Solid State Modulators
For
PIII Applications

Dr. Marcel P.J. Gaudreau, P.E.
Dr. Jeffrey A. Casey
Michael A. Kempkes
Timothy J. Hawkey
James M. Mulvaney

Presented at:
Fourth International Plasma - Based Ion Implantation Workshop
Dearborn, MI, June 1998

DIVERSIFIED TECHNOLOGIES, INC.
35 Wiggins Avenue Bedford, MA 01730 781-275-9444

Abstract

One of the key technologies in the Plasma Immersion Ion Implantation (PIII) process is the delivery of tightly regulated high voltage; high current pulsed power to the plasma implantation chamber. This requires a nearly ideal high voltage switch capable of operating at short pulsewidths and high pulse repetition rates. Existing switch technologies are limited in providing the ideal switching required for consistent, effective commercial PIII processes. By using new solid state power modulators, the required power can be delivered more effectively and reliably than with the use of older, tube-based technologies such as gridded vacuum tubes, thyratrons, and Pulse Forming Networks (PFNs). Solid-state high power technology is now available to allow PIII to be a cost-effective, commercially viable process, ready for widespread commercialization.

Plasma Immersion Ion Implantation

A recently developed surface treatment process is Plasma Source Ion Implantation (PSII) or Plasma Immersion Ion Implantation (PIII). Figure 1 below shows the major parts of a PIII treatment system.

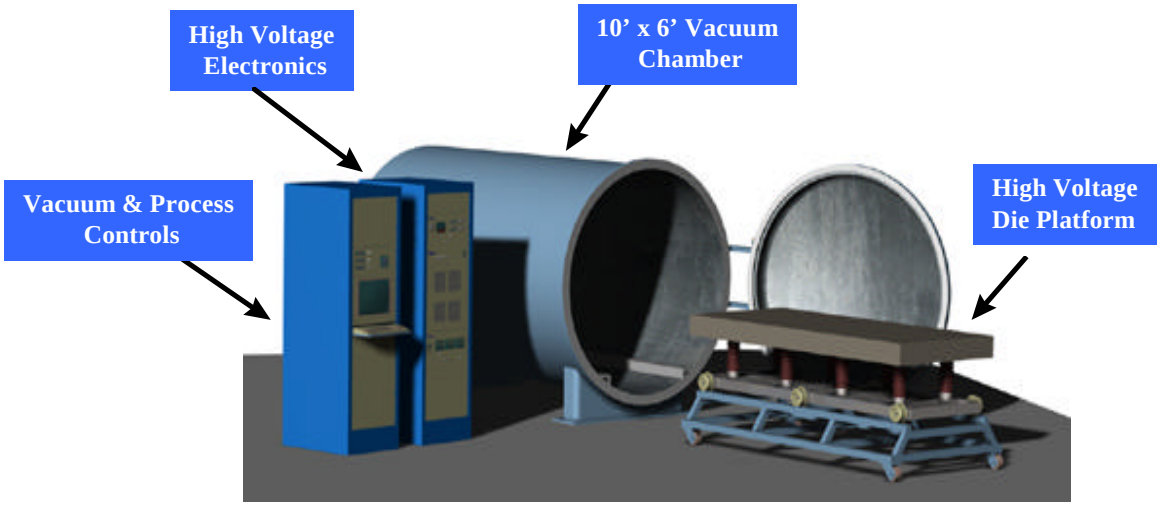

Figure 1: Components of a PIII System

The component to be treated with PIII is placed in a vacuum chamber, in which plasma is generated containing the ions of the species to be implanted. The PIII system does not use the complex, generally low-current extraction and acceleration scheme found in traditional beam-line implanters. Instead, the sample is repetitively pulsed at high negative voltages (in the 1 - 100 kV range) to implant the surface with a flux of energetic plasma ions. Because the plasma surrounds the sample (it is "immersed"), and because the ions are accelerated normal to the sample surface, plasma-source implantation occurs over the entire surface, thereby eliminating the need to manipulate non-planar samples in front of an ion beam. The PIII technique thus circumvents the line-of-sight restrictions inherent in conventional ion implantation. Therefore, dies with complex geometry can be implanted without elaborate target manipulation arrangements.

