Capacitor Bank and Outer Electrode Modifications on the ZaP Flow Z-Pinch Experiment

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and have found that it is complete and satisfactory in all respects, and that any and all revisions required by the final examining committee have been made.

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Abstract

Capacitor Bank and Outer Electrode Modifications on the ZaP Flow Z-Pinch Experiment

Jacob Lang Rohrbach

Chair of the Supervisory Committee:
Professor Uri Shumlak
Department of Aeronautics & Astronautics

The ZaP Flow Z-Pinch Experiment is an ongoing plasma-research project at the University of Washington that investigates the concept of using a radially-varying, sheared-axial flow to extend the life of an ordinarily unstable Z-pinch configuration. The experimental geometry consists of a coaxial-plasma accelerator coupled to a Z-pinch assembly region. The capacitor-bank power supply is doubled in size, from eight to sixteen 170 \( \mu \)F capacitors, increasing the energy-storage capacity from 70 to 140 kJ. The expected affects of this expansion, based on a new power-supply model, is an increase in pinch current by as much as 70 kA, leading to an increase in plasma temperature and density by 33%. In addition, a ‘rod’ outer-electrode is designed, manufactured, and installed on the outer-electrode assembly. This modification is expected to show that the Z-pinch is stabilized by sheared flows and not by the conductive wall of the outer electrode. The large open-area fraction of the design also provides the experiment with optical-access in the vertical and horizontal planes, and is a proof-of-concept for an all-rodded assembly-region.
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Chapter 1

INTRODUCTION

The Earth is a tiny oasis in a universe dominated by plasma. In fact, with the exception of a few anomalies like lighting and the ionosphere, terrestrial matter is practically never in a state of plasma. This presents numerous scientific and technical challenges that must be overcome before the astounding potential of harnessing plasma can be realized and applied. The most important of these challenges is centered on the study and advancement of plasma confinement.

The simplest plasma confinement configuration is the Z-pinch, and is the basis for investigation at the University of Washington’s ZaP Flow Z-Pinch Experiment. This thesis presents a brief discussion of the Z-pinch, ZaP’s innovative technique for stabilizing an otherwise unstable confinement configuration, followed by a general overview of the experiment itself. At the core of this thesis is a detailed description of two experimental modifications: 1) an expansion of the capacitor-bank power supply; 2) the addition of a ‘rod’ outer electrode to the outer electrode assembly.

1.1 Basis for Magnetic Confinement

Plasma is a quasineutral gas of charged and neutral particles which exhibits collective behavior [2]. The motion of these particles generates pockets of positive and negative charge, which in turn gives rise to electric fields, currents, and magnetic fields within the plasma. These fields, whether self-generated or externally-applied, pro-
foundly affect the motion of particles throughout the plasma, and provides the basis for all experimental configurations aimed at magnetically confining plasma. One such confinement configuration is the Z-pinch.

1.2 The Standard Z-Pinch

The standard Z-pinch is by far the simplest magnetic-confinement configuration available. Not surprising then, that it was one of first equilibrium studied for achieving controlled, thermo-nuclear fusion. A standard Z-pinch is essentially a dense column of a plasma held between two electrodes with an axially-driven electrical current. Two forces simultaneously act on the plasma: a radially-inward pointing Lorentz force \((j \times B)\) generated by the azimuthal magnetic field; and a radially-outward pointing pressure-gradient force from the plasma. The pinch is in equilibrium when these two radial forces are in balance,

\[
(j \times B)_r = (\nabla p)_r. \tag{1.1}
\]

Given that no external magnetic fields are applied, and substituting Ampere’s law for the current, reduces the force balance equation to

\[
\frac{B_\theta}{\mu_0} \frac{d(rB_\theta)}{dr} + \frac{dp}{dr} = 0 \tag{1.2}
\]

where \(B_\theta\) is the magnitude of the azimuthal magnetic field, \(\mu_0\) the permeability of free space, \(r\) the radius, and \(p\) the pressure. Unfortunately, this simple equilibrium is highly susceptible to gross magnetohydrodynamic (MHD) instabilities, with growth times on the order of tens of nanoseconds.

1.3 Z-Pinch Instabilities and Stabilization Techniques

A static Z-pinch is violently unstable to the MHD \(m = 0\), “sausage”, and \(m = 1\), “kink”, azimuthal mode numbers. Schematic representation for these instabilities is
Figure 1.1: Static Z-pinch MHD instability modes [7]: (a) Schematic of the $m = 0$ “sausage” instability. Necking in the plasma column grows exponentially from higher magnetic forces at smaller plasma radii (b) Schematic of the $m = 1$ “kink” instability. Off-axis bend grows exponentially from higher magnetic forces on the inner curvature.

illustrated in Figure 1.1. The “sausage” instability occurs as a result of an axisymmetric “necking” in the plasma column. At these locations, the decreased plasma radius increases the local magnetic force along the inward curvature, further pinching the column down. The instability grows exponentially until the plasma current is disrupted and confinement lost. This instability can occur at multiple locations along the pinch length, making the plasma column look like “sausage” links, hence the name. The $m = 0$ mode can be stabilized with a close-fitting conductive wall or by carefully tailoring the pressure profile of the pinch [10, 12]. This latter technique does not stabilize the $m = 1$ mode.

The “kink” instability occurs as a result of the plasma column bending off-axis. The inward curvature of the bend experiences higher magnetic forces than the outward curvature, further pushing the bend off-axis. Like the “sausage” mode, the instability grows exponentially until the plasma current is disrupted and confinement lost. The $m = 1$ mode can also be stabilized by a close-fitting conductive wall or by an applied axial-magnetic field. However, these techniques have critical drawbacks.

Image currents from a close-fitting conductive wall effectively stabilize both MHD
modes, but plasma contact with the wall is a regular occurrence. This is acceptable for low-energy plasma applications, but is not a suitable solution for fusion-grade plasma. Applying an axial-magnetic field coupled with a tailored pressure profile, on the other hand, stabilizes both modes, but restricts plasma current and density by the Kruskal-Shafranov limit [10] and opens magnetic-field lines. Another potential stabilization technique, that does not suffer from these crippling limitations, is the sheared-flow Z-pinch.

The ZaP Flow Z-Pinch Experiment investigates the effectiveness of using a radially-varying, axial velocity profile as a means to mitigate MHD instabilities. Theoretical, numerical, and experimental results all show that if a flow shear exceeds the threshold velocity

$$\frac{dv_z}{dr} > 0.1kV_A$$

(1.3)

in a no-wall limit, the MHD modes are stabilized [17, 14]. Threshold velocity is a function of the axial wavenumber $k$ and Alfvén speed $V_A$. The velocity-shear criteria for stability is plotted in Figure 1.2 with respect to wall position.

The stabilizing mechanism of flow shear is effectively a mode-mixing between instabilities at different pinch radii, due to the varying-velocity profile. As a result, destructive interference inhibits the growth times of any one mode and stabilizes the overall-plasma column. Figure 1.3 illustrates a simplified model of destructive interference for stabilizing the “sausage” mode. The mode-mixing concept is identical for a “kink” instability, just harder to illustrate with a simple model. The ZaP experiment has successfully used sheared flows to generated Z-pinches with stable periods lasting upwards of 2000 times the $m = 1$ growth period [4].
Figure 1.2: Threshold shear required for marginal stability of the $m = 1$ mode as a function of wall position $r_w/a$, where $r_w$ is the conducting-wall radius and $a$ the pinch radius [14]. A no-conductive wall limit with sheared-flows occurs when $v'_z > 0.1kV_A$.

Figure 1.3: Graphical representation of the destructive interference responsible for mitigating “sausage” instability growth times [9]. The interference is caused by the velocity shear, where instabilities at different pinch radii to go out of phase with one another.
Chapter 2

OVERVIEW OF THE ZAP FLOW Z-PINCH EXPERIMENT

The ZaP Flow Z-Pinch Experiment is an ongoing plasma-research project at the University of Washington that investigates the concept of using a radially-varying, sheared axial flow to extend the life of an ordinarily unstable confinement configuration. Presently, ZaP theoretical and experimental research results are impacting multiple plasma topics, including: aiding other confinement configurations, furthering extreme ultra violet (EUV) source technology [11], and helping to explain astrophysical phenomena [16]. Furthermore, a sheared-flow stabilized Z-pinch has many desirable properties for fusion-grade plasma applications, and if scaled properly, could provide solutions for a fusion reactor [5] or space thruster [15].

2.1 Experimental Setup

The core of the ZaP experiment is an innovative coaxial-electrode apparatus, shown in Figure 2.1, designed specifically to create sheared-flow Z-pinches. The outer-electrode assembly is 78.74” (200 cm) long and comprised of two, joined copper cylinders with an inner diameter of 8.07” (20.5 cm). Experimental modification to this component is a topic of this thesis, and is discussed in Chapter 4. The downstream end of the outer electrode is capped with a copper end wall, machined with a 2” (5.08 cm) hole in the center to mitigate plasma-flow stagnation in the experiment [3]. A hollow, 39.37” (100 cm) long, inner electrode is centered inside the outer electrode on the opposite side as the end wall. There are two inner-electrode designs: a “small,” 4.02” (10.20...
cm) outer-diameter version; and a “large,” 6.155” (15.63 cm) outer-diameter version [9]. A 45 deg nose cone, machined with rounded tip and edges, is attached to the end of the inner electrode. The annular region between the inner and outer electrodes is referred to as the “acceleration region.” The remaining volume, from the tip of the nose cone to the end wall, is referred to as the “assembly region.” All plasma-facing surfaces in these regions are sprayed with a 0.010” (0.0254 cm) layer of tungsten to protect the copper base-material from sputtering [9]. In the experiment’s coordinate system, the origin is located 6.69” (17 cm) from the tip of the nose cone at the $z = 0$ plane. The positive $z$-axis runs downstream along the centerline of the experiment towards the end wall of the outer electrode. The $y$-axis points towards ceiling of the laboratory, and the $x$-axis points horizontally according to the right-hand-rule. The electrode assembly is completely contained within a stainless-steel vacuum vessel.

