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DESIGN AND CODE VALIDATION OF THE JUPITER INDUCTIVE VOLTAGE ADDER (IVA) PRS DRIVER*

M. G. Mazarakis, J. W. Poukey, C. W. Mendel, D. Seidel, J. P. Corley, P. Pankuch, D. L. Smith, L. Bennett, and J. R. Lee
Sandia National Laboratories
P. O. Box 5800
Albuquerque, NM 87185-1193

and

I. Smith, P. Corcoran, and P. Spence
Pulse Sciences Inc.
600 McCormick
San Leandro, CA 94577

Abstract

The proposed Jupiter accelerator is a ~ 10-MV, 500-TW system capable of delivering 15-MJ kinetic energy to an imploding plasma radiation source (PRS).[1,2] The accelerator is based on Hermes-III[3] technology and contains 30 identical inductive voltage adder modules connected in parallel. The modules drive a common circular convolute electrode system in the center of which is located an imploding foil. The relatively high voltage of 8-10 MV is required to compensate for the voltage differential generated across the load due primarily to the fast increase in current (L di/dt) and to lesser extent to the increasing inductance (I dL/dt) and resistive component of the imploding foil. Here we examine the power flow through the device and, in particular, through the voltage adder and long MITL. Analytical models, such as pressure balance and parapotential flow, as well as circuit and PIC codes, were utilized. A new version of the TWOQUICK PIC[4] code, which includes an imploding, cylindrical foil as load, was utilized to compare the power flow calculations done with SCREAMER[5] and TRIFL.[6] The agreement is very satisfactory and adds confidence to the Jupiter design. In addition, an experimental validation of the design is under way this year (FY95) with Hermes III. Long extension MITLs are connected at the end of the voltage adder with inductive and diode loads to benchmark the above design codes. In this paper we outline the accelerator's conceptual design with emphasis on the power flow and coupling to the inductive load and include preliminary results of Hermes-III experimental design validation.[7]

Introduction

The plasma radiation source (PRS) accelerator was originally proposed as a simulator to produce intense x-ray radiation pulses simulating the nuclear weapon effects on various materials and components. However, because of its long pulse (~ 100-ns FWHM) and the large amount of radiation produced (~ 1000 TW), it was realized that such a device could be useful for nuclear weapon physics studies and ignition of indirectly driven inertial confinement fusion (ICF) targets. From the plasma physics point of view, this device will provide a definitive experimental verification of the scaling laws that govern the generation of x-ray radiation in a magnetically confined and imploding plasma. The PRS accelerator point design is for 8-10 MV, 50-60 MA, and although the peak voltage is relatively modest, the current exceeds that of any existing or planned pulsed power device. To achieve this large current, the accelerator is modular and consists of thirty 2-MA modules connected in parallel through a common convolute. The pulse duration is 100 ns FWHM. A 15-MJ kinetic energy is delivered into the plasma through the moving foil

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which implodes in ~ 120 ns. If we assume that all implosion energy is converted into radiation and the x-ray pulse if five times shorted than the implosion times, we estimate a 600-TW output—quite a formidable plasma radiation source.

The 500-TW PRS Accelerator

The proposed pulsed power accelerator (Fig. 1) is based on the successful Hermes-III[3] technology developed in Sandia during the last ten years in collaboration with Pulse Sciences Inc. Each of the 30 modules of Figure 1 are similar to Hermes III.

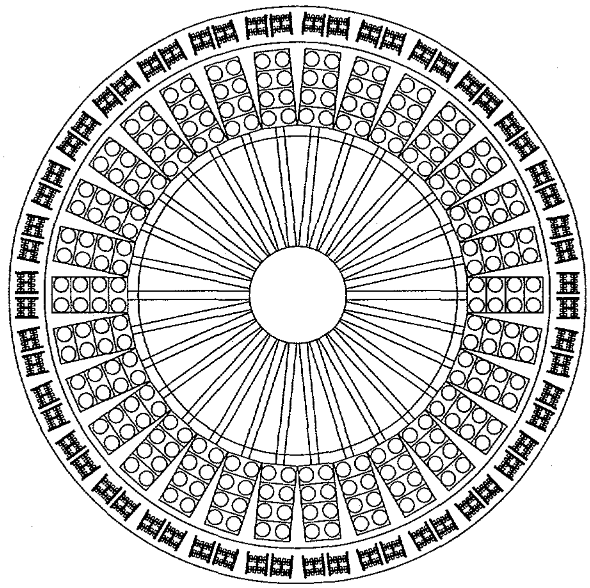

Figure 1. Top view of the PRS multimodular accelerator

Due to their radial dimensions, the voltage adders cannot be brought close to the load; therefore, long extension self-magnetically insulated transmission lines (MITLs) are required to transfer and converge the power to the load. In the present design, this length is 11.3 m. There are advantages and disadvantages to the utilization of long MITLs. It is our belief that the advantages outweigh the disadvantages. For instance, the erosion energy losses are compensated for by the flexibility of the voltage adder time isolation from the load. For most of the pulse duration, the voltage adder load impedance equals its self-limited operating impedance despite the fact that at the beginning of the pulse (t = 0 to 50 ns) the actual load impedance can be up to ten times higher.