The PIII process distinguishes itself from conventional coating and implantation processes by being:

a) A batch process, able to coat large dies and complex surfaces without target manipulation (demonstrated by the treatment of a 1000 piston run at Los Alamos National Laboratory)

c) A low temperature process, which does not distort or modify die dimensions

d) Able to produce high coating adherence

In research laboratories at LANL, University of Wisconsin, and elsewhere, processes refined so far include the deposition of long-life Diamond Like Carbon (DLC) coatings on aluminum and steel,

and the improvement of chrome plated stamping dies through nitrogen implantation. These processes have demonstrated better than 10x life improvements in many applications.

Related research at LANL has also extended these early PIII processes into more exotic organo-metallics, whose properties allow implantation of a wider range of coatings. These processes are relevant to high temperature applications such as metalcasting dies, and are similar to the DLC process.

The Need for Fast High Voltage Pulsed Power

Tightly regulated, high voltage pulsed power is critical to the PIII process. One of the technical challenges which has been addressed as this process has evolved is the development of reliable pulsed power sources capable of supporting the "recipes" developed by PIII researchers for commercial scale systems. These pulsed power sources must be able to deliver nearly "ideal" repeatable, consistent pulses to optimize the metallurgical surface properties of the treated components.

In the PIII process, the plasma is typically produced by an independent electromagnetic source, and accelerated by the pulsed power source. The polarity is arranged to accelerate the plasma ions toward the samples to be coated. In the ideal case, the plasma ions consist of a single species in a single ionization state. An accelerating pulse of constant voltage in this case will result in a mono-energetic implantation beam, and thus ideal control over the implantation depth. In practice, non-ideal effects occur due to multiple species and ionization states in the plasma, as well as an accelerating potential, which varies during the pulse. The high voltage pulse imparted to the plasma is effective for < 50μS, and only until the plasma sheath reaches the limits of the chamber. Thus, high voltage (1-100 kV) and high current (0-2000A) pulses with very fast rise and fall times are required to achieve consistent PIII results.

As PIII technology has evolved, several key issues surrounding the choice of high voltage, high power systems have emerged. To explore these issues we will look at the characteristics of pulsed power sources and discuss DTI's findings on how best to implement the ideal pulsed power source.

The Ideal Pulse Power Circuit

Figure 2 shows the "ideal" pulse power circuit for PIII. It is powered by an ideal voltage source, with unlimited current and constant voltage.

It also contains an ideal switch having the following characteristics:

- the switch is both an opening and closing switch
- the switching time is infinitesimal (fractions of a microsecond)
- it has nearly zero series impedance when closed and infinite impedance when open

With such an ideal circuit, the plasma accelerating voltage will be a perfect square pulse, independent of current, as shown in Figure 3. This ideal voltage pulse has a minimal rise and fall time and a flat top, independent of load, current and repetition rate.

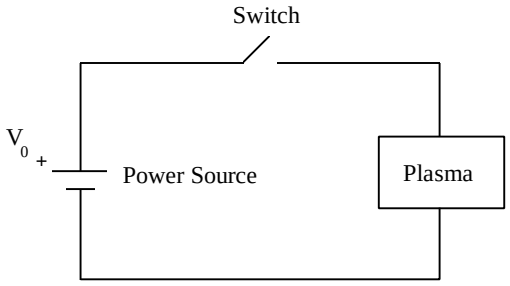

Figure 2: Ideal Circuit

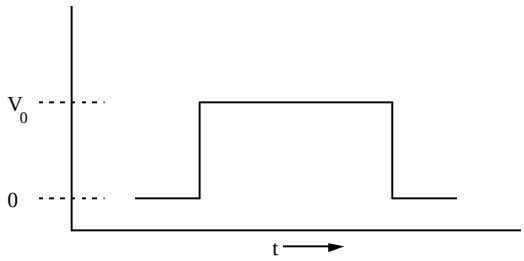

Figure 3: Ideal Pulse

Increasing Complexity

Figure 4 shows a more realistic PIII circuit than the ideal circuit discussed above. This circuit retains the ideal switch, as in Figure 2, but adds several "real world" factors to the circuit: a variable DC power supply with finite current capability, a storage capacitor for achieving high peak current, and series and parallel (pulldown) output impedance. The series impedance is

