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Voltage and Ion Current Measurements for an Ion Diode Driven by Mercury in Positive Polarity with Layered MITL Flow*

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ABSTRACT: For pulsed power machines with an inductive voltage adder (IVA) architecture and a magnetically insulated transmission line (MITL), positive polarity operation results in layered MITL flow as emitted electrons are born at different potentials in each of the adder cells[1]. Because of this layered flow, the usual prediction of the voltage using the Mendel formula is not accurate in positive polarity. In an attempt to directly measure the voltage across an ion diode on Mercury in positive polarity [2,3], a number of diagnostics have been fielded, including a vacuum wire voltmeter, stacked radiachromic films, nuclear activation, and a ^{7}Li(p,n) neutron-yield technique. Additionally, the ion current produced by the diode is measured using magnetic probes and the proton current is estimated by the same ^{7}Li(p,n) neutron-yield technique. An ion diode model is developed to predict the diode voltage and ion current based on the measured total current. This model is based on previous pinched beam ion diode work [4,5] and is only applicable when the diode presents an under-matched load impedance compared with the self-limited impedance of the MITL so that the flow current becomes part of the diode current. The self-limited impedance in positive polarity layered flow on Mercury is also investigated. PIC and circuit simulations are used to analyze the problem as well. The experimental results will be discussed and compared with the theoretical predictions.

[1] C.W. Mendel and S.E. Rosenthal, Phys. Plasmas 2, 1332 (1995).
[2] R.J. Allen, et al., Proceedings of the 2009 IEEE Pulsed Power Conference (Washington, DC, June 2009), p. 1171.
[3] D.D. Hinshelwood, et al., Proceedings of the 2009 IEEE Pulsed Power Conference (Washington, DC, June 2009), p. 227.
[4] G. Cooperstein and J.J. Condon, J. of Appl. Phys. 46, 1535 (1975).
[5] S.J. Stephanakis, et al., Phys. Rev. Lett. 37, 1543 (1976).

Executive Summary

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This work summarizes results from the following approaches to estimate the voltage and ion current of an ion diode on Mercury in positive polarity with layered MITL flow:

(1) LSP simulations

(2) Circuit modeling

(3) Diode modeling

(4) LiCl nuclear diagnostic

(5) Vacuum voltmeter

The results present a reasonably consistent outcome with V ~ 3.7 MV, I ~ 325 kA, I_{ion} ~ 70 kA, and I_{proton} ~ 50 kA for the ion diode configuration of interest. It also suggests that $Z_0/2$ is a good representation of the layered flow impedance of the line even well into the under-matched (or load-limited) regime.

1. LSP Simulation Results

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LSP was run to simulate Mercury in positive polarity with MITL flow from all 6 cells and an ion diode as a load. The driving waveforms were obtained from the forward-going waveforms for the PFLs measured on Mercury. The load configuration was also set up to model the actual hardware for the ion diode on the machine. Simulations used a 3-cm diode radius. Cases were run at a large D = 2.5 cm AK gap to model self-limited flow and for gaps of D = 0.8 cm and 1.0 cm to look at under-matched loads. The typical operating point in the experiment had a diode radius of 3.12 cm (2.5" diameter) and an initial gap setting of D = 1.23 cm. Assuming an average combined (i.e., anode and cathode) gap closure rate of ~ 2 cm/μs over ~ 50 ns yields a gap of D ~ 1.13 cm at peak power or an D/R = 1.13/3.12 ~ 0.36. This is modeled reasonably well by the LSP simulation with D = 1 cm where D/R = 1/3 ~ 0.33. The voltage for the experimental configuration, which is at slightly higher impedance, may be slightly higher than the 3.5 MV predicted by the D = 1 cm simulation. A combined closure rate of 4 cm/μs over 50 ns would be required to have them match exactly.

LSP configuration for simulating the ion diode on Mercury

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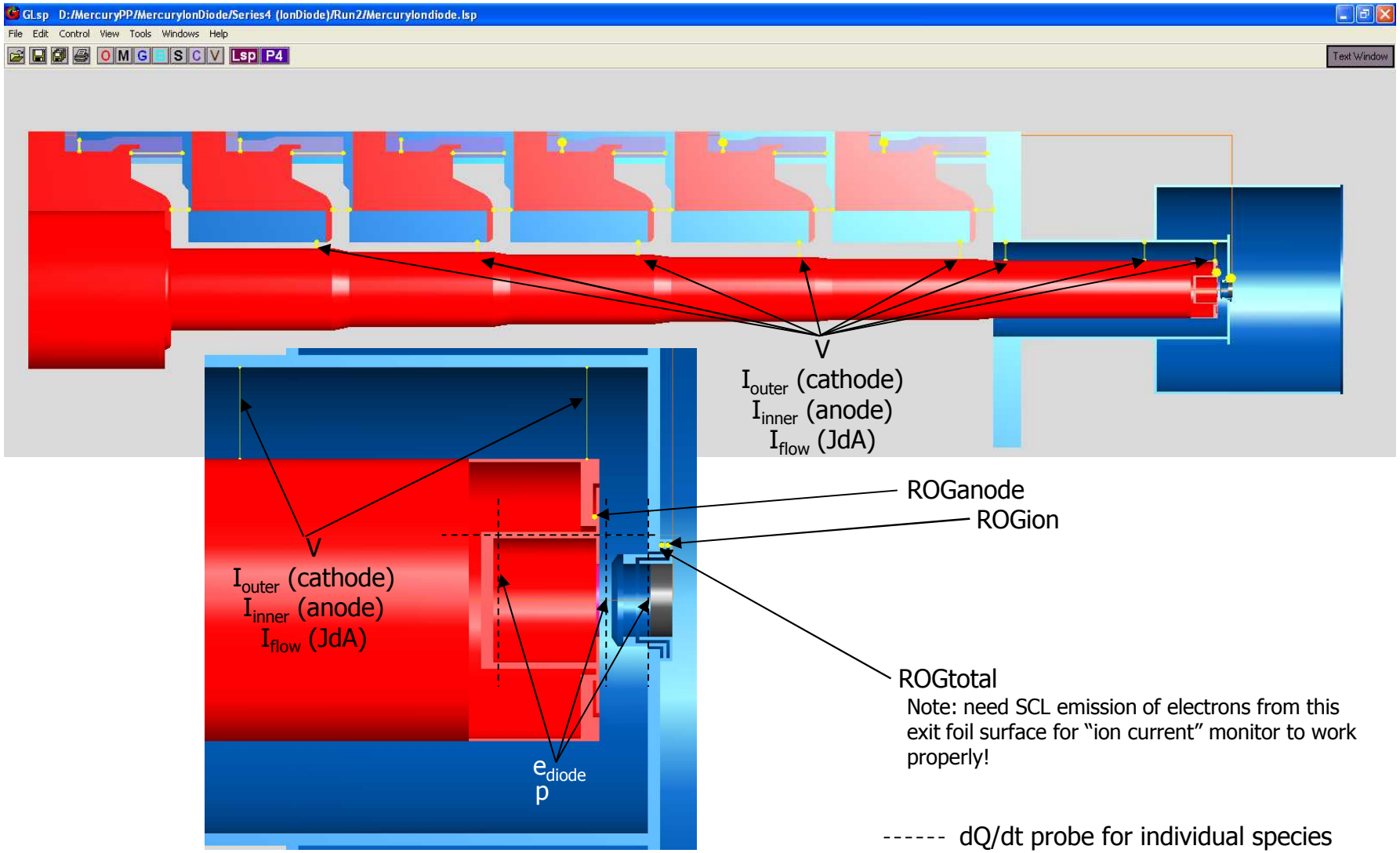

Layered MITL flow in a positive polarity IVA differs significantly from negative polarity MITL flow in the same configuration (i.e., MITL geometry and load)

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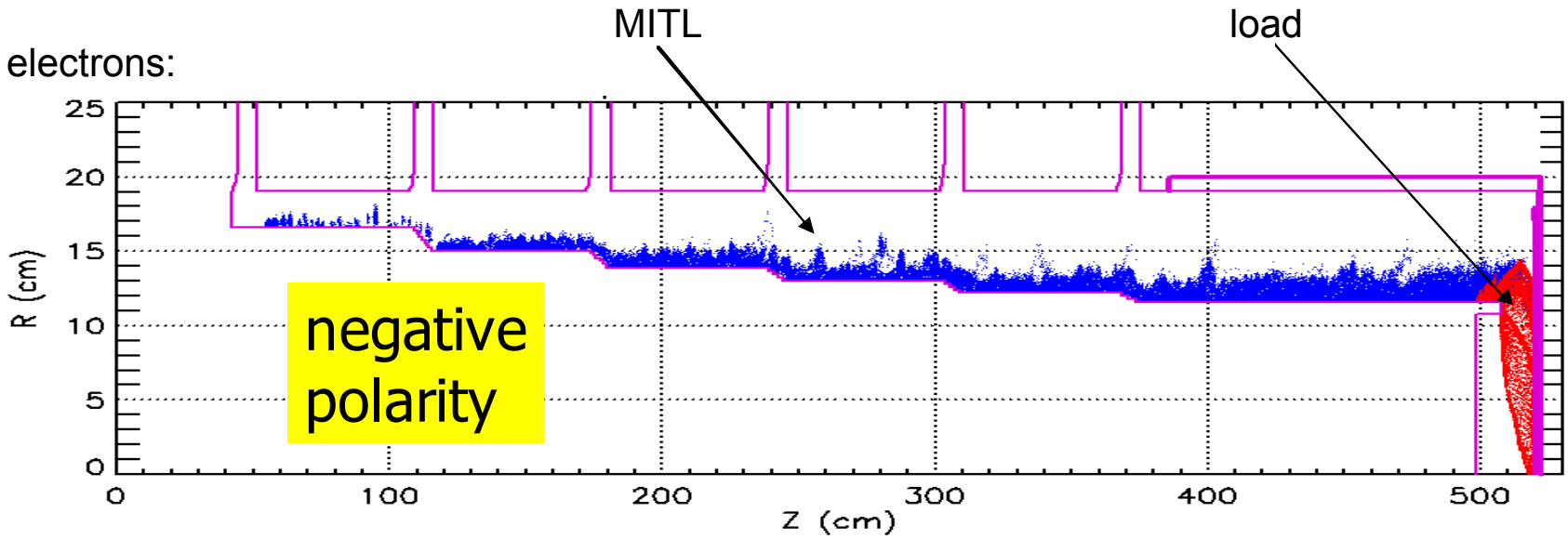

