

# Conversion of Mercury (a 2-TW Inductive Voltage Adder) to Positive Polarity\*

R. J. Allen<sup>‡</sup>, C. L. Berry<sup>a</sup>, R. J. Comisso, E. Featherstone<sup>a</sup>, R. Fisher<sup>a</sup>, G. Cooperstein,  
D. D. Hinshelwood, S. L. Jackson, A. T. Miller<sup>a</sup>, P. F. Ottinger,  
D. G. Phipps, and J. W. Schumer

*Plasma Physics Division  
Naval Research Laboratory  
Washington, DC 20375 USA*

## Abstract

After 616 shots in a negative polarity configuration, Mercury, a 6-MV and 300-kA inductive voltage adder (IVA), has been converted to positive polarity in order to extract ion beams. Conversion to positive polarity was achieved by rotating all six of the adder cells by 180°. In principle, we could have chosen to instead insert the center conductor from the other end of the adder to change polarity, but rotating the cells minimized the time required to make the transition. Although most of the same pieces were used, the center conductor had to be reconfigured in order to align the transition pieces with the cell feed gaps.

Because the electron flow was anticipated to be very different in positive polarity, a result of emission from surfaces of different potential, a simple blade diode was fielded for the initial shots to gain a better understanding of operation in positive polarity. The blade diode consisted of the same cathode used as a dummy load in the first negative polarity shots on Mercury, but with a different carbon anode that just covered the end of the center conductor. After a few short circuit and initializing shots, a series of shots were taken where only the blade diode AK gap was varied in order to characterize self-limited and load-limited operation and to compare measurements with theory and simulation.

## I. INTRODUCTION

Although Mercury was designed for either positive or negative polarity, it was previously only operated in negative polarity [1]. In positive polarity, the center conductor is positive with respect to the load chamber wall and so ion-beams can be extracted [2]. Although most of the hardware and plans for operating in positive polarity existed, there were several missing items.

Prior to this effort, there were a few shots in positive polarity, but these were done by simply charging the

Marx bank with opposite polarity. However, the charge voltage is limited in this mode due to increased possibility of breakdown in the IS (intermediate store) capacitors and PFLs (pulse-forming lines).

One key decision was whether to convert to positive polarity by inserting the center conductor in from the other side, or by rotating the cells 180° about the vertical axis and leaving the load and breach chambers in the same positions. There were pros and cons to both approaches and one important factor, the frequency of conversion from positive to negative, was not certain. The layout of Mercury in room 156 is shown in Fig.1. It was decided to rotate the cells for the following reasons:

1. We would not need to move extension rails (not shown in Fig.1), needed to extract the center conductor, to the north side of the room. Doing so would probably mean disassembly and reassembly, taking ~2 days due to the difficulty of re-alignment of the rails.
2. We would not need to move all our signal cables because the breach stays in the same spot. Many of our signal cables are routed through the breach and cables for other signals are also routed that way to stay as far as possible from the X-ray source.
3. We could use the same roughing pump hardware and would not have to connect the rough pump to the load chamber.
4. There is more room at the North end for diagnostics and load extensions.
5. We would not have to retune water switch gaps or move laser switch optics to re-order PFL firing sequence. Optics and PFL output switch gaps are tuned to give a 2-ns per cell staggered pulse feed to the cells for optimized performance.
6. We would not have to worry about using the crane in the proximity of the overhead laser pipe.

However, rotating the cells entails a significant effort, including disconnecting the PFLs, draining of oil (because we needed to rotate the elbows and because the cells weigh too much to lift otherwise), rotating the cells, and

\* Work supported by ONR and DTRA

<sup>‡</sup> email: [allen@nrl.navy.mil](mailto:allen@nrl.navy.mil)

<sup>a</sup> L3 Communications, Inc, Reston, VA.

