STATUS OF THE MERCURY PULSED–POWER GENERATOR, A 6-MV, 360-KA, MAGNETICALLY-INSULATED INDUCTIVE VOLTAGE ADDER*

R.J. Commisso+, R.J. Allen, J.R. Boller[a], G. Cooperstein, R.C. Fisher[a], D.D. Hinshelwood, T.A. Holt[a], D.P. Murphy, J.M. Neri, P.F. Ottinger, D.G. Phipps[a], J.W. Schumer, and O. Stoltz[b]

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

K. Childers, V. Bailey, D. Creely, S. Drury, D.L. Johnson, J. Kishi, M. Klatt, H. Nishimoto, and I. Smith

Titan Pulse Sciences Division, San Leandro, CA, USA

P. Hoppe and H.J. Bluhm

Forschungszentrum, IHM, Karlsruhe und Mikrowellentechnik, Germany

Abstract

Mercury is a nominal 6-MV, 360-kA, 2.2-TW magnetically-insulated inductive voltage adder that is being assembled at the Naval Research Laboratory. Mercury, originally known as KALIF-HELA, was located at the Forschungszentrum in Karlsruhe, Germany. Once assembled, Mercury will be used as a testbed for development of high-power electron- and ion-beam diodes. Applications include source development for high-resolution flash radiography, nuclear weapons effects simulation, and particle-beam transport research. This paper highlights the progress of the Mercury assembly and supporting activities, including modifications from the original design, circuit modeling to optimize the Mercury circuit, power-flow simulations to understand and optimize Mercury power flow and load coupling, and MITL theory and modeling to develop a transmission-line code capability for modeling transient effects in MITLs.

I. INTRODUCTION

The KALF-HELIA generator [1-4], originally designed by Pulse Science Inc. and located at Forschungszentrum in Karlsruhe (FZK), Germany, has been re-located to the Naval Research Laboratory (NRL) and is now called Mercury. The generator, a 6-stage, magnetically-insulated inductive voltage adder (MIVA), was originally designed for operation at 6-MV and 360-kA (2.2 TW) [1] with the primary application at FZK [2] of intense, light-ion-beam generation. The machine was designed for operation with either positive or negative high voltage on the center conductor of the coaxial output (positive and negative polarity, respectively). NRL purchased KALIF-HELIA from FZK in early winter of 2001. It was disassembled and packaged by the early spring of 2002. All the components were delivered to NRL by the fall of 2002. Site preparation activities at NRL were initiated in the early summer of 2002 and completed in May of 2003. We expect to complete the assembly of Mercury at NRL in the fall of 2003. This paper reviews the status of the machine assembly, describes modifications to the FZK design, and presents highlights of the supporting activities. These supporting activities are described in companion papers [5-7] and include: circuit modeling [5] and power-flow simulations [5,6] to better understand the operation at FZK and optimize the Mercury circuit, power-flow simulations to help design future loads for Mercury [6], and magnetically-insulated-transmission-line (MITL) theory and modeling to develop a circuit code that self-consistently captures the transient effects associated with MITL flow [7].

II. SYSTEM DESCRIPTION AND STATUS

Mercury is a 6-stage, MIVA, shown schematically in Fig. 1. The “Sandia-style” Marx bank comprises 36, 2.2-μF, 100-kV capacitors (396 kJ at 100-kV charge). The erected Marx discharges though a series resistor (not shown) into four, parallel, 1.4-m diam x 1.4-m long, 9-nF,

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+ email: commisso@suzie.nrl.navy.mil.

[a] Titan-JAYCOR Division, McLean, VA 22101.

[a] Titan-JAYCOR Division, McLean, VA 22101.

[b] Goraieb Versuchstechnik, Karlsruhe, Germany.

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14. ABSTRACT
Mercury is a nominal 6-MV, 360-kA, 2.2-TW magnetically-insulated inductive voltage adder that is being assembled at the Naval Research Laboratory. Mercury, originally known as KALIF-HELA, was located at the Forschungszentrum in Karlsruhe, Germany. Once assembled, Mercury will be used as a testbed for development of high-power electron- and ion-beam diodes. Applications include source development for high-resolution flash radiography, nuclear weapons effects simulation, and particle-beam transport research. This paper highlights the progress of the Mercury assembly and supporting activities, including modifications from the original design, circuit modeling to optimize the Mercury circuit, power-flow simulations to understand and optimize Mercury power flow and load coupling, and MITL theory and modeling to develop a transmission-line code capability for modeling transient effects in MITLs.