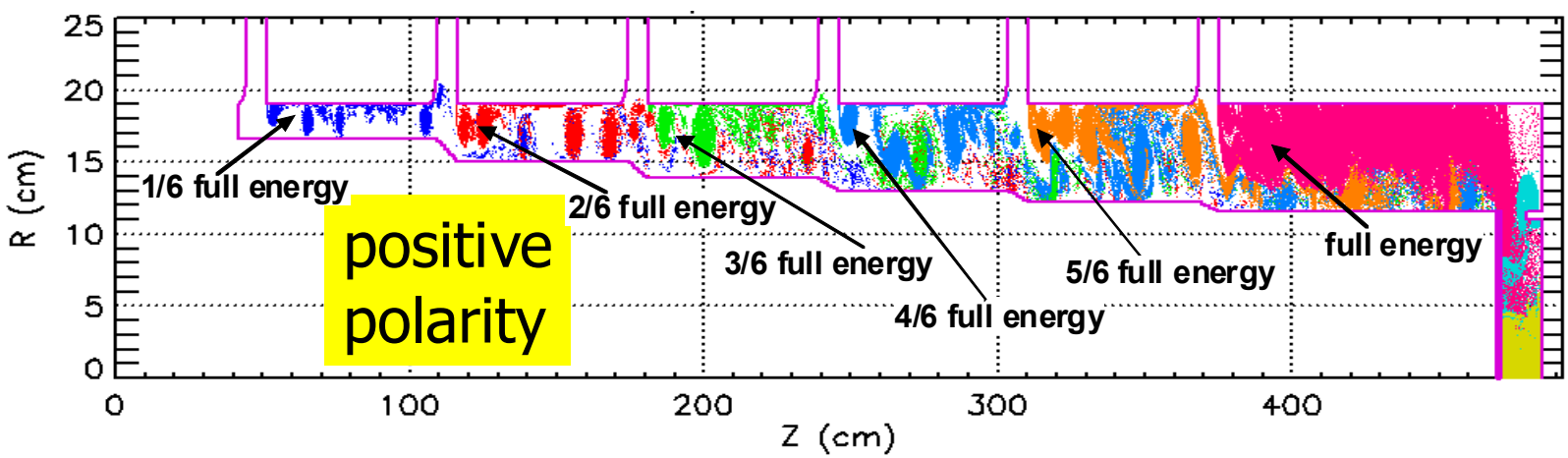

Driving waveform for the cells obtained from Shot 631 (V_{fwd} from V_{ols} and I_{ols})

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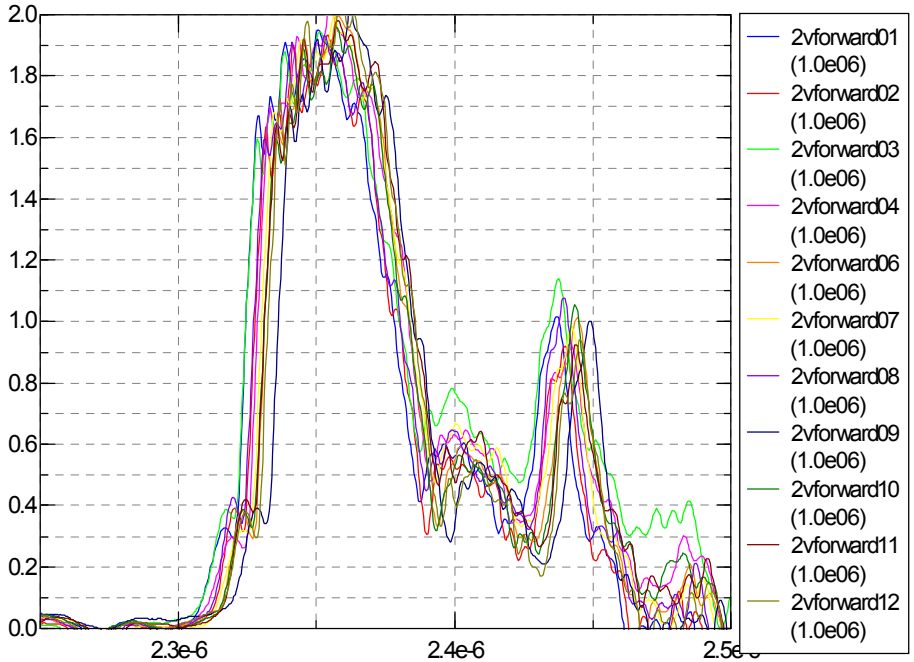

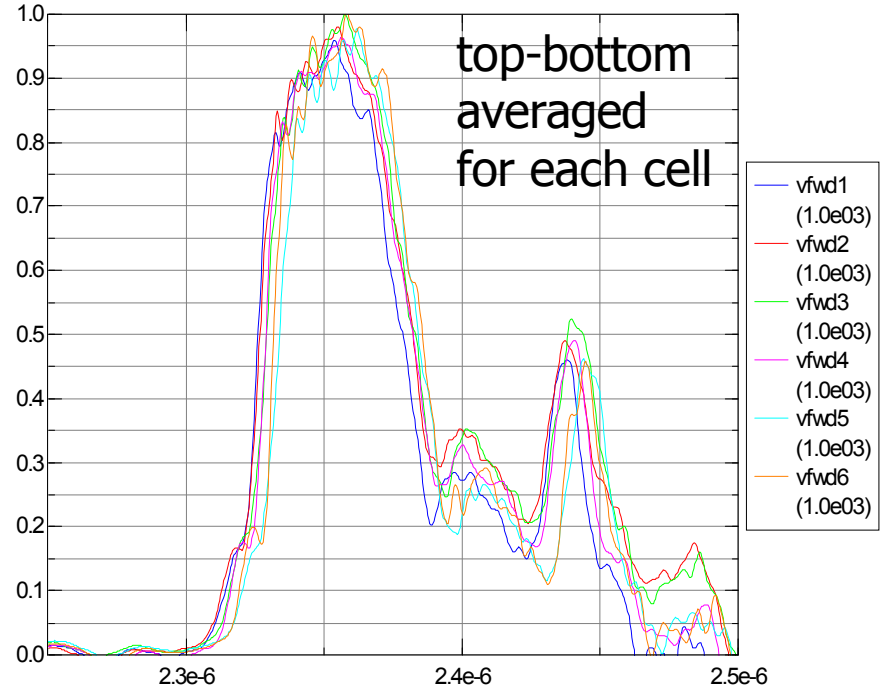

$$V_{fwd} = 0.25*[2vforward(n) + 2vforward(n+1)]$$

2vfoward is divided by 2 to obtain a top-bottom average

For LSP input, each V_{fwd} was time-shifted 2.3 μsec and put into (x,y) columns of t[ns] and V_{fwd} [kV] with dt = 1 ns; to reduce high-frequency oscillations, a 4-ns smoothing was applied to V_{fwd}.

The large gap simulation (D = 2.5 cm) models the line-limited case, yielding a peak voltage and total current of 4.9 MV and 274 kA at probe 6 (314 kA at probe 5). Current traces indicate that ~ 40 kA is lost between probes 5 and 6 for the line-limited case but, for under-matched cases, there is no current loss.

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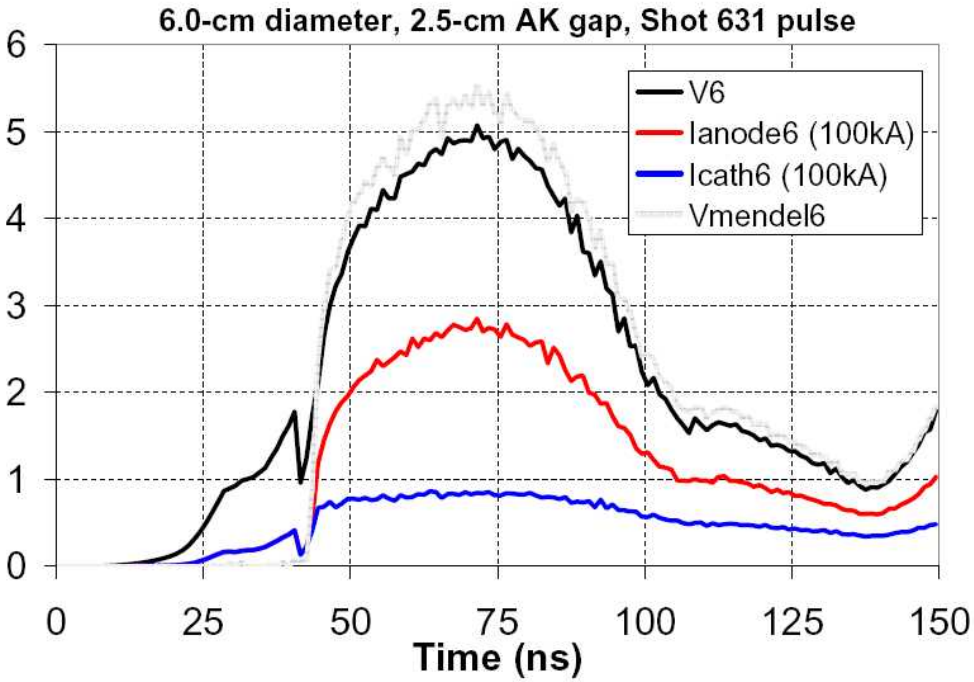

