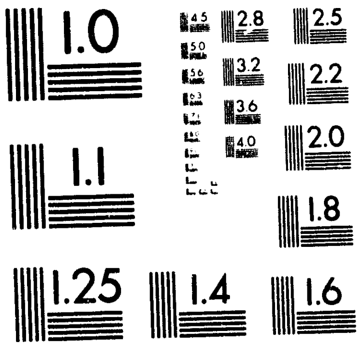

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RESULTS OF INITIAL TESTING OF THE FOUR STAGE RHEPP ACCELERATOR*

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Abstract

The low power checkout of the Repetitive High Energy Pulsed Power (RHEPP) pulse forming line (PFL) and linear induction voltage adder (LIVA) is complete. The accelerator has four LIVA cavities driven via coaxial cables from the PFL that utilizes magnetic switching to provide a 250-kV, 60-ns output pulse. The PFL is repetitively charged by a ten stage Marx generator to operate from single shot to five Hz. Results from these tests of the initial four stage RHEPP accelerator are presented and compared with design simulations. Data from a resistive cavity load and from preliminary electron diode experiments are included. While core temperatures remain low during five Hz operation, they are monitored and compared to extrapolated predictions from the design modeling. Performance of the Metglas [1] magnetic switches and blocking cores, the voltage addition in the four LIVA cavities, and system efficiencies are discussed. Sources of discrepancies from the original design models are identified, and improved models that account for the discrepancies are presented. Improved performance potential based on these models is discussed. Plans for future testing of the 1-MV system up to 120 kW at 120 Hz and for the full system with ten LIVA cavities are presented.

Introduction

Continuously operating electron beam accelerators, with average power levels of up to a few 100's of kW are useful for electron beam welding, plastic polymerization, semiconductor surface treatment, and x-ray lithography. In the future, a new class of applications will require even higher average power accelerators (many 100's of kW to MW). Cost effective treatment of medical wastes is one such application that would require higher power levels to achieve the throughput necessary in a regional disposal facility. Other waste treatment applications, as well as material transformation operations, may also require MW power levels. Many of the applications have requirements that are well above the capabilities of existing commercial accelerators. These applications would require accelerators with very high power (> few 100's of kW), high accelerating potential (500 kV to 10 MV), very long operating life (5 years on major components), low capital and operating costs, and simple maintenance and operating requirements. Accelerators using combinations of semiconductor devices, magnetic pulse compressors and magnetic voltage adders have the potential of meeting these requirements. The purpose of the Repetitive High Energy Pulsed Power (RHEPP) program is to develop this technology for use in high average power applications and to demonstrate the technology in an accelerator operating at 350 kW. At this level, RHEPP will be above the 200-kW capability of present commercial accelerators and should be extendible to much higher power levels. A block diagram of the RHEPP system is shown in Fig. 1. The chart in Fig. 1 shows the increase in output power with time as the RHEPP system undergoes testing. The switches in the block diagram show the options available for testing the RHEPP system. All of the components in the system are designed to have high efficiencies, high reliability and long lifetimes. Key technical issues in the design are thermal management in the magnetic switches and blocking cores, establishment of electrical stress levels in insulation that yield acceptable lifetimes in repetitively pulsed operation, and development of long life, high current density diodes.

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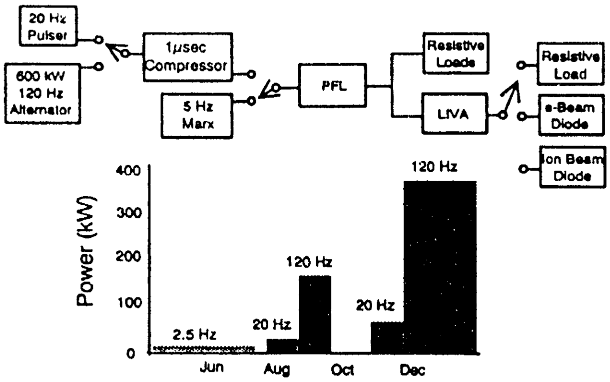

Fig. 1. Block diagram of the RHEPP system

Considerable, effort in the form of experiments and finite element analysis of the cooling channels in the magnetic cores has been devoted to the development of the thermal design. Insulation lifetime in continuous short pulse applications is limited by effects such as partial discharge and corona that cause degradation over a long period of time. Conservative electrical stress levels were used in the component designs based on the best available information. Development of long life cathodes is being addressed both on the 1-MV RHEPP machine and in parallel on a small 250-kV, 500-Hz, 35-kW diode test bed. [2] Initial testing of the RHEPP 1-μs pulse compressor began in September of 1989. The currently operating 1-MV RHEPP system uses a ten stage, 5-Hz Marx generator to drive the completed full scale PFL and four of the ten cavities from the 2.5-MV system, with the surplus power diverted to water cooled dummy loads. Testing of this 1-MV system has provided data that was incorporated into the final design of the 2.5-MV system. Fabrication of all components for the 2.5-MV LIVA has just been completed.

