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SPECTROSCOPIC MEASUREMENTS IN THE POST-HOLE CONVOLUTE ON SANDIA'S Z-MACHINE (INVITED)*

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Abstract

Pulsed power is a key driver for high energy density (HED) science. The Z-Machine is the world's largest pulsed power driver, and as such is one of the foremost platforms for HED science. The double post-hole convolute current adder is a critical element in low impedance, multi-module pulsed power device design. Post-refurbishment, the current loss in the convolute has reached as high as 5 MA (20% of the MITL current). Measurements of the plasma forming in this region will lead to a better understanding of the losses, and may help with a redesign of the system. Spectroscopic measurements of the convolute show strong continuum emission with absorption features. Most notably we observe the hydrogen H-alpha at 6563 Å. Lithium was introduced into the convolute as a tracer; this experiment put upper and lower bounds on the axial position of the observed continuum emitter, (located in the upper post-hole). Measurements of the location of continuum emission as a function of time indicate that plasma travels from cathode to anode with an apparent velocity of greater than 7 cm/µs.

I. INTRODUCTION

The Z-Facility at Sandia National Labs is the world's largest pulsed power facility. The Z-machine initially stores up to 22 MJ of energy in the Marx bank capacitors, and is capable of delivering more than 25 MA with a risetime that is less than 100 ns to the load [1,2].

These extremes in pulsed power are necessary to push the boundaries of magnetically driven high energy density physics experiments. Examples of the experimental loads used in these experiments are wire array z-pinches (radiation effects experiments [3]), flyer plates (shock physics experiments [4]), and imploding cylindrical liners (magnetized liner inertial fusion experiments [5]).

The extreme energy densities necessary for these experiments are achieved by compressing the electrical energy stored in the capacitors by many orders of magnitude in both time and space. The energy is initially stored over 100's of seconds at a radius of ~ 15 m in a ~ 7 m tall stack of capacitors. The pulse is delivered to the 1 cm tall load which is located at a radius of approximately 1 cm on a 100's of ns time scale (a compression of 9 orders of magnitude in time and 6 in space).

The Z-Machine consists of 36 pulsed power modules connected in parallel. Each module contains a Marx bank where the charge is initially stored and then erected into a high voltage, an intermediate storage capacitor with a laser triggered output switch, a pulse forming line with self-breaking output switch, and water transmission lines as shown in Figure 1. The transmission lines connect through the water convolute to the insulator stack, at which point the pulses from all 36 lines are combined and re-split into 4 parallel

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vacuum transmission lines. The conical self-magnetically insulated transmission lines (MITLs) bring the pulse from the stack to the double post-hole convolute, which combines the current from the four transmission lines in parallel to drive a single, low-impedance, radial feed A-K gap at the load as shown in Figure 2 [6]. Parallel current addition in current convolutes is a critical element in achieving the low inductances (less than 10 nH) required for 25 MA current pulses.

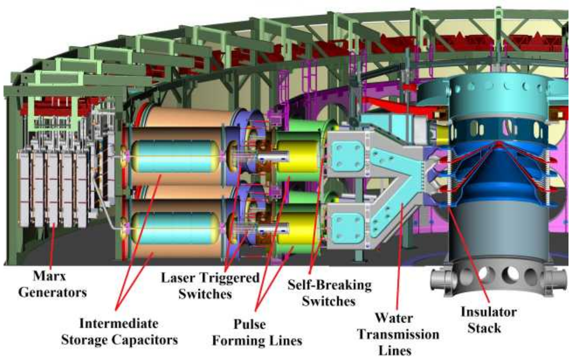

Figure 1. A solid model cross-section of the Z-Machine.