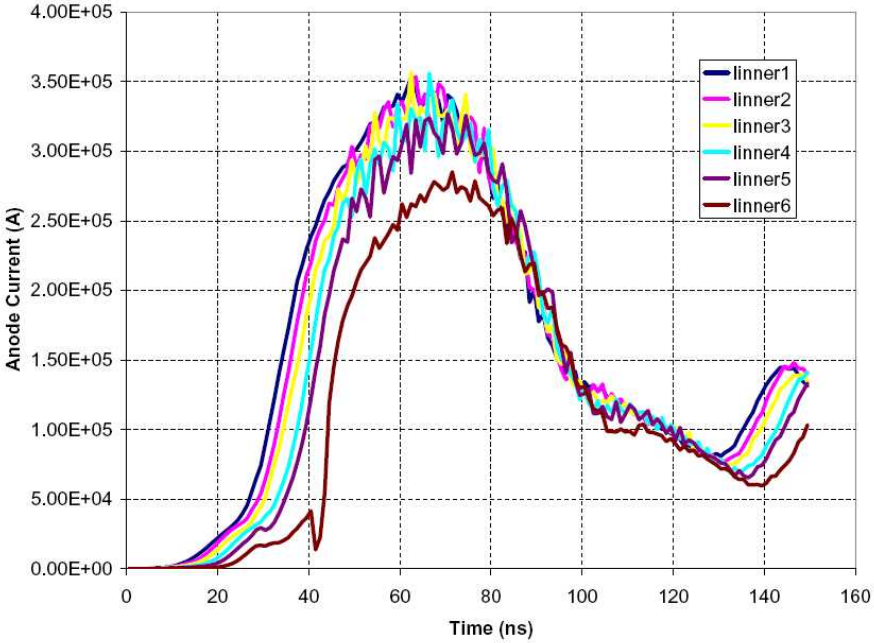

The Mendel voltage predictions greatly exceeds the calculated voltages in these under-matched LSP simulations with layered flow.

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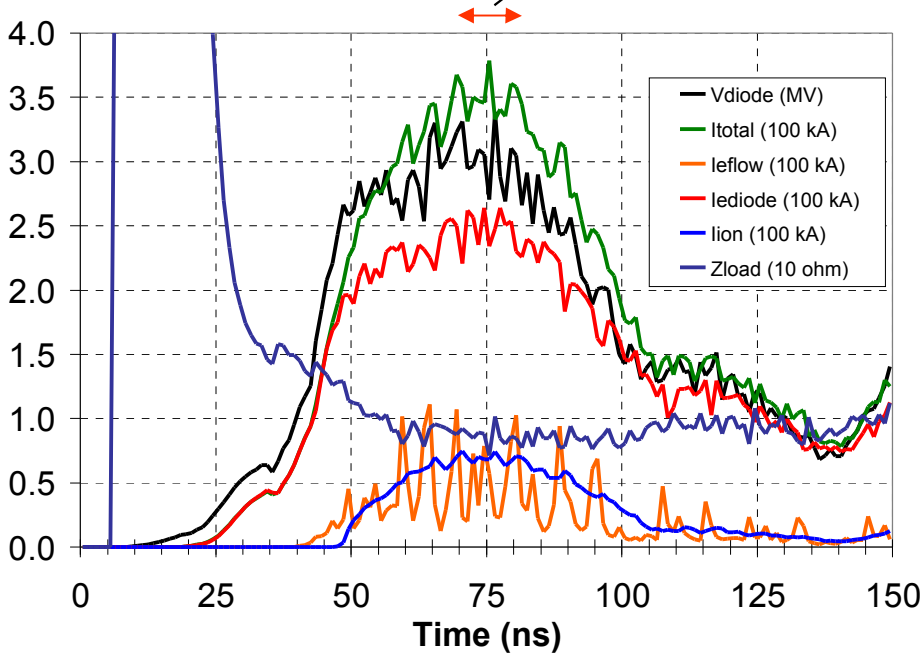
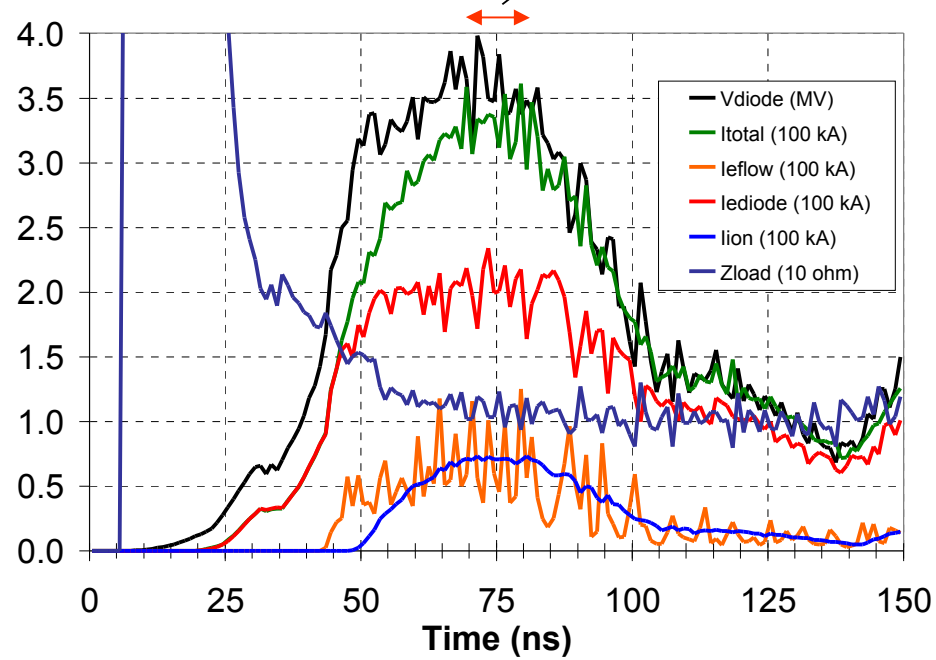
D = 0.8 cm
$\langle V_{Mendel} \rangle$ = 7.18 MV

$\langle V \rangle$ = 3.0 MV
$\langle I_{total} \rangle$ = 349 kA
$\langle I_{elec} \rangle$ = 247 kA
$\langle I_{flow} \rangle$ = 51 kA
$\langle I_{ion} \rangle$ = 69 kA
average 70:80ns



D = 1.0 cm
$\langle V_{Mendel} \rangle$ = 7.32 MV

$\langle V \rangle$ = 3.5 MV
$\langle I_{total} \rangle$ = 326 kA
$\langle I_{elec} \rangle$ = 202 kA
$\langle I_{flow} \rangle$ = 71 kA
$\langle I_{ion} \rangle$ = 71 kA
average 70:80ns



$$V_{Mendel} = Z_0 (I_a^2 - I_c^2)^{1/2} - \left(\frac{g(V) m c^2}{2e} \right) \frac{(I_a^2 - I_c^2)}{I_c^2}$$

using g ~ 0.87 at 3.5 MV

Summary of LSP results

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D (cm)	D/R	V (MV)	I_a (kA)	$Z_L \equiv V/I_a$ (Ω)	I_{ion} (kA)
0.8	0.27	3.0	349	8.6	69
1.0	0.33	3.5	326	11.0	71
2.5	0.83	4.9	314* 274**	15.6*	?

* at probe 5, ** at probe 6

Scaling the D = 1 cm LSP results with D/R = 0.33 to D/R = 0.36 for the standard experimental ion diode configuration at the time of peak power at the same peak power would suggest a voltage of 3.65 MV and a total current of 313 kA for the experimental configuration.

2. Circuit Modeling Results

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A circuit model was developed to simulate Mercury. The MITL was modeled with either its vacuum impedance Z_0 to simulate strongly under-matched cases or one-half its vacuum impedance (i.e., $Z_0/2$) to simulate cases with significant electron flow current. For layered flow in positive polarity it is speculated that this $Z_0/2$ case may better describe the situation even well into the under-matched regime. The line was terminated with a resistive load R_L to model the effective load impedance of the combined parallel loads of the diode and any flow losses. The resulting total currents were matched to AK gaps of Mercury shots with that same total current. The total current was then plotted as a function of AK gap along with the corresponding voltage and R_L for that total current found from the various circuit simulations. Cases were run for both MITL impedance models (i.e., Z_0 and $Z_0/2$). One caution here is that as the line-limited regime is approached the measured total current may be under-represented because some flow current may be lost upstream of the location of the total-current probe. For this reason, only under-matched cases are analyzed.