## Report Documentation Page

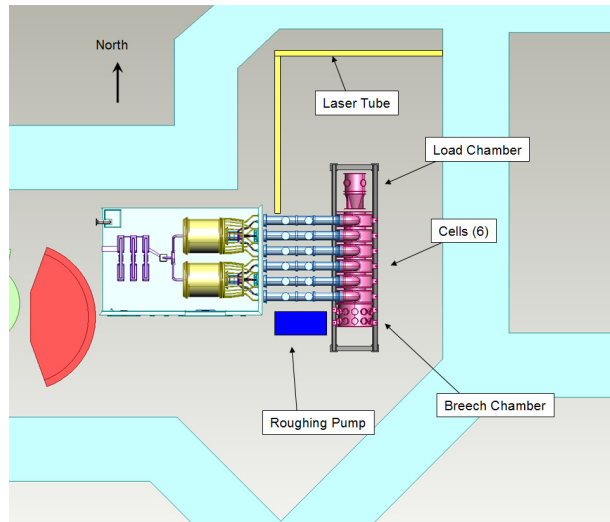
*Form Approved*  
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE <b>JUN 2009</b>	2. REPORT TYPE <b>N/A</b>	3. DATES COVERED <b>-</b>			
4. TITLE AND SUBTITLE <b>Conversion of Mercury (a 2-TW Inductive Voltage Adder) to Positive Polarity</b>		5a. CONTRACT NUMBER			
		5b. GRANT NUMBER			
		5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)		5d. PROJECT NUMBER			
		5e. TASK NUMBER			
		5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Plasma Physics Division Naval Research Laboratory Washington, DC 20375 USA</b>		8. PERFORMING ORGANIZATION REPORT NUMBER			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)			
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)			
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.</b>					
14. ABSTRACT <b>After 616 shots in a negative polarity configuration, Mercury, a 6-MV and 300-kA inductive voltage adder (IVA), has been converted to positive polarity in order to extract ion beams. Conversion to positive polarity was achieved by rotating all six of the adder cells by 180°. In principle, we could have chosen to instead insert the center conductor from the other end of the adder to change polarity, but rotating the cells minimized the time required to make the transition. Although most of the same pieces were used, the center conductor had to be reconfigured in order to align the transition pieces with the cell feed gaps. Because the electron flow was anticipated to be very different in positive polarity, a result of emission from surfaces of different potential, a simple blade diode was fielded for the initial shots to gain a better understanding of operation in positive polarity. The blade diode consisted of the same cathode used as a dummy load in the first negative polarity shots on Mercury, but with a different carbon anode that just covered the end of the center conductor. After a few short circuit and initializing shots, a series of shots were taken where only the blade diode AK gap was varied in order to characterize self-limited and load-limited operation and to compare measurements with theory and simulation.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>	<b>SAR</b>	<b>5</b>	



realigning the cells. In retrospect, if the frequency of conversion were to increase, it may be faster to leave the cells in place and swap the load and breech chambers, with center conductor inserted from the North end. In either case, it is important to note that the center conductor has to be completely disassembled and reassembled. This is a slow process as diagnostic cables have to be uninstalled/installed in every section. A second center conductor would greatly reduce turn-around time.



**Figure 1.** Layout of Mercury, indicating the location of some items considered for polarity reversal.

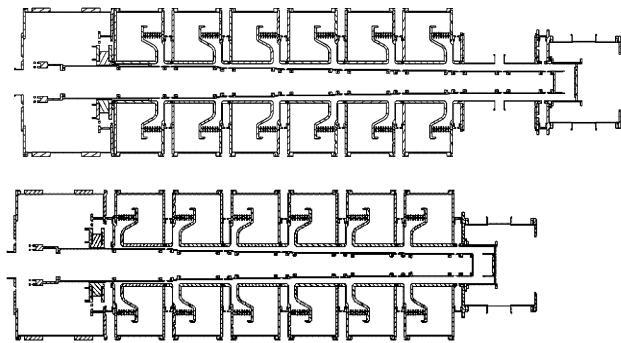
## II. IVA HARDWARE CHANGES

Besides rotating the cells, several other hardware changes were made for operation in positive polarity. One major change was rebuilding the center conductor so that the transitions in diameter aligned with cell feed gaps. Although the positive center conductor uses almost all the same parts, it had to be rebuilt, as shown in Fig. 2, to align the feeds with the transitions.