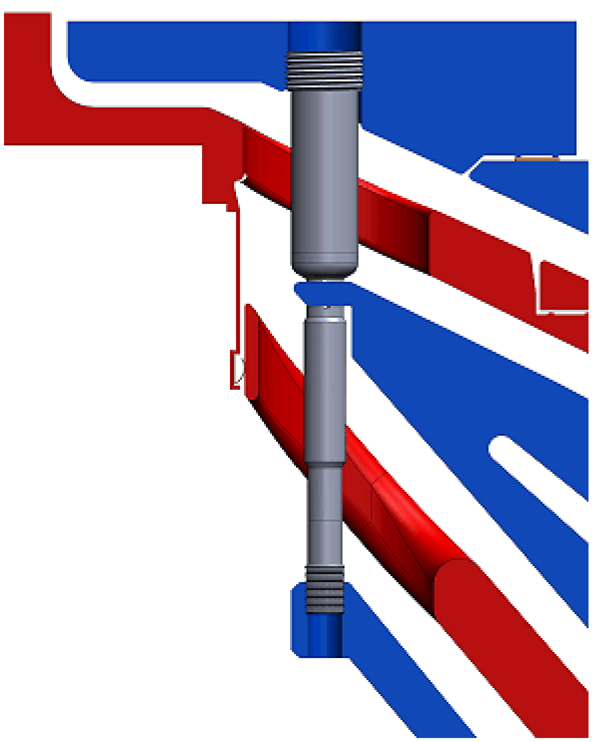

Figure 2. A solid model of the Z double post-hole convolute. The anodes are shown in blue and the cathodes are shown in red. The posts, which connect the three anode electrodes, are shown in gray.

The current is monitored at several locations in the system using B-dot monitors [7]. The MITL current is determined using B-dot measurements in the outer MITLs (at 66.4 cm) and at the insulator stack (at 165 cm). The load current is inferred from measurements made just downstream from the convolute (at 7.62 cm). The difference between these two signals is the loss current, and a significant fraction of that loss is believed to originate in the post-hole convolute. Differences in the MITL and load currents on the order of 5 MA (or 20% of the peak MITL current) have been recorded. It should be noted that not all of this loss is electron flow loss to the anode; McBride et al. have shown that some of the loss can be attributed to displacement current in the MITLs [8].

The double post-hole convolute is geometrically complex and provides little diagnostic access. As a result, the majority of the convolute studies conducted to date have been simulations. Spielman et al. measured the hard x-rays generated in the convolute on Saturn [9], but no direct experimental study of the plasma conditions in the Z convolute has been conducted previously.

Simulations of the Z convolute have been performed by Pointon et al. using Quicksilver [10-12] and by Rose et al. using LSP [13-15]. Both studies showed that the loss currents measured experimentally could not be reproduced in simulations that did not include electrode plasmas. Electrode plasma formation is not surprising given the extreme electric and magnetic fields and power densities achieved in the convolute.

In the LSP simulations, which include electrode plasmas, a fixed monolayer desorption rate is assumed for all times and all locations. The desorption rate was adjusted until the simulations matched the experimental results. The goal of these measurements is to diagnose the plasma that is believed to cause the current loss in the convolute. These measurements will be compared to convolute models to benchmark simulations.

II. DIAGNOSTIC SYSTEM AND PROBE DESIGN

Measurements of the convolute plasma are taken using a streaked visible spectroscopy system [16,17]. This system allows spectral and temporal resolution of the plasma emission. The system consists of a 1 m McPherson spectrometer (model 2061) coupled to an NSTec L-CA-24 streak camera. The signal is recorded on Kodak TMAX 400 film along with at least 2 spectral fiducials (typically HeNe laser lines applied to the film pre-shot) and absolute and relative timing fiducials (comb and impulse signals applied during the shot).

The microchannel plate (MCP) on the streak camera limits the resolution of the system at approximately 100 microns. The spectral resolution of the system is dependent on the diffraction grating used in the spectrometer; in these experiments, a 600 g/mm grating is typically used, thus the spectral resolution is between 1 and 2 Å. Similarly, the temporal resolution is dependent on the sweep duration of the streak camera; these experiments typically use 240 ns sweep durations, which corresponds to a temporal resolution of better than 1 ns.