Figure 2.1: Side-sectional schematic of the original ZaP experimental apparatus highlighting relevant hardware features [13]. Locations within the experiment are referenced to the $z = 0$ plane, where positive $z$ is to the right, or downstream, of the drawing. Strategically placed viewing ports are used for ZaP’s various diagnostics to characterize the plasma at different locations along the experiment.
2.2 Generating a Sheared-Flow Z-Pinch

ZaP produces plasma flow by first radially injecting a neutral gas, usually hydrogen, into the acceleration region of the experiment. Between nine and sixteen gas-injection valves are positioned in both the inner and outer electrodes, approximately midway down the inner electrode’s length (\(z = -75 \text{ cm})). The gas is allowed to expand in the annulus before a voltage is applied across the electrodes. The applied potential ionizes the gas, forming a current sheet in the annulus. A Lorentz force accelerates the plasma sheet downstream towards the nose cone in a “snowplow” shape, due to higher magnetic forces closer to the inner electrode [3]. As the plasma reaches the nose cone, the inner edge of the current sheet collapses on axis and attaches to the nose-cone tip, while the outer edge of the current sheet accelerates along the outer-electrode wall. As the current sheet elongates in the assembly region, the Lorentz force continues to collapse the plasma along the axis, forming a Z-pinch equilibrium. During the entire assembly process, excess neutral gas in the acceleration region is continually ionized and accelerated into the assembly region. The embedded flow of the initial pinch assembly coupled with the varying flow of later plasma effectively creates the sheared-velocity profile necessary to mitigate MHD instabilities. Reference Figure 2.2 for a schematic representation of the pinch-formation sequence at critical points in time.

2.3 Diagnostics

ZaP employs a suite of diagnostics to measure the various plasma properties, velocity profiles, and magnetic mode activity for each plasma pulse. Table 2.1 provides a general list of these tools, the location of their employment on the experiment, and the principal plasma parameter investigated.
Figure 2.2: Formation sequence for generating a sheared-flow Z-pinch [9]: (a) Neutral gas is injected into the acceleration region. (b) The gas is allowed to expand in the annulus before a voltage is applied across the electrodes. (c) The ionized gas forms a current sheet and accelerates down the experiment from generated currents and magnetic fields. (d) The current sheet flows down the accelerator to the nose cone. (e) Lorentz forces collapse the plasma on-axis, while the outer edge continues down the experiment. (f) The plasma is compressed into Z-pinch equilibrium while excess plasma continues to flow over the column until the neutral gas is extinguished or the capacitor current vanishes.
Table 2.1: General list of diagnostics employed on the ZaP experiment to measure various plasma properties, velocity profiles, and magnetic mode activity.

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<td>Rogowski Coil</td>
<td>End wall; Around the inner electrode</td>
<td>Current escaping through end wall; Measures total current</td>
</tr>
<tr>
<td>CCD &amp; PMT Spectrometer</td>
<td>Multiple horizontal view-port locations</td>
<td>Ion impurity emissions as a function of time for ion temperature estimations</td>
</tr>
<tr>
<td>ICCD Spectrometer</td>
<td>$z = 0$, vertical port $z = 0$, 35° oblique port</td>
<td>Doppler Broadening: Ion temperature Doppler Shift: Ion velocity</td>
</tr>
<tr>
<td>Imacon Fast-Framing Camera</td>
<td>Multiple horizontal view-port locations</td>
<td>Capture plasma emissions to visualize pinch structure</td>
</tr>
<tr>
<td>Interferometer</td>
<td>Multiple horizontal view-port locations</td>
<td>Four-chord integrated plasma density</td>
</tr>
<tr>
<td>Thomson Scattering</td>
<td>$z = 0$</td>
<td>Electron temperature and density</td>
</tr>
</tbody>
</table>

CCD - Charge coupled device
PMT - Photomultiplier tube
ICCD - Intensified CCD
2.4 Introduction to the Power Supply

The voltage potential used to ionize the neutral gas and provide the plasma current for the experiment is generated from a capacitor-bank power supply. The capacitor bank consists of four, 170 µF Maxwell Laboratory capacitors connected in series using a Pulse Forming Network (PFN). The original capacitor bank configuration generated an exponentially decaying, sinusoidal current waveform. A “flattop” waveform is more desirable for ZaP because of the increased current half-cycle time, enabling the study of a quasi-steady state Z-pinch. A PFN generates the “flattop” by increasing the inductance between each capacitor in the series. The drawback to this technique is that the larger impedance decreases the amplitude of the current reaching the pinch. Each capacitor in the bank has a maximum charge voltage of 10 kV and internal inductance of 40 nH.

The PFN connects the four capacitors in a bank to an ignitron tower. This assembly is responsible for triggering and transferring the stored energy in the capacitor banks to the electrodes on the experiment. Multiple capacitor-bank assemblies can be grouped together in parallel to increase the energy-storage capability of the power supply. Typical operating conditions and pinch parameters for a two capacitor-bank configuration are summarized in Table 2.2.
Table 2.2: Typical operating conditions for the ZaP experiment with a two capacitor-bank configuration.

<table>
<thead>
<tr>
<th>Power Supply Settings</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitors</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Energy Storage</td>
<td>$E_c$</td>
<td>3 – 68 kJ</td>
</tr>
<tr>
<td>Charge Voltage</td>
<td>$V_{mb}$</td>
<td>2 – 10 kV</td>
</tr>
<tr>
<td>Peak Current</td>
<td>$I_p$</td>
<td>70 – 400 kA</td>
</tr>
<tr>
<td>Half-Cycle Period</td>
<td>$T_{hc}$</td>
<td>20 – 100 $\mu$s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plasma Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Velocity</td>
<td>$v_z$</td>
<td>10 cm/$\mu$s</td>
</tr>
<tr>
<td>Quiescent Period</td>
<td>$\tau_q$</td>
<td>20 – 40 $\mu$s</td>
</tr>
<tr>
<td>Z-pinch Radius</td>
<td>$a$</td>
<td>0.5 – 1 cm</td>
</tr>
<tr>
<td>Z-pinch Length</td>
<td>$L$</td>
<td>100 cm</td>
</tr>
<tr>
<td>Total Temperature</td>
<td>$T_e + T_i$</td>
<td>150 – 200 eV</td>
</tr>
<tr>
<td>Electron Number Density</td>
<td>$n_e$</td>
<td>$10^{16} – 10^{17}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>
Chapter 3

POWER-SUPPLY EXPANSION

3.1 Motivation for the Expansion

The motivation for expanding ZaP’s power supply is simple: to drive more current through the pinch. The experiment’s coaxial geometry naturally keeps a sizeable percentage of the current in the acceleration region because it maintains a lower inductance in the system [8]. This is both a crucial property of the experiment’s design and a limiting factor. Remnant current in the accelerator is essential to creating sheared-flow profiles by continuing to ionize and accelerate remaining neutral gas after the primary current sheet exits into the assembly region. In doing so, this current does not contribute to the magnetic energy in the pinch.

Under normal two capacitor-bank, 9 kV operating conditions, the power supply generates a peak current of approximately 350 kA with just over a 90 \( \mu \text{s} \) half-cycle. Of that pulse, approximately 100 kA makes it to the pinch. A four-bank, 9 kV pulse is projected to drive over 620 kA of current with a 100 \( \mu \text{s} \) half-cycle. Assuming the ratios are proportional, the expanded-bank configuration will drive an estimated 170 kA through the pinch. Ampere’s law governs that the magnetic field goes as the current. From force balance, the magnetic force goes as the square of the magnetic field. Since the pinch is in equilibrium when plasma pressure is equal to the magnetic force, temperature and density in the pinch should increase by as much as 30\%. The expanded power supply ushers in the next phase in ZaP’s evolution, providing a means to better explore and understand the physics of sheared-flow Z-pinches.
Table 3.1: Measured inductance for all capacitors in the power-supply labeled by capacitor location. The capacitor count starts closest to the ignitron tower.

<table>
<thead>
<tr>
<th>LF Bank</th>
<th>Inductance</th>
<th>RF Bank</th>
<th>Inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>170 µF</td>
<td>1</td>
<td>171 µF</td>
</tr>
<tr>
<td>2</td>
<td>175 µF</td>
<td>2</td>
<td>176 µF</td>
</tr>
<tr>
<td>3</td>
<td>175 µF</td>
<td>3</td>
<td>173 µF</td>
</tr>
<tr>
<td>4</td>
<td>172 µF</td>
<td>4</td>
<td>175 µF</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LR Bank</th>
<th>Inductance</th>
<th>RR Bank</th>
<th>Inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>171 µF</td>
<td>1</td>
<td>184 µF</td>
</tr>
<tr>
<td>2</td>
<td>170 µF</td>
<td>2</td>
<td>184 µF</td>
</tr>
<tr>
<td>3</td>
<td>173 µF</td>
<td>3</td>
<td>185 µF</td>
</tr>
<tr>
<td>4</td>
<td>170 µF</td>
<td>4</td>
<td>184 µF</td>
</tr>
</tbody>
</table>

3.2 Capacitor Bank PFN, Grounding Rod, and the Interlock

The two sets of four, 170 µF Maxwell capacitors at the heart of the power-supply expansion were acquired at the same time as the capacitors currently in operation. Having these components grouped, tested, and positioned before the expansion effort greatly reduces completion time of the project. The four capacitor banks are staggered in position: the two existing banks, labeled Left Front (LF) and Right Front (RF), take the outside position closest to the experiment; while the two new banks, labeled Left Rear (LR) and Right Rear (RR), take the inside position and are pushed slightly away from the experiment. Each capacitor’s electrical inductance is summarized in Table 3.1.

The work required to bring the capacitor-bank assembly of Figure 3.1 online is
Figure 3.1: Isometric assembly view of a capacitor bank. The components of this assembly include: (1) upper bus-bar, (2) ‘long’ PFN riser, (3) ‘medium’ PFN riser, (4) ‘short’ PFN riser, (5) lower bus-bar, and (6) four 170 µF capacitors.
limited to manufacturing and assembly of the PFN. There are three sizes of vertical risers used in the PFN design: three 16” (40.6 cm) ‘long’ risers, one 13” (33 cm) ‘medium’ riser, and a 2.75” (7 cm) ‘short’ riser. All risers are constructed using 1” (2.54 cm) diameter, brass hex bar. The 0.15” (0.38 cm) wide, annular boss-ring design feature, highlighted in Figure 3.2, is incorporated into all PFN risers to concentrate material contact and improve the electrical connection. Note that the exposed corners of the hex-shape bellow the boss ring, shown in Figure 3.2, are actually tapered back when machined to further reduce regions of high electric-field and possible arcing between surfaces. For the purpose of uniformity, six 1-1/16” (2.7 cm) ‘long’ bars previously installed on the two existing capacitor banks are replaced with 1” (2.54 cm) brass hex stock.
The only other component required to complete the capacitor-bank assemblies is the current-carrying, upper bus-bar that connects the tops of the PFN risers. This part is machined from brass-bar stock, and is 23.75" (60.3 cm) long. Both ends of the strap are given a radius in conjunction with beveled edges to avoid creating areas of concentrated electric fields.