Machine Description

A motor driven 600-kW, 120-Hz alternator, furnished by Westinghouse Electric Science and Technology Center [3] is the RHEPP prime power source. In the unipolar mode, it provides 210 A rms with a power factor of 0.88 to the 1-μs compressor circuit. Unipolar operation of the system requires that reset circuits be used for each of the magnetic switches. A detailed discussion of magnetic switch theory can be found in the literature. [4, 5, 6] The first loop in the PCS is resonant with the source, so that the voltage on the first capacitor rings up to 15 kV, which is twice the peak voltage swing on the alternator. In order for the circuit to operate in the unipolar mode, the first magnetic switch is designed to saturate when the capacitor voltage reaches the negative peak. A Westinghouse designed transformer [7] steps the voltage up to 250 kV and the voltage doubling Blumlein configuration of the PFL gives another factor of two in voltage gain. Magnetic switching is used in all the compression stages because they can handle very high peak powers and have the potential to satisfy the long lifetime requirement. The 1-μs pulse compressor, consisting of the first five stages of pulse compression, uses open geometry magnetic switches that are designed with electric field stresses <50 kV/cm, corresponding to the limit used by the AC power industry in many long lifetime devices. The PFL was designed with a maximum electrical stress of

100 kV/cm. Since Metglas crystallizes at a rapid rate at temperatures above 150°C, all the magnetic switches are provided with cooling channels and manifolds to maintain the maximum internal temperatures below 100°C. The EMRC/NISA heat transfer and fluid flow code and the ALGOR heat transfer finite element code were used to design the cooling channels and manifolds in the magnetic cores. [8]

The PFL, Fig. 2, is a triaxial water insulated line that converts the input LC charge waveform from the 1-μs compressor to a flat-top trapezoidal pulse. The intrinsic voltage doubling in this design delivers a 250-kV voltage pulse to fifty, parallel, 44-Ω cables that feed the LIVA. The PFL uses a 166-kg Metglas, 10-nH output switch, a 600-kg Metglas, 52-nH inversion switch and a 156-kg, 77-nH charge blocking core. The inversion stage compresses the 1-μs, 250-kV-peak LC waveform to a 180-ns, 500-kV-peak LC waveform and the output stage compresses the 180-ns LC waveform to a 20-ns risetime, 60-ns Full-Width-Half-Maximum (FWHM), 250-kV peak trapezoidal pulse. Optimum efficiency and waveform shape is obtained by output switching 160 ns after the beginning of the inversion of the outer shell of the triaxial section. Two adjacent cores wound from 22-μm thick 2605CO Metglas ribbon form the output switch, each of which is 5-cm wide and wrapped on a common 11-cm wide sheet of 12-μm thick polycarbonate insulator film. The windings have a stacking factor of 0.5 that, when combined with fourteen 0.16-cm high cooling channels uniformly distributed in the build, yields a net stacking factor of 0.44. The output switch has a mandrel diameter of 85 cm and an outer diameter of 117 cm. The need to optimize the switching performance and to meet cooling requirements resulted in a core geometry with 177 volts/turn. The charging blocking core consists of four 5-cm wide 2605CO cores on a common mandrel with 12-μm thick polycarbonate film insulation. Seven 0.16-cm cooling channels are distributed uniformly in the build. The mandrel diameter is 61 cm and the outer diameter is 122 cm. These cores operate at 80 volts per turn. Oil serves as both an insulator and a flowing coolant in the PFL cores. The PFL has been tested at up to 5 Hz using the Marx as a driver and operating into the four stage LIVA with various resistive and electron beam diode loads.