Results from circuit model of Mercury

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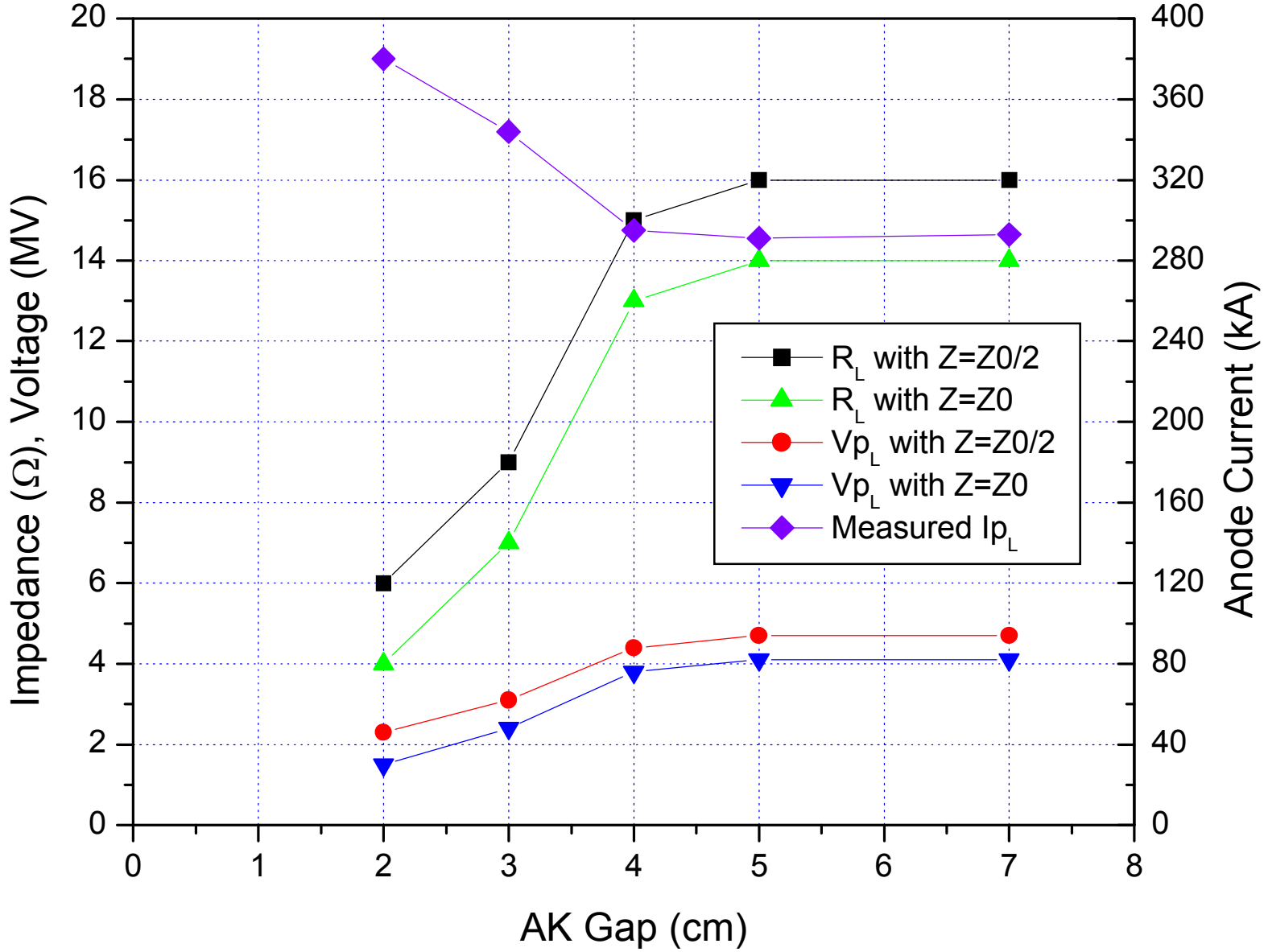

Total current traces for Mercury shots for the nominal positive polarity ion diode configuration with R = 3 cm and an initial AK gap of D = 1.26 cm show a spread in peak current from about 320 kA to 390 kA.

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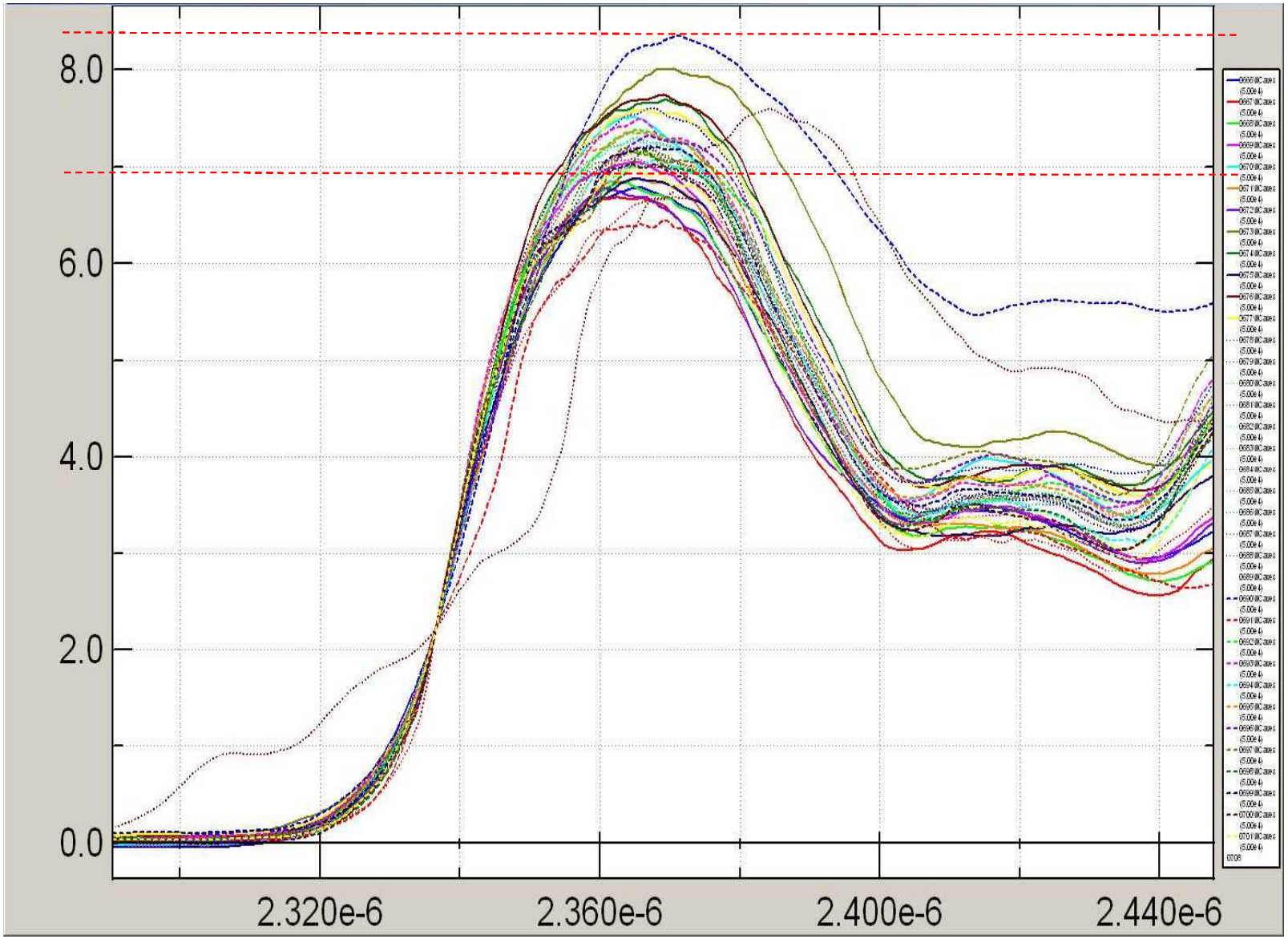

Based on the circuit model and the range of the experimentally measured peak total currents, the range for predicted voltage for this configuration is 2.2 to 3.7 MV for an effective line impedance of $Z_0/2$.