All the 30 modules in the accelerator are identically composed by a four-stage voltage adder and one extension MITL. The voltage adder is 5.6-m long and contains 4 inductively isolated cavities. The maximum voltage a cavity can withstand is ~ 2.5 MV for a 100-ns FWHM sine square shaped pulsed. Table I summarizes the axial and radial dimensions of the voltage adder as well as the vacuum and operating impedances for two-cavity operating points: 2 MV and 2.5 MV. Those correspond respectively to a 430-TW and 660-TW total accelerator power. Each module delivers approximately the same power as Hermes III (16 TW); however, the voltage is half as large and the current more than double.

Table I

R_{anode} = 38 cm

voltage adder segment i	distance from ground plate z [m]	segment voltage V_i [MV]	cathode radius r_i [cm]	operating impedance Z_i [Ω]	vacuum impedance Z_i [Ω]
1	0.30 - 1.98	2 - 2.5	37.0	1.11 - 1.16	1.6
2	1.98 - 3.65	4 - 5	36.1	2.22 - 2.28	3.08
3	3.65 - 5.33	6 - 7.5	35.3	3.33 - 3.41	4.42
4	5.33 - 7.00	8 - 10	34.6	4.44 - 4.54	5.62

Power Flow Studies

To optimize the entire device from the Marxes to the imploding foil, we used the circuit code SCREAMER which works fairly well for lumped elements and electrical components where the power flows in the form of an electromagnetic pulse propagating between two conducting surfaces. Besides the two conductors, in the self magnetically insulted voltage adders and MITLs, the sheath electrons contribute also to the power flow. SCREAMER treats those components in an approximate way which can be within 10% of the results obtained by a more accurate circuit code (TRIFL) developed recently by Cliff Mendel. A most accurate way in studying both voltage adders and MITLs is a fully electromagnetic PIC code, such as TWOQUICK, which contains almost all the power flow physics. Unfortunately, for the length of our device, a well resolved PIC simulation requires long computing times and is very costly.

Figure 2 shows one of the TWOQUICK PIC code simulations used to validate the design and benchmark SCREAMER and TRIFL. The main purpose of these simulations was to study the pulse propagation through the voltage adder and the long MITL and to calculate the erosion losses in both components. However, to make the axial dimensions reasonable only 6 m of the 11.3-m total MITL length was retained. The accelerator center section (transition convolute and imploding plasma) is simulated by a coaxial cylindrical box whose inductance is 30 times larger than the actual inductance seen by the 30 parallel modules. The end plate of the coaxial line simulates the imploding cylindrical foil.

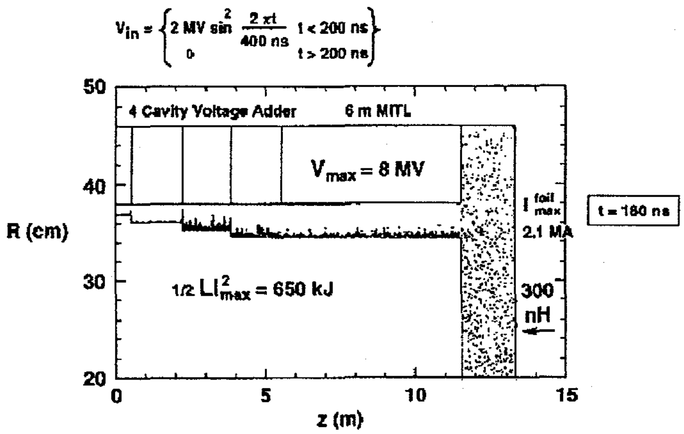

Figure 2. Numerical simulation of the voltage adder connected to a 300-nH inductive load via a 6-m long MITL. The electron map shown is simulated 180-ns later, following the injection of the voltage pulse (V_{in}) at the first cavity.