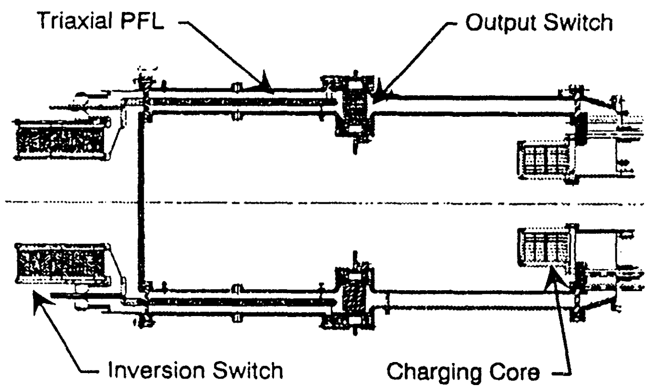

Fig. 2. The voltage-doubling, slow switched PFL.

The 1-MV RHEPP LIVA has four magnetically isolated cavities and uses oil as the insulating medium in the central transmission line. The 350-kg cores were wound by Allied Signal from 17 cm, 20-μm thick 2605-TCA Metglas ribbon on 67-cm diameter mandrels to a build height of 21 cm. The cores are designed to have a 1.05-T flux swing during the input pulse. The inter-laminar voltages are 50 V, and 12-μm thick polycarbonate film is used as the insulator. The 1-MV cores are the same as those that are used in the 2.5-MV LIVA and have served as a test bed for identifying potential problems with fabrication techniques, cooling techniques and modeling techniques. Crucial design parameters such as core loss, the effect of 2605-TCA material on the pulse shape and the validity of using a maximum electrical stress of 100 kV/cm under repetitively pulsed conditions in oil were tested and verified on the 1-MV machine. The RHEPP cavities have a 1.66-m outside diameter and are 0.47-m long. They are fed symmetrically around the circumference by five parallel connected 44-Ω Dielectric Sciences cables, yielding an impedance of 8.8 Ω per cavity. Thus, the four stage, 1-MV and ten stage, 2.5-MV LIVAs operate into 35-Ω and 88-Ω loads respectively. In both the 1-MV and 2.5-MV machines, oil is used as both the insulating medium and coolant in the cores. Ten 0.16-cm high cooling channels are wound into the cores at equal intervals to allow the coolant to circulate through the windings. The maximum temperature in the cores is maintained at below 77°C. Core biasing is provided to the cores, in the 1-MV accelerator, via 75-μH air core isolation inductors that enter each cavity through a sixth port, symmetrically placed between two of the power cable ports.

Modeling

A complete electrical model of the RHEPP system was built using PSPICE [9] to predict losses, circuit interactions, the effects of non-ideal core switching characteristics, the effects of spurious reflections on core behavior, switching synchronization among interacting cores, and the performance of the reset circuitry subject to 120-Hz operation. The switching and blocking cores were simulated using the Jiles-Atherton model provided in the PSPICE code. The shape of the B-H loops for 2605CO Metglas used in the switches and 2605-TCA Metglas used in the LIVA blocking cores were determined from data provided by Allied Signal [10,11] and from experiments conducted at Sandia. [12] The parameters in the Jiles-Atherton model were adjusted to match experimental values. A comparison of a dynamic B-H loop, measured at Sandia, for 2605-CO Metglas with one of the PSPICE models is shown in Fig. 3. It was difficult to simultaneously match the slope of the B-H loop

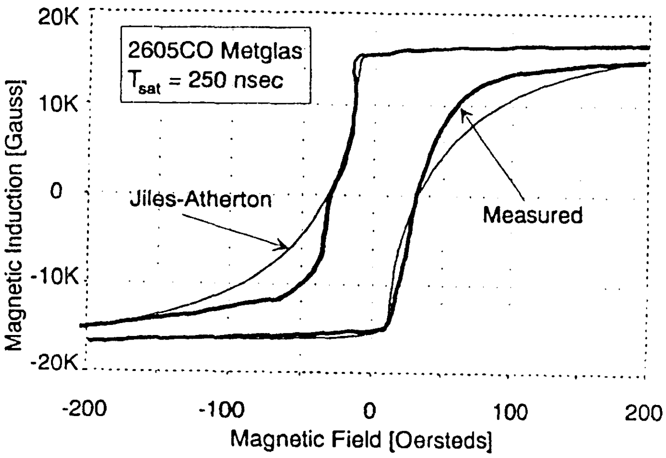

Fig. 3. B-H loop used to model the PFL output switch and the PFL biasing core.

everywhere, resulting in slightly higher loss characteristics in the model. Within the ±10% experimental error bars, the PSPICE model gave good agreement with measured machine waveforms. A comparison of the model results to measured waveforms with the LIVA operating into a 35-Ω resistive load is shown in Fig. 4. The measured results are from an integrated V-dot on the output of the PFL and from a CVR in series with the LIVA load resistor, respectively. The overshoot at the trailing edge of the PFL output pulse is due to a reflection from the bulkhead where the 50, 44-Ω cables are connected that feed the LIVA. The prepulse foot is the result of leakage through the PFL output switch. In the design of the PFL output switch, we over estimated the packing fraction that would be obtained, resulting in a lower ∫vdt product than expected. The PSPICE simulation indicates that increasing the ∫vdt product of the PFL output switch would improve the risetime and flatness of the output pulse. The 10-90% risetime obtained was 20 ns at the output of the PFL. No observable degradation in the pulse risetime was observed in the LIVA output current as measured by the CVR.

