. The $\mathbf{\Pi}$ is further divided into two parts, a pressure tensor ($p_\sigma \mathbf{I}$) and a viscous (shear) stress tensor. ($\mathbf{\Pi}$)

$$\Pi_{ij} = mn \left( \langle \omega_i \omega_j \rangle - \frac{1}{3} \langle \omega_i \omega_j \rangle \delta_{ij} \right) \quad (6.6)$$

The motion of a viscous fluid is further influenced by the viscosity and the effect of the viscous tensor, $-\nabla \cdot \mathbf{\Pi}$, should be included in the equation of motion. Not only that, the energy dissipation during fluid motion due to irreversible conversion of mechanical energy by viscosity, $-\nabla \cdot (\mathbf{\Pi} \cdot \mathbf{v})$, should be considered as well.

- **Radiative heating / cooling**: if there is an external heating / cooling process (mostly due to the radiation process in an optically thin, non-thermal equilibrium plasma), the energy equation should be changed to include those effects.

If the deviations from the ideal condition such as resistivity or thermal conduction can be neglected, the ideal MHD equations are adequate to describe behaviors of plasmas.

### 6.3 Validation of the Ideal MHD Approximation

The question is whether the experimental conditions meet the ideal MHD approximations. Considering several cases where ideal MHD is violated:

- **Plasma resistivity**: assuming the plasma density $n_0 \sim 10^{21} \text{ m}^{-3}$ and and the temperature $10 \leq T_{i+e} \leq 100 \text{ eV}$, the plasma resistivity given by the Spitzer resistivity for a fully ionized plasma is

$$\eta \sim 2.3 \times 10^{-9} \frac{z \ln \Lambda}{T_e^{3/2}} \Omega \cdot \text{m} \quad (6.7)$$

where $T_e$ is in keV, $z$ is the atomic number of the ion, and $\ln \Lambda$ is the Coulomb logarithm. Based on the formula, the plasma resistivity is on the order of $10^{-5}$ to $10^{-6} \Omega \cdot \text{m}$. For the pinching process, the typical implosion velocity is around $5 \times 10^4 \text{ m/s}$ so that the magnetic Reynolds number for the pinching is on the order of hundreds. Therefore, the ideal MHD approximation is a reasonable assumption for the pinching process. The magnetic diffusion time into the center of the plasma is approximately 300 $\mu$s or greater, implying that the whole process can be considered at ideal MHD. The plasma axial loss has a length scale of 0.15 m, which is half of the length of the tube, with a typical velocity of $10^4 \text{ m/s}$
or greater. Therefore, this condition allows the magnetic Reynolds number to range from 100 to 1000. The effect of magnetic field diffusion into the plasma by resistivity is thereby small and ideal MHD is a good approximation.

- Thermal conduction: normally, heat conduction along the magnetic field is very large for a theta pinch. It is mainly caused by electrons rather than ions, due to their much faster thermal velocity. As for the thermal conduction across the magnetic field, it arises mainly from ions rather than electrons due to an ion’s much larger Larmor radius compared to an electron [126]. Since thermal conduction across the magnetic field is mainly done by ions, the heat conduction along the field is more dominant and the thermal conduction should not be a problem for a theta pinch [106]. The thermal loss in the axial direction is faster than the particle loss due to the fact that higher energy particles are lost much faster than low energy particles. The characteristic time for axial heat loss is

\[ \tau_{tc} \propto \frac{L^2}{v_e \lambda_{ee}} \]  

(6.8)

where \( v_e \) is the electron thermal velocity and \( \lambda_{ee} \) is the electron - electron mean free path. The Eq. (6.8) is a strong function of electron temperature, since the electron thermal velocity is proportional to \( \sqrt{T_e} \) and the electron - electron mean free path given by the effective Coulomb collisionality is roughly proportional to \( T_e^2 \). Therefore, \( \tau_{tc} \) is a strong function of electron temperature (\( \propto 1/T_e^{5/2} \)). When \( T_e \) is around 10 eV, the characteristic loss time is around 100 \( \mu s \) and when the \( T_e \) is 100 eV the loss time significantly decreases to less than 1 \( \mu s \). Therefore, on the assumption that the electron temperature remains on the order of a few tens of eV, the assumption of an adiabatic process still holds.

- Viscosity: the viscosity effects of ions are dominant in the stress tensor and the dissipative effects due to the ion viscosity becoming important on timescales longer than the ion collision timescale. In ideal and resistive MHD, it is customary to neglect the viscous stress, which is usually valid for time scales shorter than ion collision time scale \( 1/\nu_i \) [127]. In the theta pinch, due to a high density during the pinching process, the ion collision time scale is much shorter than for regular fusion plasmas and the ion - ion collision time normally ranges from \( 10^{-7} \) to \( 10^{-6} \) s for 10 - 100 eV ions at \( n_e = 10^{21} \) m\(^{-3}\). Since the ion - ion collision time is very short and the viscosity effect is linearly related to the velocity gradient, the viscosity can actually play a role in the simulation.

- Radiative heating / cooling: the radiative cooling process, which is a loss of energy through radiation in a optically thin plasma, can be important for a non-thermal equilibrium plasma. The minimum density for local thermodynamic equilibrium (thermodynamic equilibrium with exception of the radiation
Figure 6.2: Minimum density to achieve local thermodynamic equilibrium based on Ref. [19]

The minimum density to achieve local thermodynamic equilibrium (LTE) is given by [19]

\[ n_e \gg 10^{19} \left( \frac{T}{e} \right)^{1/2} \left( \frac{\Delta E}{e} \right)^3 \ \text{m}^{-3} \] (6.9)

where \( T/e \) and \( \Delta E/e \) are the temperature and energy level difference in eV. Since the experimental condition does not have enough plasma density to achieve even local thermodynamic equilibrium, the cooling effect by radiation emission is not negligible. However, due to complexity in modeling, the radiation term is omitted in the simulation.

### 6.4 Athena MHD Code

Athena [125] is a grid-based MHD code, originally used for astrophysical applications. The program is characterized by two methods: (1) the Godunov method and (2) constrained transport. An operator splitting method was used between the advection and pressure force with upwind methods for the advection terms and centered differencing for the pressure force terms, and has shown to be very successful for many applications. Athena has its own specialty such that it utilizes unsplit, higher order Godunov methods for the use of adaptive mesh refinement. The Godunov method, the purest version of Riemann solvers, keeps the mathematical character of the equations intact, unlike the operator splitting method, and shows superior performance in simulating a boundary with discontinuities such as shock waves [128].
In ideal MHD,
\[ \partial_t \vec{B} = \nabla \times (\vec{v} \times \vec{B}) \] (6.10)
so that \( \partial_t (\nabla \cdot \vec{B}) = 0 \). However, this might not be the case for a finite difference treatment of the equation \[129\]. The constrained transport algorithm technique preserves magnetic divergence. The Athena code uses line-averaged electromotive forces at cell corners to enforce the divergence-free condition.

The Athena code, in a default configuration, solves a compressible, adiabatic, inviscid, and ideal MHD problem using the four governing equations written in conservative form \[125\]:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) &= 0 \quad (6.11a) \\
\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v} - \vec{B} \vec{B} + \leftrightarrow P^*) &= 0 \quad (6.11b) \\
\frac{\partial E}{\partial t} + \nabla \cdot [(E + \leftrightarrow P^*) \vec{v} - \vec{B} (\vec{B} \cdot \vec{v})] &= 0 \quad (6.11c) \\
\frac{\partial \vec{B}}{\partial t} - \nabla \times (\vec{v} \times \vec{B}) &= 0 \quad (6.11d)
\end{align*}
\]

where \( \rho \) is the fluid mass density, \( \vec{v} \) is the velocity vector, \( \vec{B} \) is the magnetic field vector, \( \leftrightarrow P^* \) is a diagonal tensor with components \( P^* = P + B^2/2 \) (with \( P \) the gas pressure), \( E \) is the total energy density:
\[
E = \frac{P}{\gamma - 1} + \frac{1}{2} \rho v^2 + \frac{B^2}{2} \quad (6.12)
\]
and \( B^2 = \vec{B} \cdot \vec{B} \). Eq. (6.11a) is a continuity equation, Eq. (6.11b) is an equation of motion (or momentum conservation), and Eq. (6.11c) is an equation for energy conversation, and Eq. (6.11d) is a magnetic differential equation without resistivity.

Note that the equations are written in units such that the magnetic permeability, \( \mu \), is equal to 1. Therefore, a proper conversion to physical units is necessary. In cgs units, the governing equations are
written in the form [124]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (6.13a)$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot \left( \rho \vec{v} \vec{v} \right) - \vec{B} \cdot \vec{B} + \vec{P}^* = 0 \quad (6.13b)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left( (E + \vec{P}^*) \vec{v} - \vec{B} \cdot \vec{B} \right) = 0 \quad (6.13c)$$

$$\frac{\partial \vec{B}}{\partial t} - \nabla \times (\vec{v} \times \vec{B}) = 0 \quad (6.13d)$$

$$P^* = P + \frac{B^2}{8\pi} \quad (6.13e)$$

$$E = \frac{P}{\gamma - 1} + \frac{1}{2} \rho \vec{v}^2 + \frac{B^2}{8\pi} \quad (6.13f)$$

Comparing Eq. (6.13) with Eq. (6.11), one may find that only $\vec{B}$ needs to be replaced by $\vec{B}/\sqrt{4\pi}$ to convert the governing equations to those with physical units. The conversion is also stated in Ref. [130].

6.5 Plasma Transport Simulation with Athena MHD Code

6.5.1 Initial Conditions

For the magnetic field produced by the theta coil, the magnetic field is simulated as an infinitely long solenoid with only a z-component. Therefore, it is necessary to find a formula which describes a more realistic magnetic field in a solenoid of a finite length. Formulas in Ref. [131] model approximate magnetic fields in an ideal and azimuthally symmetric solenoid and are thereby used for the simulation. The equations are as follows:

$$B_r = B_0 \left[ \alpha_+ C \left( \kappa_+, 1, 1, -1 \right) - \alpha_- C \left( \kappa_-, 1, 1, -1 \right) \right] \quad (6.14a)$$

$$B_z = \frac{B_0 a}{a + r} \left[ \beta_+ C \left( \kappa_+, \gamma^2, 1, \gamma \right) - \beta_- C \left( \kappa_-, \gamma^2, 1, \gamma \right) \right] \quad (6.14b)$$
where

\[ B_0 = \frac{\mu_0 n I}{\pi} \]  \hspace{1cm} (6.15a)
\[ z_\pm = z \pm b \]  \hspace{1cm} (6.15b)
\[ \alpha_\pm = \frac{a}{\sqrt{z_\pm^2 + (r + a)^2}} \]  \hspace{1cm} (6.15c)
\[ \gamma = \frac{a - r}{a + r} \]  \hspace{1cm} (6.15d)
\[ k_\pm = \sqrt{\frac{z_\pm^2 + (a - r)^2}{z_\pm^2 + (a - r)^2}} \]  \hspace{1cm} (6.15e)

where 2b is the length of the theta coil, a is the radius of the coil, and C is the generalized complete elliptic integral which is defined by

\[ C(k_c, p, c, s) = \int_0^{\pi/2} \frac{c \cos^2 \varphi + c \sin^2 \varphi}{(\cos^2 \varphi + p \sin^2 \varphi) \sqrt{\cos^2 \varphi + k_c^2 \sin^2 \varphi}} d\varphi \]  \hspace{1cm} (6.16)

Since the Athena code does not allow for an external source that drives the change in the motion of the plasma, setting an initial condition for simulation of pinching is important. The initial conditions are made such that the magnetic field from the theta pinch is locally diffused from the outside into the tube. The modified magnetic field should still satisfy the divergence-free condition. If the initial field satisfy the divergence-free condition, the field remains divergence-free for all time and it can be proven by Faraday’s law:

\[ 0 = \frac{\partial \vec{B}}{\partial t} + \nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t} + \nabla \times (\vec{B} \times \vec{u}) \]  \hspace{1cm} (6.17)

For example, when the modified magnetic field is given under the concept of the magnetic diffusion time, the field may be modified approximately to:

\[ B_{rm}(r, z, t) = B_r(r, z) \times f(r, t) \]  \hspace{1cm} (6.18a)
\[ B_{zm}(r, z, t) = B_z(r, z) \times f(r, t) \]  \hspace{1cm} (6.18b)
where $t$ is time and $f(r,t) = \exp[-t/(\mu_0\sigma(a-r)^2)]$. The divergence in cylindrical coordinates is given by

$$\nabla \cdot \vec{B} = \frac{1}{r} \frac{\partial (rB_r)}{\partial r} + \frac{1}{r} \frac{\partial B_\phi}{\partial \phi} + \frac{\partial B_z}{\partial z}$$

(6.19)

Therefore, with Eq. 6.20, it is found that the modified field in Eq. 6.18b has a divergence of

$$\nabla \cdot \vec{B}_m = f(r) \left[ \frac{1}{r} \frac{\partial (rB_r)}{\partial r} + \frac{\partial B_z}{\partial z} \right] + B_r \frac{\partial f(r)}{\partial r}$$

\[= 0 \text{ for } \nabla \cdot \vec{B} = 0 \]

(6.20)

which is non-zero within the simulation domain. Therefore, this modification does not satisfy the divergence-free condition and may add some artificial and unphysical discontinuities to the simulation.