Because the feedgaps are on the upstream side of the cells in positive polarity, the 0.8 meter long extension section between last cell and load chamber (shown in top drawing of Fig. 2), was no longer needed. It is believed that some long section of straight MITL is desirable between the feed of the last cell and the load in order to adequately diagnose the power flow to the load.

While rotating the cells, the outer conductor was coated with graphite using Aerodag (a colloidal graphite spray). It is believed that graphite coating is required to lower the electron emission threshold and thereby achieve more uniform electron flow. The anodized portions of the outer conductor were not coated. The graphite did not extend any further into the cell feedgaps than their rounded edges. The entire outer conductor from the last cell to the

load was coated. The coating was removed from current probe surfaces.

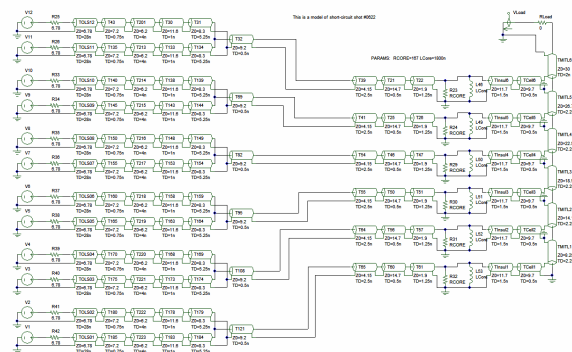


**Figure 2.** Drawings of the Mercury IVA in negative polarity (top) and in positive polarity (bottom).

## III. SHORT-CIRCUIT LOAD SHOTS

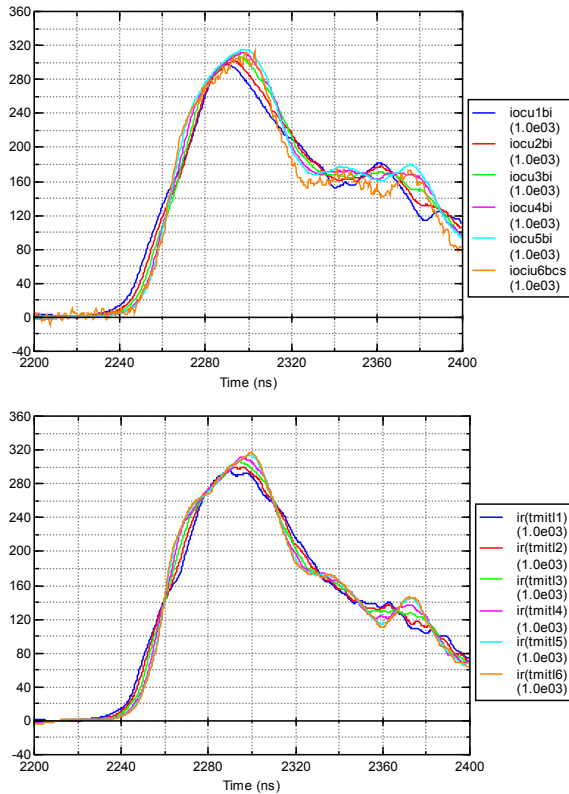
To check IVA current monitor calibrations, short-circuit load shots were taken at reduced power (50-kV Marx charge voltage instead of the usual 75 to 78 kV). Prior to this, the outer conductor load current monitors had their calibrations checked using a cable pulser test fixture. Because the current monitor waveforms vary down the MITL, a circuit model was used to deduce the calibrations for monitors away from the load.

For best accuracy, the actual forward-going waves from all 12 of Mercury's PFLs were used as inputs to the circuit model. These forward-going waves were constructed from the measured current and voltage waveforms at the same location in the PFL output lines. For this modeling of short-circuit shots, electron flow in the IVA is ignored and the vacuum impedance was used for IVA elements. A diagram of the circuit model used for short-circuit shots is shown in Fig. 3.



