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**Title:** Initial Design of a 1 Megawatt Average, 150 Kilovolt Pulse Modulator for an Industrial Plasma Source Ion Implantation Processor

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# INITIAL DESIGN OF A 1 MEGAWATT AVERAGE, 150 KILOVOLT PULSE MODULATOR FOR AN INDUSTRIAL PLASMA SOURCE ION IMPLANTATION PROCESSOR

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## ABSTRACT

Plasma Source Ion Implantation (PSII) is a materials surface modification process which can be used to improve performance characteristics of manufacturing tooling and products. Since improvements can be realized in surface hardness, reduced friction, wear, galling, and increased resistance to corrosion, PSII is applicable to a broad spectrum of manufactured items.

In PSII, the object to be implanted is placed in a weakly ionized plasma and pulsed to a high negative voltage. The plasma ions are accelerated into the object's surface, thereby changing its' chemical and physical composition.

The plasma dynamic load impedance is highly variable, dependent on implant object area, plasma density, and material composition. The modulator load impedance may be a few tens of ohms and a few thousand picofarads early in time. Late in time, the load may appear as 20,000 Ohms and 100 picofarads. The modulator system must accommodate any process changes, in addition to (frequent) initial "start-up" object arcs (from impurities). To implant the required ion densities in a minimum of time, multi-kilohertz rep-rates are often required.

An evolutionary design approach was utilized to design a cost-effective and reliable modulator system with components of established performance, suitable for a manufacturing environment.

This paper, in addition to presenting the anticipated modulator design required for the PSII application, will review similar modulator topologies and determine operational lifetime characteristics. Further improvements in system electrical efficiency can also be realized with incremental design modifications to the high voltage switch tubes. Development options for upgraded switch tubes of higher efficiency will also be presented.

## INTRODUCTION

The overall power modulator system will be designed to maximize efficient use of manufacturing floor space and enhance system reliability. As shown in figure 1, the system has three main elements: a phased [illegible] power supply system, the [illegible] stage modulator [illegible] mounted [illegible] tank of about 4'X5'X5', and the processing vacuum chamber. The power supply system consists of a 13.8 kV (or 4160) to 600 V (3Ø) step down transformer, a 600 V (3Ø) phase controller, and a 600 V to 150 kV transformer-rectifier. An optimal configuration for the power supply system is for the transformer and transformer-rectifier to be located outdoors, with the phase control electronics located indoors, near by in the adjacent building. This avoids sealed outdoor enclosures and environmental control units for the phase controller. Typical system control I/O's will also be indoors, and will not require additional cable conduits to the outdoor environment. The system high-voltage inter-connecting coaxial cables are terminated under oil, with corona free techniques, to maximize cable lifetime and connector reliability. Because the system requires little stored energy, the cost and concerns associated with a capacitor "vault" can be avoided. Power supply filtering and energy storage will be in the modulator tank. This reduces peak cable currents which can minimize induced switching noise. System communication and I/O such as "metering," electronic and equipment safeties, will be interconnected with fiber optic cables, with a fail-safe methodology.

The modulator will utilize a conventional "hot-deck" circuit topology. Power to the deck will be provided by a low capacitance "ring" type isolation transformer with control and diagnostic I/O through fiber optic cables. Modern drive electronics coupled with switch tubes of established and proven performance, will provide a compact system of reliable and long lived performance. The authors experiences with various classes of switching devices unequivocally indicate that hollow-beam crossed-field switch tubes are the devices most suited for this application (1). The tube has a non-intercepting input (mod-anode) that is high mu. The solid mod-anode has a high transient thermal conductivity and does not damage easily, like a "grid". The cathode is shielded from the collector and additionally protected with "arc" targets. Arcs directly between the collector and cathode would be almost impossible. Due to their true constant current characteristics, additional devices may be paralleled for increased output and degenerative feedback is not required to equalize current sharing. Device output switching current is solely dictated by input (mod-anode) voltage. This characteristic is of paramount importance in the operation of PSII systems. [illegible] create system transients [illegible] current [illegible] identical, with the switch tubes absorbing the system voltage. Excessive fault currents can also easily damage the valuable implantation items. When load current is detected with-out significant load voltage, tube input drive is quickly removed. If a current is detected above the tubes rated parameters, which would be the case of a "shoot-through" fault, the phase controller is aborted, minimizing the more destructive effects of long "follow-on" currents. We intend to parallel 3 Litton L-5097's, each rated conservatively at 70 Amps and 180 kV.