The diagnostic system is coupled to the probe through a series of fiber optic cables. The fiber run consists of four 100 micron diameter fibers connected in series: the input fiber, the transit fiber, the feedthrough fiber, and the chamber fiber. The total fiber length is approximately 35 m, which causes less than 1 ns temporal dispersion. Convolving this with the resolution set by the streak camera gives a temporal resolution better than 2 ns.

The chamber fiber is clad in 5.0 mm diameter, 0.7 mm thick flexible steel tubing to shield the fiber from copious x-ray radiation generated by Z. A number of background tests were conducted with the fiber light collection blocked to monitor the effect of the shielding. On radiation effects shots (the most powerful x-ray pulse of all shots used in this study), the background is not observable at the experimental diagnostic settings.

The probe used in these experiments is inserted into a vacant inner B-dot hole as shown in Figure 3a. The body of the probe is designed to electrically mimic that of the B-dot it is replacing; a side by side comparison of the two probes is shown in Figure 3b. The intent is to cause as little perturbation to the system as possible. This allowed many experiments (30+) to be conducted in a "ride-along" mode. No dedicated convolute plasma experiments were required to make progress on this issue.

The probe consists of three components: the chamber fiber, a limiting aperture, and the probe body. The limiting aperture has a 500 micron diameter opening concentrically positioned with the end of the chamber fiber, but axially offset by 7.0 mm; this allows a 4 degree full angle view (the fiber typically has a full angle view of 25.4 degrees). By narrowing the field of view, the probe gains some spatial resolution at the cost of reduced signal. At 5 cm, the region viewed by the probe is 5 mm in diameter.

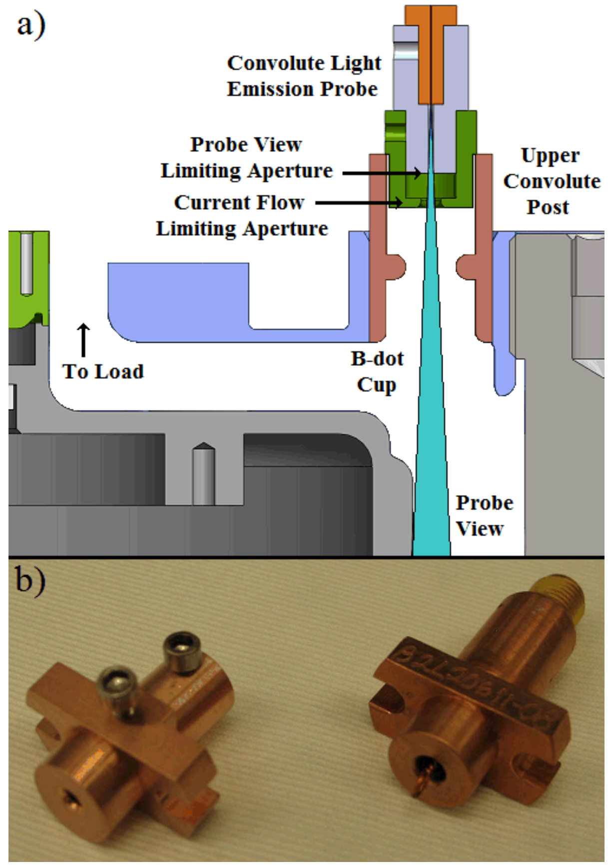

Figure 3. a) A solid model of the probe installed in place of an inner MITL B-dot. b) An example of the probes used in these experiments is shown on the left; the standard B-dot probe [6] is shown on the right.

While the design described above is simple and easy to implement, it does have draw backs. The limited spatial resolution contributes to large uncertainties in the location of the measurements. Additionally, the collection efficiency is 2.5% of a fiber without the limiting aperture. Utilizing a lens to image a region of the convolute onto the fiber would increase both the spatial resolution and the collection efficiency of the probe.

