High Average Power, High Current Pulsed Accelerator Technology

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I. ABSTRACT

High current pulsed accelerator technology was developed during the late 60's through the late 80's to satisfy the needs of various military related applications such as effects simulators, particle beam devices, free electron lasers, and as drivers for Inertial Confinement Fusion devices. The emphasis in these devices is to achieve very high peak power levels, with pulse lengths on the order of a few 10's of nanoseconds, peak currents of up to 10's of MA, and accelerating potentials of up to 10's of MV. New high average power systems, incorporating thermal management techniques, are enabling the potential use of high peak power technology in a number of diverse industrial application areas such as materials processing, food processing, stack gas cleanup, and the destruction of organic contaminants. These systems employ semiconductor and saturable magnetic switches to achieve short pulse durations that can then be added to efficiently give MV accelerating potentials while delivering average power levels of a few 100's of kilowatts to perhaps many megawatts. The Repetitive High Energy Puled Power project is developing short-pulse, high current accelerator technology capable of generating beams with kJ's of energy per pulse delivered to areas of 1000 cm^2 or more using ions, electrons, or x-rays. Modular technology is employed to meet the needs of a variety of applications requiring from 100's of kV to MV's and from 10's to 100's of kA. Modest repetition rates, up to a few 100's of pulses per second (PPS), allow these machines to deliver average currents on the order of a few 100's of mA. The design and operation of the second generation 300 kW RHEPP-II machine, now being brought on-line to operate at 2.5 MV, 25 kA, and 100 PPS will be described in detail as one example of the new high average power, high current pulsed accelerator technology.

II. TECHNOLOGY INTRODUCTION

The very high peak power, single-pulse accelerators developed during the early 60's through the present were designed to simulate weapons effects (HERMES-III [1], DECADE [2]) or as drivers for the Inertial Confinement Fusion program (PBFA-I [3], PBFA-II [4]) or to power beam devices (ATA and ETA-I [5]). The development and commercial availability of METGLAS® alloys during the early 80's allowed the development of a new class of high average power accelerator that is capable of efficient repetitive operation up to 10^4 PPS[6] using semiconductors, thyratrons, and saturable core magnetic switches. The saturable switches were employed in the ETA-II [7] accelerator, were investigated for use on PBFA-II [8], and are now employed in current high average power systems. The Physics International Company CLIA accelerator [9] is capable of high power short burst mode output, to 120 kW. The short-pulse systems, by incorporating thermal management techniques [10], can run continuously as demonstrated by the Science Research Laboratories SNOMAD-IV operating at 38 kW [11], the Sandia RHEPP-I operating at 120 kW [12] and RHEPP-II at about 240 kW [13]. Application development can follow the availability of new tools, such as the high current pulsed accererators, and these high-power systems are beginning to generate new fields of commercial interest. This paper discusses some of the application issues that are driving the development of short-pulse, high current machines and the modular technology approach taken in the development of the RHEPP systems.

III. IDENTIFICATION OF SHORT-PULSE APPLICATION REQUIREMENTS

Short-pulse, high peak power technology was developed to address specific military single-pulse threats and involves a number of stages of pulse compression to deliver the 10's of nanosecond wide output pulses. Short-pulse, high average power accelerators, with their unique capabilities, are, in general, more complex than other high voltage, high average power technologies such as the DC Dynamitron machines from Radiation Dynamics Inc. [14], the North Star Research Corp. Nested High Voltage Generator (also having pulsed output capabilities) [15], or the ELV series of accelerators from the Former Soviet Union (FSU)[16]. The new short-pulse machines, with kJ's of energy per pulse, also have capabilities that are distinct from those provided by high power RF machines such as the Atomic Energy Canada Ltd. IMPELA [17] or the Ion Beam Applications Rhodotron [18]. These presently available technologies, including the pulsed SNOMAD-IV accelerator, rely on output beams, at 1000 A or less, that are a few millimeters in diameter and are scanned across the product under treatment. The high current accelerators delivering 10's of kA per pulse, with kJ's of beam pulse energy, offer the possibility of treating 100's to 1000's of square centimeters per pulse, without beam scanning, depending on the energy per unit volume required by the target to achieve the desired internal effects. The required beam accelerating potential, for any of the above systems, is set by the desired energy penetration in the target material. The beam penetration sets the dose uniformity in the target. To offset the cost of the pulse compression stages in the short-pulse, high average power, high current machines, applications must be identified that require some combination of 1) high volume or mass throughput, 2) very high dose levels, 3) high dose rates, 4) large area uniform beams, 5) radiochemistry enhanced by short pulses, and 6) short pulses of energy to allow unique non-equilibrium material conditions. Short-pulse applications, in general, are non-thermal processes such that the temperature of the bulk treated material does go much above ambient conditions. A number of Ion Beam Surface Treatment (IBEST) [(19)] applications are processes that offer increased surface hardness, surface smoothing, increased corrosion resistance, specifically because of the short energy deposition and melt times followed by rapid resolidification through thermal diffusion into the base material. Continuous commercial applications of IBEST technology to treat polymers and metals will require simple and reliable short-pulse repetitive driver systems operating at 100's of kW. Some organic chemical decomposition processes can be enhanced by using short pulses with high dose rates and large total dose [(20)]. Current application development efforts are focusing on identifying and demonstrating basic processes that can be expected to improve when using the short-pulse beam technology.

