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SYSTEM DESIGN AND OPERATION OF A 100 KILOVOLT, 2 KILOHERTZ PULSE MODULATOR FOR PLASMA SOURCE ION IMPLANTATION

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ABSTRACT

This paper describes the electrical design and operation of a high power modulator system implemented for the Los Alamos Plasma Source Ion Implantation (PSII) facility. To test the viability of the PSII process for various automotive components, the modulator must accept wide variations of load impedance. Components have varying area and composition which must be processed with different plasmas. Additionally, the load impedance may change by large factors during the typical 20 μ S pulse, due to plasma displacement currents and sheath growth. As a preliminary design to test the system viability for automotive component implantation, suitable for a manufacturing environment, circuit topology must be able to directly scale to high power versions, for increased component throughput. We have chosen an evolutionary design approach with component families of characterized performance, which should result in a reliable modulator system with long component lifetimes.

The modulator utilizes a pair of Litton L-3408 hollow beam amplifier tubes as switching elements in a "hot-deck" configuration. Internal to the main hot deck, an additional pair of planar triode hot decks (hot decks within a hot deck), configured in a totem pole circuit, provide input drive to the L-3408 mod-anodes. The modulator can output over 2 amps average current (at 100 kV) with 1 kW of mod-anode drive. The design features of the L-3408 permit an overall circuit topology that does not require any protective crowbar networks. Diagnostic electronics monitor the load and stops pulses for 100 mS when a load arc occurs. Arc downs may be frequent during the initial implant start-up, possibly due to slight surface contamination (from cutting oils, etc.). A "shoot-through" fault only requires removal of primary AC power.

This paper, in addition to providing detailed engineering design information, will provide operational characteristics and reliability data that direct the design to the higher power, mass production line capable modulators.

MODULATOR PULSE REQUIREMENTS

The plasma sheath dynamics and work piece secondary electron coefficient make for a highly variable load impedance (1). A typical implant current waveform is shown in figure 1, and has 1 μ S risetime. The magnitude would change for different voltages, objects, and ions. In addition, the same object may be implanted with various ions at different voltages, depending on the required process "recipe." If ions could be implanted at one specific

energy, instantaneous rise and fall-times would be required in addition to infinite pulse charging currents. Unfortunately, even if these "ideal" conditions were possible, the ions would still implant with an energy distribution. The ion's mass, proximity to the object, and the object's free space capacitive effects would all contribute to an implant energy distribution. An engineering compromise is desirable that eases rise and fall time requirements and does not significantly impair the implantation properties. Shown in figure 2 is the results of a "PIC" code simulation of implanted energy distribution with various rise-times and a 5 μ S fall. This code includes expanding sheath phenomenon, which results in significantly reduced implant current at the end of the pulse. The slow fall contributes little to the energy distribution because of the limited coulombs in the "tail." There is little difference in implanted energy distribution between the 300 nS and 1 μ S rise. A modulator that provides rise-times in the 1 μ S and fall-times in the 5 μ S regimes eases system design considerably. This reduces system driver power and also helps mitigate output switching noise. The slow fall permits a passive "pull-down," simplifying circuitry and improving reliability. Modulator output ripple (60 Hz) is of little consequence, it does not effect the quality of the implant. This helps to reduce system stored energy and limits coulomb transfer in a fault condition. The Los Alamos modulator utilizes these economies to provide a more reliable system.

Figure 1. Typical Implant Current Waveforms for Different Ion Densities

SYSTEM CONFIGURATION

The Los Alamos modulator system, as shown in figure 3, is a system with modular components. Each sub-system is individually powered and interfaced with fiber optics to the central control room. There are two types of fiber optic signals, slow and fast. The slow I/O signals can directly interface with the programmable logic controller (PLC) and would typically include equipment interlocks, bank monitors, and turn-on and turn-off ladder logic