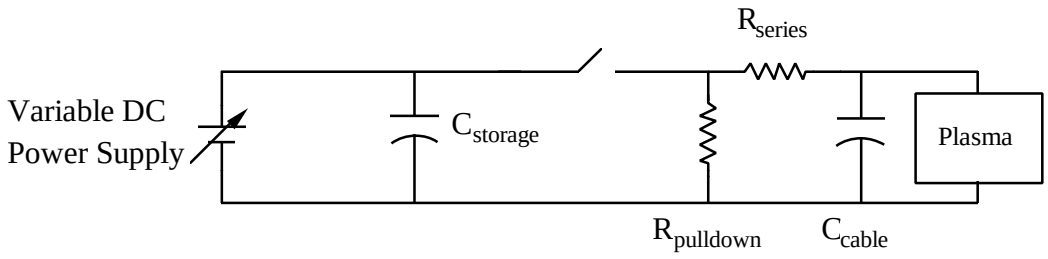

Figure 4: A More Realistic Circuit

inherent in any circuit, as is the cable capacitance between the power source and the plasma. The pulldown resistor is added to provide a discharge path for this cable capacitance when the switch is off.

The voltage waveform for the simplified circuit above is illustrated in exaggerated form in Figure 5

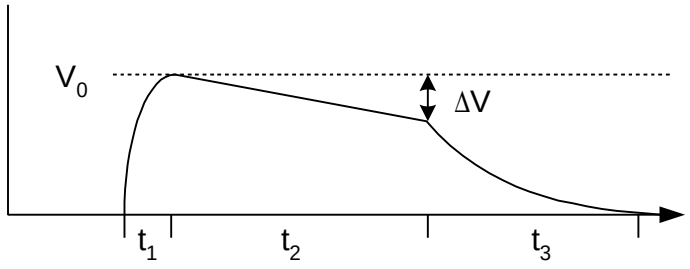

Figure 5: Voltage Waveform for the Figure 4 Circuit

Several observations can be made from this simple model. First, even with an ideal switch, the pulse shape is no longer a perfect square wave. t_1 represents the charging time of the cable and plasma capacitance through the series impedance where,

(1)

$$t_1 \approx R_{series} * \left(C_{cable} + C_{plasma} \right)$$

The pulse top can be kept nearly flat by choosing a large enough value of storage capacitor, such that the voltage droop, ΔV, from the pulse current is small. Note that longer pulsewidths or higher pulse currents will require larger storage capacitors.

(2)

$$\Delta V \approx \frac{I * t_2}{C_{storage}} \quad where\ I \approx I_{pulldown} + I_{plasma}$$

The fall time of the pulse (t_3) is given by the RC constant of the cable (and plasma) capacitance and the series and pulldown impedance. In all cases, it is desirable to keep the series impedance as low as possible. A tradeoff must be made, however, with the pulldown resistor value. A low resistance speeds fall time, but also shunts power from the load when the switch is closed. This power is:

(3)

$$P \approx \frac{V^2}{R_{pulldown}} * f * t_2$$

where *f* is the pulse repetition frequency. This shunted power can represent a significant load at high voltages for small values of pulldown resistance, and also represents a significant cooling load to the overall system. Balancing the competing desires for fast fall time and power efficiency is a critical factor in selecting the value of pulldown resistor.

Real World Simplified Model

Figure 6 shows a more complete (but still simplified) model of a high power PIII system. The previous discussion assumed that the load was resistive. Real world plasma loads are much more complex. We add to the realism of the circuit by modeling the plasma load as a complex RC circuit. Note that the ideal switch is retained in this model.

