CONF-961110--1

SAN096-2350C
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REPETITIVE HIGH ENERGY PULSED POWER TECHNOLOGY DEVELOPMENT FOR INDUSTRIAL APPLICATIONS

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The technology base for Repetitive High Energy Pulsed Power (RHEPP) was originally developed to support defense program applications. As RHEPP technology matures, its potential for use in commercial applications can be explored based on inherent strengths of high average power, high dose rate, cost efficient scaling with power, and potential for long life performance. The 300 kW, 2 MeV RHEPP II accelerator is now in operation as a designated DOE User Facility, exploring applications where high dose-rate (>10^8 Gy/s) may be advantageous, or very high average power is needed to meet throughput requirements. Material surface and bulk property modification, food safety, and large-scale timber disinfestation are applications presently under development. Work is also in progress to generate the reliability database required for the design of 2nd generation systems.

INTRODUCTION

The pulsed power science base developed for defense applications in the 1980's supported a broad spectrum of applications from laser drivers and weapons effects simulators to inertial confinement fusion accelerators (1). From this historical base, RHEPP technology development continues in support of Department of Energy (DOE) funded Defense Program applications and potential industrial applications funded through Cooperative Research and Development Agreements (CRADA's) or DOE User Facility Agreements.

Industrial uses for accelerator technologies span a wide range of applications (2,3,4). RHEPP technology development is focused in areas requiring repetitive, short-pulse, large-area beams; very high average power electron beam (100's of kW) or x-ray outputs, or where high dose rates (>10^8 Gy/sec) may be advantageous over commercially available DC or RF accelerator technologies. Magnetic switching, a key component in RHEPP technology, can also produce multi-kilojoule pulses at 100's of pulses per second (pps) rates, enabling applications not easily serviced by conventional switching technologies. Combining these features with a capability to scale cost effectively to megawatt level systems, RHEPP represents a credible building block for high power industrial applications.

RHEPP TECHNOLOGY DEVELOPMENT

RHEPP II, shown in Figure 1, has demonstrated the proof-of-principle capabilities of magnetic switching, repetitive Linear Induction Voltage Adders (LIVA), and field emission cathode technology to develop electron beams with very high average power at a nominal accelerator efficiency of 50%.

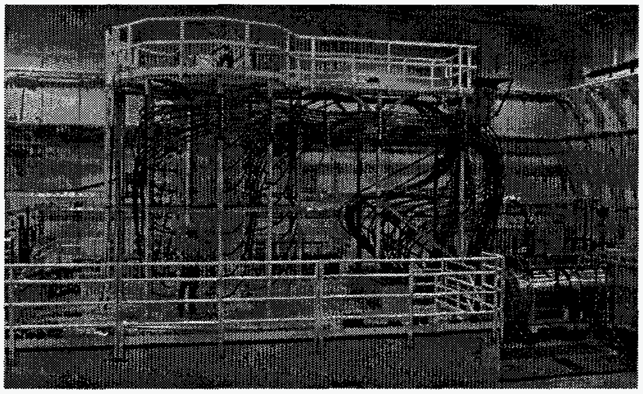


FIGURE 1. 300 kW, 2 MeV RHEPP II accelerator. 220 kV pulses from a magnetically switched Pulse Forming Line (PFL) are cabled to the vertical 10-stage Linear Induction Voltage Adder (LIVA).

A near-term transition to a robust and cost effective industrial technology base will require more than operational experience with the high power RHEPP II accelerator. Initial capital expenses, operating costs, and other life cycle costs will need to be minimized. This requires optimization of circuit topologies and components to reduce capital costs, and improved mechanical packaging for ease of manufacturing, assembly, and maintenance. Establishing design guidelines for long lifetime components also requires the near-term development of a reliability database on the high voltage and high current components used in this technology. It would be impractical and expensive to address these objectives at the RHEPP II facility. Smaller scale modulators such as Sandia's Dos Lineas accelerators, shown in Figure 2, are now available to optimize system components and develop critical reliability data.

The 250 kV, 20 kW magnetic modulator pair has already demonstrated synchronization techniques which would allow

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000

the parallel operation of multiple modulator systems to drive a common voltage adder or other voltage transformation devices such as linear induction accelerators (5). Steady-state operation at 10 kW output per modulator is possible and burst-rates to 1kHz will be explored to evaluate limitations of core reset circuits, magnetic switch cooling, and SCR switching technologies. Based on initial testing on Dos Lineas, magnetic compression circuits, such as RHEPP II, should be capable of achieving operation in the few hundred pulse per second regime. At 400 Hz, for example, RHEPP II would be capable of > 1MW performance.