Figure 1. Simplified Modulator System Block Diagram

## L-5097 MODULATORS

There are many existing modulators that utilize the L-5097 amplifier tubes, most typically in particle accelerator and radar service. The facility with the largest array of L-5097 modulators, is the MIT Bates Accelerator Laboratory. In their facility, two L-5097's are operated in parallel, as a klystron cathode modulator. As shown in figure 2, a common driver consisting of totem-pole pairs of 4PR-1000's (four total, two for the "on" deck and two for the "off" deck), drive two pairs of L-5097's (four total). This configuration, with a common driver and four L5097's, powers two cathode modulated klystrons (~12 MW beam, each). This system is typically operated at -160 kV on the L-5097 cathodes and they switch 45 to 50 amps each. The system operates at a 600 Hz rep rate and 25 uS pulse width, a 1.5 % duty. These parameters are very close to PSII applications, and direct comparisons would be realistic. The L-5097's have been in service more than 20 years, with the most recent tube to be retired, having over 70,000 hours operation. This relates to over 16 years operation in twin shift manufacturing environment. MIT Bates indicates an average tube lifetime of over 52,000 hours, as shown in figure 3, for the 24 L-5097's they have in their almost daily operations (2). The end of life is not due to cathode depletion or cathode poisoning from minute out-gassing over the years, but almost totally from anode "punch-through" or filament shorts. The anode (collector) cylindrically shaped, utilizes the inner surface as the target for the cathode electrons. A stress relieving cone is between the collector and outer ceramic envelope. Examination of failed units indicate melting on the outside of the collector in an area between these two electrodes. Although there are system protects and crowbars for the [illegible], certain failure modes may exist that would not trigger the crowbar electronics. A slight [illegible] modification to the stress ring surge arrestors, could detect arcs between these electrodes. This slight modification may increase average lifetimes beyond 52,000 hours, as anode "punch-through" causes over 60% of the tubes failures. It is also important to note that their are no recorded "shoot-through" faults for this system. Even though the PSII process desires higher initial peak current from the modulator, the dynamic plasma impedance significantly reduces the required average cathode current, similar or less than that of a square pulse cathode modulator, with it's lower rep-rate. It can be expected that a L-5097 in a PSII system would have a similar lifetime.

The Kwajalein (Marshall Islands) tracking radars also utilize the L-5097s in their systems. Their highest power modulator, in the "Altair" transmitter, has three L-5097's in parallel in a klystron cathode modulator configuration. They operate their system at 135 kV, 150 A, and usually with a 3% duty. The transmitter also operates with a variable pulse width, from 12 uS to 500 uS. The transmitter has over 40,000 hours operation, with the original switch tubes and spares (3). They initially thought they had some tube problems, but that was not the case. They cycle the tubes in and out of the sockets every 8,000 hours. One difference between the Altair transmitter and Bates Accelerator is that the Altair system uses an earlier version tube, with a permanent magnet stack instead of the later solenoid magnet. Field errors from the discrete magnet elements caused (magnetron) oscillations when the switch tubes were near saturation. The "on" deck driver has four parallel 4PR60C's with a 15 kV plate.

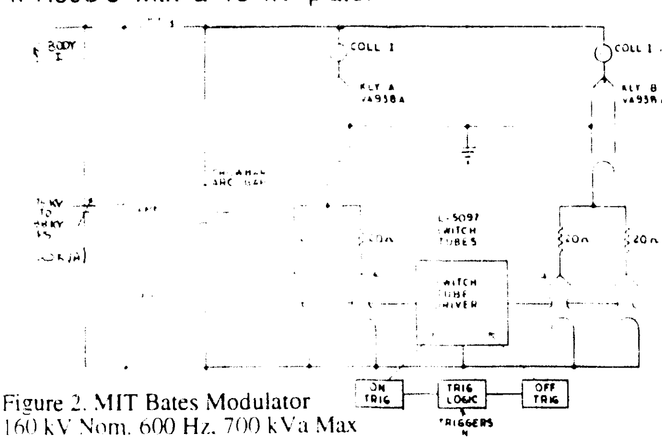
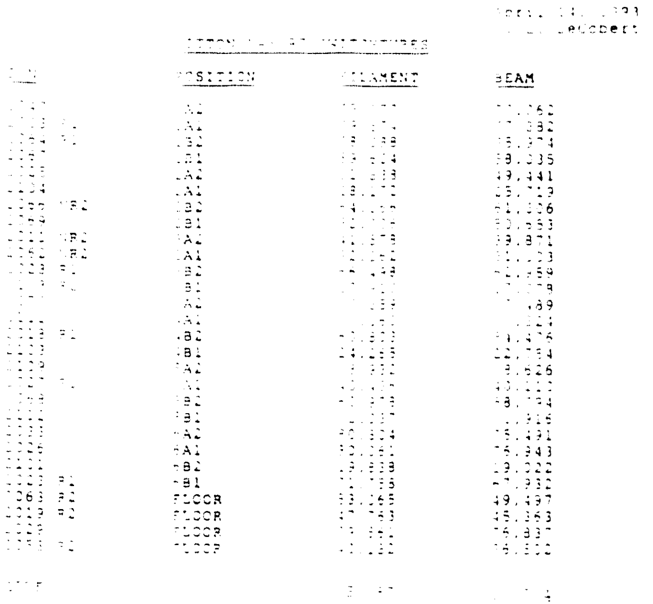