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coaxial water capacitors that make up the 36-nH intermediate-store (IS). Each IS discharges into three, coaxial, water pulse-forming lines (PFLs) through a laser-triggered gas switch (LTGS). The Mercury LTGS is a higher-voltage version of the HERMES-3 LTGS and is described elsewhere [1, references therein]. Each of the 12, 5.5-Ω, 50-ns-long (two-way transit time) PFLs [1] is switched out through a self closing, water output switch (OS) into a coaxial, water output line that connects the PFL to an induction cell through a coaxial, oil-filled elbow. Each of the 12 output lines is made up of 2 sections: output line 1 (OL1), 5.5 Ω and 50-ns long (two-way), and output line 2 (OL2), 6.75 Ω and 85-ns long (two-way). A self-closing, water pre-pulse switch (PPS) separates OL1 and OL2. The 2-way transit time of OL2 is such that the forward-going pulse can be observed over the entire pulse duration. [1,5].

Six induction cells, illustrated in Fig. 2, are each fed by two PFLs, one on top and one on bottom. Each feed point is split and distributed so that there are actually four symmetric feed points per cell. [1] The induction cells also house the high-permeability cores (Vacuumschmelze Vitrovac 7600Z, not shown) used for inductive isolation. The cells are filled with oil. On the vacuum side of the vacuum interface, the cell feed-gap cathode is anodized. The voltage from the six cells is added in vacuum along an MITL.

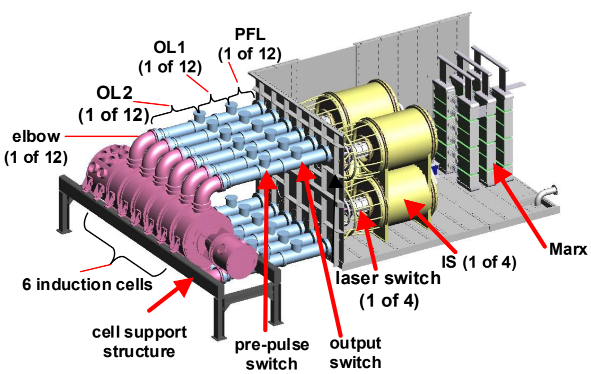

Figure 1. Schematic drawing of Mercury

We made several modifications to the KALIF-HELIA system. Originally, KALIF-HELIA had separate tanks for the Marx and IS. Space limitations at NRL required that we build a single tank, in situ, for both. We redesigned the cell (Fig. 1) and PFL (Fig. 3) support structures, consistent with space limitations in the room, to facilitate both removal of individual PFLs and access to the cell vacuum interface. Also, an additional, moveable cell support structure was designed to facilitate retraction of the center conductor. We designed and fabricated new spacers between the cells to increase the anode-cathode gap spacing in the cell feed from 4.5 cm to 7.0 cm (see Fig. 2). This change reduces the electric field in the cell feed gap to 250 kV/cm or less with 1.3 MV across the vacuum interface, reducing the probability of electron emission in the feed-gap region. If emission were to occur, the new design also assures that the electron flow would be insulated. To reverse polarity on Mercury, we plan to re-insert an appropriately configured center conductor into the opposite end of the cells. Mating flanges were modified and, in some cases, new components designed for this purpose.

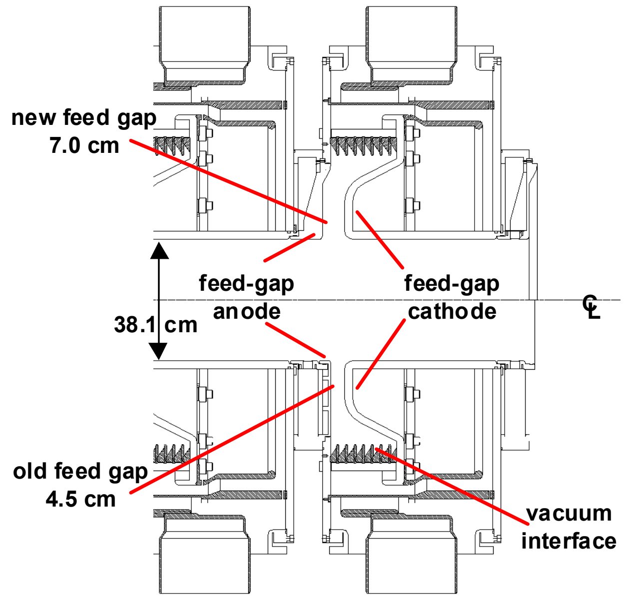

Figure 2. Drawing of induction cells. Top – new 7.0-cm feed gap, bottom – old 4.5-cm feed gap.

To date, all of the site preparation work has been completed, including relocation of the previous occupants of the site and installation of: two cranes; two, 15,000-gal oil storage tanks; three, 1,500-gal water storage tanks, and the new Marx/IS tank. In addition, the Marx, the ISs, and most of the ancillary Marx components and bus work have been installed. The PFL support structure as well as the PFLs have been assembled. Figure 3 is a recent photograph of Mercury.