sequence controls. Fast optics require a special chassis to handle system modulator pulse diagnostics, fast protects, and provide additional interface to the PLC controller. The optics are designed to have a fail-safe abort should a channel malfunction. The vacuum chamber is the system single point ground and the use of fiber optics helps maintain a lower noise topology. Typical I/O to the phase controller is the reference voltage (percent full scale) and the abort command. The abort command inhibits SCR firing and minimizes "follow-on" currents in the event of a "shoot-through" fault. The phase controller is scheduled to replace the present motor driven variac in 8/94. A fast contactor presently inhibits long follow-on currents. A transformer rectifier charges a small filter capacitor assembly rated at the power supplies maximum voltage, 150 kV. A double graded dielectric cable rated at 300 kVDC is used to connect between the filter assembly and modulator oil tank. A corona free bushing in air is used at the filter, an under oil termination is used in the modulator. The modulator internal electronics requires less than 2 kw. Auxiliary power is also required for the oil tank circulation pump, a 3/4 HP motor and the monitor electronics. Ten channels of fiber optic I/O is required between the modulator and the PLC and fast system controller. The output cable is terminated under oil in the modulator and terminated in a special oil filed bushing for the vacuum chamber. There some question in our mind if these hardwares will prove reliable. System rise and fall and appropriate damping ease cable and bushing concerns. However, much work in this area still remains to convincingly prove the reliability of the cable, vacuum feed-through, and cooling feed-through methodologies. In addition, plasma deposition may alter or change the vacuum bushing insulating characteristics. This is also a concern for the cooling feed-throughs used for the implantation object and their platform. The red epoxy bushings which are popular, seem to have thermal coefficients that do not match the metallic inserts, this eventually causes vacuum leaks.

Figure 2. Implanted Ion Energy (keV)

The main hot deck contains a pair of L3408 hollow beam switch tubes that are driven by a pair of 8941 planar triode hot decks in a totem-pole configuration. This topology is electrically efficient and provides excellent noise immunity to the low level electronics, which are completely shielded in each decks enclosure. Other support hardware include the 12 kV "B+" and -1 kV "C" supplies, the equipment safety interlock status monitor, and filament transformers. The main deck assembly is configured as shown in figure 4. The "on" deck has two 8941's, the "off" deck has one. The decks are switched from parallel fiber optic signals that emanate from the control room. The proper phasing is determined by the selection of the appropriate output on the fiber optic receiver board. The 8941's do not require positive grid drive, and the off deck can safely remain on until a light pulse turns it off. This insures appropriate cut-off bias to the L-3408's and bypasses any leakage current to the mod-anode that may occur from insulator (barium) contamination. The hot decks switching and delays are symmetrical with no detectable crossover currents. One result of operating the 8941's without positive grid drive, is that output tube current drops with decreasing plate voltage and causes a slight "roll-over" in switching speed as the tubes near saturation. This is of minor consequence, the non-intercepting mod-anode draws little current and 8941 tube drop is less than 700 volts at full drive. Figure 5 shows the L-3408 mod-anode waveform with the system powered at 95% voltage to facilitate testing in air. The TTL signal (upper trace) drives the fiber optic transmitters and the mod-anode waveform switches between the -1 kV cutoff and +10.4 kV. The plate voltage measured 11 kV for this set-up. Normal plate voltage at 100% system voltage is 12 kV. The mod-anode waveforms show good response, less than 50 nS rise and fall, with no signs of crossover currents which may cause ringing and/or glitches. The whole deck system requires less than 1500 watts to drive the modulator at full output capability, about 250 kW average. The "on" deck requires about 1 kW, the "off" deck about 100 watts. Total filament power is less than 200 watts, 150 watts for both L-3408's and 45 watts for the 3 8941

planar triodes. A system switching power gain is better than 200.