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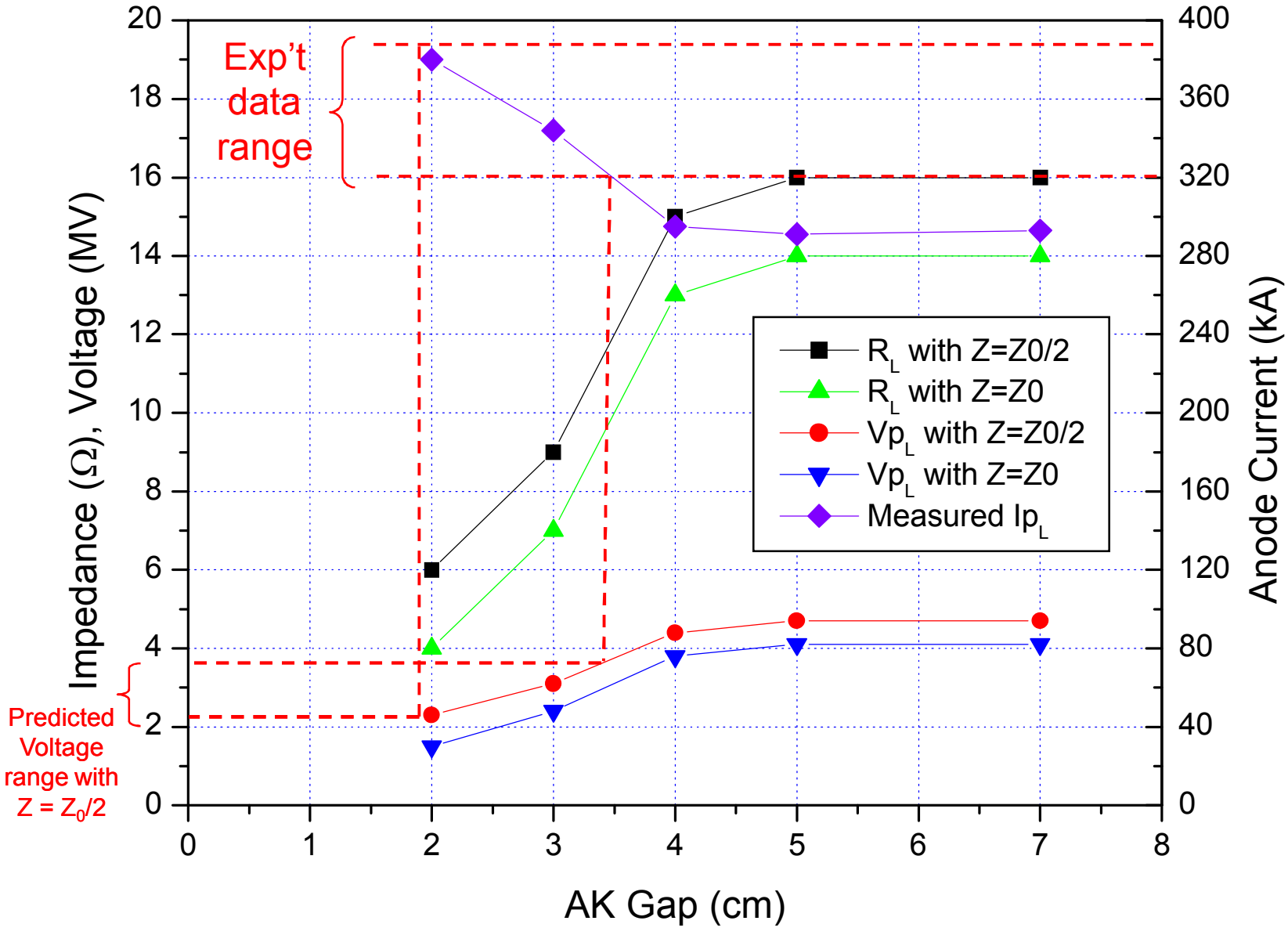

Based on matching the peak total currents, the predicted voltages of 3.0 MV and 3.6 MV from the circuit model for an effective line impedance of $Z_0/2$ agrees well with the calculated voltages of 3.0 MV (D_{LSP} = 0.8 cm) and 3.5 MV (D_{LSP} = 1.0) from the LSP simulations

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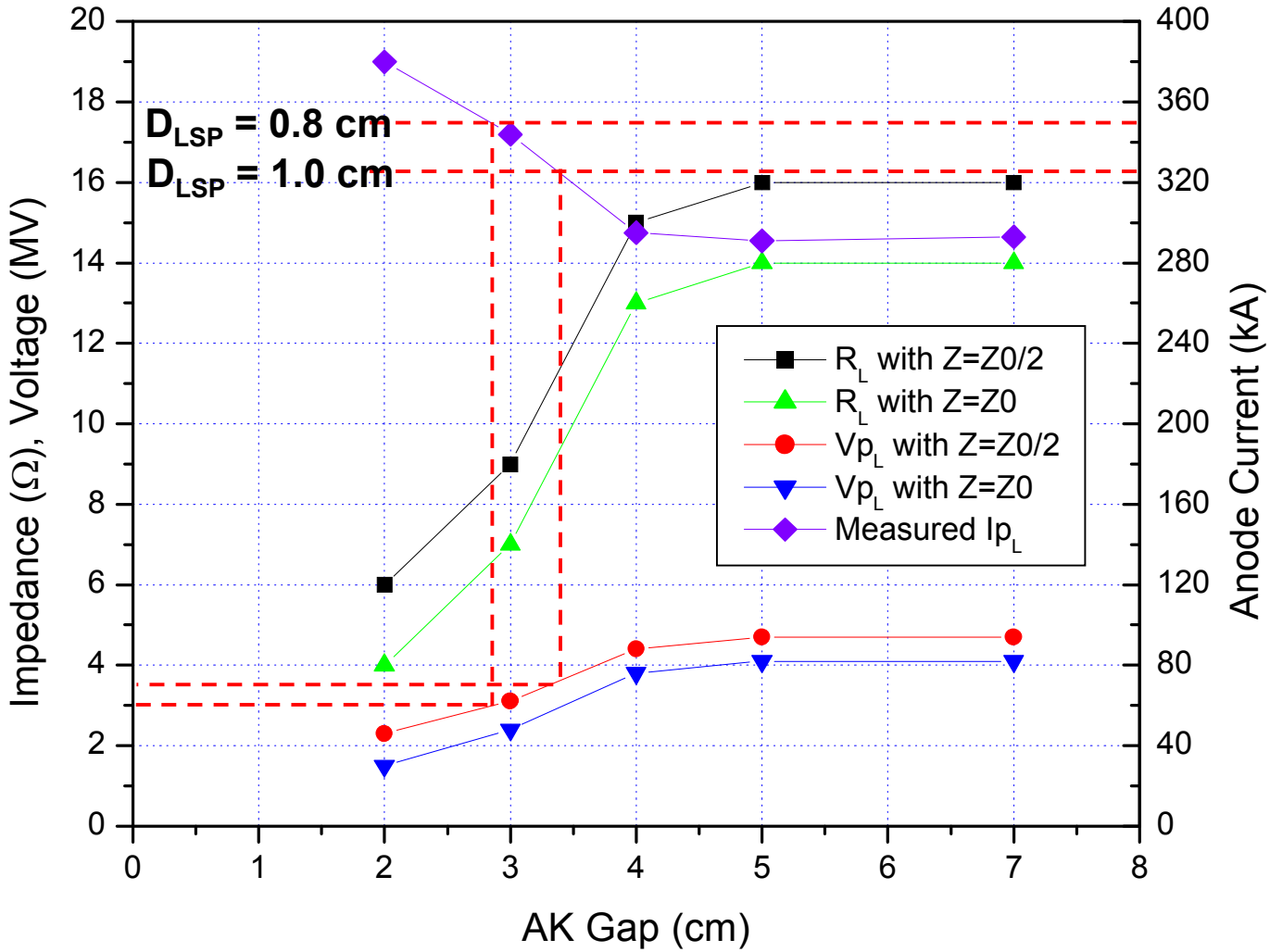

Scaled to the standard ion diode operating point at the time of peak power at 325 kA, this would suggest a voltage of 3.6 MV

3. Diode modeling

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An approach for predicting the voltage in the load-limited regime comes from estimating the load impedance. As long as the system runs in the load-limited regime, the load voltage can be determined from the pinched-beam critical current with ions. This assumes that the full flow current contributes to the total diode current and that $Z_L < Z_f^{SL}$. In this case:

$$V = -\frac{m_e c^2}{e} + \left[\left(\frac{m_e c^2}{e}\right)^2 + \left(\frac{\alpha(V) D I_a}{R}\right)^2\right]^{1/2}$$

$$\frac{I_i}{I_e} = \eta(V)\left(\frac{m_e}{2m_i}\right)^{1/2}(1+\gamma)^{1/2}\frac{R}{D}$$

Typical values for the parameters are α = 36 and η = 2. For the standard Mercury ion diode operating point, D = 1.13 cm at peak power (assuming a 2 cm/μs gap closure velocity) and R = 3.12 cm so that V = 3.76 MV and I_i = 71 kA for a total current I_a = 325 kA

4. LiCl nuclear diagnostic results

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Direct measurement of the diode voltage on Mercury is difficult because of the presence of electron flow from the MITL and the established method of predicting the voltage with MITL flow using the Mendel formula is ill-suited for use in positive polarity. The cross section for the $^{7}Li(p,n)^{7}Be$ reaction in the forward direction is a sensitive function of the proton energy, and Mn-activation detectors to measure the absolute neutron yield from this reaction are available. A measurement of the neutron yield can be compared with the yield calculated using the measured ion current and a model-dependent voltage waveform to determine the absolute voltage. The well-known cross section for the $^{7}Li(p,n)^{7}Be$ reaction is used to calculate the neutron yield as a function of proton energy for a thick LiCl target. Additionally, this technique establishes a range for the proton current produced in the diode.

Two shots were analyzed. On shot 727, the LiCl target was located at the exit of the diode and therefore intercepts the entire ion beam. On shot 726, the LiCl target is located 22 cm downstream near the end of a cylindrical transport tube and therefore it only intercepts the fraction of the beam that transports down the tube and does not include ions that are lost to the tube wall.

Mesh tally plot from MCNPX for neutron transmission with the LiCl target located at the diode (modeling for shot 727) with no lead shield surrounding the transport tube.