The probe body was designed with a larger limiting aperture, which does not affect the view of the fiber, but should reduce the current flow over the surface surrounding the hole in limiting aperture hardware. The probe body has several configurations, which allow the probe view to be adjusted throughout the convolute. The zero degree probe essentially views along the cathode surface of the upper hole, the five degree probe views roughly the center of the upper hole A-K gap, and the seven and a half degree probe views close to the upper post (anode) as shown in Figure 4. There is also a twenty degree probe that is used to observe the plasma formation within the B-dot cup itself. Tests with the twenty degree probe showed no observable signal originating within the B-dot cup itself for several load geometries. This indicates that the signals observed with the other probe views (0, 5, and 7.5) originate within the convolute.

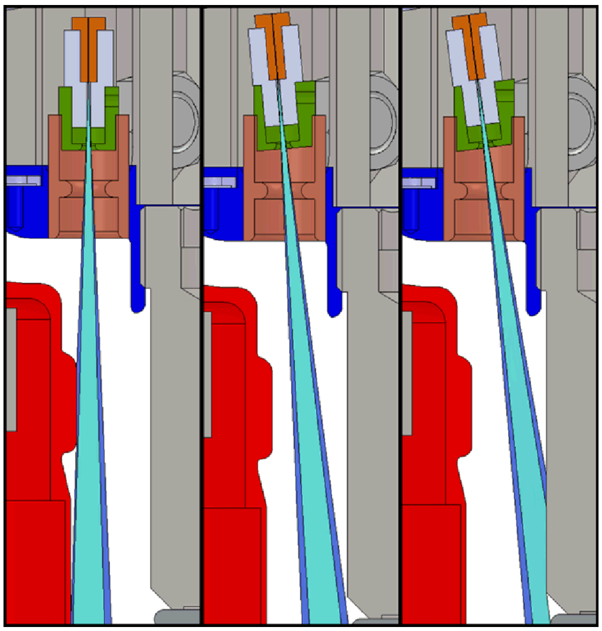

Figure 4. A solid model showing the three convolute probe views used in this experiment. The angle of the probe from left to right: 0˚, 5˚, 7.5˚. These are the cathode, gap, and anode views, respectively.

III. EXPERIMENTAL SETUP AND RESULTS

Several different types of measurements of the plasma in the post-hole convolute were conducted using the diagnostic described above, two of which will be described in this paper. A set of experiments were conducted in which a dopant was introduced into the convolute in order to confirm that the plasma observed originated within the convolute and to provide spatial resolution in the axial direction. Another set of measurements were conducted to monitor the plasma motion in the convolute. Typically, the spectra from these measurements contained strong continuum emission turning on sharply and remaining on for the duration of the sweep as shown in Figure 5. A number of absorption features were visible super imposed on the continuum; the most notable feature was the hydrogen Balmer series line at 6563 Å.

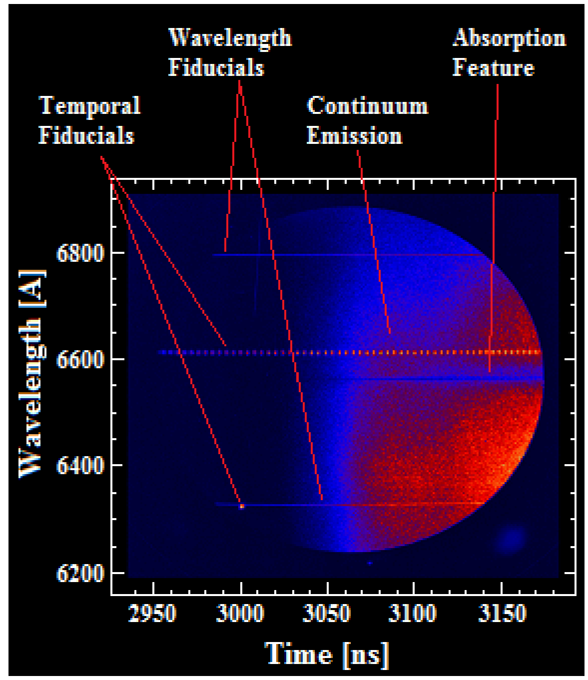

Figure 5. A sample of spectrally and temporally resolved convolute emission data. These data were from shot 2110, which used an imploding cylindrical liner load with a shaped pulse for dynamic materials testing. The absorption feature indicated is the hydrogen H-alpha at 6563 Å.