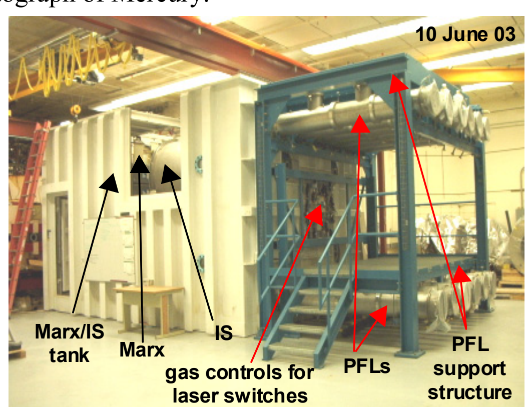

Figure 3. Recent photograph of Mercury.

III. CIRCUIT MODELING

A new, detailed circuit model was developed for Mercury based on an earlier circuit model for KALIF-HELIA. Details of this work can be found in Ref. [5]. The updated model includes new information from FZK and was benchmarked against KALIF-HELIA data in negative polarity. Electron flow in vacuum along the MITL tends to reduce the impedance for the circuit elements representing the vacuum part of the circuit. [6,7, references therein] Steady-state circuit element values for these sections and the electron-beam diode load were determined through PIC simulations and used in the circuit modeling. [5,6] An important improvement to the circuit model was an increase of about a factor of 10 in the conducting-state resistance of the water switches. Each OS requires a resistance of about 1.2 Ω for the new model to agree with measurements, compared with the 0.133-Ω design value used in the earlier model. The corresponding electric field in the switch region is 55 kV/cm, close to the 30 to 50 kV/cm recently measured by Titan Pulse Sciences Division on other machines. This increased switch resistance results in a combined OS and PPS energy loss of about 20 kJ for Mercury [5], and is ≥ twice the resistance used in any previous analyses of KALIF-HELIA.

Results of circuit analysis using the improved circuit model suggest several changes to the KALIF-HELIA circuit to optimize the electrical performance of Mercury. [5] These modifications to the KALIF-HELIA circuit include: **(1)** eliminating a resistor in shunt with the IS, **(2)** reducing the Marx output resistor from 3.6 Ω to 1.5 Ω, and **(3)** increasing the IS water resistivity from 0.8 MΩ-cm to 2 MΩ-cm. These changes should permit increasing the IS voltage from 2.6 MV to 3.1 MV and the PFL voltage from 1.86 MV to 2.15 MV, while decreasing the Marx charge voltage from 95 kV to 85 kV and reducing the Marx current from 120 kA to 110 kA. With the same 16-Ω load used on KALIF-HELIA (slightly smaller than the 20-Ω matched value), the expected load voltage peaks at 5.9 MV and the load energy, just after the main pulse (~ 50-ns FWHM), is 96 kJ. The calculated voltage and energy time histories are shown in Fig. 4. The effects of expected switch jitter would reduce the load energy by about 5 kJ.

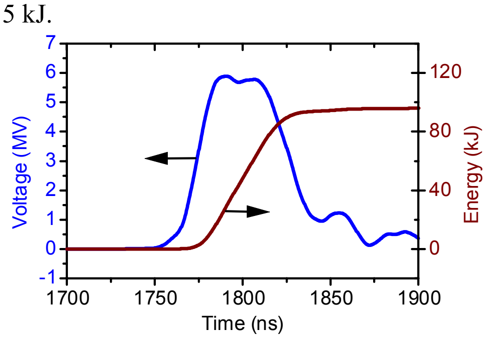

Figure 4. Expected Mercury load voltage and energy as functions of time for an 85-kV Marx charge.

IV. LOAD COUPLING

The 20-Ω low matched load impedance of Mercury [5] gives it potentially great flexibility in accommodating a variety of loads, in both negative and positive polarity. For radiographic source development in particular, two general classes of loads can be considered: low impedance (~ 20 Ω) and high impedance (> 20 Ω). For low-impedance loads, the full Mercury current could be delivered to a single load. In the high-impedance case, several loads could, in principle, be driven in parallel - each with impedance > 20 Ω (e.g., two, ~ 40-Ω loads). Low impedance radiographic diodes can be explored using either the composite diode approach [8] or the plasma-filled-diode technique [9].

Because electron emission occurs on the cathode of the MITL, current flow associated with the cathode is divided between current flowing in the metal and current flowing in the vacuum. The electron current in vacuum, or flow current, can be a large fraction of the total current and must be considered in load design. One could possibly design the load to trap and use the flow current or to shed the flow current in a benign manner before reaching the load (this is particularly important for radiographic applications). When emission occurs in the cell feed gaps, or when electrons are emitted at different potenials along the MITL itself, the further complication of layered flow occurs. Analysis of power flow in this complex geometry is underway to understand the past performance of KALIF-HELIA and to assist in optimizing the future performance of Mercury in both polarities and with various load configurations [6,7].