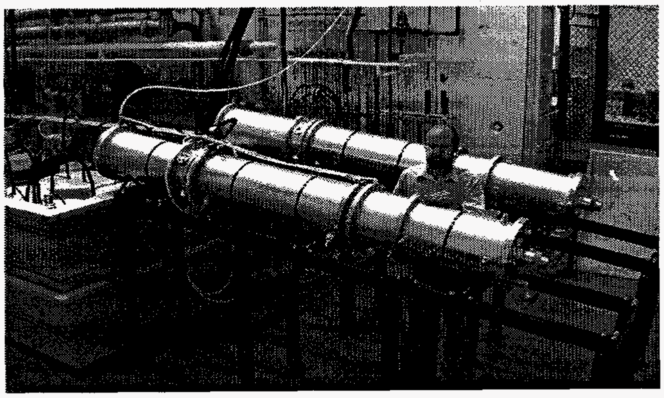


Figure 2. Dos Lineas modulators. This flexible testbed will develop reliability data on high voltage components and explore next generation circuit topologies and new concepts.

RHEPP II Characterization and Testing

Figure 3 shows RHEPP II accelerator circuit components, including the LIVA, PFL, and micro-second pulse compressor. The micro-second compressor reduces the pulse duration from approximately 5 ms at 15 kV, to 1.2 μs at 250 kV peak. The 250 kV, 0.88 Ω magnetically switched Blumlein PFL, shown in Figure 4, compresses from 1.2 μs down to an output pulse width of 60 ns (FWHM).

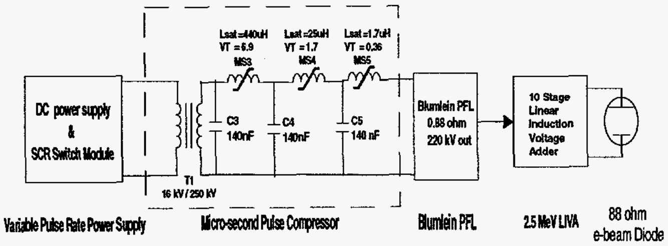


Figure 3. RHEPP II accelerator circuit.

During the design of RHEPP II, two high risk components were identified. There had been no previous experience with repetitive, magnetically insulated induction voltage adders, or with the type of high-current high-voltage cathode required for high average power operation.

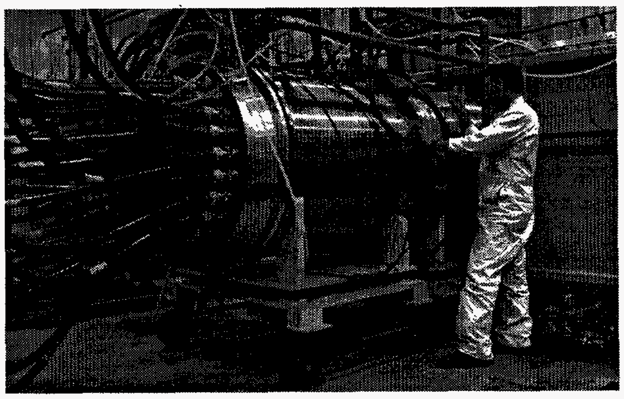


Figure 4. 420 kW Blumlein PFL shown with 220 kV output cables.

During repetitive operation, the RHEPP II LIVA operates with low losses and is extremely reproducible from pulse to pulse. Normalized LIVA output voltage and diode current are shown in Figure 5.

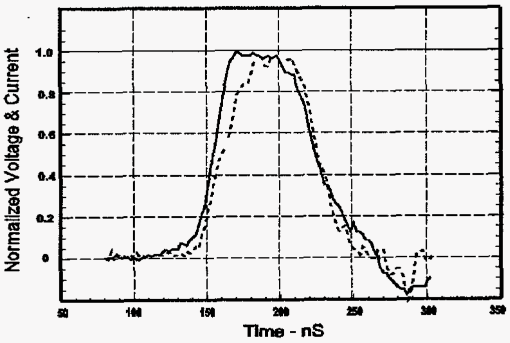


Figure 5. RHEPP II's nominial 2.2 MeV output voltage (solid-line) and 25 kA diode current (dashed-line).

The 1000 cm^2 cathode surface, developed under contract with the Institute of High Current Electronics (IHCE) in Tomsk, Russia, has shown no signs of physical damage at greater than 10^6 shots. This is consistent with results from IHCE where greater than 10^8 shots at similar current densities have been demonstrated without significant damage. The 1000 cm^2 cathode surface can be easily replaced from low-cost, commercially available metal stock when necessary. The electrical performance of the diode has been consistent with 2-D particle-in-cell simulations used during the design of this device. Current turn-on occurs in less than 10 ns, electron emission is uniform across the cathode, and the operating impedance is well matched to the 88 Ω source impedance of the pulsed power system.