For the initial condition of the magnetic field, the magnetic field from the theta coil is assumed to be locally concentrated near the outer boundary of the simulation domain due to a long magnetic diffusion timescale. Assuming that the plasma is uniformly compressed during the initial pinching, the linear transformation of the radius from $r = 0 \rightarrow r - t$, where $t$ is the thickness of the magnetic field penetration, satisfies the divergence-free condition. The variable $a$ is also changed to $t$, so that the magnetic field is confined between the plasma and the wall.

For mass density, $\rho = n m \sim 3.3 \times 10^{19} \text{ m}^{-3} \times 100 \text{ mTorr} \times 1.67 \times 10^{-27} \text{ kg} \sim 1.1 \times 10^{-8} \text{ g cm}^{-3}$. For pressure, $p = nkT_{i+e} \sim 30 \text{ kPa} = 3 \text{ kPa}$. Plasma velocity is approximated as $4 \times 10^6 \text{ cm/s}$.

### 6.5.2 Boundary Conditions

The Athena code uses the concept of ghost cells to implement boundary conditions in flux conserving cells and cell-interfaces. There are a number of different types of boundary conditions that can be implemented by the ghost cells. The common ones are the periodic boundary condition, the reflecting boundary condition, the free flow-out condition, and the conducting boundary condition [128]. How Athena code sets the boundary conditions is depicted in Fig 6.3.

Fig 6.3(a) shows the magnetic field and the momentum inside ghost cells set by a reflecting boundary condition. In a reflecting boundary condition, the system is closed because everything including mass and energy is reflected by the reflecting boundary. However, the problem with complete closure of the parameters provided by the boundary condition is that any perturbation or wave generated inside the area of interest is not damped, but is also perfectly reflected and returned into the simulation domain, affecting the simulation [128].
Figure 6.3: Diagrams of various boundary conditions in Athena code. The boundary is set at the x-axis in the diagrams. The boundary conditions are as follows: (a) reflecting (b) flow-out (c) periodic (d) conducting boundary condition.
Fig 6.3(b) shows the magnetic field and momentum inside the ghost cells set by a flow-out boundary condition. In a free flow-out condition, any wave in the model leaves the simulation domain through advection and does not return to the domain. However, the problem with this boundary condition is propagation of information in the upstream direction when the velocity is also flowing into the domain. If the ghost cells are determined by the information in the downstream, the information in the downstream (i.e., the simulation domain) starts to influence the incoming flow. Only a supersonic outflowing motion toward the boundary avoids the unphysical result [128].

Fig 6.3(c) shows the magnetic field and the momentum inside the ghost cells set by a periodic boundary condition. A periodic boundary condition is used when the simulation domain is obviously periodic in a certain direction. However, the periodic boundary condition needs to be used carefully since the periodic boundary condition eliminates any artificial boundary effects. Therefore, the periodic boundary condition is used when there are no artificial damping or forcing effects of the boundary [128].

Fig 6.3(d) shows the magnetic field and the momentum inside the ghost cells set by a conducting boundary condition. Here the momentum is reflected off of the simulation domain just as in the reflecting boundary condition. However, the tangential magnetic field is reversed while the normal magnetic field remains the same. Since the magnetic field of the incident wave induces current only on the surface of a perfect conductor and a perfect conductor has no field inside, the magnetic field generated inside the conductor should cancel the incident field. That is why the tangential field inside the ghost cells should be $\pi/2$ out of phase.

A user-defined boundary condition is also available. With a given-state boundary condition, an artificial wave or influx of matter at the boundary can be imposed [128]. However, this imposed-state boundary condition works only if the incoming momentum flux is greater than the pressure in the modeling domain, and the user-defined condition should be scrutinized.

In the simulation described here, the following boundary conditions are applied: 1) the momentum and the magnetic field are reflected at the axis with zero radial magnetic field (reflecting boundary condition), 2) the plasma is reflected at the outer wall (momentum reflecting condition), 3) the simulation is azimuthally symmetric (periodic boundary condition), and 4) the plasma freely moves out of the boundary in the axial direction (flow-out condition). Particularly, the reflecting boundary condition at the axis also ensures $B_r |_{x=x_{min}} = 0$, which is required to satisfy $\nabla \cdot \vec{B} = 0$ at the axis. The boundary conditions are depicted in Fig 6.4.

The Athena code includes a number of non-linear Riemann solvers for solving problems involving shock waves, contact discontinuities, and other high resolution flows [128]. The Roe solver, which is considered the most powerful linear Riemann solver and has advantages over other solvers for its small numerical diffusivity
and high resolution for shock capturing, can produce an unphysical result or negative values \[128\]. Therefore, in the simulations, HLLD solver is used instead. While HLL solvers are believed to be over-diffusive, the HLLD solver is found to be comparably accurate to the MHD extension of the Roe solver \[130\].

### 6.6 Results

#### 6.6.1 Plasma Gun and Guiding Magnets

Fig. 6.5 plots the mass density inside the device. The orange square and the grey square indicate the positions of the grey guiding magnet and the theta coil, respectively. Here the theta coil has no current flowing but the position of the theta coil is added to help visualize the system. In Fig 6.5(a) one can see the propagation of the plasma toward the target region. The mass density is distributed uniformly.

With the guiding magnetic field, the simulation changes dramatically. Plasma is accumulated near the guiding magnets where the magnetic field starts to increase. Fig. 6.6 shows plots of mass density and plasma pressure at the cylindrical axis of the simulation domain. Note that 0 cm of the x-axis corresponds to the center of the theta coil. It is shown that the density and pressure increases near the guiding magnets and the peak plasma pressure of 0.18 atm in Fig 6.6(b) is the same as the magnetic pressure by the guiding magnetic field (= 0.21 T in the simulation domain = 0.18 atm). The density and the plasma pressure decrease at the target chamber, and the plasma pressure, which is a good measure of plasma thermal energy, decreases by $\sim$ 30 %. The plasma velocity increases from 40 km/s to 50 - 60 km/s due to magnetic nozzle effect \[100\], while the density decreases by $\sim$ 30 % as shown in Fig 6.6(a). Therefore, the results indicate that the drift energy is similar to a non-magnetic case while the thermal energy is reduced by $\sim$ 30 %. While the simulation does not consider the loss of plasma at the wall by recombination or deposition of particle energies \[132\],

![Image of boundary conditions](image)

Figure 6.4: The boundary conditions applied to the simulations. It consists of the reflecting boundary conditions at the radial directions, the periodic boundary condition at the azimuthal direction, and the flow-out condition at the axial directions.
the results give us a clue as to the reduction in plasma energy with the guiding magnetic field.

### 6.6.2 Theta Pinch and Guiding Magnets

Fig 6.7 shows the change in density for two different conditions. The guiding magnetic field in Fig 6.7(a) is in the same direction as the theta pinch magnetic field, and Fig 6.7(b) is when the guiding magnetic field is in the opposite direction of the theta pinch magnetic field. Fig 6.7(b) shows that the plasma from the pinch starts to diverge as it moves closer to the guiding magnet. This result is in remarkable contrast to Fig 6.7(a) where the plasma is compressed and transported better than Fig 6.7(b). When the guiding magnetic field is opposite of the theta pinch magnetic field, the plasma expands rapidly at the magnetic null formed between the theta pinch magnetic field and the guiding magnetic field. Fig 6.8 shows the temporal evolution of the density and the pressure at the axis in the target chamber as a function of time. It also shows that the plasma transports more efficiently to the target chamber with the guiding magnetic field in the same direction as the theta pinch magnetic field.

### 6.7 Summary

In this chapter, it is shown that

- Ideal MHD is found to be a reasonable approximation, except the viscosity and the radiation effects for the plasma transport simulation. The Athena MHD code may be able to simulate behaviors of the plasma in the experimental condition.

- The basic physics of Athena are revisited and initial / boundary conditions are discussed. A partial compression of the plasma by the theta pinch is assumed as an initial condition. The reflecting boundary condition are applied at the axis as well as at the wall boundary. Flow - out condition is applied at the axial ends.

- Simulation results on the effect of the guiding magnetic field on the plasma gun show that magnetic pressure at the guiding magnets prevents the plasma from transport and is in agreement with experimentally measured reductions in plasma energies with the guiding magnetic field. Simulations also show the divergence of the plasma when the magnetic field of the guiding magnet is in the opposite direction to the theta pinch magnetic field.
Figure 6.5: Density plots calculated with Athena MHD code at various times for two different conditions (a) without guiding magnetic field (b) with guiding magnetic field. Data at five different times are shown: 0, 2.5, 5, 7.5, 9.5 µs.
Figure 6.6: (a) Density and (b) pressure plots calculated with Athena MHD code at the axis cell. The guiding magnetic field is present and time is 9.5 µs. 0 cm on the x-axis corresponds to the center of the theta coil.
Figure 6.7: Density plots calculated with Athena MHD code at various times for two different conditions (a) the guiding magnetic field in the same direction as the theta pinch magnetic field (b) the guiding magnetic field in the opposite direction to the theta pinch magnetic field. Data at eight different times are shown: 0, 0.25, 0.5, 0.75, 1, 1.5, 2, 3 $\mu$s.
Figure 6.8: (a) Density and (b) pressure plots calculated with Athena MHD code as a function of time at the axis in the target chamber. Black lines are when the guiding magnetic field is in the same direction as the theta pinch magnetic field and red lines are when the guiding magnetic field is in the opposite direction to the theta pinch magnetic field.
Chapter 7

Lithium Vapor Shielding Experiment

7.1 Introduction

A number of theoretical and experimental models predict a reduction in plasma energy delivered on various materials \[133, 134, 135, 80, 117\] compared to the incoming plasma energy. The reduction is attributed to the erosion and ionization of the materials. When the ablated or sputtered particles form a vapor shielding layer above the surface of the material, the dense and low temperature plasma absorbs a significant fraction of the incident plasma power. The vapor shielding phenomenon is also further verified by the difference in ablation rates between plasma gun experiments and laser / electron beam experiments \[136, 137\].

Recently, liquid metal plasma-facing components have drawn interest from researchers due to a low recycling effect and a high chemical affinity. Not only that, the benefit of the vapor shielding effect for lithium wall was also discovered by computational work \[134\]. Research results at the T - 11 M tokamak in Russia \[20, 21\] experimentally showed that 1) lithium on the vessel wall removes up to 80 % of ohmic power to the wall, 2) non-coronal radiation of lithium protected the limiter from high power loads, and 3) the emissivity of the lithium radiation may reach 1000 - 1500 eV per Li atom at \(T_e = 20 - 50\) eV. Fig 7.1 shows the amount of non-coronal radiation by one Li atom and an experimentally measured energy reduction with the lithium wall.

As part of an effort to study the dynamic effect on plasma-facing materials in fusion reactors, a conical theta pinch was constructed in the Center for Plasma Material Interactions (CPMI) at the University of Illinois at Urbana-Champaign by a former graduate student. Experiments showed an evidence of a reduction in energy with a lithium coating on a stainless-steel target \[8\]. The vapor shielding effect is also observed at a lithium-coated molybdenum target at a low gas pressure (\(\sim 2\) mTorr) \[17\]. Fig 1.6(a) shows a reduction in energy on the stainless steel and Fig 7.2 in the molybdenum target.

Here, we extended the former experimental results by performing vapor shielding experiments in the new device. Diagnostic tools measure the dynamics of the formation of the vapor cloud and are used to determine the net erosion of the lithium target as well as the total power load onto its surface. A collisional-radiative
Figure 7.1: (a) Non-coronal lithium radiation evaluation data \cite{20, 21} (b) Relative energy coming to lithium limiter vs its initial temperature in ohmic mode \cite{21}

Figure 7.2: Incident energy measurement for bare molybdenum (black square dot) and lithium coated molybdenum (blue triangle dot) indicates a reduction in the energy at low pressure \cite{17}. 

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model for neutral and singly charged lithium is used to characterize the lithium vapor and to correlate it with other measurements.