A. Dopant Shots

The primary objective of experiments using dopants was to confirm that the bright continuum emission observed originated within the convolute, as opposed to within the B-dot cup or on the surface of the probe. The secondary objective was to axially resolve the location of the observed continuum emission within the convolute. The measurements used a 1 mm tall, 1 micron thick LiF coating deposited around the surface of one of the upper convolute posts as shown in Figure 6. Li was chosen as the dopant due to past experience making visible spectroscopic measurements of the Li-I 2s-2p transition at 6708 Å [16,17].

With the Li band in the upper position (axially at the center of the hole in the upper cathode), an absorption feature was observed at 6708 Å as shown in Figure 7. This confirms that the observed continuum emission originates within the convolute as it is backlighting the Li, which only exists in the convolute.

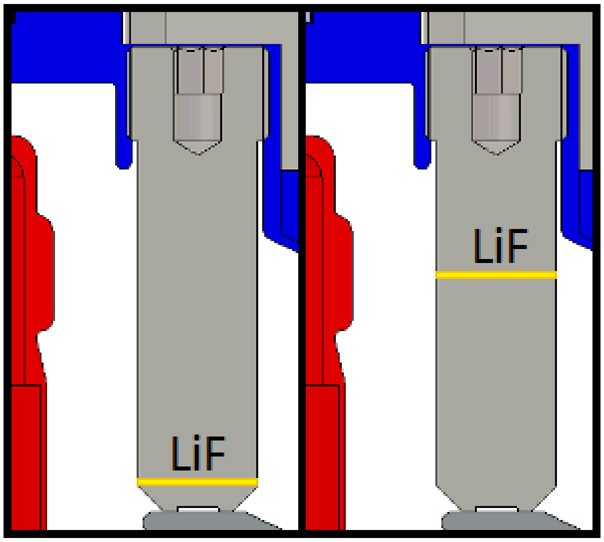

Figure 6. A solid model of the upper post-hole showing the location of the LiF dopant for the two cases. The lower position is shown on the left; the upper position is shown on the right. Cathode shown in red; anode shown in blue.

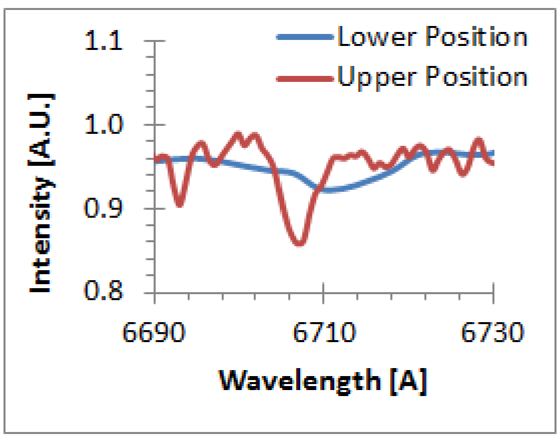

Figure 7. Spectral lineouts of the data from two shots in which the LiF dopant was included on the upper convolute post. The shot with the LiF in the upper position has a distinct absorption line at 6708 Å, where as the shot with the LiF in the lower position has no spectral feature at 6708 Å.

In an attempt to complete the secondary objective, the Li band was moved to the lower position (axially at the lowest cylindrical region of the upper post). No Li absorption feature was observed with the dopant at this location as shown in Figure 7. This indicates that a sufficient fraction of the observed continuum emitter was located above the Li dopant, such that it could not backlight the Li plasma. This result is generally consistent with the result presented by Rose et al. [15].

It is important to note a limitation associated with the passive doping technique used in these experiments. The lithium is located on the anode and requires sufficient energy to be deposited in the region to desorb the dopant. Once desorbed, the lithium must expand into the probe line of sight, thus for a significant fraction of the current pulse, the dopant cannot be observed. It is also important to note that in these measurements the diagnostic field of view did not include the lower post-hole, thus the bounds placed on the continuum emitter only establish an axial position of the upper post-hole plasma.