Per pulse beam energy was measured at 2.55 kJ (+8/-2 % accuracy) using calorimetry. Based on the energy stored in the first stage of the accelerator, the pulse compression network is 58 ± 5% efficient at the output of the Blumlein PFL. The LIVA is >80 % efficient and delivers approximately 2.9 kJ to the diode load. From initial stored energy in the accelerator to beam output energy, RHEPP II is approximately 45 % efficient. In an optimized system, input energy to beam energy efficiency of 50% is achievable.

The micro-second pulse compressor has demonstrated surprising robustness during several mechanically initiated electrical faults and inadvertent short circuit operation. Unlike thyristor and thyratron switching technologies, magnetic switches have the ability to tolerate severe over-voltage and over-current fault modes without damage.

The RHEPP II accelerator facility is now operational as a DOE User Facility, allowing non-DOE personnel access to the accelerator facility for applications development on a full-cost recovery basis. Use of the facility is also possible through CRADA's.

RHEPP PERFORMANCE CAPABILITIES AND COST SCALING

RHEPP technology can produce high energy and high voltage pulses at sustainable rates from a few to hundreds of pps. Conventional switching technologies (thyratrons, thyristors, vacuum tube devices, spark gaps, etc.) are typically limited in terms of rate of rise of current (di/dt), peak current, voltage hold-off capability, pulse repetition rate, or average power rating (6). Magnetic switching is capable of >10 MA/us di/dt, 100's of kA peak current, 100's of kV hold-off, and average power ratings approaching 1 MW per switch. Several kilojoules per pulse can also be switched repetitively with reasonable size magnetic cores. Combining these magnetic switching capabilities with the high voltage and high power capabilities of LIVA's creates a unique high power technology.

RHEPP technology is based on stages of power compression. Energy is typically stored in a capacitance and transferred via switches to subsequent stages with progressively lower circuit inductance. Figure 6 shows a typical two stage Melville magnetic pulse compression circuit with a power gain of 5.0.

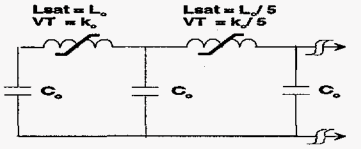


Figure 6. Two stage magnetic pulse compression circuit with a gain of 5 in power compression.

The design of magnetic switches is primarily governed by requirements for energy per pulse (E_{pulse}), switch withstand voltage, and time to peak voltage. The physical design of the switch is largely independent of the average power rating. Average power in repetitive pulsed circuits is generated by increasing the number of pulses per second, and can be expressed as;

$$P_{ave} = f\,E_{pulse} \tag{1}$$

where f is the pps rate. The required volume of magnetic core material for a given switch design, Vol_{mag}, is equal to;

$$Vol_{mag} = \frac{\mu\, k}{\Delta B^2}\,\frac{C_o V_o^2}{2}\,G^2 \propto E_{pulse}\,G^2 \tag{2}$$

where G is the stage gain, k a scale factor depending on the geometry of the core and windings, C_o the stage capacitance, V_o the peak stage voltage, and ΔB the available change in flux density in the magnetic core material.

The size and cost of the magnetic switches is governed primarily by per pulse energy requirements, not average power. This is a key factor is the ability of RHEPP technology to scale cost effectively to very high average power levels. Megawatt level systems are possible due to this characteristic of magnetic switching.

RHEPP Scaling With Output Voltage

In applications requiring electron beams or x-rays, RHEPP technology does have practical limitations in its ability to scale to higher voltages in a cost effective manner. The diode and magnetically insulated LIVA technology used in RHEPP II are limited in operation to impedances up to approximately 100-150Ω. This constrains the energy per pulse of a given accelerator design, and thus the size and cost of switching components. RHEPP II operates at approximately 2 MV, 25 kA, at a pulse width of 60 ns. The output energy per pulse is approximately;

$$E_{pulse} = V_L\, I_d\, t_p \cong 2.7 \text{ kJ} \tag{3}$$

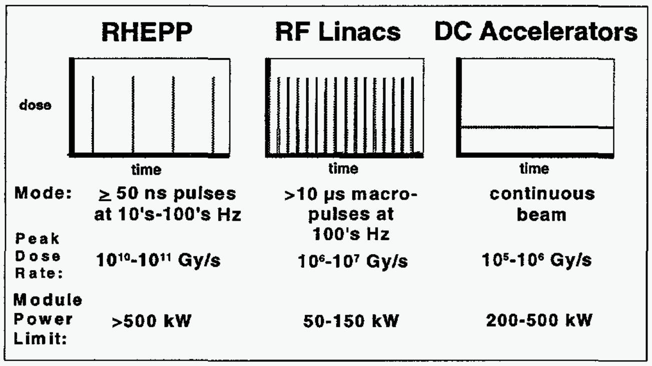
where V_L is the LIVA output voltage, I_d is the diode current, and t_p is the output pulse width. Magnetic core material in RHEPP systems constitutes approximately 1/3 the total cost of the accelerator system. As output voltage requirements increase, the total switch core volume in the accelerator, and cost, increase as;