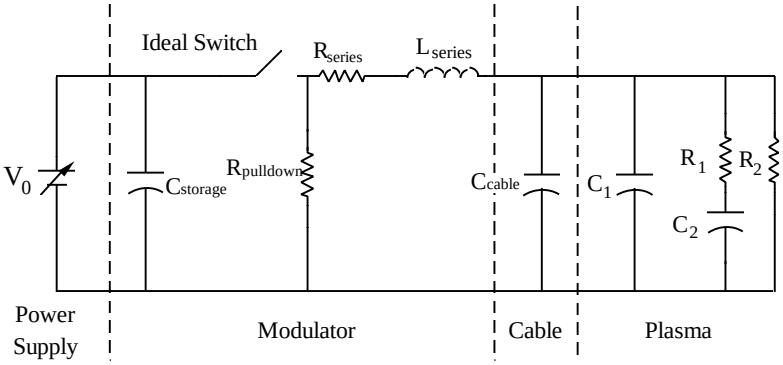

Figure 6: Real World PIII Circuit Model

Figure 5 showed the effects of impedances in the pulse power circuit on voltage rise and fall times. These factors are now compounded by the nature of the plasma load itself. Figure 7 shows the typical current drawn from the pulsed power source during a voltage pulse.

I_1 is the initial charging current, approximately given by

(4)
$$I_1 \approx \left(\frac{C_{cable} + C_1}{L_{series}} \right)^{\frac{1}{2}} * V_0$$

Provided

(5)
$$t_L = \frac{L_{series}}{R_{series}} > R_{series}\left(C_{cable} + C_1\right) = t_C$$

L_{series} may be added to limit di/dt, or may only represent stray buswork inductance. The above inequality is nearly always true for reasonable R_{series}. The peak charging current, I_1, is reached in a time t_1 given by

(6)
$$t_1 = \frac{p}{2}\left[L_{series}\left(C_1 + C_{cable}\right) \right]^{\frac{1}{2}}$$

I_3 is the "steady state" plasma current represented by:

(7)
$$I_3 = \frac{V_0}{R_2}$$

where $R_2 =$ steady state effective plasma resistance and $R_2 >> R_{series}$

I_3 is the typical pulse current normally considered in sizing PIII average power and dose rate systems. A key here is to note that the magnitude of the peak current (I_1), while relatively short in duration, will often be many times this pulse current (I_3). The transition current (I_2) between the peak current and the pulse current is determined by:

$$I_2 \approx \frac{V_0}{R_1} e^{-\frac{t}{t_2}} \qquad where\ t = R_1 C_1 \tag{8}$$

Finally, the current and voltage fall times are:

$$V \approx V_0 e^{-\frac{t}{t_3}} \tag{9}$$

$$I \approx \frac{V_0}{R_2} e^{-\frac{t}{t_3}} \tag{10}$$

$$where\ t_3 \approx \left(C_{cable} + C_1 + C_2\right) * \left(R_{pulldown} \| R_2\right)$$

This is similar to the previous falltime calculation, with the addition of the plasma model. Note that plasmas which support high pulse currents (i.e., R_2 is low) will have faster falltimes than relatively sparse plasmas, where R_2 is high.

Three major conclusions can be drawn from this level of model. First, the stability of the voltage pulse is critical over a wide range of current levels during the pulse. The switch, power supply, and storage capacitance must have the ability to support very fast dI/dt at the beginning of the pulse, and high peak current, while maintaining V_0. This requires low series equivalent resistance and inductance. Second, while the plasma characteristics are a function of the process, the PIII system should be designed to minimize external capacitance. Primarily, this can be achieved by minimizing the cable length from the switch to the plasma, and by careful design of the feedthrough for minimum capacitance. Minimizing this capacitance will reduce the peak current required from the pulse power system, and improve both the rise and fall times of the pulse. At high current levels, cable inductance will dominate this series impedance, and the circuit must be designed to minimize this inductance.

