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A PULSE POWER MODULATOR SYSTEM
FOR COMMERCIAL HIGH POWER ION BEAM SURFACE TREATMENT APPLICATIONS

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Abstract

The Ion Beam Surface Treatment (IBEST™) process utilizes high energy pulsed ion beams to deposit energy onto the surface of a material allowing near instantaneous melting of the surface layer. The melted layer typically re-solidifies at a very rapid rate which forms a homogenous, fine-grained structure on the surface of the material resulting in significantly improved surface characteristics.

In order to commercialize the IBEST™ process, a reliable and easy-to-operate modulator system has been developed. The QM-1 modulator is a thyratron-switched five-stage magnetic pulse compression network which drives a two-stage linear induction adder. The adder provides 400 kV, 150 ns FWHM pulses at a maximum repetition rate of 10 pps for the acceleration of the ion beam.

Special emphasis has been placed upon developing the modulator system to be consistent with long-life commercial service.

I. INTRODUCTION

The mission of QM Technologies is the commercialization of Ion BEam Surface Treatment (IBEST™) processes for a variety of applications. The IBEST™ process uses a high energy, pulsed ion beam to rapidly deposit energy onto the surface of a material [1]. This results in the near instantaneous melting of the surface. Thermal diffusion into the bulk of the material provides surface cooling at a rate on the order of 10^9 degrees per second. Re-solidification at such a rate results in a fine-grained, homogenous structure being formed on the surface which typically exhibits improved corrosion, hardness and wear characteristics.

The first commercial IBEST™ facility, QM-1, has been operational for about 18 months. In the QM-1 facility, an ion diode provides a plasma from which the ion beam is extracted. Beam extraction takes place when an accelerating voltage pulse, provided by the QM-1 modulator system, is placed across the anode-cathode (A-K) gap of the diode. The operating parameters of the modulator system as seen across the A-K gap of the diode are listed in Table 1.

Table 1
QM-1 modulator system parameters
as seen across the A-K gap of the ion diode

Parameter	Value
Nominal output voltage	400 kV
Pulsewidth (FWHM)	150 ns
Output impedance	10 Ω
Pulse energy	2400 J
10-90% risetime	30 ns
Maximum repetition rate	10 pps

The QM-1 modulator system has been designed to be consistent with commercial service including high reliability and simplicity of operation.

II. MODULATOR SYSTEM DESIGN

Early in the design of the system, several possible configurations were considered. It was

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decided to base the design of the QM-1 modulator system upon a multi-stage magnetic compression network. This decision was partially based upon that fact that the output parameters proposed for the QM-1 system were similar to those of the RHEPP-II facility [2]. In addition, there was a large amount of design and operational experience with a number of other magnetic modulator systems throughout the Pulsed Power Community (for example [3,4]). Such experience proved to be helpful in the design of a reliable modulator for the present application. For example, electric field levels in the QM-1 system were limited to values where reliable operation had previously been achieved. This approach increased the confidence in the reliability of the QM-1 design.

A simplified schematic of the QM-1 modulator system is shown in Fig. 1. A switched-mode power supply charges the IES capacitor Co to a maximum voltage of 30 kV. Co is then discharged through thyratron V1 into the primary of a 1:8 step-up transformer, thus charging C1 to a voltage of about 235 kV over a period of 40 μs as indicated in Fig. 2.

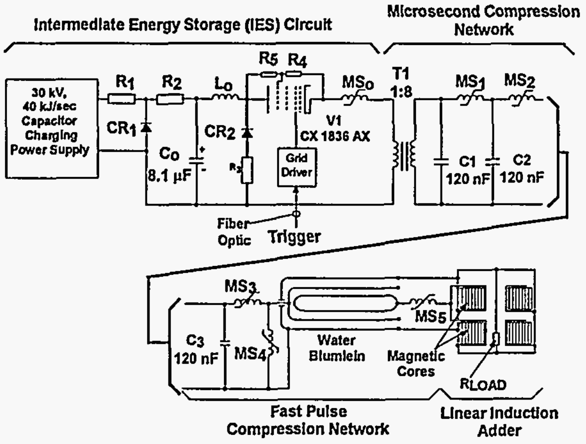

Fig. 1. Simplified schematic of the QM-1 modulator.

As VC1(t) approaches its peak, MS1 saturates and the energy begins its transfer to C2. C2 charges over a period of approximately 10 μs at which point MS2 saturates, transferring the energy to C3 over a period of about 2.5 μs. Near the peak of VC3(t), MS3 saturates and the water Blumlein begins to charge as indicated in Fig. 3. The intermediate conductor of the Blumlein charges to a maximum voltage of 210 kV over a period of 750 ns. As the Blumlein is being charged, MS4 is biased such that it blocks current flow. After the Blumlein is fully charged, MS4 saturates reversing the voltage on the outer portion of the Blumlein over a period of about 380 ns. While the voltage is being reversed, MS5 isolates the output of the Blumlein from the linear induction adder. Once the voltage has fully reversed, MS5 saturates and the Blumlein provides a 200 kV, 150 ns FWHM voltage pulse to the input of the adder assembly.