### 7.2 Theory: Corona Equilibrium Model for Lithium Vapor Shielding

#### 7.2.1 Corona Equilibrium

We use the corona equilibrium model \[\text{[138, 19]}\] for the analysis, assuming that the energy from the plasma is absorbed in the plasma and radiated out by emission processes. In this corona equilibrium model, only transitions of lithium from or to the ground state are considered. In order to satisfy the corona equilibrium, the electron density and electron temperature should meet the following inequality \[\text{[22]}:\]

\[
n_e \ll 1.4 \times 10^{20} z^7 \left( \frac{T_e}{z^2 I_z} \right)^4
\]

(7.1)

where \(n_e\) is electron density in m\(^{-3}\), \(z\) is atomic number of the ion \(T_e\) and \(I_z\) are electron temperature and ionization energy in eV. Fig 7.3 shows a plot of the necessary condition of the electron density for corona equilibrium.

![Figure 7.3: The necessary condition of electron density for corona equilibrium in hydrogenlike plasma \[\text{[22]}\]](image)

The electron - impact ionization collision cross sections and the electron - induced excitations in \[\text{[23]}\]
are taken into account for the energy absorption of neutral and singly charged lithium vapor particles. For ionizations, the 1st ionization \((E = 5.39 \text{ eV})\) and the 2nd ionization \((E = 75.6 \text{ eV})\) are considered. For the excitations from the ground state or de-exciations to the ground state of neutral lithium, quantum states of \(2s, 2p, 3s, 3p, 3d, 4s, \) and \(4p\) are included in the model. For the excitations or de-exciations of singly-ionized lithium, transitions of \(1s2s^3S, 1s2p^3P, 1s2s^1S, \) and \(1s2p^1P\) to \(1s^23S\) are considered. Fig 7.4 shows cross sections and rate coefficients of various electron-impact excitations and ionizations of lithium. These cross sections and the rate coefficients are found at International Atomic Energy Agency Numerical Database [23].

Figure 7.4: (a) The cross section of the electron-impacted excitations of lithium neutrals (b) the rate coefficients of the electron-impacted excitations of lithium ions (c) the total electron-impacted cross sections of lithium neutrals and ions as a function of electron temperature [23]

For a given \(T_e\), it is questionable what distribution function the electrons follow. Maxwellian distribution is valid if elastic collisions dominate electron energy loss and the electron-neutral collision frequency is constant. If electron’s mean free path is constant regardless of the electron energy, Druyvesteyn distribution
gives a better approximation than Maxwellian distribution and it is truly the case for many low pressure plasmas. However, here, a number of collisions between the particles takes place and thermal effect may be important so that Maxwellian distribution of electron temperature is assumed. Maxwellian distribution is given by a following relation:

$$f(E)dE = 2\sqrt{\frac{E}{\pi}} \left(\frac{1}{kT_e}\right)^{3/2} \exp\left(-\frac{E}{kT_e}\right)dE$$  \hspace{1cm} (7.2)$$

Therefore, the reaction rate for each reaction is

$$<\sigma v> = \int \sigma(v)f(v)vdv$$

\begin{align*}
= \int_E \sigma(E)2\sqrt{\frac{E}{\pi}} \left(\frac{1}{kT_e}\right)^{3/2} \exp\left(-\frac{E}{kT_e}\right)\frac{2E}{m} \sqrt{\frac{m}{2E}}dE (7.3)
\end{align*}

$$= \int_E \sigma(E)2\sqrt{\frac{E}{\pi}} \left(\frac{1}{kT_e}\right)^{3/2} \exp\left(-\frac{E}{kT_e}\right)\sqrt{\frac{2E}{m}}dE$$

where $\sigma$ is the cross section of each reaction. Here, we assume that the velocity of the lithium is very small and can be approximated as stationary. This assumption is valid because Thompson’s model predicts the energy of the sputtered particles has an energy distribution satisfying the relation [24]:

$$Y(E,\theta) = \frac{CE \cos \theta}{(E + U)^{n+1}}$$  \hspace{1cm} (7.4)$$

where $n$ normally equals 2 and $C$ is a normalization constant. The energy distribution at normal incidence is plotted at Fig 7.5. According to this relation, the energy distribution of the sputtered lithium has a peak at $\sim 1$ eV and thereby the velocity of the sputtered lithium is much lower than for electrons. Therefore, the effect of the velocity of lithium is ignored in Eq. (7.3).

### 7.2.2 Ejection of Lithium off the Target

The ejection of lithium off the target is mainly due to two processes: physical sputtering and evaporation. Here, other macroscopic lithium ejection processes such as splashing of lithium due to an MHD force or the boiling / explosion of gas bubbles in the liquid are not considered. This is valid for our case where we use solid lithium coating and the thickness of lithium film is only a few micrometers, as opposed to macroscopic particles with average sizes of a few tens of micrometers [133].
Figure 7.5: Energy distribution of lithium sputtered off the surface based on Thompson’s model [24].

The evaporation from the surface into a vacuum is given by this relation

\[ J = \frac{P}{kT} \sqrt{\frac{8kT}{\pi m}} \]  (7.5)

where \( J \) is the evaporation rate in molecules/m²s, \( T \) is the temperature in kelvin, and \( P \) is the vapor pressure of lithium in Pa. The vapor pressure of lithium is following this relation [139]:

\[ \ln P = 26.89 - \frac{18880}{T} - 0.4942 \ln T \]  (7.6)

where \( P \) is in Pa and \( T \) is in kelvin. There is another relation for lithium vapor pressure [140],

\[ P = \exp^{184 - 18750/T} \]  (7.7)

where \( P \) is in Torr and \( T \) is in kelvin. Fig. 7.6 shows the evaporation flux off the lithium surface as a function of time. Evaporation is strongly related with temperature of lithium and two analytic formulas [139, 140] produces similar results.

Physical sputtering is one of the major erosion processes induced by ions. Physical sputtering, purely a physical process, is caused by elastic energy transfer from incident particles to atoms in a target. And the atoms are ejected out of the surface if enough energy is transferred to overcome the surface binding energy.
Figure 7.6: Evaporation of lithium as a function of temperature

The sputtering yield, the average number of atoms ejected from the target per incident ion, is dependent on many factors, including the incident angle of the ion, the energy of the ion, and the surface binding energy of the target, surface morphology, the target temperature, and so on.

The physical sputtering yield of a clean and flat surface of lithium by hydrogen atoms can be calculated or found in several ways. Fig 7.7 shows the reflection and the sputtering yield of hydrogen atoms incident on lithium surface calculated using SRIM [141], the Bohdansky model, or found at [23]. For the Bohdansky model, the following empirical formula is used to estimate sputtering yield at normal incidence [142, 26]:

\[
Y(E, \alpha = 0^\circ) = Q s_n^{KrC}(\epsilon) \left[ 1 - \left( \frac{E_{th}^{2/3}}{E} \right) \right] \left( 1 - \frac{E_{th}}{E} \right)
\]

(7.8)

where

\[
Q = \frac{0.042}{E_s} \alpha_f(M_2/M_1)
\]

\[
s_n^{KrC}(\epsilon) = \frac{0.5 \ln(1 + 1.2288 \epsilon)}{\epsilon + 0.1728 \sqrt{\epsilon} + 0.008 \epsilon^{0.1504}}
\]

\[
\epsilon = E \frac{M_2}{M_1 + M_2} \frac{a_L}{Z_1 Z_2 e^2} = E / E_{TF}
\]

\[
E_{TF} = \frac{Z_1 Z_2 e^2}{a_L} \frac{M_1 + M_2}{M_2}
\]

\[
E_{th} = \frac{(M_1 + M_2)^4}{4M_1 M_2(M_1 - M_2)^2} E_s
\]

\[
a_L = 0.4685 \left( Z_1^{2/3} + Z_2^{2/3} \right)^{-1/2}
\]

(7.9)
Figure 7.7: The reflection and the sputtering yield of an hydrogen particle incident on lithium surface. The reflection coefficient (blue inverted triangles) is calculated with SRIM based on the number of backscattered ions from the lithium surface. The sputtering yield of hydrogen is calculated three different ways: (a) calculated with SRIM (green triangles) (b) from [23] (black dots) (c) from [24] considering the reflection and attraction of ions at the surface (red line).

where $E_s$ is the surface binding energy of lithium, $M_1$ and $M_2$ are the incident particle mass and target mass respectively, $Z_1$ and $Z_2$ are the nuclear charges of the incident particle and the target, and $a_L$ is in Angstroms. Fig 7.7 shows that the sputtering yield of hydrogen on solid lithium has a peak value of 0.01 - 0.03 at an incoming particle energy of 100 eV or greater.

The sputtering yield is further changed by thermal effects or surface morphology. The enhancement of sputtering yield with increasing temperature, even when the temperature is still below the melting temperature, has been reported in various cases. When the target material liquefies and the temperature increases even further, the sputtering yield is enhanced as well. For example, an increase in the sputtering yield of liquid lithium with target temperature is shown in [25]. VFTRIM - 3D, TRIM framework with surface roughness taken into account, also shows a change of sputtering yield from the smooth surface condition [26, 143].

Another factor that contributes to the sputtering yield is the change in composition of a target material. TRIDYN [144], when calculating the sputtering yield, takes into account the change of compositions by atomic collisions during ion bombardment. Ref. [145] summarizes that the trapping level of hydrogen and deuterium in lithium may reach 50% H / Li, while the phase diagram of lithium - lithium hydride in solid lithium is approximately 20%. As shown in Fig 7.9, the sputtering yield of lithium drops significantly,
approximate by a factor of 4, when the concentration level of H/Li reaches 1:1.

Fig 7.10 shows the flux of lithium from target by hydrogen bombardment. Here, the sputtering yield is assumed to be 0.01. At $n_e = 10^{21} \text{ m}^{-3}$ and $v = 50 \text{ km/s}$, the ejected lithium flux from sputtering is estimated at around $\Gamma = \gamma n_e v \sim 5 \times 10^{23} \text{ m}^{-2} \text{s}^{-1}$. Since this flux is three orders of magnitude higher than the lithium flux from the evaporation process at 400 °C ($= 4 \times 10^{20} \text{ m}^{-2} \text{s}^{-1}$), it is assumed that all lithium from lithium target is produced by a physical sputtering process.

### 7.2.3 Energy Absorbed in Lithium Vapor

The reaction rate of lithium and electrons and the total energy absorbed and radiated in a lithium cloud are given by the following relations:

$$ R = n_e n_{Li} < \sigma(v)v > $$

$$ E_{vapor} = \int_{V'} R d\nu dV dt $$

(7.10)

where $R$ is the reaction rate, $n_e$ and $n_{Li}$ are the electron and lithium densities, $v$ is the electron velocity assuming that the electron velocity is much faster than the lithium velocity, $E_{vapor}$ is the energy absorbed and radiated in a lithium cloud, and $V'$ is the volume of lithium vapor. The lithium density is approximated.
Figure 7.9: Sputtering yields of lithium by hydrogen bombardment at several elemental compositions.

Figure 7.10: Sputtered lithium flux from a target as a function of plasma density and plasma velocity.
by the following relation:

\[
\Gamma_{Li} = \gamma n_e v_{bulk}
\]

\[
\frac{dn_{Li}}{dt} \sim \frac{\gamma n_e v_{bulk}}{l} - \frac{n_{Li}}{\tau_{diff}}
\]

where \(v_{bulk}\) is the advection velocity of plasma, \(l\) is the length of lithium vapor, and \(\tau_{diff}\) is the diffusion timescale for lithium. The first term on the right side of Eq. (7.11b) is a source term, while the second term represents a sink term. \(v_{th, Li}\), the thermal velocity of lithium is approximately \(5 \times 10^3\) m/s, according to Fig 7.5. The diffusion timescale \(\tau_{diff}\) is calculated using:

\[
D = \frac{1}{2} \lambda v_{avg}
\]

\[
\tau_{diff} = \frac{\chi^2}{6D}
\]

where \(\lambda\) is the mean free path, \(v_{avg}\) is the average velocity of lithium ion / molecules, and \(\chi\) is the characteristic length of the diffusion, approximated as half the length of the side of a target. The analytical solution of (7.11b) is given by:

\[
n_{Li}(t) = \frac{\gamma n_e v_{bulk} \tau_{diff}}{l} \left( 1 - \exp \left( -\frac{t}{\tau_{diff}} \right) \right)
\]

Using Eq. (7.11b), Eq. (7.10) is written as

\[
E_{vapor} = \int V' n_e n_{Li} <\sigma(v)v> dV dt
\]

\[
\sim n_e n_{Li} v_{bulk} A \Delta t \int <\sigma(v)v> dv
\]

where \(A\) is the area of the lithium vapor and \(\Delta t\) is the duration of the plasma pulse. The area of lithium vapor is assumed to be the same as the area of the target.