Figure 4. Simplified Block Diagram of Main Hot Deck

Figure 5. Mod-Anode Drive Waveform
8941 DRIVE DECKS

The 8941 drive decks are powered by their associated low capacitance filament transformers. Power for the fiber optic receiver and line driver is rectified directly from the transformer. The 8941 -150 volt cut-off bias is derived from a small filament transformer reverse connected with its' 6.3 volt secondary winding connected to the 8941 filament, also 6.3 volts. This configuration and the transistor grid drivers are shown in figure 6. The fiber optic receiver's output drives a common base amplifier and is buffered with a darlington complementary symmetry output stage. This system has symmetrical delays, rise, and fall times. Total delays from the input to the fiber driver and the output grid driver is in the 50 nS regime, with rise and fall times in the 150 nS regime. Other circuit topologies may be faster, but this application does not warrant the added speed, complexity, expense, and possible resulting loss of reliability. As previously stated, deck phasing is determined by the output selected on the fiber optic receivers' differential line driver. The same drive electronics may be used for both the "on" deck and the "off" deck. Figure 7 shows the 8941 grid drive waveform at 95% system voltage (to facilitate testing in air), and shows switching between 15 volts and -150 volts cut-off. At 100% system voltage, grid drive switches nearly to zero. The conservative design and operation of these tubes should provide many thousands of hours of reliable operation.

Figure 6. Simplified 8941 Drive Deck

Figure 7. 8941 Grid Waveform
SYSTEM PERFORMANCE

The system has been operational from May, 1993, initially with a 60 kV power supply. Programmatic pressures and successes have dictated a delay of complete system upgrades to full 100 kV operations to enable further PSII parameter scans and determination of process envelopes. System upgrades are scheduled late summer Of 1994. However, the operation of the hot deck and modulator systems have been fully qualified at voltage and rep-rate. The vacuum processing chamber requires addition of internal cooling panels and external X-ray shielding. One concern is the vacuum feed-through bushing and output pulse cable. The present output cable has a double graded dielectric and is rated for well over 100+ kVDC, but may overheat at sustained rep-rates due to excessive pulse dielectric losses. Operations at sustained 60 kV rep rates show minimal cable heating. The present vacuum bushing with integral cooling channels is not really suitable for water circulation because of the direct flow paths between the "ground" end and HV end. Cooling water is perferred to oil as it is more benign should a vacuum leak occur. The work pieces and associated platform require cooling to minimize . Any air bubbles and/or eventual coatings with the present bushings short flow channel length may easily cause HV arcs and cause further degradation. The bushing has already had numerous vacuum leaks. The system reliability concerns are probably more related to the vacuum feed-through bushing and output cable, rather than modulator engineering concerns. No doubt, this coming year we will solve the vacuum chamber issues for reliable 100 kV operations. An ion implant waveform at 60 kV, 2 kHz is shown in figure 8. A detail of the implant

voltage pulse shape is shown in figure 9 with a few micro-seconds rise. Modulator testing at a 100 kV input and 2 kHz, with a dummy load, is shown in figure 10. The output is slightly over 90 kV, indicating efficiencies around 90%.

Figure 8. 60 kV Output at 2 kHz

Figure 9. Detail of 60 kV Implant Voltage

Figure 10. 100 kV Input, 90 kV Output at 2 kHz

ANECDOTAL INFORMATION

The author has been continually amazed at the robust nature of the modulator switch tubes and hardware. The systems certainly can easily survive an industrial environment after witnessing the many system operational anomalies that have occurred in the past year. The modulator has been abused in just about every conceivable manner. Initial system turn on can be most stressful, particularly when complex computer codes are involved. The (very experienced) computer operators did not fully check the system logic. Unfortunately, when powering up, a do loop caused system oscillations, rapidly sequencing things on and off. Other computer glitches keyed on intermittent equipment interlocks. The system would power up with water flow and drop out when the flow switch would bounce. The PLC required special logic to implement delays and latches. The vacuum chamber, originally designed for fusion experiments, has many diagnostic ports. These ports now have quartz windows, which have broken during operations because of a lack of chamber cooling. This causes severe arcing across the vacuum bushing. The physicists, in order to implant in minimum time, load down the modulator as much as possible, with high plasma pressure and full rep-rate. This has led to popping of the power feeders during full output. All cooling pumps drop out, causing transient heating of the switch tube collectors. Another event occurred when a long langmuir probe was not properly secured, the vacuum sucked it right into the work piece during operations and the scope was still hooked up!! Fortunately the protect electronics prevented any damage to the scope. The physicists sometimes become frustrated by a difficult implant and will continue the run even though frequent work piece arcs cause the modulator to "blank" continually. The switch tubes seem to take all this in stride and continue to operate daily and reliably.

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