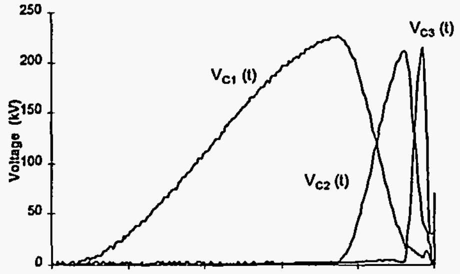

Fig. 2. Voltage waveforms on C1, C2 and C3.

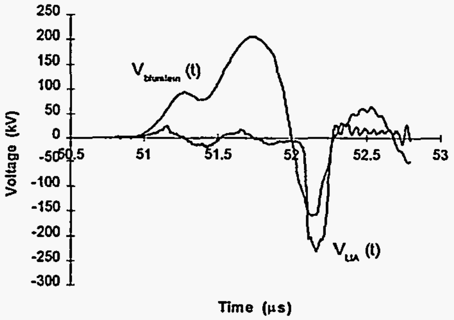

Fig. 3. Voltage waveforms on the Blumlein and the linear induction adder input.

The adder consists of a pair of magnetic cores which are driven by the voltage pulse provided by the Blumlein. Since the anode shank passes through both cores, the voltage across each core is summed, yielding an output voltage of 400 kV as indicated in Fig. 4. The observed risetime and FWHM of the output pulse are approximately 30 and 150 ns respectively. The average amplitude of the output pulse is about 410 kV. The variation on the flat-top is due to impedance variations of the ion diode.

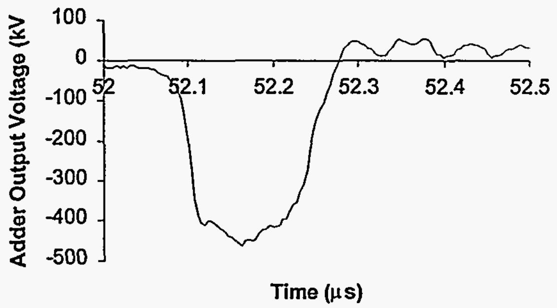

Fig. 4. Typical voltage waveform at the output of the induction adder.

III. PHYSICAL LAYOUT

The layout of the QM-1 modulator system accommodates ease of assembly and maintenance by using a modular approach. This is illustrated in the layout of the microsecond pulse compression network, shown in Fig. 5. Each of the first two compression stages consists of a capacitor assembly and a magnetic switch assembly, both of which are mounted on a common base module. The capacitor assembly consists of an oil-filled canister in which twelve individual capacitors are connected in a parallel combination. The capacitor assembly plugs into the base module that provides the connections between the individual assemblies. Similarly, each magnetic switch is housed within its own oil-filled assembly. Each switch assembly also plugs into its respective base module. Pairs of coaxial cables interconnect the base modules with each other and the fast compression network.

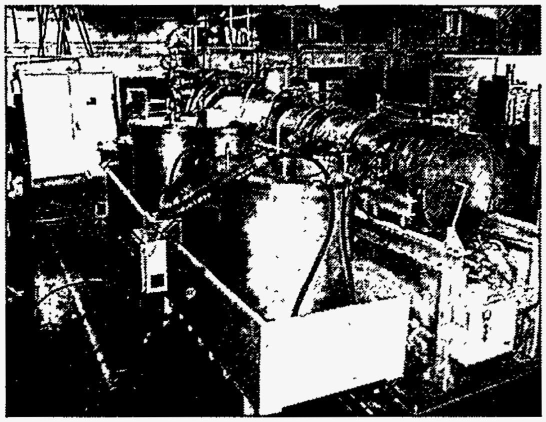

Fig. 5. Photograph of the microsecond compression network.

A view of the fast compression network is shown in Fig. 6. Individual modules mate to one another in a low inductance geometry. The module seen at the furthermost left is the reset isolation inductor for the fast compression network. It is followed by the C3 capacitor and MS3 and MS4 switch assemblies. The MS4 assembly is followed by the Blumlein and finally the MS5 output switch assembly which mates to the input of the linear induction adder assembly.

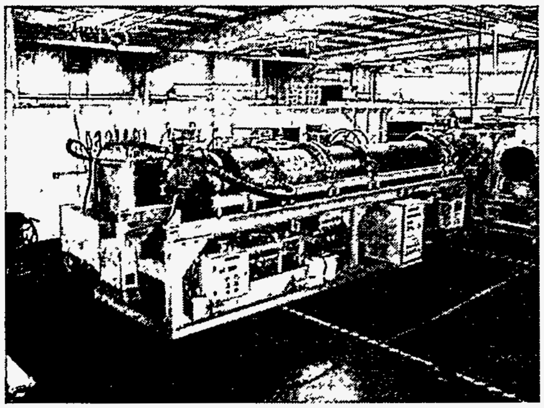

Fig. 6. Photograph of the fast pulse compression network.