*Grounding Rod and the Interlock System*

Whenever the experiment is not operational, the capacitor banks are shorted using grounding rods. This is to eliminate the chance of a bank gaining charge if left unshorted for any length of time. The grounding rod is a standard design, consisting of a 17.5" (44.5 cm) length of 3/8" (0.95 cm) copper pipe with a hook bent into the end, and an insulated 2" × 12" (5.1 cm × 30.5 cm) cylindrical Plexiglas® handle. Each grounding rod is connected to ground via 8' (2.438 m) long, copper-braid cable bolted to the capacitor’s negative terminal. When used, the grounding rod is hooked around a PFN riser and supported with a notched, L-shaped support bracket bolted to the ignitron housing.

The grounding rods are one of the various flags in the interlock system [3]. Before the banks can charge, the operator must hang the grounding rods from Plexiglas hooks below the cable rack, which activates the interlock switch. To accommodate the expanded power supply, two new interlock switches are manufactured and integrated in series with the existing system.

### 3.3 Fabrication and Assembly of the Ignitron Towers

The ignitron tower is divided into two sections: those components carrying the current from the capacitors to the plasma; and those components making up the current return-path and supportive structure. These assemblies are identified in Figure 3.3.
Figure 3.3: Isometric view of the entire ignitron assembly, highlighting the major sub-assemblies and components of the ignitron tower: (1) current-distribution assembly, (2) ignitron housings, (3) ignitron centering ring, (4) ignitron, (5) bridge assembly, and (6) base assembly.
3.3.1 Current-Carrying Components

The ignitron tower is organized into three distinguishable current-carrying assemblies: the current-distribution assembly of Figure 3.4, the ignitron of Figure 3.5, and the bridge assembly of Figure 3.6. Together, these components provide the means to efficiently transfer the energy stored in the capacitors to the experiment.

Current-Distribution Assembly

Each ignitron tower is connected to the experiment via ten, 19' (5.8 m) long RG217/U coax cables. The attachment points on the experiment are evenly spaced to insure uniform current distribution to electrodes. Since the capacitor banks are positioned approximately 8' (2.44 m) from the back of the vacuum chamber, each ten-cable bundle is routed up and over a wiring-support bridge for protection, as well as to maintain experiment accessibility. Solid electrical connections for the cabling is achieved using individual brass fittings soldered to the inner conductor of the coax cable. These brass fittings are mounted using 1/4”-20 bolts, and incorporate the same boss-ring concept as used for the PFN risers to insure good electrical contact. Since the cables must carry a significant voltage, approximately 6” (15.2 cm) of the outer conductor and shielding is cut away from the inner conductor to provide ample separation between the hot and ground leads. The attachment mechanism for the current-return loop is achieved using 1” (2.54 cm) of the outer conductor’s copper braid; which is exposed, loosened and secured to the grounding structure using a hose clamp.

The ten coax cables make connection with the ignitron tower through the current-distribution assembly, shown in Figure 3.4. Eighteen, 1/2” (1.27 cm) copper tubes are press-fit into a brass top plate, also called the ground plate, in a three-tier arrangement to avoid interferences in tightening the hose clamps that secure the coax outer-conductor. The ground plate is bolted to the ignitron housing. Four G-10
Figure 3.4: Isometric view of the current-distribution assembly. This assembly connects to the ignitron’s anode and evenly distributes the current flowing from the capacitor bank to ten RG217/U coax cables. The components for this assembly include: (1) coax-cable ground contacts, (2) ground plate, (3) G-10 insulated spacer, (4) inner-conductor brass fittings, (5) current-distribution (hot) plate, and (6) fork.
spacers insulate the ground plate, which is grounded through the coax cables to the vacuum vessel, from the current-distribution plate (CD plate) 6” (15.24 cm) below. This 1/2” (1.27 cm) brass plate provides the contact surface for the ten brass connectors of the coax cable’s inner conductor, and are secured from underneath the plate. A layer of 1/8” (0.3175 cm) thick Teflon sheeting is positioned around the perimeter of the ignitron housing to prevent arcing from the CD plate. Bolted to the underside of the CD plate is a 7” (17.8 cm) long, two-pronged brass fork that makes the connection to the ignitron’s anode.

**Ignitron**

ZaP uses D-sized ignitrons for the capacitor-bank voltage switches. The classification refers to the ignitron’s size, voltage hold-off, and current-handling capabilities. The essential components of the ignitron, shown in Figure 3.5, is a pressure vessel that envelopes a mercury-pool cathode, an anode, and an igniter. The anode terminal at the top of the ignitron is insulated from the tube with a ceramic annulus. The vessel is pressurized to mercury’s vapor pressure at room temperature. This environment creates a boundary layer of mercury vapor above the cathode pool. The igniter consists of a boron nitride tip dipped into the mercury pool such that a slight meniscus is formed. The resistance between the tip and the mercury is sufficient enough to create an arc across the pool when the igniter is triggered. The mercury vapor is easily ionized by the igniter discharge, and quickly spans the gap to the anode above and creates an arc-discharge electrical connection. The conduction channel(s) formed are essentially small Z-pinches, maintained by the abundance of electrons in the mercury pool and the current flowing from the capacitor banks. ZaP’s ignitrons have the capability for water cooling over the stainless-steel pressure vessel; however, the operational pulse frequency of the experiment does not necessitate an active cooling
ZaP’s acquisition of D-size ignitrons was a bulk operation, with the lab receiving over twenty ignitrons from various past experiments. However, the comforts gained in quantity do not extend to quality. Many of the devices have issues needing serious attention before reaching operational status. The most notable problem with most ignitrons is a degradation of the anode cable and insulator. Two ignitrons are selected based on the tightness of the anode-cable braid, and on the general appearance of the igniton. Each igniton is also subjected to a high-potential (HiPot) test to insure that the voltage stand-off capability of the switch is operating as advertised. This test is conducted using an existing test stand and stand-alone power supply capable of generating the necessary voltages. Both igniton candidates did not reach breakdown conditions with applied voltages upwards of 22 kV, well over the 10 kV maximum charge voltage of the capacitors.

The final diagnostic performed on the ignitrons prior to installment is to determine which ignitor to use. There are three independent ignitors incorporated into the ignitrons design to extend their operational life. An ignitor becomes inoperative when: the resistance between the ignitor and the mercury becomes too small to produce an adequate arc; or when the ignitor loses connection completely, making an arc impossible. A simple test using a multimeter and two probes is sufficient to find an operating ignitor. The desired ignitor resistance is between 7-12 Ω.

Bridge Assembly

The igniton’s cathode is directly connected to the capacitor-bank PFN via a bridge assembly, illustrated in Figure 3.6. The igniton’s lower structural support and electrical contact is achieved using a modified, igniton-stand bracket. The existing bracket is utilized because of the connection mechanism to the igniton, which consists of
Figure 3.5: Cut-away schematic highlighting relevant hardware features of a generic ignitron design. The components making up the ignitron include: (1) anode, (2) cathode, (3) ignitor, (4) mercury, (5) ceramic insulators, and (6) pressure vessel.
two brass L-brackets brazed to a 1/2” (1.27 cm) thick brass plate properly spaced to fit the cathode connector, including the two clearance holes required for the 1/2” (1.27 cm) bolts. The vice design and configuration provides great electrical contact and structural characteristics to support the ignitron in an upright position. As Figure 3.6 shows, the bracket is cut-away from its square-shaped stand such that the long side of resulting bar is flush to the edges of the bracket, and perpendicular to the opening in between. However, the brass plate that the bracket is cut from is only 10” × 10” (25.4 cm × 25.4 cm), which is not long enough to reach the PFN from the cathode. The 18” (45.7 cm) gap is spanned using an auxiliary-brass bar, which is supported by a ceramic spacer bolted to a base plate on the ignitron stand, and the PFN on the capacitor-bank. Good electrical contact between the cathode bracket and auxiliary bar is achieved using donut-shaped, 1/32” (0.08 cm) thick copper spacers positioned at each of the two bolt locations.

3.3.2 Structural and Ground-Return Components

The structural and ground-return components of the ignitron tower are grouped into the housing and base assemblies. Both are crucial in providing a current-return path for the bank discharge, as well as support the significant weight of the ignitron tower.

Ignitron-Housing Assembly

The first, and most notable structural component of the ignitron tower, shown in Figure 3.7, is the solid brass, ignitron-housing assembly that encapsulates the ignitron, electrical connections for both cathode and anode, as well as the current-distribution assembly. The housing is composed of an upper and lower section, each with identical, major dimensions, but with different hole patterns on the circumference and connection flanges. The upper section’s main design difference is two opposing win-
Figure 3.6: Exploded, isometric view of the ignitron’s bridge assembly. This assembly serves as the bridge that connects the capacitor-bank PFN to the cathode of the ignitron. The components include: (1) L-bracket cathode clamp, (2) support bar brazed to L-bracket, (3) copper washers, and (4) bridge bus-bar.
dows approximately midway up the tube. The openings serve as access ports when connecting and disconnecting the ignitron’s anode from the fork. This operation on the existing towers is difficult because the openings are just large enough to access the 1/2” (1.27 cm) bolts with the necessary tools. To make assembly and disassembly procedures easier, the windows on the new housings are increased in height by 3/4” (1.91 cm) to allow for more tool maneuverability. The other holes, in both the upper and lower housings, are identical to the existing housing designs, and are used for inspection of the inner components. Multiple upper and lower housing sections were acquired when ZaP procured the ignitrons for the lab, making the acquisition of these materials for the new towers a matter of finding the housings in the best condition.

Since the ignitron housing is grounded to the experiment, it must be elevated from the base plate with stand-off bars in order to create an air gap between the bridge assembly and ground. This is accomplished using four, 6” (15.2 cm) tall brass-hex bars. Good electrical contact on both ends of the 3/4” (1.91 cm) diameter bar is made using the same boss-ring design as the PFN risers.

When the ignitron is in the upright position secured to the bridge assembly, its lateral motion inside the housing is restricted with a Plexiglas centering ring placed on top of the pressure vessel. The ring is not in contact with the anode insulator, but maintains placement using an annular step that seats inside a recession on the top of the ignitron. Using this design, the centering ring does not damage or interfere with the anode in any way, but still provides the lateral support for the ignitron.