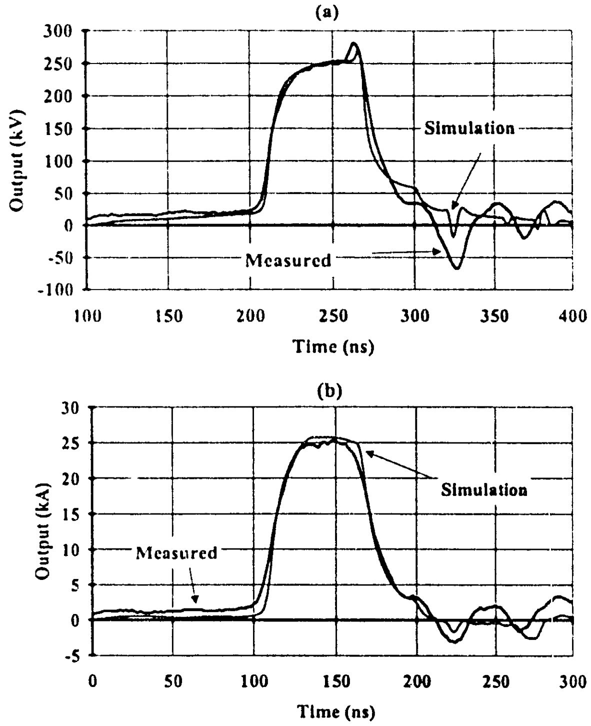

Fig. 4. Comparison of simulated and measured waveforms for the 1-MV RHEPP machine: (a) output voltage pulse from the PFL, (b) output current pulse from the LIVA.

The electrical field stresses and energy transmission characteristics of the PFL and LIVA were determined through extensive modeling with the EMAS 3-D transient field code [13]. An example of the use of this code to model the electric fields and effective risetime for the vacuum interface and diode feed structure at the output end of the LIVA is presented in Fig. 5. The EMAS code allowed modeling of the dynamic voltage division on the vacuum interface and determination of the wave distortion caused by the radiation shielding bulb and associated feed structure. The simulation indicated a maximum electric field on the vacuum interface of 63 kV/cm with ±5% voltage division uniformity. The maximum electric field in the vacuum and oil part of the feed is 100 kV/cm. The EMAS simulation was used to launch a 12-ns risetime trapezoidal pulse through the structure, yielding a 12.3-ns pulse at the load, corresponding to a 3-ns risetime for the vacuum interface and diode feed.

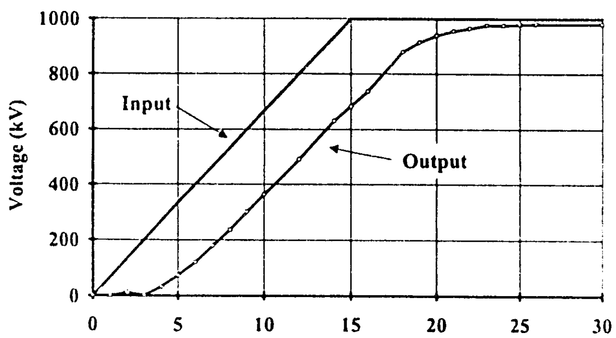

Fig. 5. EMAS simulation of a pulse launched through the vacuum interface and diode feed structure.

Experiments

The 1-μs pulse compressor, consisting of the first five stages of pulse compression, has been successfully tested as a unit [14] at 120 Hz and full power of 600 kW.