**Figure 3.** Diagram of circuit model used for short-circuit shots showing overall topology with 12 inputs on the left and IVA elements on the right.

This method if using measured PFL waveforms as inputs to the circuit model gives very close agreement between measured IVA currents and voltages and those from the circuit simulation. As an example, the MITL outer conductor currents just after each of the six cell feeds are plotted in Fig. 4 for both measurement and simulation of shot #0637. Several nuances in current waveform shape down the MITL are reproduced in the simulation.



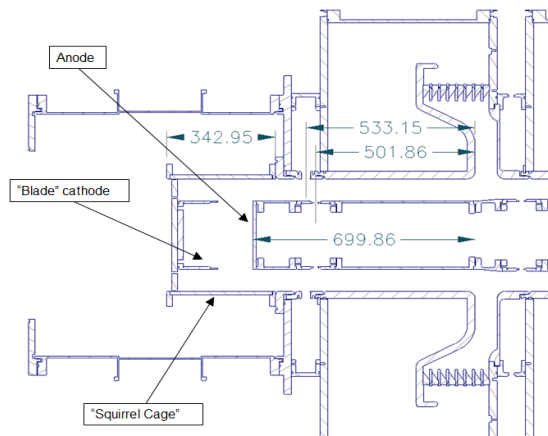
**Figure 4.** Comparison of measured MITL currents after each feed (above) to those from circuit simulation driven from actual PFL waveforms (below) for shot #0637.

#### IV. BLADE LOAD SHOTS

A positive polarity version of the “blade” load was fielded to test Mercury in positive polarity with a benign load. The blade cathode is simply the end of a hollow tube, the same diameter as the center conductor, as shown in Fig. 5. The same cathode was used as in previous work in negative polarity [2].

In negative polarity, a graphite anode was on a sliding plate and the blade cathode was fixed to the end of the center conductor. In positive polarity the same setup was used except the cathode was attached to the sliding plate and a graphite anode, the same OD as the cathode and

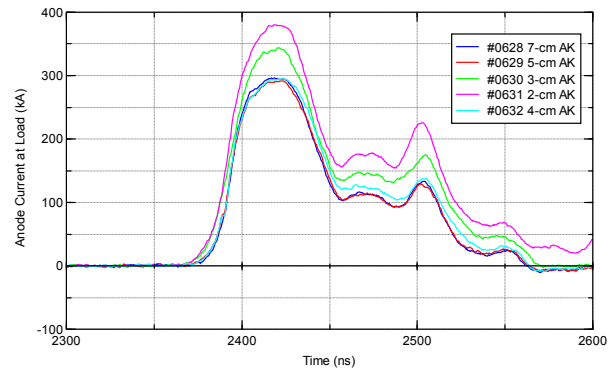
center conductor (9.09”), was placed at the end of the center conductor.



**Figure 5.** Cross-sectional view of Mercury load chamber (left side) and last cell (right side) with “Blade” load (Note: Power flow is from right to left).

Unexpectedly, the graphite anode was severely damaged for both of the first two shots in this mode, even though the AK gap was quite large (11 cm). PIC simulations have revealed that the electrons strike the anode at shallow angles instead of the almost normal angles calculated for negative polarity. It is believed that this causes more energy to be deposited closer to the graphite surface. Also, most of the electrons strike within a radius smaller than the anode, which is speculated to cause anode damage simply by overheating.

Anode damage was mitigated by simply drilling a 1” hole in the center of the anode. This completely prevented anode damage even with AK gaps as small as 2 cm. However, it was found that a beam-stopping plate had to be inserted inside the center conductor (about 6” behind the anode) to prevent electrons from interfering with center conductor current probe signals.



**Figure 6.** Inner conductor (anode) currents (aligned in time) for Mercury blade load AK gap scan shots.

Another dramatic difference between the positive and negative versions of the blade load was found in the response to AK gap. In negative polarity, the AK gap had to be increased to about 11 cm before anode current fixed to the self-limited value. However, in positive polarity, the anode current became self-limited with an AK gap of just 4 cm, as shown in the measured data of Fig. 6.