IV. HIGH POWER, HIGH CURRENT SYSTEM CONSIDERATIONS

High peak power capabilities were achieved by combining very high voltages, to 20 million volts[(2)], with very high current handling capabilities, to 30 million amperes [(4)]. High voltage operation was made possible by using the increase of dielectric strength of various materials and interfaces that occurs when using sub-microsecond pulses [(21)]. Pulses, with a FWHM of a few 10's of nanoseconds can be added together in transmission line structures, with or without magnetic blocking cores [(22)], to efficiently achieve higher voltages in more compact structures than are possible with directly switched compression schemes.

A. High average power switching techniques

The required pulse compression in the high peak power accelerators is achieved by employing switching techniques in the pulse compression stages based on plasma formation, or control, between metal electrodes either in a vacuum or immersed in a gas or liquid insulant. These switching techniques, while suitable for single pulse or low repetition rate systems are difficult to use in very high average power systems because the energy deposited in the insulant during the transition from high-to-low impedance results in electrode damage and erosion. Saturable core magnetic sxwitches, first proposed for use in pulse compression lines by Melville [(22)], became an economically viable replacement for plasma switches with the development of the METGLAS® alloys by AlliedSignal in the early 80's. A prototype magnetic switch that operates at 500 kW in the RHEPP system is shown in Figure 1 with oil cooling manifolds.

Figure 1. Fifth stage RHEPP 250 kV magnetic switch, with oil cooling manifold

The energy lost during each switching cycle, which requires the addition of cooling, is held to about 1% in the windings plus another 1% in the alloy core. While the switch of Figure 1 does compression on the microsecond time scale, similarly wound magnetic switch cores are employed in a coaxial geometry to produce the 60 ns FWHM pulse forming line output pulses at 250 kV, 130 kA, and 350 kW. The simplicity of the basic switch design combined with the low energy losses during switching, allow such devices to pass currents greater than 1 MA [8] without difficulty. Magnetic switch volume can be shown to be proportional to pulse energy, but practical considerations limit the operating voltage while operating currents and pulse risetimes are limited by circuit impedances.

B. High average power voltage multiplication

The high pulse current capabilities of magnetic switches can be combined with high-current linear induction voltage adder (LIVA) technology that has demonstrated operation up to 20 MV and 700 kA in HERMES-III [2]. The basic adder geometry has been described elsewhere. The central transmission line may be oil insulated as in the RHEPP-I accelerator, as a magnetically insulated transmission line (MITL) when fields are sufficient to cause electron emission, or as a vacuum insulated line when fields are at or below emission thresholds as in RHEPP-II.

V. RHEPP-II SYSTEM DESIGN AND OPERATION

A. Power compression to the microsecond time scale

The five stage magnetic compressor shown in Figure 2, previously employed on the RHEPP-I system, has been modified to use an SCR switcher between the compressor and a DC charged energy storage capacitor, rather than the fixed 120 Hz, 600 kW Westinghouse alternator used in the previous system [X].

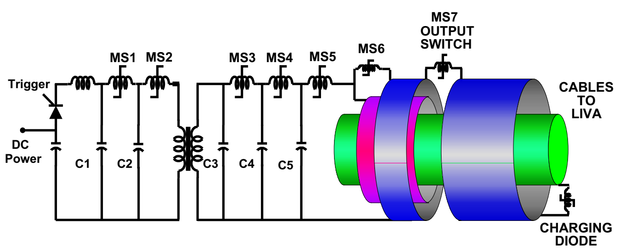

Figure 2. Basic RHEPP pulse compression circuit

This change was dictated by the desire to demonstrate applications on RHEPP-II at a specified pulse repetition rate, specified total number of pulses (burst-mode), and specified total dose. The variable pulse rate also improves the conditioning of the vacuum insulated LIVA transmission line and cathode holder. This 5 stage modulator has a measured energy transfer efficiency of approximately 85%, includes active cooling of all components, and has operated for several hours at full power. All switches are high power semiconductors or tape wound magnetic switches with oil cooling channels. Similarity of construction to capacitors should allow long-life reliable operation, however this has not yet been quantified. The high overall system efficiency minimizes operating costs in commercial applications.