*Base Assembly*

The return current traveling through the ignitron housing is routed back to the capacitors through the base plate, which is not only bolted to the first capacitor in the bank series, but is supported by four phenolic posts attached to phenolic platform. These
Figure 3.7: Isometric assembly view of the structural and current-return components of the ignitron tower. Components of this assembly include: (1) upper and lower ignitron housings, (2) grounding-rod support bracket, and (3) stand-off posts.
components comprise the base assembly, whose primary function is to transfer the bulk weight of the above components to the floor. Leveling and height adjustments are made using four bolts spaced close to the corners of the phenolic platform, and can raise the assembly by as much as 3/4” (1.91 cm). All four base assemblies were fabricated and assembled together, one for each capacitor bank, and only requires installation. Note that the “blue” capacitor bank (RR) is 1/2” (1.27 cm) shorter than its white capacitor-bank counterparts, and is accounted for in the height of phenolic posts of its specific base assembly.

The final structure that completes the current-return circuit are the lower busbars bolted to the negative terminals on the capacitors. Each of the four capacitors in the bank have four negative terminals, positioned near the corners of the casing. Each grounding strap, one on each side of the capacitor, makes electrical contact with the base plate via the first negative terminal on the first capacitor. The straps then span the remaining three capacitors, making contact with all sixteen negative terminals. The grounding straps were fabricated and installed at the acquisition of the capacitors in order to secure and properly short the capacitors for storage.

3.4 Probes

The power supply is equipped with two probes: a high-voltage (HV) probe for monitoring bank voltage and a Rogowski coil to measure discharge current. The placement and purpose for these two diagnostics are detailed below.

3.4.1 High-Voltage Probe

A Fluke, 80K-40 HV probe is installed on each of the four capacitor banks to monitor the charge voltage at all times during ZaP operations. The probe is a precision 1000:1 voltage divider with a measurement range of 1 kV to 40 kV. All four HV
probes are directly connected to a quad-input, quad-display voltmeter mounted to the hardware tower next to the screen room. Complete with a power supply, the quad-voltmeter and HV probe measurements allow for constant, stand-alone monitoring of the bank voltages, which is crucial for safety and as a secondary check when using a programmable logic controller (PLC) for ZaP operations.

A former ZaP researcher, Joseph Blakely, designed and implemented the PLC to automate the control of the vacuum system, the charging of the capacitor banks, and the triggering of the experiment [1]. This automation greatly simplifies operator procedures, decreases the time between pulses, and improves pulse repeatability by removing the vast majority of human inputs into the system. However, the PLC only draws voltage measurements from the LF capacitor bank during operation, making the assumption that the other banks are behaving in the same manner. The stand-alone voltmeter diagnostic allows the operator to verify proper charging and discharging across all banks with a quick glance.

### 3.4.2 Rogowski Coil

The current waveform produced by each capacitor bank is measured using a Rogowski coil. Widely used for its simplicity and functionality, the Rogowski coil is a looped solenoid of coiled wire, where the total current enclosed by the loop is directly measured independent of its distribution [6]. Due to the diagnostic’s unique geometry, the underlying analytical theory is completely described by Ampere’s law,

\[
\oint_l B \cdot dl = \mu I
\]

(3.1)

where \( I \) is the total enclosed current, \( B \) is the magnetic field produced by that current, \( l \) is the loop path, and \( \mu \) is the magnetic permeability of the material that the wire is coiled around.
Assuming a constant solenoid area $A$ and number of coil turns per unit length $n$, the rate at which the magnetic flux changes within the loop is a measurable voltage, and is expressed as,

$$V = -\dot{\Phi} = -nA\mu\dot{I}$$

(3.2)

This voltage signal is digitized and integrated back in the screen room, and is directly proportional to the total current that passes through the loop.

The greatest aspect of the Rogowski coil’s simplicity is the convenience of in-house fabrication, countless design options, at practically no expense. ZaP uses a coaxial-cable based design. A length of RG58 cable is cut between 48” (122 cm) to 52” (137 cm), and approximately 24” (61 cm) of the outer shield is stripped off to expose the insulation around the inner conductor. 32-gauge magnetic wire, soldered to the tip of the inner conductor, is wrapped around the exposed insulator, creating a tight and uniform coil with an insulated return-wire back down the center. Contributing no flux to the coil, the return wire does not affect the measured voltage. The other end of the magnet wire is soldered to the outer conductor of the cable. Shrink wrap is applied immediately after winding to keep the coil loops as tight and uniform as possible. The coils parameters are: $A = 6.7\text{mm}^2$ and $n \approx 4.3\text{mm}^{-1}$ [3]. The ignitron Rogowskis are taped to the Teflon® shielding inside the upper housing, positioned so that the loop surrounds the anode cable of the ignitron. When the looped is formed and fastened with cable ties, it is important to line up the first and last windings of the coil, as illustrated in Figure 3.8. Self-integration of the Rogowski signal is eliminated using a $1\ \Omega$ series resistor.

ZaP’s Rogowski coils are usually calibrated using current transformers mounted on the experiment [3]. However, since a calibrated Rogowski is already installed on the LF ignitron, calibrating the new Rogowskis is simply a matter of securing them on the LF ignitron together, and then comparing the waveforms against one another after a
Figure 3.8: Schematic of a coax-cable Rogowski coil design. A length of the outer conductor and shield is removed from RG58 cable. Magnetic wire is tightly wrapped around the exposed insulation and soldered to the inner conductor on one end, and the outer conductor on the other. It is important to line up the first and last windings when the loop is secured around the current-carrier of interest.

capacitor pulse. A calibration factor is applied to the signal output of the integrator to match the amplitudes of the waveforms. The calibration factor determined for the LR and RR Rogowski coils are 0.220 and 0.231 respectively.

### 3.5 Charge and Dump Circuit

The charge and dump circuitry is expanded to accommodate the two additional capacitor banks in the power supply. The expansion consists of the installation of an additional four Ross relays, connecting those relays to the PLC system, and routing
Figure 3.9: Ross relays are used for the HV switching when performing charge and dump operations on the capacitor banks.

High-current cable to the new circuit components.

Ross Relays

High-performance switches for charge and dump operations is achieved using HV relays by Ross Engineering Corporation. As figure 3.9 illustrates, the relays are relatively simple in design. The circuit closes using a 120 V actuator, which clamps a silver-coated bar across two contact rods. Complete with threaded-screw clamps, the contact rods serve as the attachment points for the HV cable.

The two-bank configuration requires five Ross relays: two charge, two dump, and a ground. In expanding to a four-bank configuration, four additional relays are required for charge and dump switches. One ground relay is still sufficient, and is connected to the additional components as needed.

The Ross relays are organized and mounted onto two, elevated phenolic boards shown in Figure 3.10: one for charging components, and the other for dump compo-
nents. This division, coupled with a closed circuit, wall mounted camera feeding back into the screen room, provides for an easy, visual check to insure proper switch operation. All nine relays are upside down, mounted under G-10 L-brackets bolted to the phenolic boards. The relay’s orientation, together with proper actuator positioning, is designed to have gravity pull the actuator into the safe position when not activated. The original design had three L-brackets, each wide enough to mount three relays. In keeping the division between charge and dump components, an extra bracket is added to the dump board below the dump resistors to provide enough mounting space.
Figure 3.10: Graphical layout of the dump-board control circuit. The yellow lines represent the dump-relay control cable, the blue lines the charge-relay control cable, and the black lines the circuit-return cable for those controllers. The charging power-supply’s negative terminal (red line) is connected to the capacitors through the charge relays (labeled as 2, 3, 4, and 5). The ground cable (green line) connects to the capacitors via the ground relay (labeled as 1) and the dump resistors. In the nominal position, the dump relays (labeled as 6, 7, 8, and 9) are closed and continuously discharge the capacitors over the dump resistors.
**Wiring Up the Relays**

The Dump Board Control Circuit, illustrated in Figure 3.10, is located in the control rack outside the screen room, and supplies the 120 V signal to engage and disengage all relays. The controller signals the sent over two cables that go to the power supply: one which connects to the ground and charging relays, and the other which connects to the dump relays. The relays in each group are wired in parallel, and therefore cannot be individually activated.

**Organization of the High-Current Cable**

The addition of four Ross relays to the charge and dump board brings along wiring issues with the limited space. The HV cable used to make the electrical connections is RG217/U cable with the outer conductor and shielding removed. This proves to be very effective seeing that the cable is already insulated, easy to cut and manipulate, yet stiff enough to hold its shape. The cabling organization shown in Figure 3.10 is designed to minimize cable length and cross-overs, and to bundle cables when possible. These efforts greatly reduce clutter in the system, and make maintenance and modifications to the charge and dump boards far more user friendly and safe.

### 3.5.1 Operational Overview

The charge and dump system relays are in the nominal position when: ground and charge are open, and the dumps are closed. This insures that the capacitors are continually discharging across the dump resistors before and after a pulse. The dump resistance is determined such that the capacitors are fully discharged before anyone can reach the power supply from outside the lab. Under normal operating procedures, the PLC charges the capacitors to the desired voltage by first disengaging the dump relays, then engaging the ground and charge relays. This command connects the
capacitors to the charging power supply through a bank of charge resistors and to ground. The charge and ground relays remain closed until the bank voltages slightly overshoot the desired value, and are then disengaged to cease charging. When the bank voltage decays to the desired value, the PLC triggers the ignitrons to discharge the banks. The dump relays are immediately re-engaged until the next charging sequence.

3.6 Triggering System

ZaP utilizes a Krytron triggering mechanism to fire the ignitron(s). Krytrons are cold-cathode, gas-filled tubes with four electrodes: the primary anode and cathode, a pre-ignition electrode, and a triggering electrode grid. The pre-ignition electrode is positioned next to the primary cathode and carries a small positive charge, ionizing a region of gas right above the cathode. The anode is held at a large positive voltage. When the firing signal is sent from the screen-room PLC to the trigger receiver via fiber-optic cable, a positive voltage is applied to the electrode grid, causing an arc discharge to occur between the HV anode to the cathode.

The resulting HV pulse from the triggered Krytron travels into a splitter box via RG58 cable. Originally, the splitter box had two outputs, one for each ignitron. The box is modified to accommodate two extra banks by simply adding two more outputs in parallel. Four RG58 cables transfer the signal pulse from the splitter box to each of the four ignitron towers. Note, the D-size ignitrons used for ZaP’s power supply require a positive HV pulse to trigger the mercury rectifier; the pulse generated by the Krytron trigger is negative. The trigger pulse must first go through a 1:1 transformer before being sent to the ignitron’s ignitor.