An example of this ongoing load-design work is given in Fig. 5. Details of this work are found in Ref. [6].

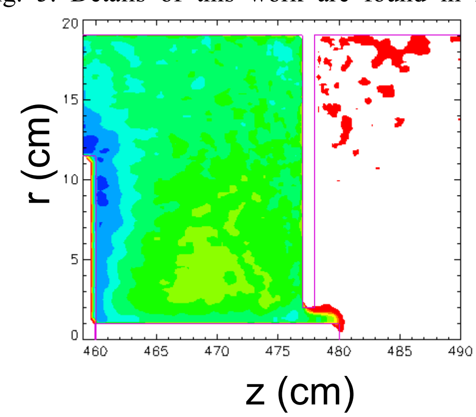

Figure 5. Current contours (25 kA to 300 kA, with 25-kA contours) for a positive polarity rod-pinch on Mercury.

Current-enclosed contours in the r-z plane at t = 50 ns from a simulation of a positive-polarity rod-pinch driven by Mercury are shown. In this simulation, the 23-cm-diam center conductor is truncated abruptly at z = 460 cm (z = 0 is the start of the center conductor), and a 20-cm long, 2-cm diameter anode rod is attached. The cathode extends downward radially from the outer conductor, forming a rod-pinch diode [8], references therein]. Proton-emission was allowed along the anode rod between 475 < z[cm] < 480. The current-contours show that about 187 kA flows through the diode. The remainder of the 310-kA total current is equally distributed along the anode rod and the machine center conductor upstream of the rod-pinch cathode. The machine voltage is 5 MV.

V. MITL PHYSICS AND MODELING

Although very valuable, PIC codes take much longer to run than transmission line codes and are not coupled to power flow in the generator. The goal of the MITL modeling work (see Ref. [7] for details) is to develop physics-based MITL circuit-element models so that a transmission-line code can properly treat transient power flow [10] in the MITLs (including, e.g., the effects of impedance transitions and time-dependent loads) while modeling the full machine.

Because of the electron flow current, the flow impedance, Z_f [10], rather than the vacuum wave impedance, Z_0, describes the effective impedance of an MITL. The general form for Z_f is:

$$Z_f = \frac{V}{\left(I_a^2 - I_c^2\right)^{1/2}} \quad , \qquad (1)$$

where V is the voltage across the line, I_a is the current flowing in the anode, I_c is the current flowing in the cathode, and $(I_a - I_c)$ is the electron flow current. This definition for Z_f is independent of the distribution of space charge in the AK gap. Also, Z_f is a function of the instantaneous voltage on the line, so that Z_f is a dynamic quantity. The basis for the analytical analysis of MITL flow is pressure balance when space charge limited (SCL) emission occurs at the cathode. [10,11] SCL emission implies that the cathode is turned-on and that sufficient space charge exists in the gap to drive the cathode electric field to zero. We assume that there is no ion emission from the anode, that the electrons are emitted from the cathode with zero energy (and, hence, at zero pressure), and that the electron pressure is negligible compared to the electromagnetic field pressure at the anode. With the above assumptions and for the case of uniform space-charge density in the flow layer, pressure balance gives

$$V = Z_0\left(I_a^2 - I_c^2\right)^{1/2} - \frac{mc^2}{2e}\frac{I_a^2 - I_c^2}{I_c^2} \quad , \qquad (2)$$

where m and e are the mass and charge of an electron, respectively, and c is the speed of light. The last term is the space charge correction. Knowing Z_0, Eqs. (1) and (2) are used to solve for either $Z_f(V)$ and $I_A(V)$ given I_C, or $Z_f(V)$ and $I_C(V)$ given I_A, for application in transmission-line codes. [7] The voltage in Eq. (1) agrees quite well with results from PIC simulations in negative polarity. This work is ongoing.

VI. SUMMARY

The assembly of Mercury at NRL, formally KALIF-HELIA at FZK, is nearly complete. Modifications have been made to facilitate maintenance and conversion between polarities, and to reduce emission in feed gaps. First pulsed-power testing should begin in the fall of 2003. A new circuit model has been benchmarked. Results of circuit analysis show that the resistance of the water switches had been previously underestimated by about a factor of 10. These circuit-modeling results also suggest that reducing the value of the series resistor between the Marx and IS, eliminating the IS shunt resistor, and increasing the IS water resistivity is required to optimize the Mercury circuit. With these changes, we can expect ~ 90 kJ delivered to a 16-Ω e-beam diode load from a 5.9-MV, ~ 50-ns FWHM pulse. Power-flow PIC simulations and analytical work are ongoing, with the goal of optimizing the load designs for Mercury in both positive and negative polarity, and of developing the capability to model transient MITL effects in a transmission-line code.

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