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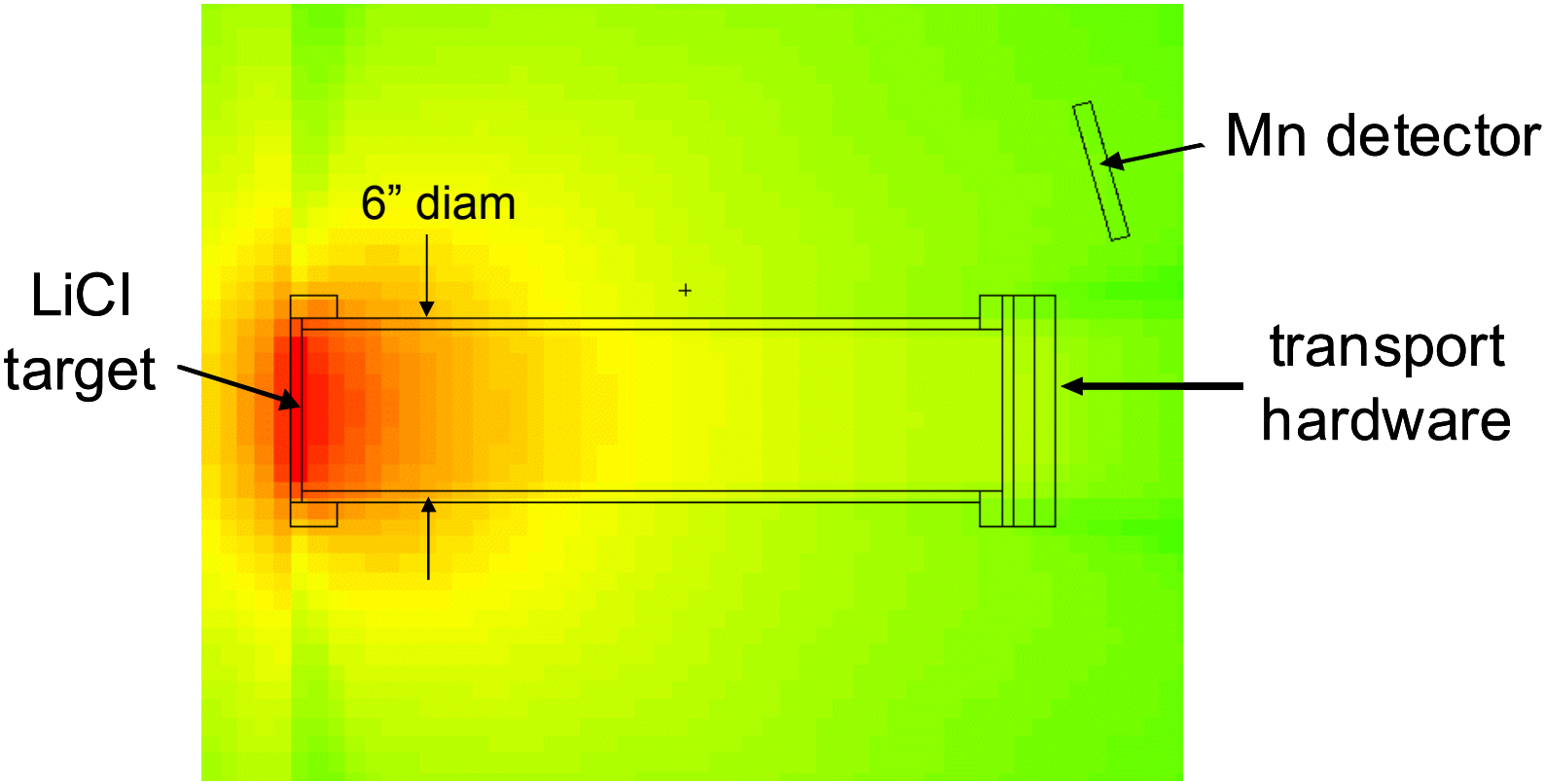

Mesh tally plot from MCNPX for neutron transmission with the LiCl target located downstream from the diode (modeling for shot 726) with a lead shield surrounding the transport tube.

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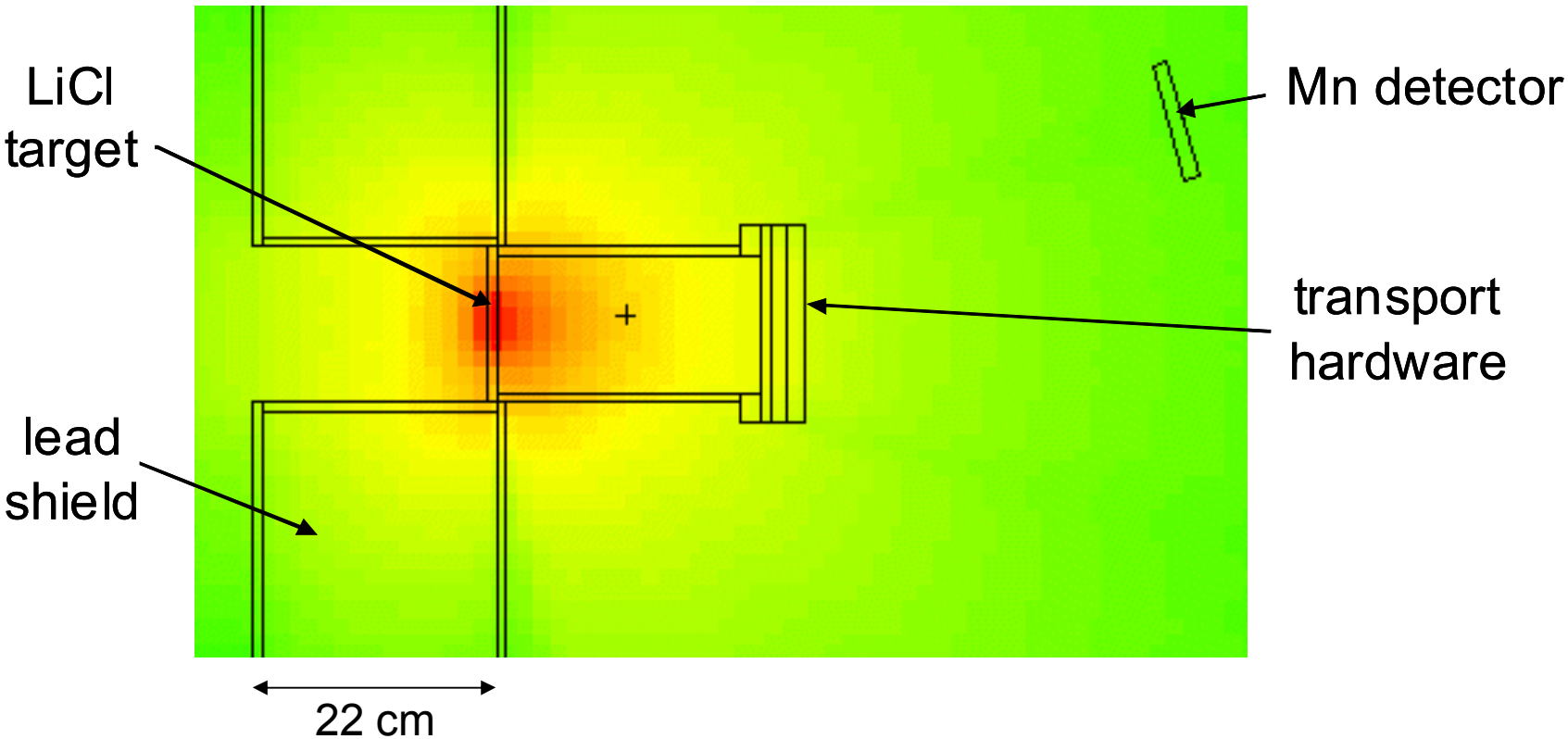

Electrical and neutron yield data. The transmitted fraction obtained from MCNPX calculations show that neutron yields at the LiCl target are similar indicating that little of the proton beam is lost to the transport tube walls.

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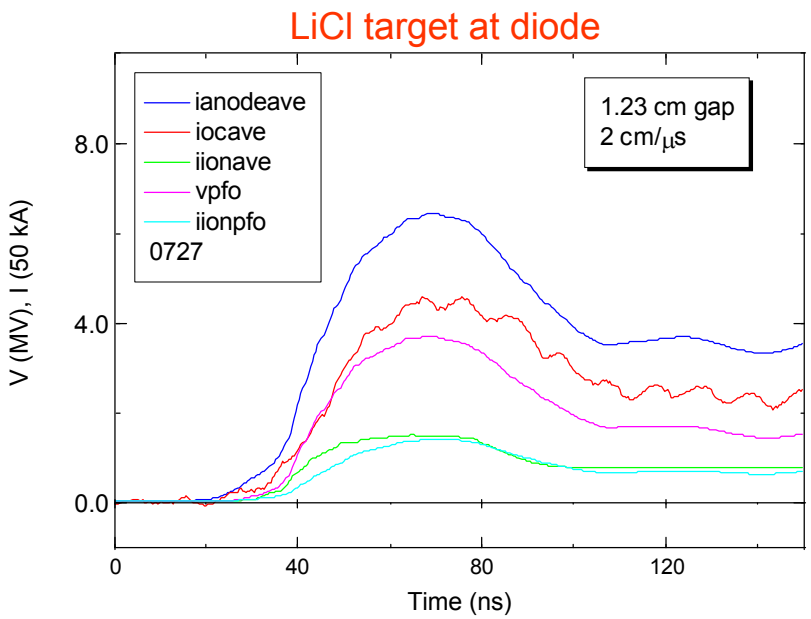

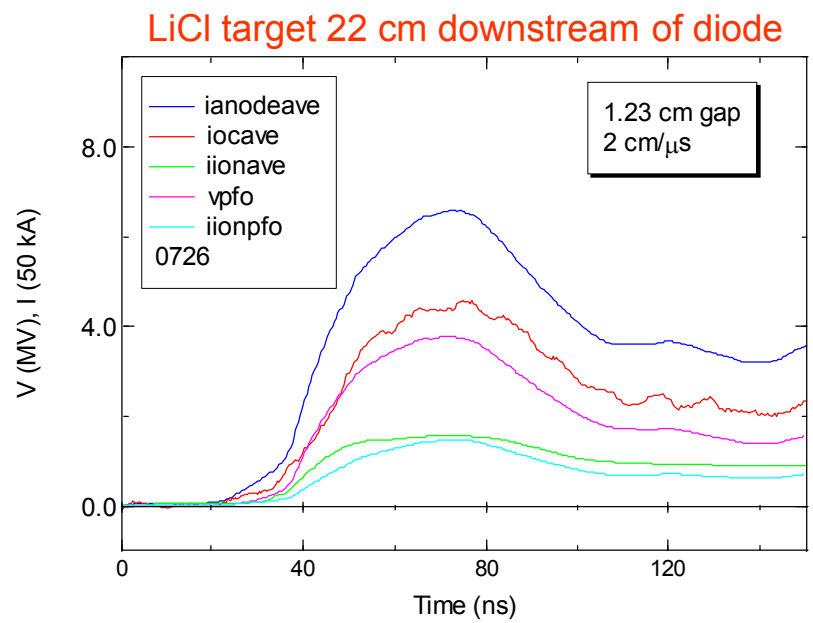

Shot No.	Neutron Yield at Detector (neutrons/sr)	Fraction Transmitted	Neutron Yield at LiCl Target (neutrons/sr)
726	$(1.30 \pm 0.13) \times 10^{11}$	0.85	$(1.53 \pm 0.21) \times 10^{11}$
727	$(1.19 \pm 0.12) \times 10^{11}$	0.82	$(1.45 \pm 0.20) \times 10^{11}$

Peak Voltages and Ion Currents Required to Fit the Measured Neutron Yields.