Much of the modulator system is filled with oil to provide high voltage insulation and thermal management. Oil is continuously circulated through the assemblies by a oil circulation system situated under the left portion of the fast pulse compression network as seen in Fig. 6. As the oil is circulated, it is continuously filtered, de-aerated and cooled.

De-ionized water, used as in the Blumlein assembly, is provided by a de-ionized water system situated under the Blumlein assembly.

IV. AUTOMATED CONTROL SYSTEM

The QM-1 modulator system is designed to operate from an automated programmable logic controller (PLC) –based system, shown in Fig. 7.

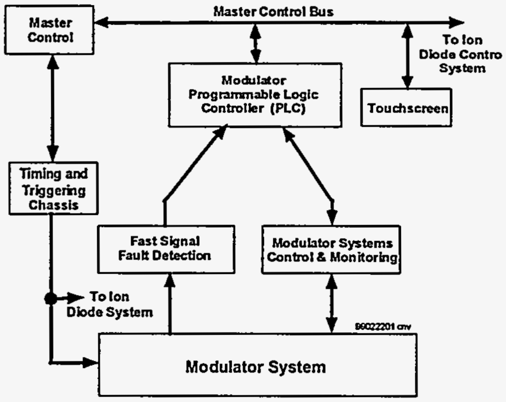

Fig. 7. Simplified block diagram of the control subsystem for the QM-1 modulator system.

The PLC orchestrates and monitors much of the operation of the modulator system. Local control of the modulator is achieved from a touchscreen panel on the modulator control chassis, shown in Fig. 8. From the touchscreen, an operator can control various functions of the modulator system and monitor the status of a number of parameters. The PLC also interfaces with the ion diode control, permitting the operation of the diode system to be coordinated with that of the modulator system. In addition, the PLC provides an interface with an external control system. As such, the operation of the modulator and diode systems can be coordinated with a material handling system which may be required for a specific IBEST™ process.

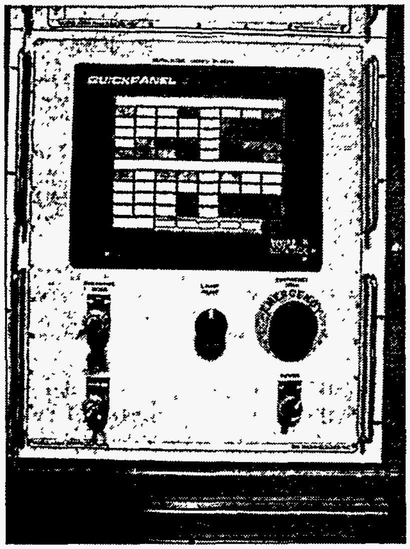

Fig. 8. Photograph of the touchscreen panel for the QM-1 modulator system.

The PLC provides top-level control of three principal control and diagnostic functions in the modulator system. The *modulator control and monitoring function* supervises a number of parameters associated with the subsystems such as oil and water flow, high voltage power supply enable signals and programming levels, etc. In addition, a number of parameters are monitored to determine the operational readiness of the system.

The control system also provides precise *timing and triggering signals* to various portions of the modulator and diode systems. In addition to providing signals to trigger various subsystems, timing signals for diagnostic and data collection are provided.

Finally, evaluation of the operation of the modulator system is achieved by providing a *fast fault detection capability.* A number of waveforms in the system are monitored to determine if they are within an acceptable range. If a waveform is not within the specified range, the control system will inhibit the operation of the modulator and the waveform which is found to be out-of-specification will be indicated.

V. OTHER COMMERCIALIZATION CONSIDERATIONS

The commercialization of the QM-1 modulator system goes well beyond its basic design and implementation. For example, safety constraints imposed on the modulator had to be consistent with those found in typical commercial settings.

Since the operation of the system involves multiple transfers of energy over relatively short time scales, there is opportunity to produce high levels of pulsed electromagnetic interference (EMI). In an effort to mitigate potential EMI problems, good grounding and shielding practices were carefully used.

Finally, a significant effort was committed to developing detailed training, operation and maintenance documentation for the modulator system. This documentation was developed so that the system could be operated and maintained at a nominal level by personnel who may not have had previous experience with pulsed power systems.

VI. OPERATIONAL EXPERIENCE

The QM-1 modulator system has been operational in the first commercial IBEST™ facility for about 18 months. During most of that period, the operation of the modulator system has been involved with the treatment of customer components. Although treatment activities have prevented extensive modulator reliability evaluation, the modulator system has performed very well with only two failures observed. An individual capacitor in the C2 assembly failed. A current contact also failed in the same assembly. In both instances, the situation was addressed in less than four hours after which the system was fully operational once again. As a result, the modulator system has achieved an availability for treatment of 99.74% during the 18 month period. As operation of the modulator system continues over the next year, its reliability will continue to be evaluated.

VII. REFERENCES

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