Figure 2. MIT Bates Modulator
160 kV Nom. 600 Hz. 700 kVa Max

## THE GENERAL MOTORS "ALPHA" MACHINE

The modulator system for large scale PSII pilot plant for determination of manufacturing parameters will be based on three parallel L-5097's [illegible]. This system is shown in figure 4. The power supply system will be as outlined in the introduction. It is anticipated that a "tail-biter" (which is not in any present system) will not be necessary to quickly discharge the load capacitance at the end of each pulse. Plasma loading significantly alters (reduces) the discharge time constant. The switch tubes will operate at voltages up to -180 kV and each will have the capability to contribute over 3 amps average current. This is well within the anodes maximum dissipation at saturated voltage switching levels. Also with the 3 amps



| [illegible] | POSITION | FILAMENT | BEAM |
| --- | --- | --- | --- |
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Figure 3. L-5097 Operational Hours, Abridged Listing

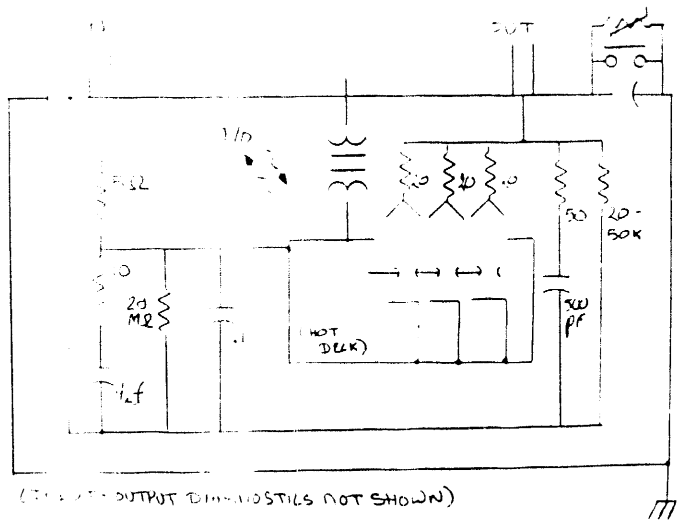


Figure 4. Simplified Circuit of Modulator Oil Tank

average current, (average) cathode loading is also light, less than 100 ma/cm2. To better match the plasma dynamics and provide a fast load risetime, cathode current will be peaked to around 100 A for a few microseconds, and then limited to about 50 Amps. Even for the 100 A case, the peak pulsed cathode loading is very conservative, around 3 A/cm2 . The "peak-plateau" mod-anode input voltage will be generated by a pair of fiber optic controlled "totem-pole" hot decks. These decks will be of identical design, except that the [illegible] deck will have an extra "drive" tube. Proper phasing is obtained by switching the output polarity of the fiber optic receiver. The decks will utilize Varian-Eimac YU-113's, a 60 kV, 15 A planar triode. These devices require about 120 volts peak-to-peak drive between cut-off and full output and are easily driven by solid state electronics. This should result in mod-anode drive waveforms with rise and fall times better than 700 nS for the three parallel L-5097's. The anticipated design for the hot deck system is shown in figure 5.

The area that requires careful consideration, is the vacuum feed-through bushing. High-voltage cabling between the power supply and modulator is relatively easy, with many types of double graded dielectric coaxial cables available. These will terminate in oil and should not be a problem in a well designed system. The output pulse cable is more problematic, but does not suffer in this application from handling fast rise and fall waveforms. An un-graded dielectric system with a solid center conductor and foil under the braid, similar to the "SLAC" AA-840, would be desirable, but with more polyethylene between the conductors. The high voltage vacuum feed-through bushing needs additional testing and development. The authors experience suggest that an oil filled bushing would be the best for high-voltage reliability. Careful considerations should be made to insure thermally compatible materials, such that vacuum leaks do not develop. Cooling water for the work piece and stage should have their own helical insulators.

## ITERATIONS TO IMPROVE THE L-5097 EFFICIENCY

To provide better dynamic switching at low operational voltages, for enhanced PSII flexibility, various options are available to improve overall system efficiency. These modifications would possibly increase tube lifetime and reduce input mod-anode drive parameters. The improvements would be socket compatible with existing devices and only require slight changes to the drive deck electronics.