The 1:1 transformer is a very straightforward design, using RG58 coax cable wrapped thirteen times around a ferrite core. Since the pulse from the Krytron is
negative, the inner conductor of its transmission cable is negative, and outer conductor positive. In order to make the inner conductor of the transformer coax positive for connection to the ignitron’s ignitor, the outer conductor of the trigger coax is spliced to the outer conductor of the transformer coax. To complete both circuits, the other end of the transformer-coax inner conductor is secured to the ignitron cathode via the bridge assembly, while the inner conductor of the trigger coax is spliced to the other side of outer conductor on the transformer. A graphical representation describing the current flow through the transformer is illustrated in Figure 3.11.

3.7 Modifications to the Experiment

The power-supply expansion to four capacitor banks has been considered since the experiment’s initial design iterations. The original, two capacitor-bank configuration only uses twenty of the available forty hot and cold plate RG217/U coax-connection points on the experiment. Therefore, the only major modification to the experiment to accommodate the twenty additional coax cables is to a plate-mounting bracket bolted to the cold plate. This component, made from 14-gauge aluminum sheet and struts and originally used for a Faraday cage around the hot and cold plates, provides the structure necessary to mount the value assembly for the gas-puff injectors. In its mounted position, the bracket creates a barrier between the copper-connection fittings on the backside of the cold plate and the connection points on the hot plate. This creates an assembly issue with snubber cables when all forty coax connections are in use.

The snubber assembly, designed and installed on ZaP in 2007 by former ZaP researcher Dean Chahim, greatly reduces signal noise in the experiment by absorbing high frequency oscillations created from voltage spikes in the plasma. The snubber assembly connects to the hot and cold plates using ten, RG58 coax cables, and uses the
Figure 3.11: Schematical representation of the current flow through the 1:1 transformer used to change the negative trigger pulse from the Krytron to a positive pulse for the ignitron ignitor.
same connection method as for the power-supply coax cables. Originally, the snubber cables simply passed through unused copper fittings in the cold plate. However, since this is no longer possible with the expanded power supply, ten 1/2” (1.27 cm), evenly-spaced holes are punched around the inner diameter to accommodate the snubber cable connections.

3.8 **Modeling the Power Supply**

ZaP’s electrical system is modeled using the commercial software, ISPICE, as a means to better understand the electrical properties of the experiments overall system circuit, as well as simulate the effects of doubling its power supply. The effort to create a robust model may also provide the means and intuitive understanding necessary to better design and implement the PFN.

The modeling effort discussed in this paper is not the first attempt to construct an accurate means of simulating ZaP’s power supply. Since the program’s conception, efforts using now outdated software have come close to grasping the circuit’s characteristics, but had not been updated to account for recent modifications to the power system. To compound the issue, the licenses for software used in past simulations are expired, furthering the need for a new modeling effort in ISPICE. ISPICE simulation work on the power supply to date has been accomplished by ZaP researcher’s Dan Jackson and Ray Golingo, and have laid the ground work for the new simulation effort [3].

Every model constructed for the analysis of the power supply is fine-tuned using manual comparison of current waveforms between the simulation output and experimental data. Due to ISPICE limitations with non-linear electrical components, only the first half-cycle of the waveform is considered. This limitation is not an issue when simulating ZaP, because the Z-pinch is all but extinguished by the first half-cycle.
Initial values for the electrical parameters are calculated based on the geometry of each component.

3.8.1 Initial Modeling

The initial, trial-simulation effort is an intuitive, brute-force method, with much of the initial design structure based on previous models. The initial process also provides a tutorial, of sorts, to learn the subtleties of ISPIE. However, the first iteration is destined for failure because there are too many unknowns being modeled in the system.

The entire electrical circuit for the experiment is included in the model, illustrated in Figure 3.12, with initial conditions based on normal, 9 kV operating conditions of a two capacitor-bank configuration. For the first iteration, the electrical-parameter approximations are applied to all components in the model to generate a fairly accurate simulation. Each successive iteration is used to modify a certain component of the model to converge the simulated output with experimental data. The three major components of concern in the power-supply model is the PFN, ignitron, and the electrical characteristics created from the experimental plasma.

After numerous iterations and fine-tuning, the manual method for this model provides an acceptable simulation output, as illustrated in Figure 3.13, even with three problematic components and only one waveform comparison to verify their electrical characteristics. However, the accuracy seen in Figure 3.13 is due largely to two model features: a convergence in total inductance, total capacitance, and total resistance in the system; and the piece meal inductance generator used to model the plasma as it accelerates downstream in the experiment. This waveform generator adds just the right amount of inductance to the circuit to effectively “step through” the distinctive double-humped shape of the current waveform flattop. This allows
the simulation to closely mimic the experiment, but the individual components of the model cannot be verified due to any small irregularity being masked by the inductance generator.

The first power-supply model does not meet the mission objectives because it is not robust. The model will only confidently simulate the current profile used for its creation, let alone forecast the behavior of a four capacitor-bank configuration. However, the time spent varying the inductance and resistance in each of the circuit components greatly enhanced the intuitive feel for what drives the initial rise of the current, the necessary frequency profile for the double-hump of the flattop region, and for the final declivity approaching the half-cycle crossing point.

A rejuvenated and more promising modeling effort rides on the calibration data for the replacement magnetic-field probes, which must first be characterized before being installed on the experiment. This process calls for multiple capacitor-bank
Figure 3.13: Current-waveform simulation output of the initial modeling attempt as compared to experimental current-waveform data.
Figure 3.14: ISPICE circuit schematic of the first calibration configuration with one capacitor and no PFN. This model is used to determine the circuit-parameter values for the ignitron components.

configurations as a means to generate different waveform frequencies needed in the calibration. Access to this new waveform data provides for a progressive build-up of sub-models to reach an accurate final model, while also allowing for individual component validation.

3.8.2 Single-Capacitor Model

The first power-supply configuration of the magnetic-probe calibration uses a one capacitor, one ignitron setup with no PFN from the LF capacitor bank. This configuration provides a convenient starting point for the power-supply model because the electrical properties of the ignitron and its current-carrying structure are the only unknown variables. The capacitor’s electrical properties are documented from the manufacturer, and the calibration stand/cables are accurately modeled based on their simple geometries. As Figure 3.14 illustrates, the single-capacitor model boils down to a relatively simple inductance-resistance-capacitance (LRC) circuit.

The unknown parameter values for the ignitron and connecting bus structure are
Figure 3.15: Current-waveform simulation output of the first calibration-stand configuration as compared to experimental current-waveform data for probe calibration.
determined using the same manual, iterative technique used in the first modeling attempt. Figure 3.15 illustrates the plot comparison of the current waveforms after acceptable convergence is reached.

The accuracy of the simulation from the initial rise through the waveform peak suggests that total inductance in the system is correct since the frequency of an LRC circuit is $1/\sqrt{LC}$. However, as the waveform approaches the crossing point of the half-cycle (denoting the time when the ignitron’s polarity reverses), inductance and resistance begins to vary within the ignitron. This variability could account for the crossing point of the simulated current occurring earlier in time than the experimental-current waveform. Another possible variability not accounted for in the simulation is the magnetic field soaking into the calibration stand. Further investigation into this phenomena is required and is not covered in this thesis.

3.8.3 Single Capacitor-Bank Model with PFN

The single capacitor-bank configuration adds three more capacitors, of known electrical properties, and a PFN to the single-capacitor setup. Since the ignitron is characterized in the first step of the model progression, this configuration’s only unknown circuit variables are the PFN inductance. The inductors for the PFN are highlighted in the circuit model of Figure 3.16. The finalized model produces the current-waveform illustrated in Figure 3.17 as compared to experimental data.

The challenge in determining the inductance of the PFN between capacitors is that a change in each component has a different effect on the current-waveforms behavior. The shape is a result of constructive interference between the capacitors output frequency. In order to better understand this relationship, a characteristic study of the PFN is conducted based on the single-bank model. The conditions and results of this study are presented in Figure 3.18.
Figure 3.16: ISPIE circuit schematic of the second-calibration configuration with a full capacitor bank with PFN. This model is used to determine the circuit-parameter values for the PFN components.

![ISPIE Circuit Schematic](image)

Figure 3.17: Current-waveform simulation output of the second calibration-stand configuration as compared to experimental current-waveform data for probe calibration.

![Current Waveform Simulation](image)
Figure 3.18: Characteristic study of the capacitor-bank PFN used to better understand the effect each inductor has on the current waveform. The study is conducted using the single-bank model of Figure 3.16: (a) Increase inductance of L3 & L7 from 330 nH to 400 nH; (b) Increase inductance of L23 from 315 nH to 400 nH; (c) Increase inductance of L6 and L14 from 135 nH & 115 nH to 180 nH; (d) Increase inductance L2 from 230 nH to 330 nH; (e) Neglect inductance of L6 & L14
Figure 3.19: ISPICE circuit schematic of an operational, two capacitor-bank configuration with plasma simulator. Since the electrical parameters for the ignitron and capacitor bank models are verified, this model is used to determine the circuit-parameter values for the plasma simulator.

3.8.4 Dual Capacitor-Bank Model with PFN and Plasma Simulator

The dual capacitor-bank model with PFN and plasma simulator is identical to the setup addressed in the initial model of section 3.8.1, and is the original power-supply configuration. Since the capacitor banks are identical in construction, the electrical properties for both ignitron and PFN are set to the values determined in sections 3.8.2 and 3.8.3 respectfully. The electrical properties of the individual capacitors are matched with their experimental counterparts from Table 3.1. The only variable in the circuit model that requires modification is the plasma simulator, illustrated in the circuit diagram of Figure 3.19.

There are three components that make up the plasma simulator: plasma resistiv-
Figure 3.20: Current-waveform simulation output of an operational, two capacitor-bank configuration as compared to current-waveform data from five experimental plasma pulses.
Figure 3.21: Plot of variable inductance for the initial and current plasma models as determined from the two capacitor-bank configuration simulations. The variable inductance generator is used to model changing system inductance as the current sheet propagates down the experiment. The comparison between the initial and current simulation efforts confirms that the new modeling effort is improving.