The PFL and four stage RHEPP accelerator have been operated at up to 3 kW in a repetitive mode with an electron beam diode load. A single run comprised 25,000 shots with 18,000 shots at 2.5 Hz and the remaining shots at 5 Hz with a diode voltage of approximately 800 kV. An impedance of 33 Ω at peak power was achieved with a 15.2-cm diameter carbon felt cathode spaced 3.8 cm from a 0.2-mm thick titanium anode foil. Approximately 20% of the electron beam power was deposited in the anode foil, with no observable damage. The remainder of the beam power was absorbed directly into the continuously flowing water used as a coolant on the backside of the anode foil. A variety of cathode materials have been tested for short runs, however, most experiments have been performed with a carbon felt cathode due to superior turn on and beam uniformity characteristics. More careful consideration will be given to the new cathode materials after the initial trials and characterization of the RHEPP accelerator have been completed.

Comparisons of scanning electron beam micrographs of samples of carbon fibers from the cathode and from unused carbon felt indicate that emission may be from nodules on the sides of the fibers. The fibers showed a greater density of nodules after use as a cathode than in the unused material. Visible damage was evident on some small localized areas of the cathode; the nodules were eroded away and the fiber tips were melted as a result of emission current flow. A radiachromic film scan of the radiation out of the anode indicates a two to one variation in dose from the center to the edge of the beam. This variation is attributed mainly to the bow in the unsupported anode foil that results in a smaller anode-cathode gap at the center of the diode.

In general, the cores in the PFL switch in the proper sequence and at the correct times. The blocking cores in the LIVA are doing a good job of insulating the cavities and transmitting the pulse. There has been no evidence of arcing or core degradation. Voltage probes in the oil adder section of the LIVA indicate that the cavity voltages are adding up as they should. During the 25,000 shot run, the diode voltage had a variation of less than 10%, as shown by the twelve shot overlay in Fig. 6.

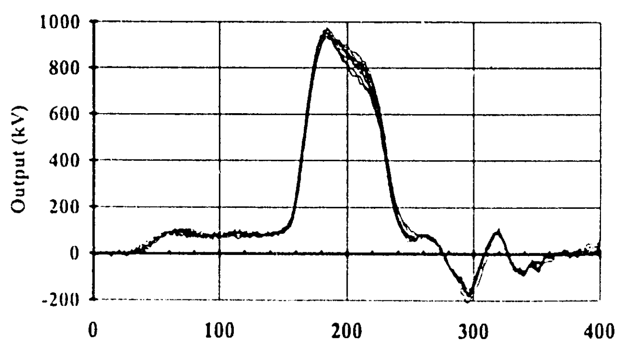

Fig. 6. Twelve shot overlay of the diode voltage, spanning 10,000 shots.

The energy delivered to the load was 850 J/pulse at a repetition rate of 2.5 Hz, corresponding to an average power of 2.1 kW. In light of the fact that the machine, as driven by the Marx, is only operating at $1/48^{th}$ of the normal repetition rate, the charge voltage obtainable from the Marx is 16% lower than will be achieved from the 1-μs pulse compressor, and the 1-MV LIVA only uses 20 of the 50 cables that the 2.5-MV LIVA will use from the PFL, an output power of 350 kW is expected from the 2.5-MV machine. The measured efficiencies of the components are within experimental error of the values predicted by the modeling and are summarized in Table 1.

Table 1. Measured versus Predicted Efficiencies

Component	Predicted Efficiency	Measured Efficiency
PFL	90%	95±10%
LIVA	80%	80±10%
OVERALL	72%	76±20%

During initial series of short runs with the RHEPP machine, the biases to the PFL and LIVA were varied to determine the minimum levels required to obtain stable operation. The experiments showed that 20 amps of bias on the PFL is sufficient and that no bias is required for the LIVA. We expected that only a small bias would be required for the PFL cores since they are made from box annealed 2605CO Metglas. Very few ampere-turns are required to push the quiescent operating point past the sharp knee on the B-H loop. We are certain, however, that some bias is required for the PFL, and due to uncertainty as to where the energy would go if the bias were insufficient, no attempt has been made at this time to find the minimum bias required. From the modeling of the LIVA, the possibility that no bias would be required was anticipated. The DC B-H loop for the 2605-TCA Metglas used in the LIVA cores is so rounded and laid over that the remanent magnetic induction is nearly at the origin. Thus, if sufficient time is allowed between pulses for the transients to die away, the operating points of the LIVA cores naturally return to very near the origin before the next pulse. In view of this, the cores were designed so that the flux swing of 1 T would be below the saturation point of the core of >1.4 T. The fact that very little bias is required for the PFL and no bias is required for the LIVA represents an enormous simplification of the hardware with concomitant savings in cost and efficiency.