Since Eq. (7.14) considers only one reaction, the total energy absorbed in the lithium cloud is the summation of all possible reactions between electrons and lithium. Assuming that electron - impact excitation and ionization are the dominant processes of energy loss between lithium vapor cloud and electrons, the
reaction rate is determined by the following equations:

\[
\begin{align*}
\Delta E_{\text{exc},0} & \sim \sum_n \frac{1}{3} n_e n_{Li} < \sigma_{\text{exc},0} v > k E_{\text{exc},0} n \Delta t \\
\Delta E_{\text{ion},0} & \sim \frac{1}{3} n_e n_{Li} < \sigma_{\text{ion},0} v > k E_{\text{ion},0} n \Delta t \\
\Delta E_{\text{exc},1} & \sim \sum_n \frac{2}{3} n_e n_{Li} < \sigma_{\text{exc},1} v > k E_{\text{exc},1} n \Delta t \\
\Delta E_{\text{ion},1} & \sim \frac{2}{3} n_e n_{Li} < \sigma_{\text{ion},1} v > k E_{\text{ion},1} \Delta t \\
\Delta E_{\text{vapor}} & \sim \Delta E_{\text{exc},0} + \Delta E_{\text{ion},0} + \Delta E_{\text{exc},1} + \Delta E_{\text{ion},1}
\end{align*}
\]  

where the subscripts exc and ion mean excitation process and ionization process, respectively, the subscripts 0 and 1 mean neutral lithium and singly ionized lithium, respectively, \(E\) is energy change in a certain transition in eV, and \(n\) is the excited quantum energy level of the neutral and ionized lithium.

Fig 7.11 shows the energy radiated by lithium vapor as a function of \(T_e\) according Eq. 7.3. Here the plasma density is assumed to be \(1 \times 10^{20} \text{ m}^{-3}\) and the sputtering yield is 0.02. It shows that the de-excitation of the neutral lithium is the most dominant radiation loss process and the total radiation loss increases rapidly up to \(T_e \sim 50\) eV. Since the cross sections of electron-neutral lithium reactions start to decrease as electron temperature increases above approximately 10 eV, radiation loss also starts to decrease with its peak at \(\sim 50\) eV. Note that (7.15) is a function of the electron temperature, the incident ion energy, the plasma density, the duration of pulse and the plasma flow velocity. Since many physical quantities such as sputtering yield, electron temperature, and plasma density change with time and the measurements have large uncertainties, the model is only approximate, and an order of magnitude comparison is adequate.

### 7.2.4 Deviation from Corona Model and Optical Depth

When the lithium cloud has a high density, re-absorption may take place. The optical depth is a measure of transparency and radiation transfer. These quantities can be summarized in the optical depth, which is a measure of transparency and radiation transfer. For example, complete thermal equilibrium is achieved when all radiations produced by the plasma are reabsorbed. In order for the plasma to be optically thick, \(\kappa_{\nu} \times l \gg 1\) where \(\kappa_{\nu}\) the absorption coefficient for free-free transitions in a hydrogen-like plasma and \(l\) is the plasma dimension. \(\kappa_{\nu}\) is given by [146]:

\[
\kappa_{\nu} = 3.692 \times 10^8 g Z^2 T^{-1/2} \nu^{-3} n_e n_i
\]  

\[\text{(7.16)}\]
where $\kappa_\nu$ is in cm$^{-1}$, $g$ is the Gaunt factor, $\nu$ is the frequency for the radiation of interest, $Z$ is the ionic charge, $n_e$ are $n_i$ are the electron and ion densities in cm$^{-3}$, $T$ is the temperature of electrons in kelvin. For example, $n_i = n_e = 10^{16}$ cm$^{-3} = 10^{22}$ m$^{-3}$, $T$ is 11400 (= 1 eV), $\nu = 10^{14}$ s$^{-1}$ gives an absorption coefficient of $1.6 \times 10^{-6}$ cm$^{-1}$ and $l \gg 6.3 \times 10^5$ cm = $6.3 \times 10^3$ m. Therefore, in a laboratory plasma, complete thermal equilibrium cannot be generally realized. However, the situation is quite different for the bound - bound transition. The fact that the plasma emits a specific wavelength of radiation implies that it can also reabsorb the same wavelength of radiation as well. When the optical depth for the resonance lines approaches or exceeds unity, photo - excitation may become significant and the assumption of spontaneous decay in the corona model no longer holds. A collisional radiative model is the best way to take into account both radiative processes and collisional processes, but the modeling becomes very complex. Here, an optical depth compensation is introduced.

For Doppler broadened spectral lines, the optical depth $\tau$ at the central wavelength $\lambda_0$ in a plasma of depth $d$ is

$$\tau = 5.5 \times 10^{-17} \lambda_0 N d (\mu/kT)^{1/2} \quad (7.17)$$

with $d$ is in cm, and $\mu$ is the atomic mass number, $kT$ is electron energy in eV, $N$ is the absorbing particle density in cm$^{-3}$, $\lambda_0$ is the wavelength of radiation of interest in Angstroms, and $f$, the absorption oscillator strength, is assumed to be 0.5.

Fig 7.12 shows optical depths for hydrogen and lithium as a function of the plasma density and electron temperature. It is found that the re - absorption of lithium lines is significant when the lithium cloud density

Figure 7.11: The energy radiated by lithium vapor (a) for each reaction and (b) all reactions. Here the plasma density is $1 \times 10^{20}$ m$^{-3}$ and the sputtering yield is assumed 0.02. Total plasma energy is included for comparison.
increases to over $10^{19}$ m$^{-3}$ when the thickness of the lithium vapor is 0.5 cm. This is truly the case based on Fig. 7.5. With $\tau \gg 1$, the radiation transfer is changed to:

$$I_\lambda \approx S_\lambda = \frac{\epsilon_\lambda}{\kappa_\lambda} = \frac{\epsilon_\lambda I}{\kappa_\lambda l} = \frac{I_0}{\tau}$$

Therefore, when the density of lithium is greater than $10^{19}$ m$^{-3}$, the optical depth correction needs to be taken into account. This approximation is more valid when $\tau \gg 1$. For the new device, the lithium density can be as high as $\sim 10^{20}$ m$^{-3}$ so that the corona model is incorrect and the optical depth correction for de-excitation transfer needs to be included.

### 7.3 Experimental setup

#### 7.3.1 Lithium Magnetron and Lithiated Molybdenum Target

The 55 mm wide, 55 mm long, and 0.076 mm (= 0.003 inch) thick molybdenum target has a K-type thermocouple bead spot welded on its back surface to measure the temperature increase. A commercially available, 2 inch magnetron is used to deposit lithium onto the molybdenum sheet. The lithium target for the magnetron is fabricated in an argon-filled box to reduce its reaction with air and is discharge-cleaned for 30 min to sputter off the remaining lithium impurities on the target. The deposition process is carried out at 200 - 300 V, 250 mA discharge voltage and current for 1 hour. The distance between the magnetron...
and the molybdenum target is less than 1 cm so that most of the sputtered lithium from the magnetron is deposited on the molybdenum. Assuming 100 % deposition to the target and considering the sputtering yield and the secondary electron emission, the thickness of the lithium coating is approximately 1 - 3 µm. Fig 7.13 shows the sputtering yield of argon on lithium calculated with SRIM. Fig 7.14 shows the plasma during the deposition process, the racetrack of the lithium target after cleaning and deposition, and a lithiated molybdenum target after lithium deposition and a number of shots.

7.3.2 Thermal Response Model for the Molybdenum target

The behavior of lithium is highly dependent on the surface temperature of the target. While it is extremely difficult to experimentally measure the surface temperature of a target without dual-band infrared thermography, and thermocouples have very slow response time, an approximation of the calibration factor for the measured temperature of the target and the surface temperature using a thermal response model [8] gives a rough estimate of the surface temperature of the molybdenum target.

The thermal response model is using a with PSPICE simulation. Because the lithium is very thin (∼ 1µm) and the effect of lithium on the thermal response of the molybdenum target is negligible, the model does not take into account the thermal properties of lithium. According to Eq. (2.9), the thermal capacitance of the target is estimated to be 0.6 J/K. The resistance of the target for the thermal conduction from the front to the back is approximately 2 ×10⁻⁴K/W, while the thermal resistance from the side to the center
is 24 K/W. These thermal resistances and capacitances lead to a thermal response time of 100 $\mu$s for the conduction from the front to the back surface and 14 s for the conduction from the side to the center. Since a 2 mm diameter exposed thermocouple bead has an approximate thermal resistance and capacitance of 10 K/W and 0.02 J/K, this calculation shows that the thermocouple does not have enough time resolution to compensate for heat loss from the front of the target to the end. Moreover, the thermal capacitance of the target is comparable with the thermocouple bead, again implying the necessity of a proper thermal response model.

The values of thermal resistance and capacitance for the target are estimated using Eq. (2.9). Due to difficulty in estimating the thermal elements of the thermocouple and the wires, these values are fitted with experimental data. The relation of the measured temperature and the actual temperature is plotted in Fig 7.15(b). Fig 7.15(b) shows that the surface temperature for the molybdenum is approximately 1.3 times higher than the peak temperature measured by the thermocouple.

7.4 Results: Theta Pinch Plasma Vapor Shielding Experiment

Here, we initially use the previous version of the theta pinch device with an inductively - coupled plasma source to test vapor shielding. This device is characterized with a smaller plasma density ($\sim 10^{20} \text{ m}^{-3}$) and a lower operating pressure ($p \leq 10 \text{ mTorr}$). A single-turn, four-segmented theta coil with a conical angle of 1 $^\circ$ is connected to a 36 $\mu$F main capacitor bank. In this experiment, the charging voltage is fixed at 20 kV, yielding 7.2 kJ energy in the capacitors. A four - turn coil for the preionization is located next to the the
theta coil. The preionization coil is driven by an 1 $\mu$F capacitor charged at 9 kV. The preionization coil is fired 30 $\mu$s before the main capacitors to the theta coil is triggered.

Fig. 7.16 shows temporal behaviors of the plasma density and electron temperature measured using a triple Langmuir probe at 2 mTorr and 9.5 mTorr. At 9.5 mTorr, the electron temperature stays almost constant and remains at 2 - 5 eV. The 2 mTorr case shows more fluctuations in the density between $1 - 3 \times 10^{20}$ m$^{-3}$ and the temperature between 20 - 40 eV. This difference results from the fact that the plasma suffers from more collisions at higher pressures, as they are transported to the target and lose their energy to the nearby particles. Since the theta pinch preferentially heats ions over electrons, the ion thermal temperature is assumed to be identical to that of electron. Moreover, sheath potential drop at a surface is given by:

$$V_{\text{sheath}} = T_e \left[ \frac{1}{2} \ln \left( \frac{m_i}{2\pi m_e} \right)^{1/2} \right]$$

(7.19)

the energy of the ions when reaching the target is $\sim 2.8 T_e$ without a presheath potential drop. Therefore, ions reaching the target at 2 mTorr may have ion energies $> 50$ eV since the mean free path at 2 mTorr is approximately 3 cm and the Debye length is only a few micrometers. At 9.5 mTorr, however, the ion energy gain drops to $< 10$ eV. These differences result in a difference in sputtering yield, and thereby a change in the absorbed energy.

In order to verify the reasonability of the triple Langmuir probe data, a comparison between transferred energy to the target measured by the thermocouple and by the triple Langmuir probe is carried out. The incident energy to the target is calculated with parameters from the triple Langmuir probe with the heat
Figure 7.16: Temporal behavior of (left) plasma density and (right) electron temperature (top) at 2 mTorr and (bottom) at 9.5 mTorr with two shots at each pressure. Black and red dots indicate two independent experiments at the same condition [17].

transfer coefficient $\gamma_{\text{heat}}$ defined in [10], assuming that secondary electron emission is negligible. While the approach has many assumptions and the triple Langmuir probe analysis contains a large degree of error, Fig. 7.17 shows that the calculated energy from the triple Langmuir probe measurements and thermocouple data are on the same order.

Fig 7.18 shows the difference in the measured energy on the molybdenum foil with and without a lithium film, and energy loss predicted by the corona model in chapter 7.2.3. Here, the sputtering coefficient is approximated as $\gamma = 0.025$ according to Fig 7.9 with an assumed pulse length $t_p$ of 40 $\mu$s, a $T_e$ of 20 eV, and a plasma density of $1-3 \times 10^{20}$ m$^{-3}$ based on the triple Langmuir probe data. The energy absorbed in the lithium vapor predicted by the corona model is $2.5 \pm 2$ J at 2 mTorr and approximately 0 J at 9.5 mTorr due to a lack in sputtering yield of lithium and very low plasma density ($\sim 2 \times 10^{19}$ m$^{-3}$). The energies experimentally obtained are $2.7 \pm 1.7$ J at 1.6 $\pm 0.3$ mTorr and $2.8 \pm 2.2$ J at 5.2 $\pm 0.3$ mTorr. Therefore,
Figure 7.17: Incident energy on the target estimated by triple Langmuir probe data with $\gamma_{\text{heat}} = 6.5$ (solid squares) and $\gamma_{\text{heat}} = 4.8$ (empty squares) shows the similar behavior as the actual temperature increase measured by thermocouple (triangle) [17].