Plasma resistivity and the initial inductance are based on the experiment’s geometry assuming the current sheet is formed at the neutral gas injection plane. The variable inductor is structured and modified as in the initial model of section 3.8.1. A comparison of the variable inductance for this model against the initial model of section 3.8.1 is illustrated in Figure 3.21. The simulated-current output of the finalized model is compared to current waveforms from five separate, 9 kV plasma pulses to test consistency, and is illustrated in Figure 3.20.
The inductance comparison in Figure 3.21 gives new insight to both initial and new modeling attempts. The inductance generator for the initial model ends up being a catch-all to correct errors in the unverified electrical parameters of the PFN and ignitron. The jumps and valleys in the waveform reflects the piece meal method for aligning the simulated current with the experimental waveform. The general amplitude of the inductance is larger to compensate for a discrepancy in total inductance not accounted for in the rest of the circuit.

3.8.5 Simulation of Capacitor-Bank Expansion

With the electrical properties of the power supply known with confidence using the progressive-modeling approach, simulating the expansion is accomplished by merely doubling the number of capacitor banks in the model from two to four. The model for the expanded power-supply is shown as figure 3.22.
Figure 3.22: ISPICE circuit schematic of the expanded, four capacitor-bank configuration with plasma simulator. The capacitor inductances reflect the measured parameters listed by the manufacturer. This model incorporates all of the verified circuit components determined from the previous sub-models.
As figure 3.23 shows, the expanded power-supply will increase the current output of a 9 kV pulse from approximately 350 kA to 620 kA. Since the capacitor banks are added in parallel, the pulse duration will effectively remain unchanged. However, since current amplitude is almost doubling, the increased decay-time of the waveform elongates the half-cycle. This accounts for the increase in pulse duration from 80 μs to 100 μs seen in figure 3.23.
Simulated Current Profile of the Finalized 16 Capacitor Configuration

Figure 3.23: Predicted current-waveform of the expanded, four capacitor-bank configuration. The current waveform of the finalized, two capacitor-bank configuration is shown for reference. The dashed-line plots are the associated current waveforms from the initial model, showing the difference between the two simulations.
Chapter 4

‘ROD’ OUTER-ELECTRODE EXTENSION

4.1 Motivation for the Extension

The installment of the ‘rod’ outer-electrode is a proof of concept for an entirely new approach to ZaP’s innovative coaxial-electrode design. The primary motivation for the extension is to conclusively show that the shear-stabilized pinch is not wall supported. The new section also adds 13.27” (33.71 cm) of length to the assembly region, while providing another point of optical access through the slots of the outer electrode. Should the concept prove effective, the ultimate application would be an assembly region constructed entirely from rods. Compared to a solid electrode, this design will provide unprecedented optical access for diagnostics and observation. Other advantages to the concept is a drastic decrease of mass in the system, which will prove vital should this technology be developed for space applications.

The design of the rod electrode begins with a set of initial design parameters and basic concept objectives. From these parameters, a series of design iterations, primarily based on structural analysis, is performed to converge upon a final design. Consideration of magnetic forces acting on the rods are also applied to the electrode to insure structural integrity.

4.2 Determining the Design Parameters

The initial stages of the rod electrode’s design are primarily draft meetings, where design criteria and project goals are outlined and prioritized. These efforts make the initial design iterations efficient and highly progressive. The first parameters
considered are the most basic: major dimensions, materials, and assembly position on the experiment. These factors determined, the remaining rod parameters and connection mechanism are considered and implemented.

4.2.1 Dimensions, Materials, and Position

The length of the rod electrode is 13.27” (33.71 cm). The dimension is driven from two design considerations: the plasma surge volume at the end of the outer electrode assembly; and alignment of the extension electrode’s optical access. The relevant components are highlighted in Figure 4.1. The surge volume is designed to allow plasma streaming through the end-wall opening to expand and dissipate, reducing the possibility of plasma attachment to sensitive components within the vacuum vessel. The axial length of this volume should be approximately 10” (25.4 cm). This constraint provides a gauge for the approximate location of the outer-electrode assembly with respect to the conflat viewports on the vacuum extension. The rod-electrode length is then adjusted to align the optical-access port in the extension electrode with the vacuum extension conflat. The surge volume is slightly shortened to 9.31” (23.65 cm).

The outer diameter (OD) and inner diameter (ID) of the rod electrode is 8.08” (20.52 cm) and 7.605” (19.32 cm) respectively. The OD is identical to the extension electrode. The ID is determined by taking measurements of the extension, and radially subtracting 0.010” (0.0254 cm) to compensate for a protective layer of tungsten. The final ID of the rod electrode with tungsten is 7.585” (19.27 cm). The primary motivation for matching these dimensions is to allow for the extension and rod electrodes to be interchangeable in axial location.

Note that there is a discontinuity in ID and OD between the original electrode and extension electrodes. The cause for the difference is a result of three factors: the raw dimensions of the material used in fabrication, machining tolerances as a function of
Figure 4.1: Side view of the outer-electrode assembly positioned in the vacuum chamber highlighting relevant hardware and the first and second length constraints for the rod electrode. The surge volume’s axial length is first set to 10” (25.40 cm) to gauge the approximate position of the outer-electrode assembly in relation to the vacuum chamber. The rod-electrode length is then adjusted to 13.27 (33.71 cm) in order to align the optical-access port in the extension electrode with the vacuum extension viewport. This makes the axial length of the surge volume 9.31” (23.65 cm).

segment length, and required maintenance for wear and tear from repetitive operation. The rod electrode is fabricated from the same oxygen free electronic (OFHC) copper alloy 101 pipe used for the extension electrode. This inherently makes duplicating their final dimensions possible, and desired. The material for the original electrode is machined from completely different copper-tube stock, adding as much as 0.020” (0.051 cm) to the machined diameters. The original electrode is also 78.74” (200 cm) in length as compared to the 35.5” (13.98 cm) extension or 13.27” (33.71 cm) rod electrodes. Facing a surface, while keeping the cut depth shallow, is far more difficult with longer parts because the impact of defects in the raw material are amplified over the length of the component. Finally, the original electrode is exposed to more violent plasma processes that, over time, break through the protective tungsten barrier and
wreak havoc on the soft copper below. In December of 2009, the original outer electrode was sent to Flamespray Northwest Inc to have the inner surface refaced and tungsten sprayed due to significant sputtering and globulization of copper in the acceleration region. The current ID and OD are 7.616” (19.34 cm) and 8.095” (20.56 cm) respectively.

The rod electrode is positioned between the original and extension electrodes. Experimentation shows that the pinch is adversely affected by the end wall, also known as end-wall effects. Should the rod electrode be placed at the end of the assembly, distinguishing between end-wall effects and how the rod electrode influences pinch behavior would be difficult, if not impossible. Positioned further upstream of the end wall isolates the rods around a stable, and well-behaved pinch. The other motivating factor to the electrode’s positioning is the availability of optical access. There are two pairs of large, 6” (15.24 cm) conflat viewports: one at the downstream end of the main vacuum tank, and the other at the downstream end of the extension vacuum tank. Utilizing one of these viewports for observations is highly desirable, and can only be accomplished by positioning the rod electrode after the original electrode.

4.2.2 Rod Parameters and Connection Mechanism

Eight rods are incorporated into the electrode design. Evenly spaced around the circumference of the electrode, the eight-rod configuration provides unimpeded, horizontal and vertical optical access to the pinch. In machining the viewing slot, all cut surfaces are perpendicular to the electrode’s inner and outer circumference to mitigate field concentrations. These surfaces are plasma facing, and require a 0.010” (0.0254 cm) thick coating of tungsten that seamlessly joins with the layer sprayed on the inner surface. The cut edges on the outer surface, which are not tungsten sprayed, are given a 1/16” (0.16 cm) radius to reduce concentrated fields. Each rod is joined
Figure 4.2: Side view of the rod electrode labeled with the relevant features requiring design parameters. The electrode is oriented as if looking through the horizontal plane when assembled on the experiment.

together with its neighbor using a radius of curvature proportional to their spacing. This design feature insures a smooth transition for current flowing downstream from the solid to rodded sections of the outer electrode.

Originally, the large conflats were exclusively outfitted with DB-25 vacuum feed-through connectors for the various diagnostic and control leads mounted on the electrodes. A four-way vacuum fixture, also called a “cross”, is fastened to one side of the tank to double the available conflats for feed-through connections. Fortunately, optical access through the cross fixture is possible using a combination of DB-25 pin organization and feed-through placement.

The four conflat, feed-through arrangement left multiple DB-25 pins without input. An under-graduate student working on ZaP, Michal Hughes, took advantage of these openings by efficiently consolidating the pin-layout of each DB-25, satisfying connection requirements with the minimum number of feed-throughs. The consolidation effort alone, however, could not accommodate the loss of two conflats required for horizontal line-of-sight through the rod electrode. The leads are organized into two separate groups: an upstream group that feed-through two conflats via the cross; and a downstream group that feed-through two, 6” (15.2 cm) conflats on the extension
Figure 4.3: Side view of the rod electrode as seen through the 6”, horizontal conflat viewport. The left edge of the rod-electrode’s viewing slot is aligned with the left edge of the conflat window to maximize optical access. Since the electrode is axially symmetric, the length of the rod is determined to be 7.734” (19.64 cm). The electrode’s centerline is included for reference.

The upstream grouping consists of all probe leads from the original and rod electrodes, as well as all vacuum side, gas-puff value control leads. The downstream grouping consists of probe leads from the extension electrode and end-wall Rogowski coil. The cross is oriented horizontally to allow the wire leads to make contact with their feed-throughs, while limiting interference with the viewport’s field-of-view.

The line-of-sight through the 6” (15.2 cm) conflat is not centered on the rod electrode, but is situated slightly upstream of the electrode’s centerline. As a result, the viewing slot is optically aligned with the conflat’s field-of-view to maximize visibility of the pinch, as illustrated in Figure 4.3. This design parameter, coupled with symmetry, motivates a rod length of 7.734” (19.64 cm).

The rod electrode uses the same connection mechanism as the extension elec-
trode, illustrated in Figure 4.4. A pair of T304 stainless-steel split-rings clamp onto the joining electrodes in 3/4” (1.91 cm) annular grooves, noted in Figure 4.2. The split rings are identical in design with the exception of the bolt-hole pattern; the upstream split ring is threaded while the downstream split ring has 3/8” clearance holes. This orientation allows the extension electrodes to be connected and removed from the original without having to remove the entire outer-electrode assembly from the vacuum chamber. The bolts are accessible by removing the vacuum extension tank. A T304 stainless-steel contact-ring is sandwiched between the joining electrodes. Seated on the outside diameter of both joining electrodes, the ring serves as a centering device during assembly.