B. Fast Blumlein pulse forming line operation

The 5-stage microsecond compressor charges a magnetically inverted, water-filled coaxial Blumlein pulse forming line (PFL) also shown in Fig. 2. A magnetic switch, MS6 in Fig. 2, inverts the outer transmission line to causing 500 kV to be impressed on the final output switch. The magnetic switch, MS7 in Fig. 2, forms the 60 ns wide output pulse which is delivered by 50 coaxial cables to the 10 stage voltage adder shown in Figure 3.

Figure 3. 2.5 MV RHEPP-II voltage adder

C. 10 stage linear induction voltage adder

Each of the 10 LIVA cavities are fed by five, 44 ohm Dielectric Sciences cables and each cavity delivers a 250 kV pulse through an oil-vacuum insulator to the center transmission line stalk. The center transmission line operates with fields below 300 kV/cm so that it is not expected to operate in the MITL regime, but rather as a vacuum insulated transmission line. Inner and outer wall B-dot measurements indicate that vacuum electron flow is absent after very few pulses. The output of the 10 stage, 80% efficient, voltage adder is approximately 2.3 MV and 25 kA in a 60 ns FWHM pulse at up to 100 PPS, as set by the primary SCR trigger.

D. Broad area e-beam cathode and beam measurements

The design and implementation of a long-life cathode structure capable of emitting 25 kA of current in a 60 ns pulse at repetition rates of up to 120 PPS could pose a difficult problem. Low current RF accelerators or Linear Induction Adders (LIA's) typically use dispenser cathodes, which require good vacuum conditions, to create the very low emittance beams that propagate through the accelerating structure

Figure 4. 10 cm by 100 cm flashover cathode assembly

With the single accelerating gap approach used in the RHEPP machines, field emission cathodes, with simple construction, have demonstrated lifetimes of about 10^8 shots at current densities of about 25 A/cm^2 at the Institute of High Current Electronics in Tomsk, Russia. The Rhepp-II accelerator uses a 10 cm by 100 cm cathode, shown in Fig. 4, that matches the accelerator impedance of 88 ohms with an anode-to-cathode gap of 20 cm.

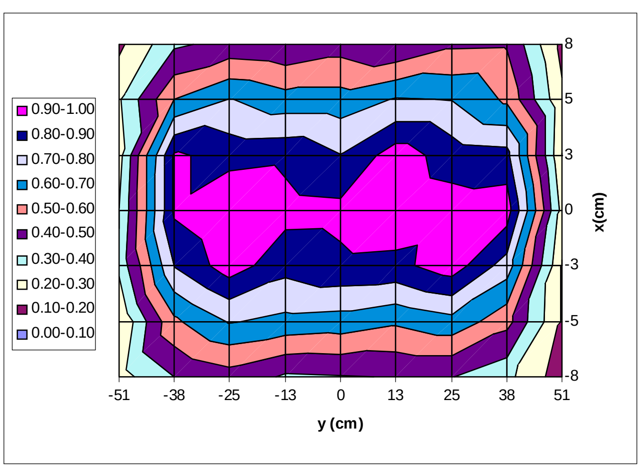

Figure 5. Measured electron beam uniformity 10 cm below the foil window (10% bands)

The preliminary beam uniformity (measured when oil was present in the adder and diode system) is shown in Fig. 5. The measurement were made by an array of 63, 1 cm^2 radiochromic film dosimeters that were located in a plane 10 cm below the 15 mil titanium beam exit window. The dosimeters were mounted in a rectangular beam confinement box, at atmospheric pressure. We are characterizing the operation of this system in both the electron beam and x-ray modes of operation.

E. Operational controls

The RHEPP systems are designed to allow the acquisition of experience necessary to design systems capable of operation in a full scale production plant. The required power operating costs are low due to high system efficiency (50% wall-plug-to-beam). To reduce manpower costs, we have simplifyied and integrated operational aspects around low cost Programmable Logic Controllers (PLC's) which use simple commands from a touch screen panel to set all accelerator operating parameters. This aspect of the accelerator implementation is still in the early stages of development but we are already experiencing the benefits provided by this approach.

Figure 6. Programmable Logic Controller operational center for the RHEPP-II system

VI. CONCLUSION

The high average power, high current pulsed accelerator technology development, as represented by the RHEPP machines, offers new opportunities in commercial applications. The short pulses can deposit energy in specific product volumes by using large area beams of ions, electrons, or x-rays without raising the temperature of the bulk material. This non-thermal deposition gives rise to high overall system efficiencies because only the desired effects are targeted by the beam. Ion beam treatment of surfaces is one example where short pulses can cause rapid melting and re-solidification for increased hardness, corrosion etc. Recent demonstrations, at greater than 200 kW average power and 2.5 MV on the RHEPP-II accelerator, offer exciting possibilities for industrial application developments.

VII. ACKNOWLEDGMENTS

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