The results show that theoretical values are in agreement with experimental values and the model reproduces relatively well the trend of the energy absorption at two different pressures.

### 7.5 Results: Vapor Shielding Experiment in a New Device

The upgraded device is characterized by 1) a higher density ($\geq 10^{21}$ m$^{-3}$) plasma generation and a higher pressure operation ($\geq 100$ mTorr) and 2) modified plasma transport with the guiding magnetic field when operating the guiding magnets and crowbar in conjunction. The transport of the plasma with the guiding magnetic field may be able to deliver highly energetic particles to the target more efficiently.

However, a relatively large operating pressure ($\sim 100$ mTorr) results in numerous collisions of ions with the background neutral particles so that the ions may lose a considerable amount of energy through momentum transfer. Ejected lithium particles will also have numerous collisions with neutrals, and the plasma has a larger plasma pressure, meaning that the thickness of the lithium vapor will be reduced as well.

**Chemical Reaction of Lithium**

As described earlier, hydrogen is retained in the lithium surface with a maximum retention ratio of 1:1. The chemical reaction forming lithium hydride or lithium hydroxide is exothermic, so that the temperature
may actually increase. For example, the chemical reaction of lithium and hydrogen forming lithium hydride has an enthalpy of -22 kcal at room temperature. If all the lithium is converted to lithium hydroxide, the reaction gives off a maximum of $\sim 60$ J (for hydroxide, -116 kcal ($\sim 300$ J).

Fig 7.19 shows the change in the target temperature as a function of time. An $\text{H}_2 / \text{O}_2$ plasma is formed by a DC discharge at 50 mA of current to stimulate lithium oxide / hydroxide formation. The plasma treats the lithium in the magnetron for 30 minutes before lithium deposition. Two noticeable changes are observed. First, the temperature drops much slower for regular cases. Second, the chamber reaches base pressure much quicker after lithium deposition. These results suggest that lithium absorbs $\text{H}_2 / \text{O}_2$ and the formation of a lithium compound releases heat, increasing the target temperature. The increase of the target temperature is also shown in the first few plasma shots in the new device. Therefore, for the experimental data presented below, a lithiated molybdenum target is conditioned with a few plasma gun shots before taking data.

**Lithium Vapor Shielding: Plasma Gun**

Fig 7.20 shows the temperature changes measured with the molybdenum foil with and without a lithium coating. Five different operating scenarios are tested: 1) plasma gun at 5 kV, 2) plasma gun at 5 kV with guiding magnetic field, 3) plasma gun at 6 kV, 4) plasma gun at 6 kV with guiding magnet, and 5) plasma gun at 6 kV, theta pinch at 15 kV, guiding magnetic field, and crowbar. Temperature increases in the new
device are much greater than those in the prototype device in Fig 7.2, increasing over 300 - 400 °C. Two or more shots are tested at each experimental condition to determine statistical variation.

In Fig 7.20, a lithium film on the target results in negligible differences in temperature for the plasma gun shots. Fig 7.21 shows an electrical signal and the evolution of the plasma parameters as a function of time. A plasma density of $1 \times 10^{21} \text{m}^{-3}$ and an electron temperature of 20 - 30 eV are obtained during a 150 µs pulse duration. The advection velocity of the plasma is approximately 25 - 40 km/s, resulting in an ion drift energy of 4 - 8 eV. This value is reasonable since the theoretical plasma energy using Eq. (2.4) with $n_e = 2 \times 10^{21} \text{m}^{-3}$, $T_e = 20 \text{eV}$, $v = 2.5 \times 10^4 \text{m/s}$, $t_p = 150 \mu\text{s}$, is approximately 200 °C. Considering uncertainties in the triple Langmuir probe measurement, the measured plasma parameters are in good agreement with the temperature increase on the target.

Since the mean free path at 100 mTorr is less than 1 mm and the typical length of vapor shielding is ~ 5 mm, the lithium vapor is collisional. This causes the lithium to diffuse out slowly. The diffusion time calculated using Eq. (7.12) is approximately 50 µs. According to (7.19), the sheath potential at the surface can be $V_{\text{sheath}} > 50 \text{eV}$ and the sputtering yield of the hydrogen-enriched lithium surface by hydrogen bombardment is approximated as 0.003, as shown in Fig 7.9.

In this case, the sputtering of lithium by hydrogen may be low. Assuming $n_e = 1 \times 10^{21} \text{m}^{-3}$, $T_e = 20 \text{eV}$, $t_p = 120 \mu\text{s}$, $v = 4 \times 10^4 \text{m/s}$, $\gamma = 0.003$, the lithium density in the vapor is approximately a $5 \times 10^{20} \text{m}^{-3}$ on the assumption of a 5 mm thickness (as shown in Fig 7.5). Since the model in chapter 7.2.3...
Figure 7.20: Temperature increases measured with the molybdenum foil with and without lithium coating in various operating scenarios. Operating scenarios are as follows: 1) plasma gun at 5 kV, 2) plasma gun at 5 kV with guiding magnetic field, 3) plasma gun at 6 kV, 4) plasma gun at 6 kV with guiding magnet, and 5) plasma gun at 6 kV, theta pinch at 15 kV, guiding magnetic field, and crowbar.

is normally accurate only in corona equilibrium with negligible collisions with neutrals and other ions, the corona model does not hold when additional processes such as collisional deexcitation, radiative excitation, photoionizations starts to play a role. Using the eq. (7.15) and optical re-absorption, the energy loss through radiation is found to be approximately 28 J (\(\sim 50^\circ\text{C}\)), which is similar to the range of the error for cases #1, 3, and 4 (30 - 70 \(^\circ\text{C}\)) in Fig 7.20.

**Lithium Vapor Shielding: Theta Pinch**

With the theta pinch and the crowbar, a reduction in the temperature by 73 ± 41 °C (= 40 ± 23 J) is observed. Fig 7.22 displays results of the triple Langmuir probe measurement when the device is operated with - 6 kV plasma gun, 15 kV theta pinch, 300 V guiding magnets, and the crowbar. \(n_e \sim 5 \times 10^{20} \text{ m}^{-3}\) and \(T_e\) is approximately 30 eV for \(\sim 100 \mu\text{s}\) of pulse. While the error bar is large, the reduced plasma density is in agreement with the reduced optical signals in Fig 5.14(c). The plasma velocity based on the optical signals in Fig 5.14(c) is \(\sim 100 \text{ km/s}\), which in turn gives a drift energy of 50 eV or higher for ions. Considering an additional sheath acceleration at the surface and a higher ion thermal temperature with theta pinch, the incident ion energy can be greater than 100 eV, and a higher sputtering yield may occur.

According to the model in chapter 7.2.3 \(n_e = 5 \times 10^{20} \text{ m}^{-3}, T_e = 30 \text{ eV}, \gamma = 0.007, t_p = 100 \mu\text{s}, v = 1.2 \times 10^5 \text{ m/s}\), the density of sputtered lithium within 5 mm of the vapor cloud (as shown in Fig 7.5) is
Figure 7.21: (a) Triple Langmuir probe measurement at 6 kV plasma gun shot. Average plasma densities, electron temperatures, and plasma velocities are plotted in (b), (c), and (d). (b) Average plasma densities for the first 30 µs (c) Average electron temperatures for the first 30 µs (d) plasma velocities measured using time of flight technique.
estimated to be $\sim 1 - 2 \times 10^{21} \text{ m}^{-3}$ and predicts a radiation energy transfer of less than 41 J ($\sim 73 ^\circ \text{C}$), which is in agreement with the experimental data.

The main differences of the plasma parameters in the theta pinch device from the plasma gun is greater sputtering with crowbar due to a faster plasma velocity and presumably hotter ions / electrons. While this calculation is very rough and the plasma parameters measured with the triple Langmuir probe have large errors, this model still gives a basic physical understanding and interpretation of the interaction of the plasma with the lithium vapor cloud.

### 7.6 Summary

In this chapter, it has been shown that

- The lithium vapor shielding phenomenon draws an interest from researchers since it can reduce the incoming plasma energy onto fusion wall materials. Sputtered lithium particles from the surface may form a vapor cloud and absorb a significant fraction of the incident plasma energy.

- Various physical quantities related with the lithium cloud formation, such as the lithium sputtering yield and the cross sections of various electron - impact lithium reactions, are revisited. A theoretical model for the plasma energy absorbed in a lithium vapor cloud is derived based on corona equilibrium.

- Experiments in a prototype theta pinch device show a reduction in plasma energy incident on a target, of $2.7 \pm 1.7 \text{ J (29 \pm 19 \%)}$ at 1.6 mTorr and approximately 0 J at 9.5 mTorr. The theoretical model
using parameters from a series of triple Langmuir probe measurements predicts $2.2 \pm 1.8$ J of energy reduction at 2 mTorr and approximately 0 J at 9.5 mTorr. The data obtained from two different approaches are in agreement with each other.

- Experiments conducted with a new plasma gun do not show much visible difference in terms of target temperature. The experiments with the plasma gun, theta pinch, guiding magnetic fields, and crowbar show approximately $40 \pm 23$ J ($26 \pm 15\%$) of energy reduction. The model predicts a similar energy level for these cases and finds that the main differences in plasma parameters for the theta pinch device and the plasma gun is a larger sputtering yield with the crowbar due to a faster plasma velocity and presumably hotter ions / electrons.
Chapter 8

Compact Toroid Experiment

8.1 Introduction

As discussed in the earlier chapters, good plasma transport from the theta pinch to the target region is necessary to allow for a high energy plasma experiment. If the plasma is confined in a magnetic field before pinching and transported to the target region while maintaining its confinement, we may be able to deliver the pinched plasma with better transport.

A compact toroid is a self-stable and self-confining toroidal plasma configuration. Therefore, better plasma transport is expected if a compact toroid is formed and maintained during magnetic pinching and translation. Since a compact toroid is normally produced in a theta pinch device or a plasma gun, this experiment can be done with minimal change to the device. A question is then whether the plasma confinement is enhanced by forming a compact toroid, and will a subsequent pinching of the compact toroid with the theta pinch further enhance further plasma transport. In this chapter, preliminary results of compact toroid experiments are presented.

8.2 Theory

The compact toroid is divided into two sub-categories: field reversed configuration and spheromak. Fig. 8.2 illustrates the difference between field reversed configuration and spheromak. In a field reversed configuration

Figure 8.1: A difference between field reversed configuration and spheromak [27]
the poloidal magnetic field is much stronger than the toroidal magnetic field. In a spheromak [29], the poloidal magnetic field is similar in magnitude to the toroidal magnetic field. Table 8.1 summarizes various compact toroids according to $s$, which is the ratio of the torus minor radius to the average ion gyroradius, according to the relative magnitudes of the poloidal magnetic field $B_p$ and the toroidal magnetic field $B_t$.

For the formation of a field reversed configuration, a field reversed theta pinch or a rotating magnetic field technique are used [3]. For spheromak formation, helicity injection or a coaxial plasma gun are typically used [29]. While the current device can be ideally applied to produce both a field reversed configuration and a spheromak, the formation of a field reversed configuration requires a sophisticated setup as well as a very fast field reversal, typically a few Alfvén transit times ($<1\,\mu s$), making the field reversed configuration harder to achieve in the current device. Therefore, the formation of spheromak using the current coaxial plasma source is considered.

Taylor found that the minimization of the total magnetic energy with a constant magnetic helicity leads to the following criterion [148]:

$$\nabla \times \vec{B} = \lambda \vec{B}$$

(8.1)

which is so called the force-free condition, since $\nabla \times \vec{B} = \mu_0 \vec{J}$ and $\vec{J} \times \vec{B} = 0$. A resistive MHD plasma dissipates its energy, while conserving magnetic helicity, to approach the Taylor state of minimum magnetic energy. This process is called relaxation and a spheromak is a Taylor state configuration.

For spheromak generation using a coaxial plasma gun, two parameters determine the formation of a spheromak [149, 150]:

$$\lambda_{\text{gun}} = \frac{\mu_0 I}{\Phi}$$

$$\lambda_{\text{geom}} = \frac{k}{r_e}$$

(8.2)

where $I$ is the current through the plasma gun, $\Phi$ is the bias magnetic flux linking the inner and outer electrodes, and $r_e$ is the effective radius of the plasma gun. $k$ is the geometrical threshold factor where the magnetic field from the gun is the same as the bias magnetic field. $k$ is normally greater than 2, and 3.3817 for an infinite cylinder [151]. A spheromak-like structure is formed when $\lambda_{\text{gun}} \sim \lambda_{\text{geom}}$ [149, 150].

Fig 8.2 shows the relation between the plasma gun current and the required magnetic field to satisfy $\lambda_{\text{gun}}$.