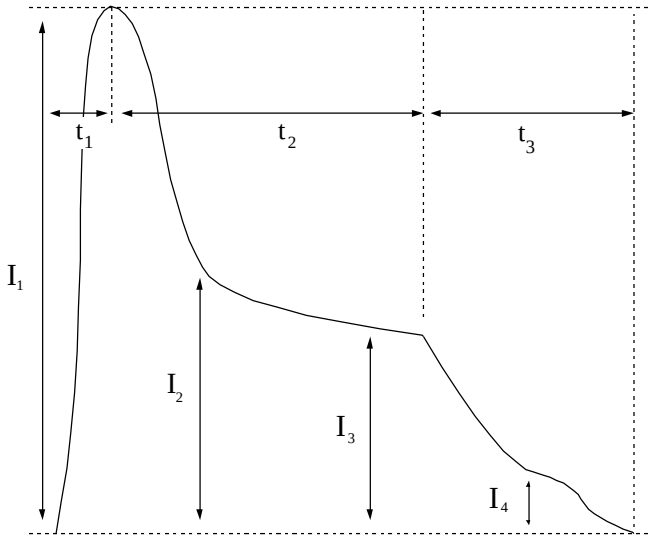

Figure 7: Current Waveform for Figure 6 Circuit

Finally, note that all of these effects are seen even with an ideal switch model. The net result is that, even with an ideal switch, it is not possible to achieve perfect PIII pulses. The objective is to

minimize the effects of each of the previously discussed factors on the pulse. The next section will discuss options for realizable high voltage switches.

High Voltage Switching Options

So far, we have discussed several requirements for high voltage switching for PIII. These requirements include:

- Low switch impedance
- Very fast voltage rise and fall times (typically less than 1 μS).
- High peak current handling (10-3000A)
- Very high dI/dt capability (100 - 2000 A/μS)

Three basic technologies are in use today to address the requirements listed above. These include (1) vacuum electron switch tubes (e.g., tetrodes); (2) pulse forming networks with thyratrons; and (3) the relatively new approach of high voltage, solid state switching developed by DTI.

Switching Options - Vacuum Electron Tubes

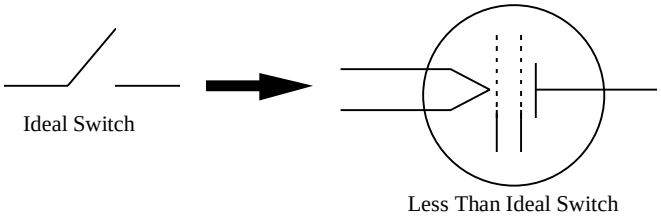

Figure 8

A conventional approach to high voltage switching is to use a gridded vacuum switch tube, such as a triode or tetrode, as the series switch for a pulse modulator.

This approach, while capable of providing the high voltage switching required for PIII, has three major drawbacks. First, the switch tube itself is current limiting - and many applications of these tubes are specifically designed to utilize that capability. This current limiting, however, is detrimental to pulse rise-time, as shown in Fig 9. The risetime of the pulse (V_1), is shown by:

$$t_1 = \frac{V_0}{I}\left(C_{cable} + C_{plasma}\right) \qquad (11)$$

Such a switch tube forces a linear risetime slope due to the limited current available for charging of the cable and load capacitance (versus the series reactance $(LC)^{\frac{1}{2}}$ time constant previously shown). This can have a serious impact on the PIII process itself, since the pulse spends more time at low voltages and high current simultaneously during the risetime. Falltime is essentially unchanged from the previous example with an ideal switch, since most vacuum switch tubes have relatively short turn-off times and low leakage current.

The second drawback of the switch tube is that there is a very large voltage drop across the tube - which may be 20% or more of the total switched voltage (V_0). This means that the power supply must operate at a higher voltage than required by the PIII process (e.g. a 120 kV DC supply is required for a 100 kV implant). Additionally, this voltage drop, at high current, means a significant amount of power is being dissipated in the tube itself. This significantly increases the cooling, prime power, and infrastructure required for a PIII system.