B. Convolute Plasma Motion

These measurements were conducted to determine the direction of plasma motion in the convolute (anode to cathode, or vice versa) and to estimate the apparent plasma closure velocity. These experiments were conducted on four nominally identical radiation effects shots, which typically have the highest convolute loss current. The load was not varied shot to shot, and the diagnostic settings were held constant with the exception of the angle of the probe and the MCP gain. The initiation shot had a direct view of the cathode and used the highest gain setting possible for this diagnostic. This shot was used to determine the time at which plasma was first detectable with our diagnostic. The other three shots used the same, lower gain setting and thus have the same sensitivity as one another.

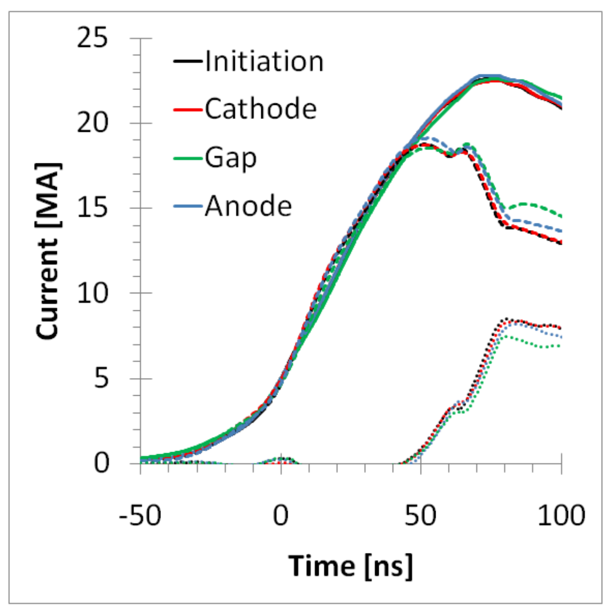

Figure 8. A plot of the current traces for shots 2077, 2078, 2079, and 2080. The solid lines represent the MITL current, the dashed lines represent the load current, and the dotted lines represent the loss current, which is a combination of actual current lost across the A-K gap and displacement current.

The MITL and load currents for the four shots are overlaid in Figure 8. The traces have been time shifted such that the 5 MA points all occur at T = 0. The loss current is on the order of 4 MA at the time of peak x-ray for these shots and is very reproducible shot to shot.

Temporal line outs were taken of the continuum spectrum at 5000 +/- 100 Å, and these traces were time shifted in the same manner as their respective current traces. A plot of the four lineouts is shown in Figure 9. These traces show very clearly that the continuum emission is observed at the cathode first. This indicates that plasma is expanding from the cathode towards the anode.

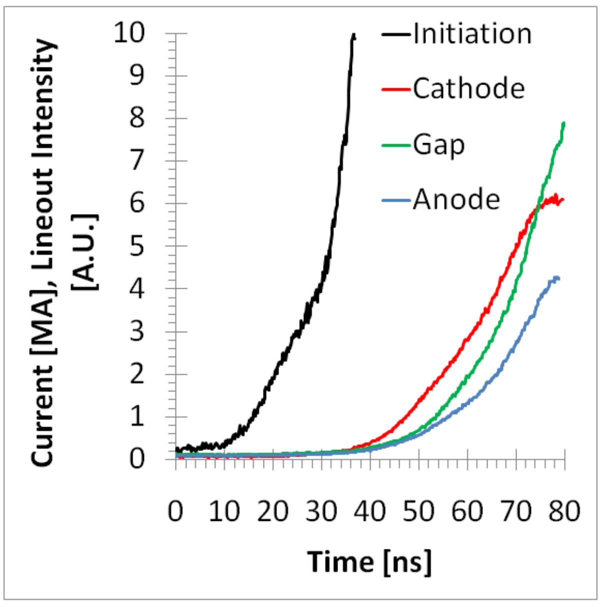

Figure 9. A plot of the temporal lineouts of the data at 5000 +/- 100 Å from shots 2077, 2078, 2079, and 2080. There is a clear trend in turn-on time from cathode to anode.