Sound electrical contact between electrodes is insured with a double knife-edge feature incorporated into the ring design, shown by the cross-sections of Figure 4.5. Due to the discontinuity between original- and extension- electrode dimensions, the knife-edge feature makes the contact rings position specific. The knife edge on the existing contact ring, shown on the left in Figure 4.5, is given a four-degree cut angle to accommodate the larger ID of the original electrode after being refaced. If the contact edge is clamped to the tungsten layer instead of the copper, there is a high probability that the tungsten layer will be damaged. The right image of Figure 4.5 is symmetric because it connects the rod and extension electrodes together, who share the same ID and OD. The flat, inner surfaces of the knife edges are plasma facing and require a 0.010” (0.0254 cm) layer of tungsten.

4.3 Structural Analysis and Design Iterations

The outer-electrode assembly is essentially a cantilever beam fastened to the cold plate. As a component in this assembly, the rod electrode must be strong enough to withstand applied loads and maintain structural integrity. Naturally, the rods are
the weakest link in the electrode. The cost of increasing their load-bearing capacity is a decrease in open-area fraction of the viewing slots. The rods also experience outward pointing magnetic forces due to the coaxial geometry of the experiment. The structural-analysis capabilities of the commercial software, COSMOSWorks, is used to optimize the relationship between rod strength and slot size, and converge upon a satisfactory design.
Figure 4.5: Contact-ring cross-section schematics for the (a) original-to-rod electrodes and (b) rod-to-extension electrodes. Notice that (a) has a slight, four-degree cut angle on the knife edge. This is to accommodate the larger ID of the original electrode after being refaced.

4.3.1 Setting Up the Model

COSMOSworks is a sub-program of SolidWorks, which is the primary software ZaP uses for computer aided design. This makes drawing compatibility between design and analysis programs a non-issue. Components of the outer-electrode assembly considered in the structural analysis model are shown in Figure 4.6, and consists of all three electrodes with associated split- and contact-rings, the gas-puff valve assembly, and the end wall. After these objects are imported to COSMOSworks, the model requires four pre-conditioning parameters before meshing and simulation: material properties, boundary constraints, contact/gap conditions, and applied loads. The meshed assembly is shown in Figure 4.7.

The material properties for each component are input into the model using the material library in SolidWorks. The only boundary constraint for this model is at
Figure 4.6: Isometric view of the outer-electrode assembly as modeled in COSMOSworks. The boundary constraint and gravity load are shown for reference.

Figure 4.7: Isometric view of the meshed outer-electrode assembly from COSMOSworks.
the cold plate where the original electrode mounts to the vacuum chamber. Ceramic spacers are installed under the outer-electrode during the assembly process for vertical support, but are not considered in this model to find the worst-case scenario. All contacts and/or gaps in the assembly are set to a non-slip condition. Finally, the applied loads are divided into two simulations: a pure gravity model to determine if the rods can support the weight of the extension and end wall; and a pressure simulation to verify that the rods can withstand magnetic-repulsion forces.

4.3.2 Rod-Electrode Design Iterations for Load-Bearing Capacity

According to National Electronic Alloys Inc, the yield stress of annealed, half-hardened OFHC copper alloy 101 is 30-44 ksi (207-303 MPa). The electrode is considered moderately half-hardened because it is tool-hardened when machined. Conservatively, the lower bound of the yield-stress range, 30 ksi (207 MPa), is used as the electrodes maximum allowable stress before structural failure.

After four design iterations, looking at 1/4”, 1/2”, 3/4” and 1” rod-widths, the 1” (1.27 cm) rod is chosen to optimize open-area fraction of the viewing slot considering the structural integrity of the electrode. Static-analysis von Mises stress and displacement plots from applying gravity to the outer-electrode assembly are presented in Figures 4.8 and 4.9 respectively. The maximum stress in the electrode occurs in the curvature region of the rods, peaking at 15.52 MPa. The electrode assembly will displace less than 0.039” (0.1 cm) at the end wall. Based on this analysis, the rod electrode has a structural factor-of-safety (FOS) of 13 for gravitational forces.

4.3.3 Consideration of Magnetic Forces

The coaxial geometry of the ZaP experiment induces an outward-pointing Lorentz force on the rods of the electrode. The repulsive force is created from current flowing
Figure 4.8: Contour plot of the von Mises stresses of the rod electrode with gravity applied to the COSMOSworks model. The maximum stress occurs in the curvature region of the rods, peaking at 15.52 MPa.
Figure 4.9: Contour plot of the displacements of the rod electrode with gravity applied to the COSMOSWorks model. The maximum displacement is 0.039” (0.1 cm) at the end wall.

In opposite directions in the Z-pinch and the in rods. In order to analyze the rod’s structural response to this force in COSMOSWorks, a uniform pressure is applied to inner surface of the rod electrode. The pressure is calculated for two experimental scenarios: a perfectly-centered Z-pinch with 500 kA of current equally distributed between all eight rods; and a worst-case scenario with an off-center Z-pinch and 500 kA of current going through one rod.

Calculating the Magnetic Pressure

The magnetic force on a rod is given by

\[ F = I_r B_p L_r \]  

(4.1)
where $I_r$ is the rod current and $L_r$ is the rod length. The magnitude of the magnetic field from the pinch, $B_p$, is calculated using

$$B_p = \frac{\mu_0 I_p}{2\pi r}$$  \hspace{1cm} (4.2)$$

where $\mu_0$ is the permeability of free space, $I_p$ is the pinch current, and $r$ is the radius from the pinch centroid to the inner wall of the rod electrode. For this calculation, the pinch is assumed to be perfectly centered and the return current evenly distributed between all eight rods. This allows $I_r = I_p/8$. Making these substitutions into Equation 4.1 gives

$$F = \frac{\mu_0 I_p^2}{16\pi r L_r}$$  \hspace{1cm} (4.3)$$

Given that pressure is force per unit area, the magnetic pressure becomes

$$P = \frac{\mu_0 I_p^2}{16\pi r w_r}$$  \hspace{1cm} (4.4)$$

where $w_r$ is the width of the rod. Using the parameters

$$\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$$
$$I_p = 500 \text{ kA}$$
$$r = 0.0965 \text{ m}$$
$$w_r = 0.0254 \text{ m}$$

in Equation 4.4 returns a magnetic pressure of 2.550 MPa. The same analysis is used for the worst-case scenario, where the parameters are now

$$I_r = 500 \text{ kA}$$
$$I_p = 500 \text{ kA}$$
$$r = 0.0483 \text{ m} \text{ (1/2 of the radius off center-axis)}$$

and resulting in a pressure of 40.8 MPa. COSMOSworks von Mises stress and displacement plots for the nominal and worst-case pressure scenarios are presented in Figures 4.10, 4.11, 4.12, and 4.13 respectively.
Figure 4.10: Contour plot of the von Mises stress in the rod electrode for the nominal-pressure scenario. A uniform 2.55 MPa of pressure is applied to the inner surface of the rod electrode. For a static analysis, the maximum stress on the rods is 988.5 MPa.

Consideration of Pulse Duration

The 988.5 MPa and 16 GPa von Mises stress concentrations from the two pressure scenarios should be cause for concern considering that the rod-electrode’s yield strength is only 200 MPa. The discrepancy is due to the linear-static analysis used to generate them, which is based purely on material properties. During ZaP operation, a plasma shot only lasts on the order of 100 µs, significantly reducing the impulse of the applied force on the rod. Using the linearity property, the maximum von Mises stress over the lifespan of the pinch is determined using a ratio of maximum displacement.

In the nominal-pressure scenario, the applied force on a rod, using Equation 4.3, is 12.73 kN. If the rod were unattached to the rest of the electrode, it would have an estimated mass of 0.2667 kg based on its dimensions and mass density, and an
Figure 4.11: Contour plot of the displacements of the rod electrode for the nominal-pressure scenario. A uniform 2.55 MPa of pressure is applied to the inner surface of the rod electrode. The maximum displacement of the rods for a static analysis is 0.2” (0.51 cm) outwards.
Figure 4.12: Contour plot of the von Mises stress in the rod electrode for the worst-case pressure scenario. A uniform 40.8 MPa of pressure is applied to the inner surface of the rod electrode to simplify COSMOSworks model. The worst-case scenario calls for all current flowing through one rod, which would apply a force only to that rod. This plot extends that pressure to all rods. For a static analysis, the maximum stress on a rod is a catastrophic 16 GPa.
Figure 4.13: Contour plot of the displacements of the rod electrode for the worst-case pressure scenario. A uniform 40.8 MPa of pressure is applied to the inner surface of the rod electrode to simplify COSMOSworks model. The worst-case scenario calls for all current flowing through one rod, which would apply a force only to that rod. This plot extends that pressure to all rods. The maximum displacement of a rod for a static analysis is 3.31” (8.4 cm) outwards.
acceleration of 47730 m/s². Using the kinematic equation of motion

\[ x_e = \frac{1}{2}at^2 \]  

(4.5)

where \( a \) is the acceleration and \( t \) is the pulse duration, the estimated displacement \( x_e \) of the rod is 0.0239 cm. Using linearity and the displacement ratio,

\[ \sigma_e = \frac{x_e}{x_s} = \frac{988.5 \text{ MPa}}{0.0239 \text{ cm}} = 41815 \text{ MPa} \]  

(4.6)

the estimated von Mises stress \( \sigma_e \) for the nominal-pressure scenario is reduced to 45.9 MPa. The rod-electrode’s FOS under these conditions is 4. Applying the same analysis to the worst-case scenario yields a estimated von Mises stress of 722 MPa. Under this stress, the rod would fail catastrophically. However, this is an extremely conservative estimate for two reasons. First, the worst-case pressure scenario assumes that the Z-pinch would stabilize off-axis with 80% of the supplied current for the entire 100 µs pulse duration. This is a highly improbable situation, if not impossible. Second, the impulse analysis on the COSMOSwork results does not include material properties in determining an estimated displacement of the rod. A transient analysis of the rod electrode using the pulse duration would provide a more accurate structural-response. In all, the 1” rod-design provides more than adequate load-bearing capacity, will maintain structural integrity under the worst of applied-magnetic forces, and provides the best horizontal and vertical viewing capability on the experiment.