## V. LOAD VOLTAGE DETERMINATION IN POSITIVE POLARITY

LSP [3] PIC simulations have shown that the standard Mendel voltage calculations employed in negative polarity [4] do not work well in positive polarity. In particular, with an under-matched load the calculated Mendel voltage is much too high. The discrepancy is not due to the polarity, but due to the layered flow that results from having electrons emitted from the different potentials of the outer conductor, introduced by the cell feedgaps. In PIC simulations, the Mendel voltage does work for long pulses in self-limited mode, but is too high for realistic Mercury pulses [5].

Another way to obtain the load voltage is via circuit simulation with a resistive load. By varying the load impedance in the circuit model, driven by measured PFL waveforms, an estimate of the load voltage can be obtained. The effective impedance of the MIVA vacuum lines,  $Z_{Flow}$ , is not known exactly, but is expected to be bounded by the vacuum impedance,  $Z_0$ , and the saturated flow impedance,  $Z_0/2$ . It is generally believed that a self-limited MITL with layered flow will be fully saturated and therefore have  $Z_{Flow}=Z_0/2$ . A very undermatched load will have little flow and there for have  $Z_{Flow}=Z_0$ . So, the circuit simulation was run twice, once with  $Z_0$  values for vacuum lines and once with  $Z_0/2$  values, to gauge the effects of flow impedance.

Others have shown that a modified version of the Mendel voltage, where it is assumed that  $Z_{Flow}=Z_0/2$ , can give a good estimate of the load voltage [6]. But, this is applicable only in the case of fully saturated flow, i.e., only when running self limited.

For shot #0628, with 7-cm AK gap, circuit simulation gives a load impedance of 16  $\Omega$  with MIVA element impedances set to  $Z_0/2$ , and 14  $\Omega$  with impedances set to  $Z_0$ . Both simulated load currents agree equally well with the measured load current as shown in Fig. 7. The calculated load voltages are about 4.5 MV for the  $Z_{Flow}=Z_0/2$  case and 4.0 MV for the  $Z_{Flow}=Z_0$  case. However, these load voltages are much lower then the >6 MV given by the Mendel formula using inner and outer conductor currents at the load location with  $G=1$ , as shown in Fig. 8.

This circuit simulation procedure was performed for all the AK gap scan shots #0628 to #0632 and the results are plotted in Fig. 9. It is believed that shots with large AK gap are running in the self-limited mode and are therefore are better modeled by the  $Z_{Flow}=Z_0/2$  case. The

shot with 2-cm AK gap was very undermatched and may be better modeled by the  $Z_{Flow}=Z_0$  case.

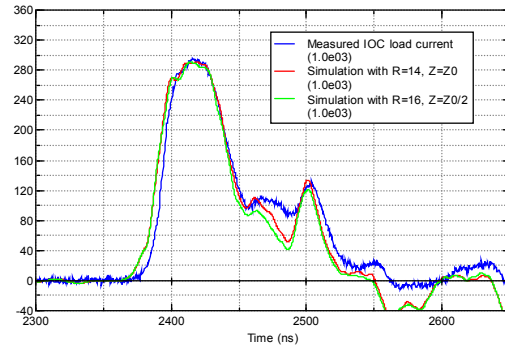


Figure 7. Measured and simulated load currents for shot #0628 (7-cm AK gap).

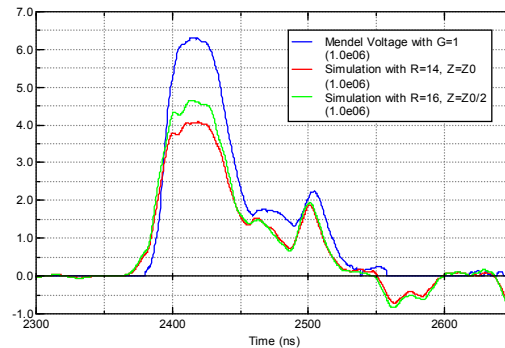


Figure 8. Calculated load voltages for shot #0628 (7-cm AK gap).