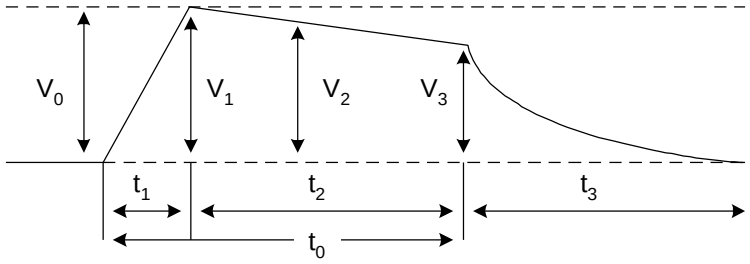

Figure 9

Third, tubes, in general, arc, which reduces their lifetime and mandates complex conditioning, arc detection and crowbar protection systems.

Switching Options - Pulse Forming Network (PFN)

A second option for PIII switching uses a Pulse Forming Network (PFN). Typically, a PFN consists of a number of inductor and capacitor (LC) stages, which are tuned to provide a pulse of a fixed pulsewidth into a matched load. Typically, the PFN is discharged into the load circuit by a hydrogen thyratron or other fast closing switch.

While this approach is often used in radio frequency (RF) particle accelerators with constant load impedance and pulsewidth, it has several drawbacks for PIII.

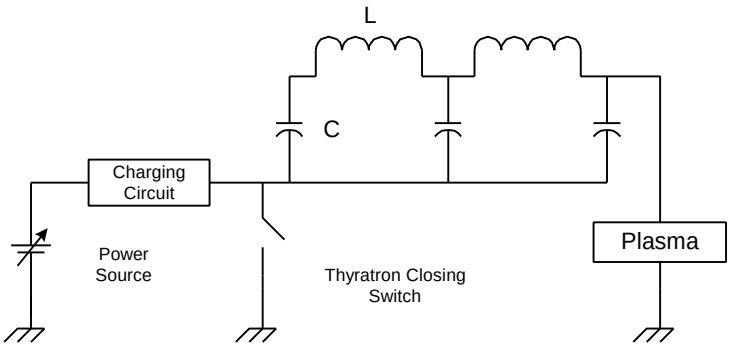

Figure 10: Fixed Pulse Length Matched Line PFN

The first drawback is the fixed pulsewidth itself. Many combinations of process and target require flexibility in balancing average power available, cooling, implant dose, and process time. One critical method of achieving this balance is to vary the pulsewidth and PRF of the high voltage pulses. A fixed pulsewidth can seriously limit the flexibility of the PIII process, especially where

multiple implant steps are required, or where different processes must be performed in the same system. High PRFs are also problematic for thyratron/PFN pulsers.

Second, as previously shown, the plasma load in a PIII system is complex. This makes it very difficult to tune the PFN performance for optimal voltage pulses due to the changing load impedance. In addition, the target component to be treated is part of that complex plasma load, meaning that additional tuning is required whenever the PIII target changes. This can significantly complicate the job of the PIII operator in setting up for each process step. It also significantly constrains the level of PIII process control and consistency achievable with a PFN.

Third, the thyratron typically used to drive a PFN has a finite lifetime, and must be replaced at regular intervals. At high levels of operation, this can be a noticeable cost factor in the operation of a PIII system.

Fourth, a thyratron can only serve as a closing switch, and cannot open during a pulse in the event of an arc. The damage thresholds of the target often require additional hardware (opening switch tube or crowbar) to limit arc damage.

Finally, the DC power supply required to drive a PFN must typically operate at about twice the voltage desired at the output (e.g., a 20 kV PIII system will require a 40 kV DC power supply) unless a step up pulse transformer is used. Again, this increases the cost and complexity of the PIII system.

Switching Options - Solid State

Recent innovations[2] have produced a third choice - high voltage, high current, solid state modulators. These modulators feature state-of-the art insulated gate bipolar transistor (IGBT) switches in series and parallel configurations that allow nearly arbitrary high voltages (1kV-200kV) and currents (10A-5kA) to be reached. They operate as both opening and closing switches, providing extensive flexibility in pulsewidth, and very fast fault protection.