### 4.4 Magnetic-Field Probes

Surface-mounted magnetic-field probes on the ZaP experiment are critical to analyzing time-varying plasma dynamics of the flow Z-pinch. The probes measure the change in the magnetic field at the inner surface of the outer-electrode assembly. The probes are arranged in both axial and azimuthal arrays at different key locations on the experiment. The axial array extends from the cold plate to the end wall (excluding
the rod electrode), with probes spaced every 2” (5 cm). The azimuthal magnetic-field measurements from this array are used to determine axial location, velocity, acceleration, and mass of the current sheet as a function of time [3]. There are four azimuthal arrays, each consisting of eight, equally spaced probes mounted around the circumference of the outer electrode. The azimuthal and axial magnetic-field measurements from these arrays are used to determine the radial location and average magnetic field of the Z-pinch, which directly impact the stability analysis of the plasma column.

The rod electrode is designed with an eight-probe, azimuthal array situated upstream of the viewing slot, in the space between the rods and the split ring. The probe settings in the array are centered on the axis of each rod, as shown in Figure 4.14. The purpose of this array is two-fold: 1) to add a fifth azimuthal array location to the magnetic-probe diagnostics suite; 2) provide the azimuthal magnetic-field measurements necessary to back-out current flow through each rod as a function of time. The structural implications of adding the probe setting to the electrode design are included in the COSMOSworks analysis of section 4.3.

The magnetic probes installed on the rod electrode consist of 32-gauge magnetic wire wound ten times around a Kel-F® probe-form, secured inside a stainless-steel probe cup. Tantalum foil is stretched over the cup and held in place with a copper washer to protect the probe from the plasma environment. This assembly is illustrated in Figure 4.15.

4.5 Outer-Electrode Collar Shielding

Openings in the outer electrode intended for diagnostics inevitably allow some of the plasma flowing in the acceleration and assembly regions to escape. Once outside the confines of the outer electrode, the high-energy particles tend to attach to probe leads and other sensitive equipment not designed to withstand direct-plasma contact.
Figure 4.14: Sectional view of where the probe setting is located on the rod electrode. The probes are situated upstream of the viewing slots, in the space between the rods and the split-ring groove, centered on the rod axis.

The result can be crippling. The addition of the rod electrode to the outer-electrode assembly greatly increases the potential volume of escaping plasma. As a means to mitigate damage to the sensitive components in vacuum, a collar shield is installed on the upstream split-rings of both the rod and extension electrodes, as shown in Figure 4.16.

The collar shield is very simple in concept, but rather tedious in design and manufacturing. The collar is divided into two segments so that they can be installed and removed from the outer electrode without removing the split rings. A shield segment consists of a T316 stainless-steel bracket covered with stainless-steel foil. A flat-pattern for the bracket is shown in Figure 4.17. The tab design on the bracket is based on the location of magnetic probes in relation to the split-ring bolt pattern. Due to limited space, split-ring bolts that interfere with magnetic-probe locations must be inserted prior to mounting the probe cups. The shield’s attachment tabs are designed to use the bolts that are not inserted prior to assembly. This feature, shown
Figure 4.15: Isometric, cross-sectional view of a magnetic-field probe installed on the rod outer-electrode. The probe consists of a Kel-F\textregistered form (red component) wrapped in 32-gauge magnetic wire (not shown) secured in a stainless-steel cup (grey component). Tantalum foil (blue component) is stretched over the cup and held in place with a copper washer to protect the probe from the plasma environment.

in Figure 4.18, allows the shielding to be installed and removed without having to disassemble the electrodes. The drawback to this intricate design is that a waterjet is required to cut the shapes out. Fortunately, the University of Washington has this capability, and the parts are fabricated in-house. The tabs are bent 60° from a flat position using a sheet-metal bending break. Once the brackets are fabricated, a template is made for the shielding by shaping aluminum foil over the bracket. The template is traced onto stainless foil and cutout for final-shield assembly.
Figure 4.16: Side view of the experimental apparatus with the collar shields (yellow components) included in the assembly. The shields are secured to the upstream splitting of both the rod and extension electrodes.

Figure 4.17: Flap-pattern view of a collar-shield bracket. The five tabs are bent 60° from a flap position using a sheet-metal bending break.
Figure 4.18: Sectional view highlighting the collar-shield tab design (red component) mounted on the rod electrode. The design is motivated by the split-ring bolt pattern in relation to the magnetic-probe locations (blue components). The bracket’s attachment tabs are only positioned over split-ring bolt holes that do not have probe-cup interference.
Chapter 5

SUMMARY AND CONCLUSIONS

The ZaP Flow Z-Pinch Experiment at the University of Washington investigates the concept of using radially-varying, sheared-axial flows to stabilize a Z-pinch plasma column. The ZaP experiment uses an innovative coaxial-electrode geometry consisting of a three-segment outer-electrode assembly, an inner electrode with nose cone, and an end wall. Plasma flows are created by injecting and ionizing neutral gas into the annulus of the plasma acceleration region. This current sheet is accelerated towards the assembly region with Lorentz forces, and a Z-pinch is created. Residual-neutral gas in the acceleration region is continually ionized and accelerated, replenishing the plasma in the pinch and producing the radially-varying velocity profile. The Z-pinch equilibrium has been stabilized for up to 2000 times the growth rate of the kink and sausage instabilities.

ZaP’s capacitor-bank power supply has been doubled in size, from two to four banks. Each capacitor bank consists of four 170 $\mu$F capacitors, a PFN, a D-sized ignitron, a triggering system, as well as numerous structural and current carrying components. The additional capacitor banks increases the energy-storage capacity of the system from 70 to 140 kJ. In order to gauge the affect this expansion has on the system, the power supply was modeled using the commercial software, ISPICE. The estimated current-output from a standard, 9 kV capacitor-bank charge will increase from 350 kA to over 620 kA. Linearly scaled from current measurements on a two-bank configuration, the pinch current pinch will rise by approximately 70 kA, leading to plasma temperature and density increases by as much as 33%.
A rod outer-electrode has been designed, manufactured and installed on the ZaP experiment. The primary motivation for the extension was to conclusively show that the shear-flow stabilized pinch is not wall supported in any way. The electrode is also a proof-of-concept for an all rod assembly-region, which has many advantages over its solid-electrode counterpart. The new section is 13.27” (33.71 cm) long and has eight 1” rods. The viewing slot between rods provides the largest vertical and horizontal optical-access to the pinch on the experiment, at 2.17” (5.5 cm) wide and 7.7” (20 cm) long. The rod electrode has identical ID, OD, and connection mechanism as the extension electrode, making them interchangeable in axial location. An azimuthal, magnetic-field probe array is situated just upstream of the rods, and provides critical measurements for determining pinch stability and the current distribution flowing through individual rods. In order to protect the magnetic probes from escaping plasma, a collar shield was designed and implemented on both rod and extension electrodes.

The modifications to the ZaP experiment during the time of this publication has been extensive. As a result, less than 30 low-energy pulses using only two capacitor banks have been recorded, and the data not sufficiently analyzed to be included in this thesis. Utilization of the four capacitor-bank configuration will occur after the experiment is properly tested and brought back to full operational capacity.
APPENDIX A: CAPACITOR-BANK MACHINE
DRAWINGS
Figure A.1: Capacitor-Bank Assembly Drawing
ZAP FLOW Z-PINCH  
UNIVERSITY OF WASHINGTON  
PART NAME: Ignitron_PFN_Top_Bar  
MATERIAL: Brass  
UNITS: Inches  
SCALE: 1:4  
DATE: 3/18/2010  
DRAWN BY: Jacob Rohrbach  
CONTACT: (206) 543-2108  

Figure A.2: Upper Bus-Bar Machine Drawing
PART NAME: Ignitron_PFN_Posts
MATERIAL: Brass
UNITS: Inches
SCALE: 1:2.5
DATE: 3/18/2010
DRAWN BY: Jacob Rohrbach
CONTACT: (206) 543-2108

ZAP FLOW Z-PINCH
UNIVERSITY OF WASHINGTON

TAPER SHARP CORNERS BACK WITH LATHE

Figure A.3: PFN Riser Machine Drawings
Figure A.4: Lower Bus-Bar Machine Drawing
Figure A.5: Ignitron-Tower Assembly Drawing
Figure A.6: Current-Distribution Assembly Drawing

COMPONENTS:
1) COAX_GROUND_CONNECTORS
2) GROUND_PLATE
3) UPPER_SPACER
4) COAX_HOT_CONNECTORS
5) HOT_PLATE
6) FORK
Figure A.7: Coax-Cable Ground Connector Machine Drawing
Figure A.8: Ground Plate Machine Drawing
Figure A.9: Insulated Spacer Machine Drawing
MACHINE 1/8" RADIUS
ON TOP EDGE

φ .375
.107 ⊖ .375

1.000
.500
.450
.375

φ .201 ⊖ .500
.201 ⊖ .500
1/4-20 UNC ⊖ .500

ZAP FLOW Z-PINCH
UNIVERSITY OF WASHINGTON

PART NAME: Ignitron_Coax_Hot_Connector
MATERIAL: Brass
UNITS: Inches
SCALE: 1:8
DATE: 3/18/2010
DRAWN BY: Jacob Rohrbach
CONTACT: (206) 543-2108

Figure A.10: Coax-Cable Hot Connector Machine Drawing
Figure A.11: Current-Distribution Plate Machine Drawing
Figure A.12: Current Fork Machine Drawing
Figure A.13: Upper-Ignitron Housing Machine Drawing
Figure A.14: Igniton Centering-Ring Machine Drawing
Figure A.15: Grounding-Rod Support-Bracket Machine Drawing
Figure A.16: Lower-Ignitron Housing Machine Drawing
Figure A.17: Hex Stand Machine Drawing
APPENDIX B: ‘ROD’ ELECTRODE MACHINE
DRAWINGS
Figure B.1: Rod Electrode Machine Drawing
Figure B.2: Rod Electrode, Upstream Split-Ring Machine Drawing
Figure B.3: Rod Electrode, Downstream Split-Ring Machine Drawing
Measured Original Outer Electrode ID before W spraying:
   High: 7.618"
   Low: 7.615"
   Contact 0.025" on radius above W layer.

Measured Outer Electrode OD:
   High: 8.097"
   Low: 8.094"

Detail B
SCALE 3 : 1

Note:
Drill four pairs of trapped volume holes equally spaced around the ring; each pair consists of a #68 hole on either side of the knife edge.

Figure B.4: Original-to-Rod Electrode Contact Ring Machine Drawing
Note:
Drill four pairs of trapped volume holes equally spaced around the ring; each pair consists of a #68 hole on either side of the knife edge.

Figure B.5: Rod-to-Extension Electrode Contact Ring Machine Drawing
BIBLIOGRAPHY