The electron map is for 180 ns after the beginning of the pulse, coincident with the 2.1-MA maximum current through the load. Incidentally, this current is equal to the total current, bound plus sheath electron current, flowing in the MITL. Therefore, a voltage adder/MITL is current efficient in driving a plasma radiation source. The energy coupled into the inductive load is $L I^2_{max}/2$ = 630 kJ out of a total of 1,090 kJ energy input into the voltage adder, yielding a system efficiency of 58%.

The simulation of Fig. 3 was performed to find the total energy loss in the 11.3-MITL. The input and output voltage pulses are shown in Fig. 4. The 60-ns erosion of the leading edge corresponds to 92-kJ lost. Besides the pulse shortening by ~ 60 ns, there is a small energy loss (20 kJ) in the main body of the pulse. Together, this gives an average erosion rate of 10 kJ/m. Hence, if all the MITL length had been included in the simulation of Fig. 2, the energy efficiency would have been ~ 50%. Precise energy balance using TWOQUICK suggests the missing 50% of the input energy is distributed between reflections at the load (3%), erosion (10%), sheath electron losses at the load (20%), and field energy remaining inside the MITL (10%).

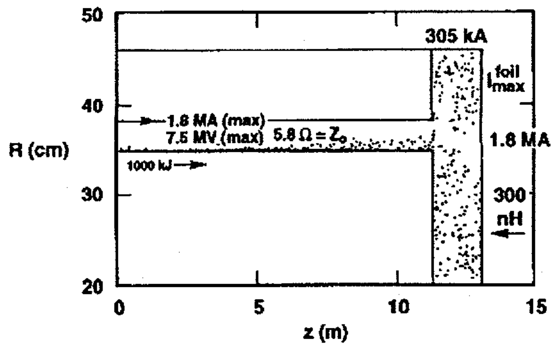

Figure 3. Simulations of the power flow in the 11.3-m long extension MITL of an accelerating module. The electron map is taken at 120 ns following injection.

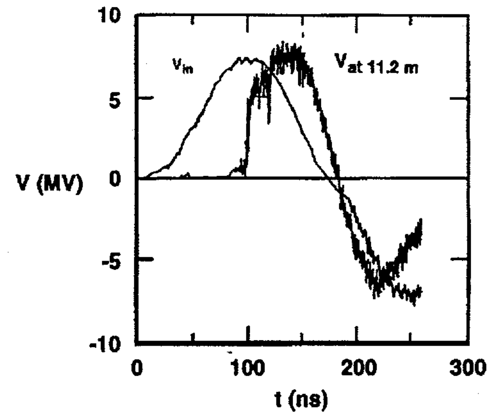

Figure 4. Voltage input and output pulses at the beginning (z = 0) and end (z = 11.3 m) of the long extension MITL of Fig. 3. The erosion at the leading edge of the output pulse is ~ 60 ns.

The above simulations do not include dL/dt effects. In most recent simulations (Fig. 4), the dL/dt term was included. A new version of TWOQUICK, which includes an imploding cylindrical foil as load was utilized. Again, a 300-nH fixed inductance was assumed per line plus the dL/dt introduced by the imploding cylindrical foil. This time the 2-m long 50-Ω coaxial box load of Fig. 2 was replaced by a lamped inductance of the same value (300 nH).

The parameters of the imploding foil correspond to a 130-mg, 2-cm radius, and 4-cm high cylinder; these parameters were reduced in the simulations to represent only one Jupiter Module. The same circuit was studied by TRIFL, TWOQUICK, and SCREAMER. The input voltage pulse was trapezoidal with 200-ns base, 70-ns rise time and fall, and 8.84-MV flat top. Table II summarizes and compares the results. The agreement of the 3 codes is within 8%.

To calculate the overall accelerator efficiency driving an imploding plasma radiation source, we used the SCREAMER circuit code, which gave an energy efficiency of 17%. That is, for a total of 90 MJ stored in the Marx generators of the 30 modules, 15 MJ is delivered to the imploding plasma.

Table II

Output Parameters at the load	TWOQUICK	TRIFL	SCREAMER
V(MV)	7.5	7.8	7.3
I(MA)/module	1.73	1.70	1.73
*t(ns)	219	208	219
KE(MJ)/module	.410	.443	.406

*t is the foil implosion time driven by the 30 modules

Validation of Jupiter Design with Hermes-III Experiments

An experimental validation program of the Jupiter design is in progress. One of the most important design questions is the power flow in the 11-m long MITL and the energy coupling to the inductive load. To address the issue as soon as possible, even before a Jupiter module is available, a series of experiments are underway with Hermes III.