In the present configuration of the tube, there exists a shield ring between the collector and mod-anode. This shield is placed at cathode potential (typically deck common) to reduce the effective capacitance between the mod-anode and collector. If the shield is connected to a positive bias, secondary electrons can be better suppressed, further increasing switching efficiency. An optimal bias can be determined by examination of the tubes electron optics with trajectory codes, along with operational confirmation. Iterations of the tubes collector design may be realized to further reduce secondary emission.

Another approach that has a more direct effect on switching losses, is to increase the tubes perveance. Various methods are presently available, but careful examination is required to determine tube design trade-offs and socket compatibility. Modern designs with 200 uperv's (or more) are possible, but must not deviate from the L-5097's internal rugged design.

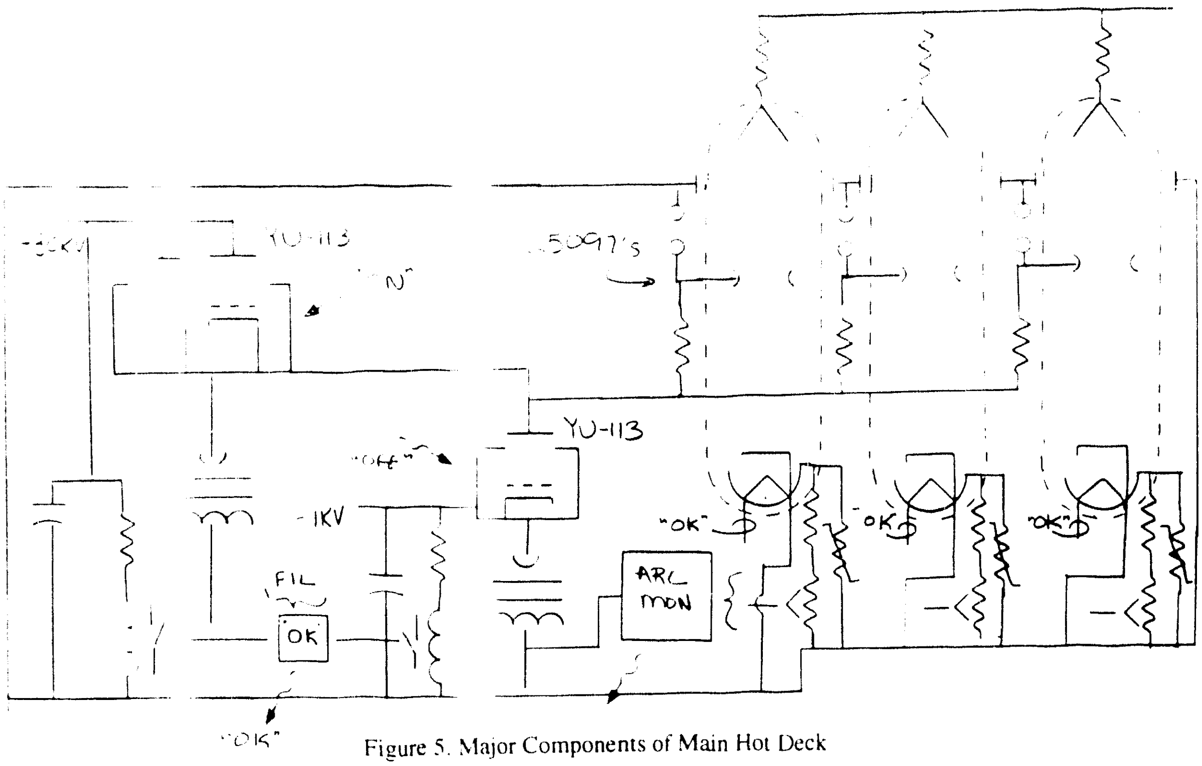


Figure 5. Major Components of Main Hot Deck

## CONCLUSION

A design plan has been formulated that utilizes proven switch technology of documented reliability. The tubes rugged internal architecture and fault protective features provide the reality to operate high voltage modulator systems in an abusive industrial environment. When this hardware is utilized with modern drive and control electronics, coupled with compact system packaging, reliable and noise free modulator systems can be implemented that would be un-obtrusive to existing manufacturing environments.

## ACKNOWLEDGMENTS

The authors would especially like to thank Jed DeCobert of MIT Bates Accelerator for the extensive data and records made available to evaluate tube life history at voltages, current, and rep-rates suitable for PSII. Ec Natter of MIT working on the Altair transmitter was helpful in describing system operation and providing helpful hints for future system design. The authors also appreciate the technical advice and useful discussions with J. Siambis, R. True, and R Symons of Litton Electron Devices with matters concerning tube internal designs and efficiency considerations.

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