Table 8.1: The Compact Toroid Family [3]

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<th>$s &gt;1$</th>
<th>$s &lt;1$</th>
</tr>
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<tbody>
<tr>
<td>$B_p \gg B_t$</td>
<td>Field Reversed Configuration</td>
<td>Field Reversed Mirror</td>
</tr>
<tr>
<td>$B_p \sim B_t$</td>
<td>Spheromak</td>
<td>Astron</td>
</tr>
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Figure 8.2: Formation of a compact toroid in two ways. (a) Field reversed configuration formed in a field reversed theta pinch device [3] [28]. Four stages are specified: preionization, field reversal, reconnection, and contraction to an equilibrium. (b) Spheromak formation using a coaxial plasma gun [29]. The formation consists of three stages: elongation of the initial magnetic field, expansion into a flux conserver, and relaxation.
Figure 8.3: The relation between gun current and the required magnetic field to satisfy $\lambda_{\text{gun}} = \lambda_{\text{geom}} = \lambda_{\text{geom}}$. Note that two different $k$ values are considered. Based on the geometry of the device, $\lambda_{\text{geom}} \sim 50$, with $k = 3.8317$ and 80 kA of the plasma gun current, a bias magnetic field of $\sim 0.1$ T ($\sim 2$ mWb) is required.

8.3 Experimental Setup

The main addition to the current device is a magnet set at the plasma gun chamber. The new magnet set is composed of three electromagnets; each magnet is 11.25 inches in inner diameter, 13 inches in outer diameter, and 2 inches in thickness. The number in turns of each coil is approximately 360 turns. The inductance and resistance of each magnet is 53 mH and 1.2 Ohm, respectively. The center magnetic field per current is $1.4 \times 10^{-3}$ T/A at the center of the magnet according to a gauss meter measurement.

Fig 8.3 shows the magnet set installed outside of the plasma gun chamber. Three magnet coils are assembled and installed at the plasma gun chamber. The coils are separated from one another by 2 inches. The center magnetic field is reduced to $1.1 \times 10^{-3}$ T/A at the center of the magnet assembly where the current is the total current of the three magnets. The field, however, decreases by a factor of $\sim 4$ at the end of the plasma gun according to COMSOL and Maxwell 2D simulations. The magnet set is extended to the end of the chamber so that the gas puff valve is located inside the coils. This setup allows little variation of the magnetic pressure in the plasma gun as the plasma is accelerated from the end of the chamber to the front.
The same type of capacitor bank as those used for the guiding magnets are used to pulse the magnet set. Here, the capacitor bank is 2 mF and the switch is changed to S6025 SCR (350 A peak one - cycle forward surge current) due to lower holding current (< 50 mA) than the 50RIA60 SCR (200 - 400 mA). Since the inductance of the magnets is greater than that of the guiding magnets, the 50RIA60 is not latched up to 400 V. The S6025 SCR switch can be triggered with the current trigger circuit at a magnet voltage of 200 V or higher.

8.4 Results

Fig 8.5 shows the current and the magnetic field obtained with the magnet assembly with the pulse circuit. Approximately 0.11 T of maximum magnetic field at the center of the coils is achieved at 450 V of capacitor voltage.

Fig 8.6(a) shows plasma energies measured with the magnetic field at the plasma gun. The plasma gun is discharged at - 5 kV. The plasma energy remains similar with increasing magnetic fields. However, Fig 8.6(b) shows a different trend. The plasma energy decreases significantly when the voltage on the magnets is 200 V and 400 V, while 400 V gives more plasma energy than 200 V.

The results in Fig 8.6 are interesting since there is an insignificant change of plasma energy in Fig 8.6(a) while Fig 8.6(b) shows a clear reduction at 200 V, and increase in plasma energy from 200 V to 400 V. These results imply that an embedded axial magnetic field affects the plasma transport when the field is combined with the theta pinch field. While the preliminary results show a decrease in energy, the results still open up a possibility to manipulate the plasma energy with the additional field. For example, the magnetic field at
Figure 8.5: The current and the magnetic field of the magnets as a function of the voltage at the capacitor.

The plasma gun chamber decreases dramatically at the end of the plasma gun chamber; therefore, a stronger magnetic field may be required. Additional magnets or higher voltage operation of the pulse circuit may enable the higher magnetic field experiment.

### 8.5 Summary

In this chapter, it is shown that:

- A compact toroid has been suggested to control plasma confinement at the plasma gun chamber and to possibly enhance plasma transport to the theta pinch and the target chamber.

- Several methods to form a compact toroid have been revisited. Spheromak formation using a coaxial plasma gun and magnets is considered as the initial candidate due to its simplicity and minimization of hardware reconfiguration. Theoretically, 0.1 - 0.25 T of magnetic field is required at the plasma gun to form a compact toroid.

- Three electromagnets are added to the current plasma gun chamber. A capacitor bank with an accompanying witching circuit is manufactured. A maximum of 0.11 T magnetic field is achieved at the center of the magnets with a capacitor voltage of 450 V.

- Experiments show little change in the plasma energy at the target chamber with the magnetic field. However, the plasma energy decreases with the magnetic field when the device is operated with the
Figure 8.6: (a) Plasma energies measured with magnetic field at the plasma gun. The voltages at the magnets are 0, 200, and 400 V (b) Plasma energies measured with magnetic field at the plasma gun, theta pinch, guiding magnets, and crowbar. The voltages at the magnets are 0, 200, and 400 V
theta pinch. This suggests that the embedded magnetic field in the plasma can change the plasma transport when interacting with the magnetic field from the theta pinch.
Chapter 9

Conclusions and Future Work

9.1 Conclusions

The prototype theta pinch device, DEVeX, typically produces a plasma energy of 3 - 4 kJ/m$^2$ which is too low to study the interactions of plasma and plasma facing components in fusion-relevant conditions. With no or little preionized plasma, and a ringing of magnetic field, collisions of high energy particles with background gas have been reported as the main issues.

The objective of the proposed work is to build a test facility specifically designed for LiMIT experiment, using a new plasma gun and the existing theta pinch facility, so that the device may produce a similar pulsed-plasma heat load to simulate fusion-relevant conditions (0.1 - 1 GW/m$^2$). In this dissertation, it is shown that the new device is developed and the performance of the device is characterized. The main conclusions are as follows:

- As part of an effort to develop a pulsed plasma simulator to simulate fusion-relevant plasma and to provide a test-stand for the liquid-lithium infused trenches device, the existing theta pinch operation has been modified to be equipped with a coaxial plasma gun and guiding magnets.

- The coaxial plasma gun is equipped with a 500 $\mu$F capacitor and a gas puff valve. A density of $\sim 10^{21}$ m$^{-3}$, an electron temperature of $T_e \sim 10 - 20$ eV and a velocity of 25 - 40 km/s for 150 $\mu$s are obtained. These plasma parameters are consistent with the calorimeter data and theoretical predictions of the plasma velocity.

- The two-turn coil achieves a maximum current of 300 kA (= 1.2 T) with 20 kV of the main capacitor bank voltage, and the operation of the crowbar allows for a monotonically decreasing current. With the two-turn theta coil, without the crowbar and with the delay time greater than 50 $\mu$s, a maximum plasma energy of $\sim 0.08$ MJ/m$^2$ (=0.4 GW/m$^2$) is achieved at - 6 kV of the plasma gun voltage and 20 kV of theta pinch voltage. Plasma velocities of 34 - 74 km/s are observed at the first few peaks of the theta pinch current. A problem in plasma transport with short delay times is observed.
• A reduction in plasma energy is observed with optical emission and calorimeter measurements for plasma gun and guiding magnet experiments. Two additional effects are observed in the theta pinch and guiding magnetic field experiment. 1) Less of a delay time results in less of a decrease in plasma energy. 2) When the theta pinch magnetic field is reversed, the plasma produces less emission in the transport region. A crowbar experiment, in conjunction with the theta pinch and the guiding magnetic field, achieves $\tau_{\parallel} < \tau_{\perp}$ and $\tau_{\parallel} < \tau_{\text{comp}}$. This condition shows enhanced plasma transport and a plasma energy of 0.042 MJ/m$^2$ ($\sim$ 0.42 GW/m$^2$) with plasma velocities of $\geq$ 100 km/s.

• Ideal MHD simulations show an accumulation of plasma at the guiding magnetic field due to strong magnetic pressure. The simulations also show the divergence of plasma when the magnetic field from the theta pinch is in the opposite direction to the guiding magnetic field. These results explain the reductions in plasma energies with the guiding magnetic field in some experimental cases.

• Experiments in the prototype theta pinch device show a reduction in plasma energy on a target of 2.7 $\pm$ 1.7 J (29 $\pm$ 19 %) at 1.6 mTorr and approximately 0 J at 9.5 mTorr. Plasma gun experiments do not show much of a visible difference in terms of target temperature. The experiments with the plasma gun and theta pinch, guiding magnetic fields, and the crowbar shows approximately 40 $\pm$ 23 J (26 $\pm$ 15 %). The corona model predicts similar energy reductions to experimentally obtained energy reductions under various experimental conditions.

• Preliminary results on the compact toroid experiment show that little change in the plasma energy is observed with the plasma gun operation. However, the plasma energy decreases significantly with the compact toroid magnetic field when the device is operated with the theta pinch. This suggests that the embedded magnetic field in the plasma can change the plasma transport when interacting with the magnetic field from the theta pinch.

Overall, the new device, TELS, has achieved a similar plasma energy level to the off-normal events in the current tokamak devices such as ASDEX, NSTX, or DIII-D. A maximum heat flux of $\sim$ 0.4 GW/m$^2$ is close to the power level of the most major tokamaks, as shown in Table 9.1. The achievement and the comparison with the major tokamak devices are shown in Fig 9.1 and Table 9.1. The effects of the theta pinch / the guiding magnetic fields / the crowbar on the plasma transport have been studied and it is specially important for the LiMIT study which requires a long pulse of the magnetic field to drive liquid lithium. TELS device is applicable to the vapor shielding effect / modeling study, compact toroid experiment, and LiMIT study.
Figure 9.1: (a) Plasma parameters in the TELS and comparison of the parameters with achieved values in the DEVeX (b) TELS plasma energy allows for plasma-wall interaction study in an off-normal tokamak regime such as ELMs.
9.2 Future Work

9.2.1 Upgrade of High Voltage Pulse Power Systems

Pulse Power System and Feedthrough for Plasma Gun

While the capacitor bank for the plasma gun can store as much energy as 75 kJ, the maximum energy in the plasma gun capacitor bank for actual experiments is only 9 kJ. There are numerous limitations that hinder the higher energy operation: 1) mechanical failure of feedthrough occurs when shots are repeated, 2) the spark switch is not rated for a high coulomb transfer so that the switch degrades severely after a number of shots, 3) the high voltage supply for charging the capacitor bank has too low of a maximum current (20 kV, 5 mA).

The electrical feedthrough currently used for the plasma gun is rated at 20 kV and 150 A. While no mechanical failure has occurred at the inner side of feedthrough, the connection between the electrode and the capacitor bank results in a high contact resistance, which often ends up in arcing and erosion. Since larger energy in the capacitor results in a higher plasma energy and the capacitor bank for plasma gun can be easily upgraded to 1000 µF or 1500 µF, a feedthrough that holds up against a much higher current and has a better connection with the capacitor bank is necessary.

The current spark gap switch is also suggested to be replaced with a railgap switch or an ignitron to handle more current and charge. Ignitron switches can sustain a very high current (∼ 100 kA) and transfer a high amount of charge. However, the switch typically has a large jitter, needs very good orientation, and requires a much higher - energy deliverable driver circuit.

As mentioned in chapter 2, the plasma gun electrode made of tungsten will generate much less sputtered particles than copper. The heavy weight of the tungsten can be problematic unless a proper mounting structure is installed to sustain the weight of the tungsten electrode. Alternative ways such as a coating of tungsten on copper may be an option.