A 12-m long extension MITL is installed at the output end of the device, and the power flow is being investigated with resistive and inductive loads. To approach Jupiter operating conditions of 100-ns FWHM pulse, the Hermes-III pulse forming network was modified to produce a comparable length pulses (175-ns FWHM). The PFLs and picking switches were shorted for those experiments, and the pulse from the intermediate store capacitors (I.S.) was transmitted directly to the cavities without further compression following the closure of the laser triggered gas switches.

The experiments was completed most recently and the analysis is in progress. Preliminary analysis of the diode results suggested good agreement with code predictions. No erosion at the peak was observed. The FWHM is eroded by less than 5 ns (Fig. 5). The inductive load experiments show full conversion of the sheath current to boundary current ("retrapping") following an L/R delayed reflection (Fig. 6). The anode and cathode currents are practically the same and equal to 500 kA. The numerical simulations (Fig. 7) are in good agreement with the observations.

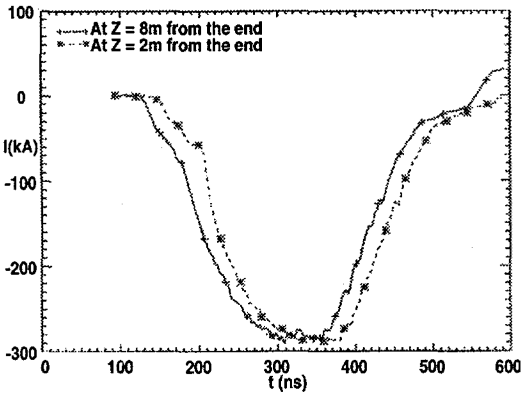

Figure 5. Total currents measured at 8 m and 2 m from the end of the diode load. No erosion is noticeable at the FWHM or at the peak of the pulse. Only the leading edge of the pulse near the load (z = 2 m) appears sharper. The precursor pulse (foot of the pulse) is well resolved. Its maximum corresponds ~ 150 kV/cm emission threshold.

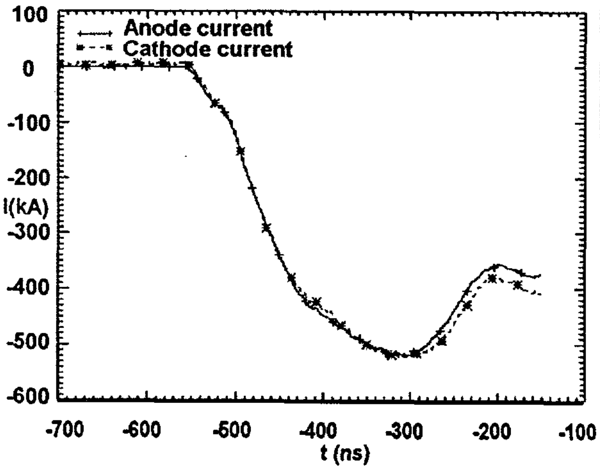

Figure 6. Anode and cathode current near the shorted downstream end (L = 0) of the MITL. These results are characteristic of all the shots with inductive loads.

Conclusion

The present PRS accelerator design is based on the Hermes-III technology of inductively insulated voltage adders (IVA). It has 30 parallel modules and can deliver the required 15-MJ kinetic energy to an imploding plasma radiation load. The total energy erosion in the thirty 11-m long MITLs is of the order of 3.3 MJ and the overall energy efficiency of the accelerator is 17%. The modular configuration offers flexibility and risk mitigation by an anticipated stages construction.

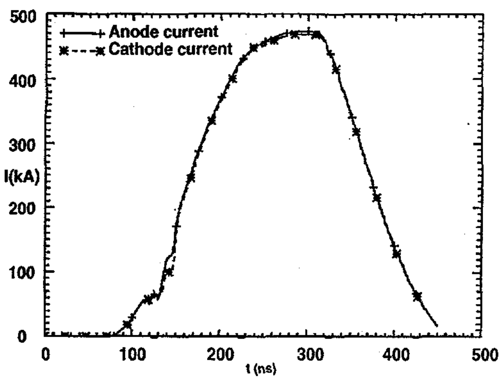

Figure 7. TWOQUICK simulated anode and cathode current traces near the shorted end of the MITL. The voltage input pulse it was calculated analytically from the measured current (Fig. 5) and the parapotential theory.

Components of the first test module are currently under construction. Validation of the design with Hermes-III experiments shows good agreement with numerical simulations and modest energy losses due to erosion as predicted. (The Hermes-III impedance is ~ 4 times larger than Jupiter). The inductive load experiments show full conversion of the sheath current to boundary current following an L/R (≈ 30 ns) delayed reflection. Further experimental investigation with small MITL radial gaps (~ 4 cm) are underway.

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