$$\sum Vol_{mag} \propto V_L^2\, t_p / Z_d \tag{4}$$

where Z_d is the diode impedance. Reducing the pulse width below approximately 60 ns is not practical for most applications. RHEPP based systems using LIVA and flashover diode technology are probably limited to $\leq$ 5 MeV operation. Several commercial technologies are available for applications above 5 MeV, including RF linacs produced by Titan-Beta (USA), IMPELA (Canada), MeV Industrie (France), and a recirculating beam accelerator manufactured by Ion Beam Applications (Belgium) (7).

INDUSTRIAL APPLICATIONS

RHEPP technology has unique characteristics when compared to existing commercial technologies, as shown in Figure 7, and very well suited to applications requiring high average power and high dose-rate. The short-pulse, high-energy capabilities of RHEPP technology, combined with Magnetically insulated Anode Plasma (MAP) diode technology, enables a new commercial technology called Ion BEam Surface Treatment (IBEST) (8,9).



	RHEPP	RF Linacs	DC Accelerators
dose	time	time	time
Mode:	≥ 50 ns pulses at 10's-100's Hz	>10 μs macro-pulses at 100's Hz	continuous beam
Peak Dose Rate:	10^{10}-10^{11} Gy/s	10^{6}-10^{7} Gy/s	10^{5}-10^{6} Gy/s
Module Power Limit:	>500 kW	50-150 kW	200-500 kW

Figure 7. RHEPP e-beam characteristics in comparison to commercial accelerator technologies.

IBEST technology uses repetitive pulsed ion beams to deposit energy on the surface of materials. Efficient deposition in a 1-20 μm surface layer allows melting with relatively low energies (1-10 J/cm^2), and rapid cooling into the material substrate at rates as high as 10^9 °K/sec. The rapid resolidifacation leads to the formation of amorphous layers and non-equilibrium microstructures which improve surface hardness, wear, and corrosion resistance. This is an ideal application of RHEPP technology due to the relatively high energy per pulse and lower voltage requirement which precludes the use of a several stage LIVA. Figure 8 shows a preliminary design of a 450 kV, 150 ns, 20 kW modulator system for commercial IBEST applications. Sandia is supporting the development of this commercial system under a CRADA with QM Technologies, Inc., based in Albuquerque, NM.

Application of RHEPP technology to the large-scale disinfestation of Russian timber is being explored through a CRADA with the United States Industrial Coalition. Sandia National Laboratories, RAIES International Corp., and Russia's Khoplin Radium Institute and Ministry of Atomic Physics will jointly evaluate RHEPP for use in Russian log irradiation facilities. Irradiation treatment of timber imported into the USA is strictly regulated for threats such as insects, fungi, and nematodes. X-ray irradiation will be required to produce dose levels of 0.5-2 kG in the 30 cm diameter logs. Megawatt level accelerator systems will be needed at each processing facility.

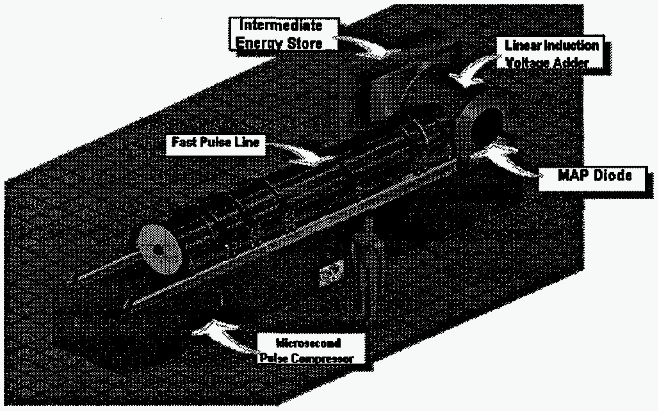


Figure 8. QM Technologies^{SM} QM-1 accelerator for IBEST applications development.

Although initial facilities will use Co^{60} in this application, there is not a sufficient and stable world supply to expand to multiple irradiation facilities.

SUMMARY

RHEPP technology development continues in support of commercial applications such as Ion Beam Surface Treatment and high throughput processes requiring high average power or high dose-rate. The development of 2nd generation systems is underway with a focus on reducing life cycle costs and characterizing component reliability.

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