A variety of loads have been tested on the 1-MV LIVA including a 35-Ω resistive load, an ion diode [15] and an electron beam diode. The goal of the electron diode experiments is to determine a technology that exhibits fast turn on, <10-ns, long life, $>10^8$ shots, and a uniform beam profile. The electron beam diodes tested to date have used flat and hemispherical graphite, carbon felt, porous silicon, tungsten and velvet cathodes. Cathodes using (111) diamond, (111) silicon, gated Spindt type, and ferroelectrics are slated for future investigations. The preliminary experiments have used unsupported 0.2 mm and 0.25 mm titanium anode foils with water coolant impinging normally on the center from the back side. A magnetically insulated transmission line (MITL) extension has been built and tested on the 1-MV LIVA to determine how magnetic insulation works in the repetitive mode. The use of a MITL in the central transmission line of the 2.5-MV LIVA is important for size, cost, and efficiency considerations.

Summary

Initial tests of the four stage 1-MV RHEPP system using a 5-Hz Marx generator as the prime power source indicate that the machine is performing as expected. Measured waveforms are in good agreement with those predicted by the design models. The measured efficiencies of the components are within the error bars of the expected efficiencies. The 20-ns risetime of the output pulse is greater than the expected 16 ns due to a smaller realized ∫vdt product in the PFL output switch than was planned for in the design. Simulations indicate, however, that increasing the ∫vdt product would restore the output risetime to the expected value. Experiments show that 20 amps is sufficient to bias the PFL and no bias is required for the LIVA, resulting in a significant hardware cost savings and some gains with respect to system efficiency. During repetitive runs, a shot to shot voltage variation on the load of less than 10% was obtained. The 25,000 shot continuous repetitively pulsed run was not sufficient to raise the temperatures in the cores enough to provide a good comparison to the expected values. The components for the full scale 2.5-MV machine have been manufactured and are currently being assembled with planned completion in December of 1993.

References

[1] Metglas Products, 6 Eastmans Road, Parsippany, NJ 07054, (201) 581-7700.

[2] C. R. McClenahan, L. E. Martinez, G. E. Peña, G. J. Weber, "Repetitive, Electron-Beam Diode Development", 9th IEEE International Pulsed Power Conference, Albuquerque, NM, June, 1993.

[3] R. M. Calfo, D. J. Scott and D. W. Scherbarth, "Design and Test of a Continuous Duty Pulsed AC Generator", Proceedings 8th IEEE Pulsed Power Conference, pp. 715-718, June, 1991, San Diego, Ca.

[4] H. C. Harjes, et. al., "The Repetitive High Energy Pulsed Power Module", Proceedings of the 19th Power Modulator Symposium, pp. 168-173, June 1990, San Diego, Ca.

[5] W. S. Melville, "The use of Saturable Reactors as Discharge Devices for Pulse Generators", Proceedings, Institute of Electrical Engineers, London England, Vol. 98, pt. 3, pp. 185-207.

[6] H. C. Harjes, et al., "Status of the Repetitive High Energy Pulsed Power Project", 8th IEEE International Pulsed Power Conference, San Diego, Ca., pp. 543-548, June, 1991.

[7] Pavlic, D., et al., "Detailed Analysis and Physical Design of a 254 kV, 600 kW Continuous Duty Pulse Transformer," Proceedings of the 8th IEEE Pulsed Power Conference, San Diego, CA, pp. 232-236.

[8] R. W. Wavrik, et al., "Thermal Management in High Average Power Pulsed Compression Systems", Conference Record of the 1992 Twentieth Power Modulator Symposium, pp. 223-226, June, 1992, Myrtle Beach, SC.

[9] MicroSim Corp., 20 Fairbanks, Irvine, California 92718, (714) 770-3022.

[10] C. H. Smith, "Magnetic Pulse Compression by Metallic Glasses", J. Appl. Phys. 64(10), pp. 6032-6034, November 1988.

[11] C. H. Smith, private communication.

[12] H. C. Harjes, private communication

[13] The MacNeal-Schwendler Corp, Electromagnetic Applications, 4300 Brown Deer Road, Suite 300, Milwaukee, WI 53223-2465, (414) 357-8723.

[14] H. C. Harjes, et. al., "Characterization of the RHEPP 1 μs Magnetic Pulse Compression Module", 9th IEEE International Pulsed Power Conference, Albuquerque, NM, June, 1993.

[15] R. W. Stinnett, "The Use of Pulsed, Intense Ion Beams for Thermal Surface Treatment", Twentieth IEEE International Conference on Plasma Science, Vancouver, B. C., Canada, June 1993.

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