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<tr>
<td>(n_e (m^{-3}))</td>
<td>(\sim 10^{24})</td>
<td>(10^{24} - 10^{22})</td>
<td>(10^{19})</td>
<td>(\sim 3 - 5 \times 10^{19})</td>
<td>(\sim 5 \times 10^{19})</td>
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<tr>
<td>(T_e (keV))</td>
<td>0.03 ± 0.01</td>
<td>(\sim 1)</td>
<td>0.1</td>
<td>(\sim 0.5)</td>
<td>1-3</td>
</tr>
<tr>
<td>Flow velocity (m/s)</td>
<td>(\geq 5 \times 10^4)</td>
<td>(\geq 1 \times 10^5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(t_p (ms))</td>
<td>(\sim 0.1)</td>
<td>0.1 - 1</td>
<td>(\sim 1)</td>
<td>(\sim 0.2-0.3)</td>
<td>(\sim 0.1-0.2)</td>
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<tr>
<td>Plasma Energy (MJ/m²)</td>
<td>(\leq 0.1)</td>
<td>1-5</td>
<td>(\sim 0.1 - 1)</td>
<td>(\sim 0.2)</td>
<td>0.1 -0.5</td>
</tr>
<tr>
<td>Heat Flux (GW/m²)</td>
<td>0.1 - 1</td>
<td>(\leq 10)</td>
<td>(\leq 1)</td>
<td>(\sim 0.1)</td>
<td>(\sim 1)</td>
</tr>
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Pulse Power System for Theta Pinch

High energy in the capacitor bank is critical; assuming a maximum of 100 % energy efficiency at a 25 kJ capacitor discharge, one can get a maximum plasma energy of 3 MJ/m$^2$. Due to low energy coupling ($\leq$ 5%), a much larger energy is required to increase the plasma energy level over 1 MJ/m$^2$ which is typical for type - I ELMs.

The main capacitor bank for the theta pinch can store as much as 130 kJ of energy. However, only 15 kJ of energy are used during the experiments. The main limitations are 1) insulation failures in the mylar, switches, and coaxial cables, and 2) too low of a maximum current (50 kV, 5 mA) in the charging power supply.

The main capacitor bank for the theta pinch requires a much higher charging voltage than the plasma gun capacitor bank, so high voltage insulation is essential. A pressurized spark gap switch will enable to expand the range of operation voltage and multiple switches connected in parallel will reduce current at each switch and decrease the total inductance of the switches. It is important to point out that the multiple switch configuration requires an additional design considerations, such as a protection circuit and an isolating inductance between each switch in case of a premature fire. A switch cover may need to be installed as well to muffle unbearable noise during the operation.

Failures of high voltage insulation is also frequently observed when the voltage at the theta pinch increases. High voltage coaxial cables with solid dielectrics may be able to withstand higher voltage. More cables at the transmission line may be able to further reduce the inductance as well as the current through each cable.

Multi - Channel Trigger Unit for Main Switch and Crowbar

It is found that the inductance of the crowbar switch currently installed in the device is too high to give a monotonically decreasing magnetic field. When the number of turns of the theta coil is changed from 1 turn to 2 turns, the slower rising time of the current in the theta coil may result in less efficient compression. Therefore, an ideal way of achieving optimum crowbar operation is to reduce the inductance of the crowbar switch.

Previous studies have shown that reducing the length of current path [110] and multi - channel triggering [114] result in a reduction of the switch inductance. Spark gap igniters used on the current device are based on the technology of pulse transformers, which have very slow rising times ($\sim 5$ $\mu$s, $\sim 10$ V/ns). Therefore, with the slow igniter, only one channel is formed when the spark gap switch is closed, which has been shown with only one mark generated on the surface of the crowbar switch and the main switch after each shot. The multi - channel trigger unit, however, requires a voltage rising time of a few kV/ns [114] or so, since the gap
closure time is on the order of a few tens of ns. This multi-channel trigger unit normally consists of a pulse forming network or multi-stage triggering system \[28\] to provide a fast response. The multi-channeling will allow for a reduced inductance in the crowbar switch and successful crowbarring without changing the number of turns on the theta coil.

9.2.2 Diagnostics

Time-Resolved Optical Emission Spectroscopy and Interferometers

The fast-changing plasma over a short time \((\sim 100 - 200 \mu s)\) in the device makes it very difficult to use traditional optical emission spectroscopy. Currently the photodiodes are used to obtain temporal evolutions of specific wavelengths, but the large bandwidth of filter \((10 \text{ nm})\) does not allow for an accurate measurement of line intensities. Since most of the plasma characterization methods using optical emission such as emission line ratio or broadening require good spectral resolution, a new experimental setup is needed for non-intrusive plasma parameter measurements. A calibrated monochromator with a PM tube can provide a temporal evolution of a specific line emission and enable line ratio measurements. A high wavelength-resolvable spectrometer with a specific time can provide information of broadening on the a line with a proper triggering.

Interferometry utilizes a physical effect called the Interference effect. This effect results from different refractive indexes in plasma. A phase difference between a reference and probing beam results in an averaged plasma density. The density can be calculated from the following relation:

\[
\Delta \phi = \frac{e^2}{4\pi\epsilon_0 m_e c f} \int n_e dl
\]  

(9.1)

where \(c\) is the speed of light, \(m_e\) is the mass of an electron, \(\epsilon_0\) is the permittivity of free space, \(f\) is the frequency of a probing wave, \(n_e\) is the density of plasma being measured, and \(l\) is the length of the total path of the probing wave in the plasma. Based on Eq. (9.1), plasma density of \(10^{21} \text{ m}^{-3}\) in a 0.1 m tube gives a phase change of \(\sim 10^\circ\) at 632 nm. However, a single-chord interferometer is not able to deduce the spatial distribution of a pinched plasma since an interferometer measures a line-integrated density. A multi-chord interferometer with Abel inversion \[152\] may be able to reconstruct the density distribution in the device.
Ion Energy Analyzer

The ion energy and thermal temperatures are important quantities in this experiment. However, it is difficult to measure ion temperatures with conventional diagnostics such as a Langmuir probe. Typically in tokamak devices, the ion temperature is measured by 1) a neutral particle detector using charge - exchange reaction, 2) neutron / gamma ray detection since neutron / gamma production depends on the energy of the particle, and 3) the doppler broadening of line radiation observed in charge - exchange spectroscopy. However, these techniques are challenging in this experiment for the following reasons: as shown in Fig 9.2, the broadening is very small even at high ion temperatures (\( \sim 100 \) eV). Here, the broadening is calculated using the relation \[ \frac{\Delta \lambda D}{\lambda} = 2.43 \times 10^{-3} \left( \frac{T_i}{M_i} \right)^{1/2} \] (9.2)

where \( T_i \) is in keV and \( M_i \) is the atomic number. While hydrogen gives the largest broadening at a given temperature, hydrogen lines cannot be used since hydrogen ion has no electron. Other impurities have even less broadening so that even when \( T_i = 1 \) keV, the broadening is less than an angstrom, while the plasma lasts for only 150 \( \mu \)s or so. Therefore, broadening measurements are very challenging in this experimental setup.

The first and third techniques require a high energy neutral beam to induce a charge - exchange reaction. Neutron measurements are not realistic when the device is not equipped with any neutron shielding.

Therefore, a retarding field energy analyzer [153, 154, 155] can be used to measure the ion temperature.
The advantage of the analyzer is that it can measure the ion temperature as a function of time as long as the sweeping frequency is faster than the characteristic time of the ion temperature variation. However, in this experimental condition, the plasma temperature varies with the current from the theta pinch so that a minimum of a few hundreds kHz of sweeping frequency is required. Therefore, multiple shots need to be taken at one experimental condition with various ion reflecting voltages to obtain the ion current as a function of the voltage. An initial design of the analyzer by a graduate student in CPMI is shown in Fig. 9.3.

9.2.3 Design Variations

So far, it has been shown that the energy efficiency of the theta pinch measured with a calorimeter is lower than with the plasma gun alone. It was found that the main issue is plasma transport to the target chamber. While plasma transport is enhanced with the crowbar, there is still a design variation that could enhance the plasma transport and energy utilization.

Plasma in the device is initially generated and accelerated inside the plasma gun. The total amount of the plasma is initially set by the volume of the plasma gun chamber. Also, plasma heating by theta pinch mostly occurs only within the theta coil. While this is not a big problem for a steady-state device, since gas is continuously fed into a chamber, a typical duration of the pulse for this kind of device is around 100 µs. Therefore, these geometrical constraints inherently limit the maximum amount of charged particles produced and heated in the chamber. The theta coil may need to be elongated in the axial direction to cover more area for heating. At the same time, the plasma gun chamber may be scaled-up to deliver more plasma at a faster speed to the theta coil and the target chamber. Note that the change of geometries of the theta coil and the plasma gun involves the change of electrical parameters of the coil and the gun as well.
Therefore, additional changes of the pulse systems for the coil and the gun may also be required.

Interaction of the plasma with neutral particles still remains problematic. This problem may be mitigated if 1) the plasma gun is modified so that it may be operated at lower pressures. This allows for the theta pinch to produce a much hotter plasma, but possibly with fewer particles. 2) We implement multiple gas puff valves on the device and turn them on for a very short time so that we can achieve the same operating pressure and large pressure gradient between the plasma gun and the target chamber.

Modification to the positions of the theta coil, guiding magnets, and the target chamber may easily increase plasma energies at the target chamber. Because of the wall loss, the plasma reaching the target chamber may be only a small fraction of plasma produced in the device. A decrease in the distances between the theta pinch and the target chamber and between the plasma gun and the target chamber will reduce the plasma loss to the wall. This work involves the installation of a smaller guiding magnet and a reduction in the size of the target chamber.

9.2.4 Future Experiments

Vapor Shielding

The corona model described in chapter 7.2.3 predicts energy absorbed in the lithium vapor measured in chapter 7.4 fairly well. However, the model still needs an improvement for the following reasons. This collision effect results in change of the plasma equilibrium and change in the ion energy / electron temperature. While the optical depth may be able to take into account the re-absorption of lithium radiation, a corona-radiative model may be able to predict the energy absorption more accurately. The corona-radiative model allows us to measure the plasma density and electron temperature in the presence of lithium vapor. Since the plasma lasts only for a very short time (≈ 100 - 200 µs) and plasma parameters changes over the short duration of the pulse, the necessity of a time-resolved optical emission spectroscopy as described in chapter 9.2.2 is again emphasized.

Compact Toroid

Chapter 8.4 summarizes the necessity of the higher magnetic field operation. Therefore, it is necessary either 1) to extend the magnetic field by adding more magnets, 2) to reduce the length of the plasma gun electrode so that the end of the plasma gun electrode may be placed where the magnetic field is at its peak, or 3) to insert ferrite in the center of the plasma gun electrode so that the field may diverge more dramatically at the end of the gun.

Moreover, it is also necessary to find an optimal experimental condition to form a compact toroid, and
how it is translated through the chamber. A high speed camera will allow for a visual understanding of compact toroid formation and translation in the chamber. Not only that, magnetic field measurements with a bdot probe will allow quantification of the compact toroid structure.

LiMIT: Lithium - Metal Infused Trenches Study

One of the motivations of this research is to observe the behaviors of LiMIT with a high heat flux on a short timescale and understand the subsequent phenomena. A self-flowing liquid lithium trench using an external thermal gradient has been developed and currently being tested at CPMI. The characterization of liquid lithium velocities / temperature increases in the TELS test-stand and the ejection of lithium off the surface due to a TEMHD force with fast framing camera and IR measurement will allow to explore the engineering feasibility of the LiMIT concept for application in nuclear fusion devices.
References


[84] G. Scoles, ed., *Free jet sources, atomic and molecular beam methods*, vol. 1, pp. 72–74. Oxford Uni-

*Nuclear Fusion*, vol. 6, no. 3, p. 223, 1966.

Scientific Laboratory Report, Los Alamos, New Mexico, August 1972.


plasma gun for magnetic bubble expansion experiments,” in *Pulsed Power Conference, 2009. PPC

[90] F. Witherspoon, R. Bomgardner, A. Case, S. B. S.J. Messer, L. Wu, R. Elton, S. Hsu, J. Cassibry, and
M. Gilmore, “Overview of plasma guns for PLX,” Presented at the 52th American Physical Society

[91] F. D. Witherspoon, A. Case, S. J. Messer, R. Bomgardner, II, M. W. Phillips, S. Brockington, and
Instruments*, vol. 80, no. 8, p. 083506, 2009.

of power flow and performance phenomena in a multimegawatt coaxial plasma thruster,” *Plasma

for fusion at megagauss energy densities,” *Plasma Science, IEEE Transactions on*, vol. 38, pp. 1864


1962.

simulator,” Presented at the 25th Symposium on Fusion Engineering, San Francisco, California, USA,
2013.


Laboratory Report, Los Alamos, New Mexico, March 1955.

hydrodynamic flow physics of magnetically nozzled plasma accelerators with applications to advanced


Appendix

A.1 Particle Collision Time

The characteristic collision time is important to understand how the plasma behaves in an experimental setup. All the formulas are adopted from [67].