Modulator Architecture

The core technology for a solid state pulsed power system is exemplified in DTI's PowerMod™ HVPM 20-150 Pulse Modulator, shown in Figure 11. This solid state modulator contains the series IGBT modules, pull down resistor, storage capacitor, controls, and protection circuitry required to provide 20 kV, 150A pulses, at arbitrary pulsewidths from 1 µS to DC, at up to 30kHz, in a single 19" rack-mountable unit.

Figure 11: HVPM 20-150 Pulse Modulator[1]

A typical 20 kV, 100A pulse from this unit is shown Figure 12. This solid state switch is very nearly ideal - current through the switch has very minimal impact on output voltage.

As shown in Figure 12, typical switch times for this approach are

[1] Selected by R&D Magazine as "One of the 100 Most Significant Technological New Products of 1997".
[2] Developed and patented by Diversified Technologies, Inc. Bedford, MA

typically 500 nS - independent of the voltage being switched. When the switch is closed, the voltage drop across it is less than 3 V / kV, so the switch adds very low series impedance into the PIII system. This also means that the DC power supply voltage required with these switches is virtually the same as the implant voltage required - a 100 kV process requires only a 100.3 kV power supply. Finally, the current rate limit for larger IGBT switches can be as high as 5000 A / µS.

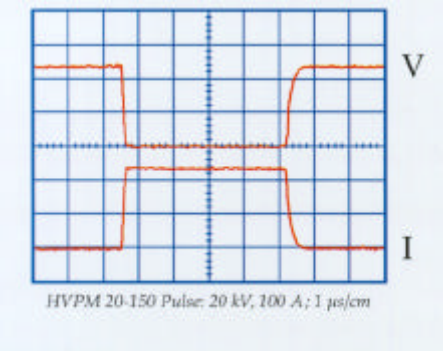

Figure 12: HVPM 20-150 Pulse

The only drawback to this approach at the present time is that solid state switch components are more expensive than switch tube or PFN components at low average power. When the complete pulsed power system infrastructure is considered, however, considerable cost and performance improvements can be realized with solid state switching. When the additional cost savings of power and cooling are considered, the cost and performance of solid state switching are typically more attractive.

High Current, Low Voltage

For high current low voltage, commercial-scale PIII processes such as DLC, the most cost-effective solution uses high current (1200+A), high voltage (3.3kV+) IGBTs in series.

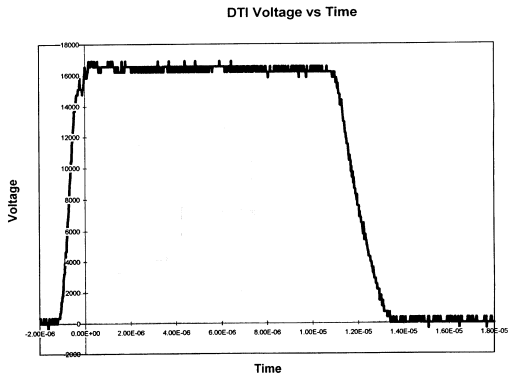

Figure 13: Constant Voltage of 16.5kV, 12µS into Varying Plasma load (Source: LANL)

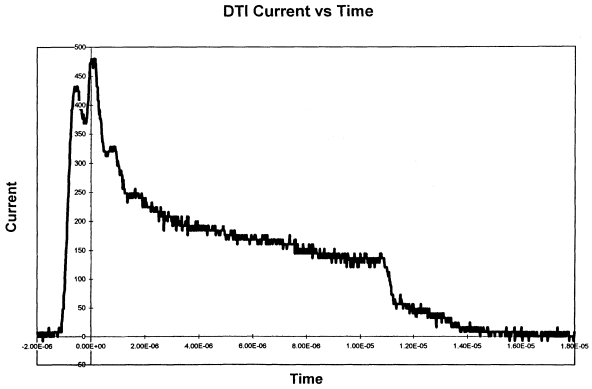

Figure 14: Varying Current (475A peak) of 16.5kV, 12µS Pulse into Plasma Load (Source: LANL)