We make the assumption that the axial position of the continuum emitter is at the lower edge of the upper cathode hole as shown in Figure 10. This is supported by the Li dopant measurements and by previous simulations [15]. We also assume that the radial position of the leading edge of the plasma is at the center of the probe view at the 50% point of the temporal lineout of each spectrum. Using the distances from the cathode to points and the difference in the turn-on time of each view relative to the initial observed emission (initiation trace), we estimate the apparent velocity of the continuum emission. The data indicate that the closure velocity is greater than 7 cm/μs, which is considerably higher than expected based on other measurements of dense electrode plasma gap closure in transmission lines [18]. Several other independent spectroscopic measurements of the apparent plasma velocity, the description of which are beyond the scope of this article [19], qualitatively agree that the apparent plasma velocity is considerably greater than expected. Additional measurements with improved spatial resolution (i.e. using a lens collection system) are necessary to better measure the closure velocity of the plasma.

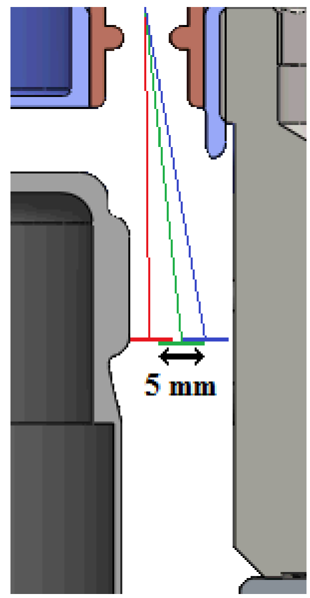

Figure 10. A solid model of the upper post-hole gap. Red, green, and blue lines mark the axes of the cathode, gap, and anode views, respectively. The horizontal lines at the end of the lines indicate the axial position at which the plasma is assumed to be located and the spatial extent of the probe view at that location.

This estimate of the apparent closure velocity is likely a lower bound on the actual value. It assumes that the first observable light emission from the cathode indicates the start of plasma expansion into the gap, and that this same plasma is being observed by the other views. Since the other three shots used a lower diagnostic gain setting, the sensitivity of those measurements was much less than that of the initiation shot. Thus the density of plasma that was being monitored on those shots was much higher than on the initiation shot. Based on these calculations, there is a clear increase in apparent closure velocity with distance from the cathode, which indicates that the apparent closure velocity could be much larger than the value reported above.

IV. CONCLUSIONS

The first experimental measurements of the plasma in the Z-machine's post-hole convolute have been conducted. This paper describes the diagnostic and probe utilized in the measurements as well as two of the experiments conducted to date.

The measurements made with the Li dopant indicate not only that the continuum emitter is located within the convolute, but also give some information about the axial position of the continuum emitter within the convolute. Based on these results, the dense plasma that produces the continuum is located in the upper level of the two level post-hole region, and the bulk of the plasma is located below the center of the hole in the upper cathode.

The measurements of the A-K gap closure show that continuum emission is first observed from the cathode view, then in the gap view, and finally in the anode view. This is an indication that plasma originates at the cathode and then moves towards the anode. Based on these measurements, the apparent velocity of the propagation across the A-K gap is greater than 7 cm/μs, which greater than what is expected in a traditional anode-cathode gap by at least a factor of 3. This may not be an actual velocity, but only an apparent velocity. We may be observing an ionization front propagating towards the anode at a much larger velocity than the hydrodynamic motion of the cathode plasma, typically observed to be about 2 cm/μs.

The results presented in this paper provide a basis to begin an experimental study of the complex physics taking place in the convolute. Additional experimental measurements are being actively pursued with different load impedance histories. Future work will include lens coupled probes, more dopant experiments, and detailed spectroscopic analysis. A comparison of the convolute simulations to the experimental results is also crucial to this research. We hope this work will provide insights into current loss mechanisms, methods to mitigate the loss, and help in the design of future convolutes.

V. ACKNOWLEDGEMENTS

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