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Neutron yields were calculated using voltage and ion current waveforms produced by the diode model for the measured total ion current. These calculated yields were compared to the measured yield to find appropriate voltage and ion current ranges to fit the data. Using the voltage and full ion current as proton current predicts a neutron yield shown in the first row for each shot that is larger than the measured yield. Assuming the full measured ion current was proton current the voltage must be reduced to ~ 3.2 MV to obtain the correct yield. Assuming the full voltage, the proton current must be reduced to ~ 48 kA. This latter case is most plausible because previous data indicates that this reflects the proper proton fraction of the ion beam. So this nuclear diagnostic technique predicts a voltage of ~ 3.7 MV and a proton current of ~ 48 kA for these shots for an average total current of 327 kA.

Shot No.	Peak vpfo (MV)	Peak iionpfo (kA)	Calculated # neutrons/sr	Measured # neutrons/sr
727	3.67	69.8	2.06×10^{11}	1.45×10^{11}
	3.19	69.8	1.40×10^{11}	
	3.67	47.4	1.40×10^{11}	
726	3.75	72.2	2.28×10^{11}	1.53×10^{11}
	3.22	72.2	1.52×10^{11}	
	3.75	48.1	1.54×10^{11}	

Applying the circuit model to the total currents of 332 and 322 kA for Shots 726 and 727 yields a predicted voltage of between about 3.45 and 3.75 MV in reasonable agreement with the 3.7 MV predicted by the LiCl nuclear diagnostic.

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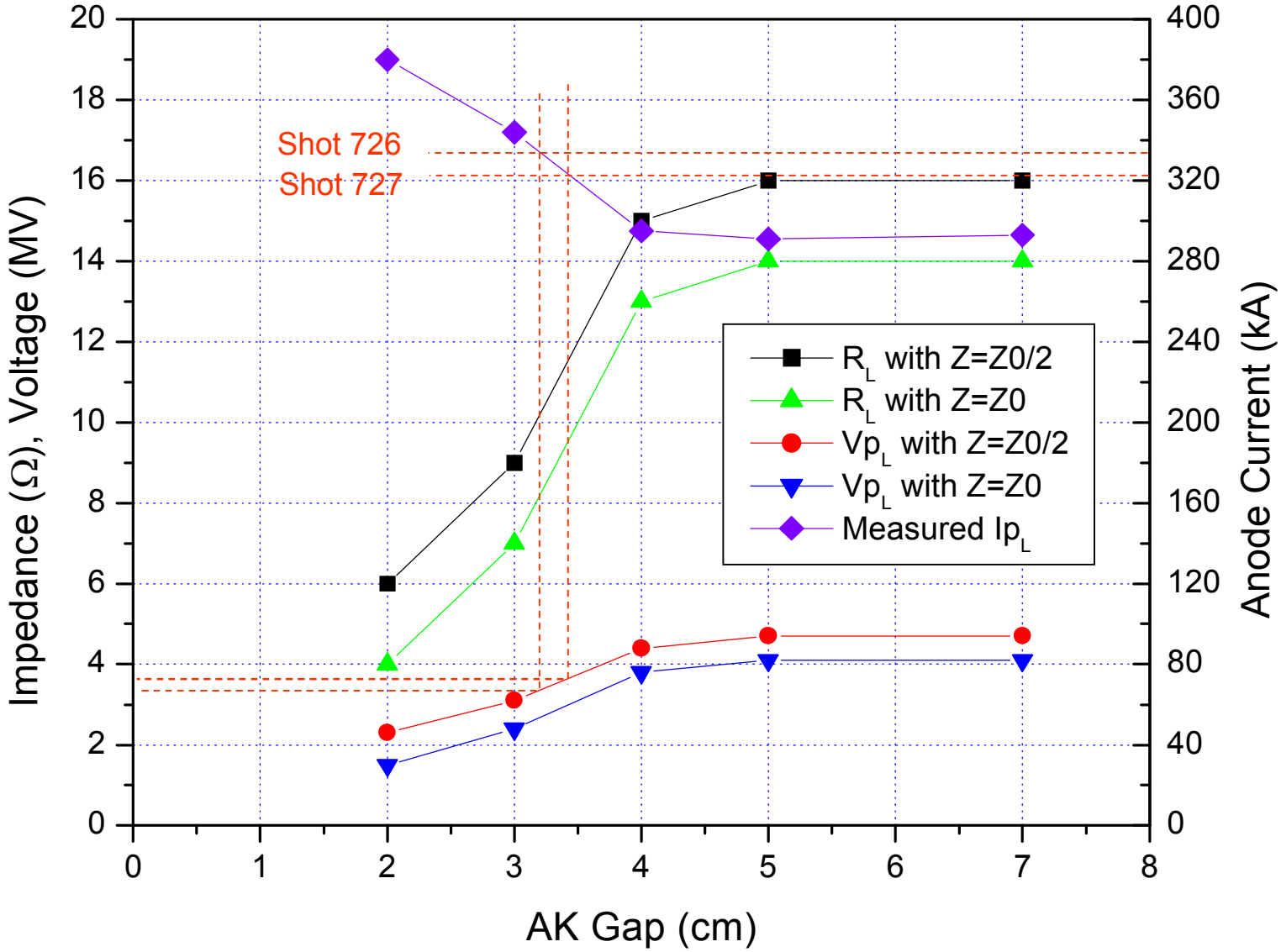

5. Vacuum voltmeter

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In an attempt to directly measure the voltage, a vacuum wire voltmeter has been fielded on Mercury in positive polarity. The diode that was used in these experiments was larger than the standard operating ion diode so comparisons with data from the standard diode need to be scaled to match impedances. There were also some issues with the voltmeter operation. Thus, the data is not conclusive but only suggestive.

Mercury front-end hardware with the vacuum voltmeter mounted vertically showing a field-shaping torus and its vertical position inside the tube.

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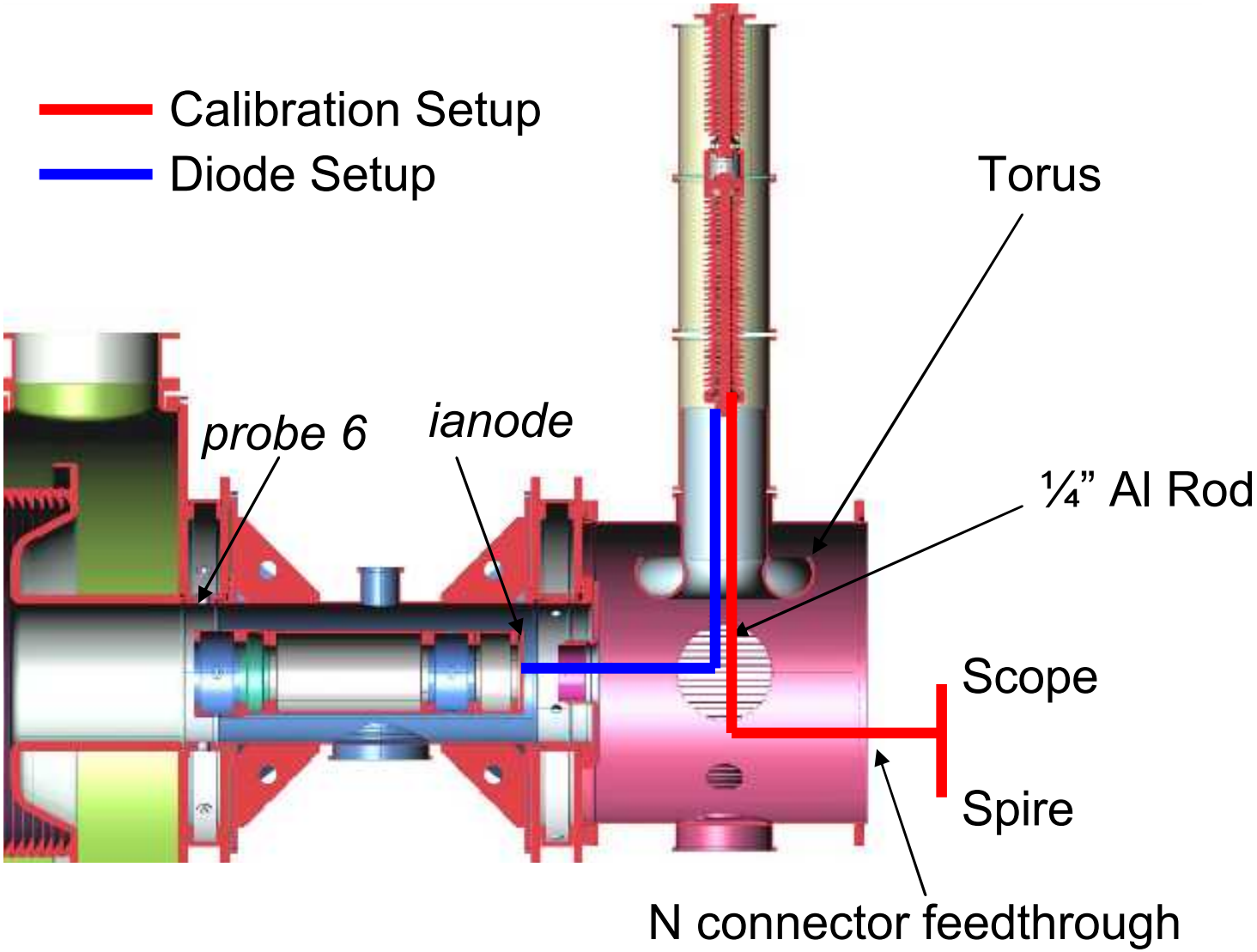