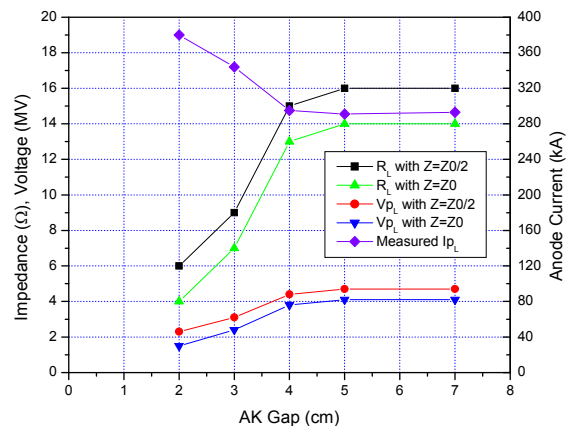


Figure 9. Measured peak current and calculated load impedance and peak voltage ranges deduced from circuit simulation AK gap scan shots.

## VI. SUMMARY

The Mercury IVA has been successfully converted to positive polarity. We chose to change polarity by rotating the cells although we could have inserted the center conductor from the opposite end instead. Note that this is the same approach taken in the past at Sandia National Laboratories with the HERMES III and SABRE IVAs [7][8]. Only a few changes in the vacuum section had to be made, including Aerodagging the outer conductor surface.

Short circuit shots were performed to calibrate MITL current monitors. Also, a circuit model of Mercury, driven by measured PFL waveforms, was fine tuned to closely match calibrated load currents. This allowed for calibration of MITL current monitors in locations difficult to access with the calibration fixture.

A blade load diode was fielded to test operation in positive polarity. Although the blade load hardware was very similar to that used in negative polarity, several differences in operation were found. In particular, the anode was damaged unless a hole was added to the center. Also, this positive polarity blade diode became self-limited at a much smaller AK gap, compared to the negative polarity case.

Determining the load voltage in positive polarity presents a challenge, especially when considering under-matched loads. The Mendel equations used in negative polarity overestimate the voltage, sometimes dramatically. The Mendel solution for known fully saturated flow would only be applicable to the self-limited case. The circuit model approach presented here provides another way of estimating the voltage in positive polarity. We hope to soon field a vacuum voltmeter [9] on Mercury to shed more light on the load voltage in positive polarity.

## VII. REFERENCES

- [1] R.J. Allen, et al., "Initialization and operation of Mercury, a 6-MV MIVA," 15th International Pulsed Power Conference, June 13-17 (2005).
- [2] R.J. Commisso, et al., "Application of TW-level pulsed power to the detection of fissile materials," these proceedings.
- [3] LSP is a software product of ATK Mission Research, Albuquerque, NM87110.
- [4] P.F. Ottinger and J. W. Schumer, "Rescaling of equilibrium magnetically insulated flow theory based on results from particle-in-cell simulations", Physics of Plasmas 13, 063109 (2006).
- [5] J.W. Schumer, et al., "Positive-polarity power flow in multiple-adder MITLs," these proceedings.
- [6] D.L. Hanson, et al., "Ion coupling efficiency for an extraction applied-B ion diode on HELIA linear-induction adder in positive polarity," IEEE Trans. Plasma Sci., Vol. 19, No.3, pp.831..839 (1991).

[7] D.L. Johnson, et al., "Hermes-III positive polarity experiment," 7th IEEE Pulsed Power Conference, (Monterey, CA, 11- 14 June 1989), p. 32.

[8] J.P. Corley, et al., "SABRE, a 10-MV linear induction accelerator," 8<sup>th</sup> IEEE Pulsed Power Conference, (San Diego, CA, 15-19 June 1991), p. 920.

[9] B.V. Weber, "-6 MV vacuum voltmeter development," these proceedings.