For the particle collision time (which is equivalent to momentum relaxation time and mean collision time):

\[
\tau_{ee} = \left( \frac{3\sqrt{6}\pi \epsilon_0^2}{e^4} \right) \sqrt{\frac{m_e(kT_e)^{3/2}}{n_e \ln \lambda}}
\]  
(A.1a)

\[
\tau_{ee} = \left( \frac{3\sqrt{6}\pi \epsilon_0^2}{e^4} \right) \sqrt{\frac{m_i(kT_i)^{3/2}}{z^4 n_i \ln \lambda}}
\]  
(A.1b)

\[
\tau_{ei} = \left( \frac{6\sqrt{3}\pi \epsilon_0^2}{e^4} \right) \sqrt{\frac{m_e(kT_i)^{3/2}}{z^4 n_i \ln \lambda}}
\]  
(A.1c)

\[
\tau_{ie} = \tau_{ei} \times \frac{m_i}{m_e}
\]  
(A.1d)

and for the energy confinement time (which is equivalent to energy relaxation time, temperature relaxation time, and equilibration time):

\[
\tau_E \sim \tau_{ee} \sim \tau_{ei} \sim \tau_{ie}
\]  
(A.2a)

\[
\tau_E \sim \tau_{ee} \sim \sqrt{\frac{m_i}{m_e}} \tau_{ee}
\]  
(A.2b)

\[
\tau_E \sim \tau_{ie} \sim \frac{m_i}{m_e} \tau_{ie}
\]  
(A.2c)

where \( \ln \Lambda \) is Coulomb logarithm, defined as \( \ln 12\pi \sqrt{\frac{\epsilon_0 kT_e}{n_e e^2 z^2 T_e^2}} \) and \( z \) is 1 for hydrogen.

Fig. A.1 shows various particle collision times using Eq. (A.1).
Figure A.1: Various particle collision times (a) electron-electron collision time (b) ion-ion collision time (c) electron-ion collision time (d) ion-electron collision time. Y-axis is rescaled for every plot for readability.
A.2 Ambipolar Diffusion Coefficient and Plasma Conductivity

The collision frequency is required to estimate the ambipolar diffusion coefficient. For fully ionized plasma, the collision frequency is approximated as $\nu = \nu_{ii} + \nu_{ie} \sim \nu_{ii}$, which is obtained at Fig A.1. The ion-ion collision frequency is approximately $10^6$ Hz. Assuming that $\mu_i \ll \mu_e$ where $\mu_{i,e}$ is mobility for ion and electron, the ambipolar diffusion coefficient is determined by (5.2b). Fig. A.2 shows the ambipolar diffusion coefficient in a fully ionized plasma with $\nu_i = 10^6$ Hz.

The plasma conductivity is determined either using electron - neutral collision frequency or the electron temperature. In weakly ionized plasmas, the charged particles collide mostly with neutral atoms and molecules. In this case, the plasma conductivity is

$$\sigma = \frac{n_e e^2}{m_e \nu_{en}} \quad (A.3)$$

where $\nu_{en}$ is electron collision frequency with neutrals.

However, in fully - ionized plasmas, collisions with neutrals is no longer of importance; the collision process between charged particles, and Coulomb collisions, becomes important and dominant in determining the plasma conductivity. Given the particle collision times in A.1 the plasma resistivity, called the Spitzer resistivity, is given by

$$\eta \sim 2.3 \times 10^{-9} \frac{2 \ln A}{T_e^{3/2}} \Omega \cdot m \quad (A.4)$$
Figure A.3: A plot of the plasma conductivity (a) for weakly ionized plasmas and (b) for fully ionized plasmas

where \( T_e \) is keV.

The plasma conductivities in these two cases are plotted in Fig. A.3. As shown in Fig. A.3(a), the plasma conductivity in weakly ionized plasmas is proportional to the plasma density and inversely proportional to the electron collision frequency. Since the electron collision frequency is roughly proportional to the electron temperature, the plasma conductivity decreases with higher electron temperatures.

However, in fully ionized plasmas, the plasma conductivity becomes independent of the plasma density. This is because the plasma conductivity is also inversely proportional to the plasma density and inversely proportional to the collision frequency, which again increases with density in fully ionized plasmas. Therefore, the plasma conductivity is a function of only the electron temperature, giving approximately \( 10^4 \) S/m at 10 eV and \( \sim 10^6 \) S/m for 100 eV.

### A.3 Triple Langmuir Probe Error Propagation

Since the error becomes extremely large as the electron temperature increases close to a half the bias voltage, error estimate for the triple Langmuir probe measurements constitute an indispensable task. The following equations are used to calculate error propagation. The triple probe data for a vacuum shot are used for the determination of error for \( \frac{\partial T_e}{\partial \phi_{12}}, \frac{\partial T_e}{\partial \phi_{13}}, \frac{\partial n_e}{\partial \phi_{12}}, \) and \( \frac{\partial n_e}{\partial \phi_{13}}. \) While errors caused by change in the sheath size are important issues for the thick sheath case, Fig. A.4 shows that our experimental data belongs to collisionless and thin sheath approximation. Therefore, only errors from \( \phi_{12} \) and \( \phi_{13} \) are considered to determine error propagation.
Figure A.4: A diagram that shows the sizes of probe radius, mean free paths at several pressures, and Debye lengths at a few electron temperatures

For $T_e$,

$$\frac{\partial T_e}{\partial \phi_{12}} = \frac{2T_e \exp\left(-\frac{\phi_{12}}{T_e}\right)}{2\phi_{12} \exp\left(-\frac{\phi_{12}}{T_e}\right) - \phi_{13} \exp\left(-\frac{\phi_{12}}{T_e}\right)}$$ (A.5a)

$$\frac{\partial T_e}{\partial \phi_{13}} = -\frac{T_e \exp\left(-\frac{\phi_{13}}{T_e}\right)}{2\phi_{12} \exp\left(-\frac{\phi_{12}}{T_e}\right) - \phi_{13} \exp\left(-\frac{\phi_{12}}{T_e}\right)}$$ (A.5b)

and for $n_e$,

$$\frac{dn_e}{d\phi_{12}} = \frac{\partial n_e}{\partial \phi_{12}} + \frac{n_e}{\partial T_e} \frac{\partial T_e}{\partial \phi_{12}}$$ (A.6a)

$$\frac{dn_e}{d\phi_{13}} = \frac{\partial n_e}{\partial \phi_{13}} + \frac{n_e}{\partial T_e} \frac{\partial T_e}{\partial \phi_{13}}$$ (A.6b)

$$\frac{\partial n_e}{\partial \phi_{12}} = -\frac{n_e}{T_e} \left( \frac{T_e \exp\left(\frac{\phi_{12} - \phi_{13}}{T_e}\right) - (\phi_{12} - \phi_{13}) \exp\left(\frac{\phi_{12} - \phi_{13}}{T_e}\right) \left(\frac{\partial T_e}{\partial \phi_{12}}\right)}{\exp\left(\frac{\phi_{12} - \phi_{13}}{T_e}\right) - 1} \right)$$ (A.6c)

$$\frac{\partial n_e}{\partial \phi_{13}} = \frac{n_e}{T_e} \left( \frac{T_e \exp\left(\frac{\phi_{12} - \phi_{13}}{T_e}\right) + (\phi_{12} - \phi_{13}) \exp\left(\frac{\phi_{12} - \phi_{13}}{T_e}\right) \left(\frac{\partial T_e}{\partial \phi_{13}}\right)}{\exp\left(\frac{\phi_{12} - \phi_{13}}{T_e}\right) - 1} \right)$$ (A.6d)
A.4 Derivation of Triple Langmuir Probe Theory from Double Probe

As discussed earlier, the triple Langmuir probe is a combination of a double probe and a floating probe. Recalling Eq. (2.7), where $I = I_{\text{sat}} \tanh \left( \frac{e \phi}{2kT_e} \right)$, the equation tells us that we need only a little data to reconstruct a full I - V curve of a double probe: they are the electron temperature $T_e$, which is obtained from Eq. (2.6) and one voltage / current pair $(I_{\text{meas}}, V_{\text{meas}})$ from the $\phi_{13}$ and current into the triple Langmuir probe. Once one finds $I_{\text{sat}}$ using those values, one can also obtain the plasma density $n_0$ with an appropriate model such as the thin collisionless sheath approximation. It is easy to see that the voltage / current pair $(I_{\text{meas}}, V_{\text{meas}})$ doesn’t have to be at the saturation region, but is at any point along the I - V curve.

The floating probe basically measures a floating potential where ion and electron currents collected by the probe are equal. Therefore, the floating potential is the same as the potential at the double probe where the collected current is zero. This is because of the fact that if there is no voltage applied at the double probe, the voltages at probe 1 and probe 2 in Fig A. 5(a) are the same and no current can flow between probe 1 and probe 2.

The remaining question is to prove that the I - V relation in Eq. (2.7) is the same as the I - V relation...
for a triple Langmuir probe in Eq. (2.8), namely,

\[ I_{\text{sat}} \tanh \left( \frac{e\phi_{13}}{2kT_e} \right) = I_{\text{sat}} \left[ 1 - \exp \left( -\frac{\phi_{23}}{kT_e} \right) \right] \]

(A.7)

Eq. (2.6) can be rewritten

\[ \exp \left( \frac{e\phi_{21}}{kT_e} \right) = \frac{1 + \exp \left( \frac{e\phi_{31}}{kT_e} \right)}{2} \]

(A.8)

When Eq. (A.8) is multiplied by \( \exp \left( \frac{e\phi_{13}}{kT_e} \right) \), Eq. (A.8) is changed to

\[ \exp \left( \frac{e\phi_{23}}{kT_e} \right) = \frac{1 + \exp \left( \frac{e\phi_{13}}{kT_e} \right)}{2} \]

(A.9)

Since \( \tanh \left( \frac{x}{2} \right) = \frac{1 - \exp(-x)}{1 + \exp(-x)} \),

\[ \tanh \left( \frac{e\phi_{13}}{2kT_e} \right) = \frac{1 - \exp \left( \frac{e\phi_{13}}{kT_e} \right)}{1 + \exp \left( \frac{e\phi_{13}}{kT_e} \right)} = \frac{2}{1 + \exp \left( \frac{e\phi_{13}}{kT_e} \right)} - 1 \]

(A.10)

With Eq. (A.8), Eq. (A.10) is rewritten

\[ \tanh \left( \frac{e\phi_{13}}{2kT_e} \right) = \exp \left( \frac{e\phi_{12}}{kT_e} \right) - 1 = \frac{\exp \left( \frac{e\phi_{13}}{kT_e} \right) - \exp \left( \frac{e\phi_{23}}{kT_e} \right)}{\exp \left( \frac{e\phi_{23}}{kT_e} \right)} \]

(A.11)

Using the relation in Eq. (A.9), Eq. (A.11) is further changed to

\[ \tanh \left( \frac{e\phi_{13}}{2kT_e} \right) = \frac{\exp \left( \frac{e\phi_{13}}{kT_e} \right) - \exp \left( \frac{e\phi_{23}}{kT_e} \right)}{\exp \left( \frac{e\phi_{23}}{kT_e} \right)} = \frac{\exp \left( \frac{e\phi_{23}}{kT_e} \right) - 1}{\exp \left( \frac{e\phi_{23}}{kT_e} \right)} = 1 - \exp \left( -\frac{e\phi_{23}}{kT_e} \right) \]

(A.12)

which proves Eq. (A.7).

A.5 A Resistor Loading Effect on the Triple Langmuir Probe

When a triple Langmuir probe collects current from a plasma, it is normally conventional to use a resistor to estimate the current. While this method is easy to implement and relatively accurate, the method becomes problematic when the plasma density and electron temperature are very high and a significant voltage drop occurs across the resistor. Fig. A.6 shows the Bohm hydrogen ion current collected by a probe with 0.01 inch in diameter and 0.1 length. It shows that at a high plasma density and electron temperature, a very
One can understand the effect of the resistor on the measurement through a load line approach. If the bias voltage is $V_0$ and the resistor is $R$, the one can find such a relation according to the Ohm’s law:

$$I = \frac{(V_0 - V)}{R} \quad (A.13)$$

where $I$ is the current at the probe. Therefore, $R$ determines the slope of the load line and the measured voltage - current pair ($V_{\text{meas}}$, $I_{\text{meas}}$). Fig A.7 shows the $I$ - $V$ curve of a double probe and two load lines with different resistance values. It is found that a low resistance allows for the measurement of ($V_{\text{meas}}$, $I_{\text{meas}}$) closer to the saturation region than a high resistance at the same bias voltage. While, in the ideal Maxwellian case, the measurement with a triple Langmuir probe in the non-saturated region yields the same $n_0$ and $T_e$, a deviation from the ideal condition such as a non-Maxwellian distribution [156], non-saturation of the ion current [157] and a finite ion temperature [158] may cause inaccurate measurement of $n_0$ and $T_e$. This is more important for plasma with a high $n_0$ and $T_e$ since a larger voltage drop occurs.
Figure A.7: An I - V curve of a double Langmuir probe [32] and load lines of the probe for two different measuring resistors at the same bias voltages. The red solid line is a load line with a lower resistor than the resistor for the blue dotted line on the graph. When the resistor is low, the obtained voltage - current pair is at the point A. However, as the resistor increases, the pair moves to the point B where the current is no more saturated.