Vacuum voltmeter shots on Mercury

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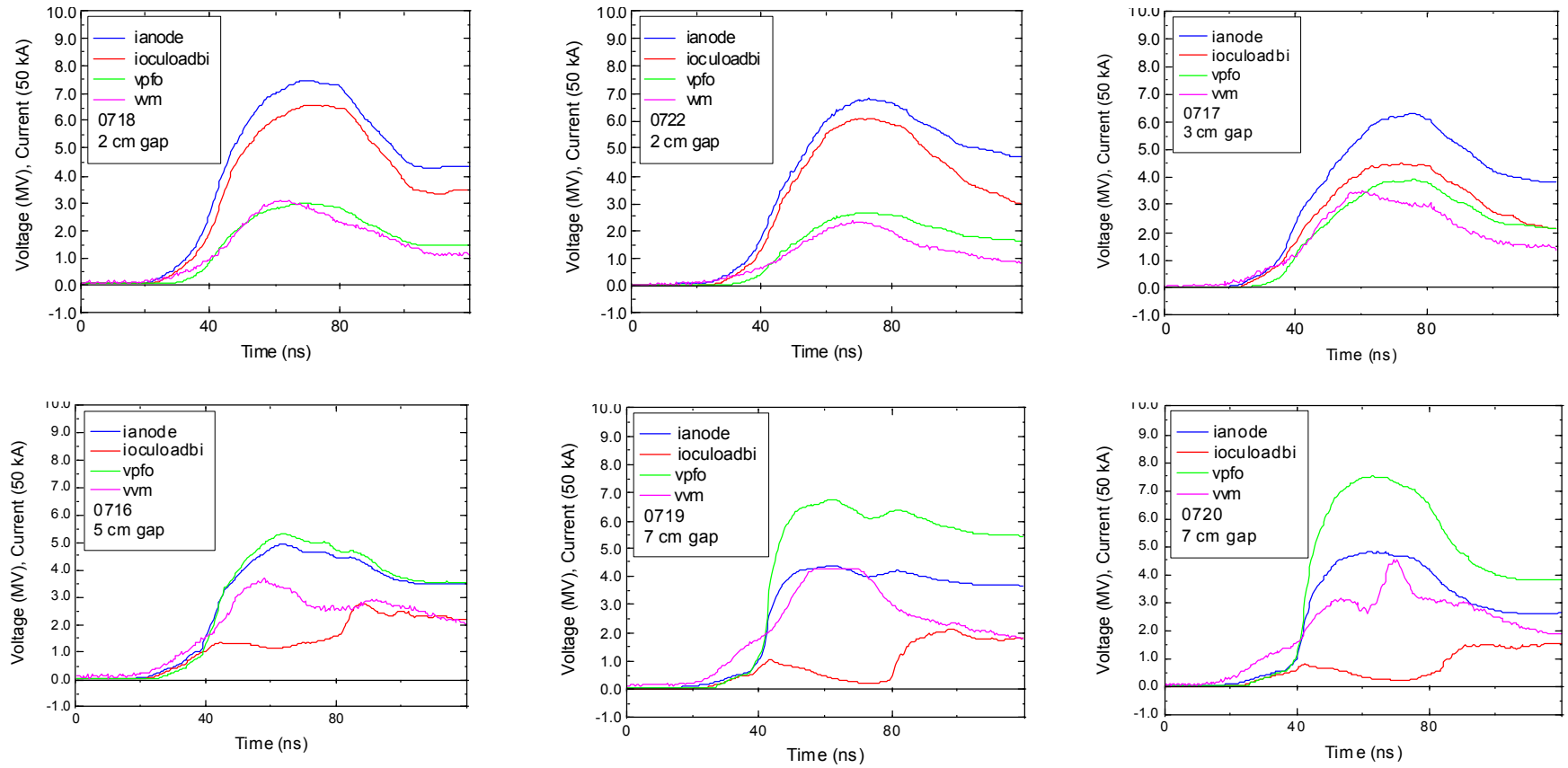
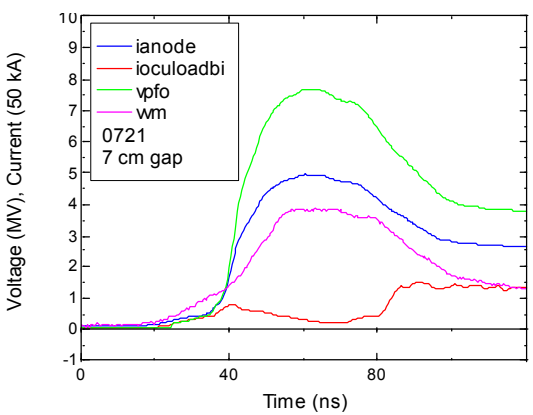
The diode used in these shots had a radius of 7.5 cm compared to 3.12 cm for the standard ion diode. Assuming 1 mm gap closure in all cases, the initial AK gap of 1.23 cm of the standard ion diode translates into an initial gap of about 2.8 cm for this diode, which is bracketed by the data for D = 2 and 3 cm. This implies a gap of D = 2.7 cm at peak power. The diode is running line-limited for D = 7 cm with a peak voltage of ~ 4.2 MV and is probably transitioning to line-limited at D = 5 cm. The voltmeter results exhibit unphysical impedance changes on some shots (particularly above 3.5 MV) possibly indicating electron emission from the wall of the tube encasing the voltmeter stack. The diode model over-estimates the voltage in the line-limited regime so the values listed below for vpfop are not accurate for the larger D = 5 and 7 cm gaps noted in red.

Table I – Mercury shots with vacuum voltmeter.

Shot #	D(cm)	36D/R(Ω)	vvmp(MV)	vpfop(MV)	ianodep(kA)
716	5	24.0	3.5	5.4	250
717	3	14.4	3.5	3.9	315
718	2	9.6	3.0	3.0	375
719	7	33.6	4.2	6.7	220
720	7	33.6	4.5	7.5	240
721	7	33.6	3.9	7.6	250
722	2	9.6	2.3	2.6	340

Electrical data from vacuum voltmeter shots on Mercury





Electrical data for shots listed in Table I. The total current (ianode, blue), the bound current (ioculoadbi, red), and the voltage measured by the vacuum voltmeter (vvm, magenta) are shown. The voltage predicted by the diode model is shown as vpfo in green

The voltmeter measurements and data analysis suggest a voltage of 3.75 MV at the standard operating point of the Mercury ion diode

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The voltmeter data (at D = 3 cm, R = 7.5 cm) suggests that close to the established operating point of the Mercury ion diode (D = 1.23 cm, R = 3.12 cm) the diode voltage peaks at about 3.5 MV. The diode model agrees well with the measured voltage with the small D = 2 cm gap diode. At D = 3 cm, the model predicts a peak voltage of about 3.9 MV, which is somewhat higher than the voltmeter-measured voltage. The fact that the diode model closely tracks the voltmeter measurement up to 3.5 MV may indicate that the voltmeter was compromised late in the pulse (after about 55 ns) on this shot by electron emission from the wall encasing the voltmeter. Thus, all that can be said is that the data and analysis are consistent with a voltage between 3.5 and 3.9 MV. Scaling this result down from an initial gap of D = 3 cm to D = 2.8 cm at the same power to match the impedance of the standard operating point, predicts a voltage of 3.38 to 3.77 MV for a total current of 324 kA at the standard operating point of the Mercury ion diode. Here, the lower voltage reflects the predicted value from the peak of the voltmeter measurement and the higher voltage is derived from the diode model that tracks the voltmeter to its peak but then continues to a higher peak value about 13 ns later in the pulse.

SUMMARY

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- Predictions for V from all methods are in reasonable agreement
- V_{Mendel} significantly over-estimates the voltage in positive polarity with layered flow
- $Z_{flow} \sim Z_0/2$ in positive polarity with layered flow
- $I_{ion} \sim 70$ kA in this configuration with about 48 kA in protons

Method	V(MV)	I_a(kA)
LSP simulations	3.65	313
Circuit model	3.6	325
Diode model	3.76	325
LiCl diagnostic	3.7	327
Voltmeter	3.38 – 3.77	324
Average	3.62 – 3.7	323

Results quoted for the standard configuration of a Mercury ion diode with R = 3.12 cm and D = 1.13 cm at peak power