Figure15 shows DTI's HVPM 20-2000 solid state modulator, which uses 18 series connected very high current IGBTs to provide up to 40 MW of peak power at 20 kV. Figure 13 and Figure 14 show typical voltage and current pulses in the PIII processing of 1000 automotive engine pistons at (LANL). The flattop of the voltage pulse, during a current pulse, which varies by a factor of three, demonstrates the nearly ideal performance of this solid state modulator. At these parameters, the largest impact on efficiency and pulse shape becomes the cable series inductance, rather than cable capacitance. These losses are given by:

$$P = 2ft = fLI^2 \qquad (12)$$

The modulator and the LANL PIII system were both carefully designed to minimize series inductance.

Figure15: PowerMod™ 20-2000

Two Approaches for High Voltage - Low Current PIII Processing

For very high voltage (20-100kV) implantation, and low current (<100A) either a directly coupled power supply and modulator; or a step up pulse transformer with a lower voltage pulse system may be utilized. DTI has developed R&D and commercial pulsed power systems using both approaches. The tradeoffs between these two approaches include cost, peak power, efficiency, waveform shape (rise/fall times and flattop), and flexibility.

Directly Coupled

A typical commercial high power 100 kV direct-coupled modulator is shown in Figure 16. DTI's HVPM 100-150 PowerMod™ modulator contains a 0.75 µF storage capacitor, a 100 kV, 150A peak, solid state IGBT switch, and all the control monitoring and protection circuitry required to pulse up to 5 kHz or more. A representative voltage pulse from this unit is shown in Figure 17. The clean pulse shape shows the near ideal behavior of the switch system.

Figure 16: DTI PowerMod™ HVPM 100-150

Transformer Coupled

Alternatively, it is possible to use a lower voltage modulator (typically less than 20 kV), coupled with a pulse transformer to achieve high voltage, low current pulses - albeit with constrained flexibility in pulsewidth due to the limited volt-second capability of the transformer core. The major advantage of this approach is that it is typically half the cost of a direct-coupled solid state modulator at low current.

The sizing of the peak current on the primary side of the pulse transformer is critical to this approach. Not only is the secondary peak current reduced by the voltage step-up ratio, but also the cable capacitance seen by the modulator will be multiplied by this ratio squared. As previously discussed, charging this capacitance at the beginning of each pulse can lead to very high surge currents - this problem is greater by the turns ratio squared when using a pulse transformer. Figure 18 shows an output pulse from a from a 5.5:1 pulse transformer driven by the HVPM 20-150. Using a 20kV modulator and a 5:1 pulse transformer to achieve 100 kV pulses, for example, requires a primary current 75 times the peak current seen at the load.

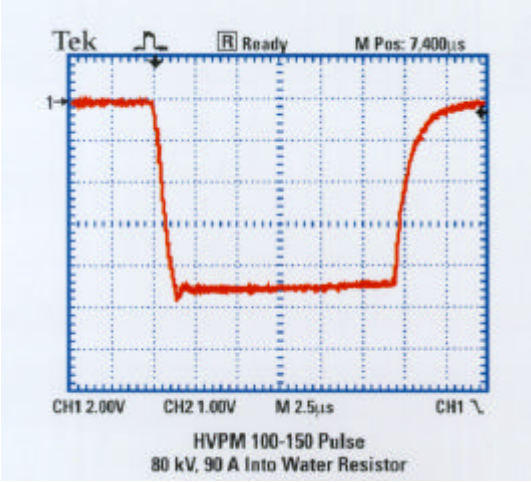

Figure 17: Nearly Ideal Current Pulse into a Resistive Load; 80kV, 90A Pulse, 2.5 µS/cm. Pulse current 20A/div.

In either configuration, cable capacitance can be a major source of inefficiency in the PIII system. For example, the power lost to repetitively charge and discharge the cable capacitance of six feet of coaxial cable between the modulator and PIII chamber at 100kV and 5kHz is:

$$P = 2fE = fCV^2 \approx 9kW \qquad (13)$$

One impact of this capacitance is that when specifying a PIII system, the DC power supply must be capable of providing both the power required by the PIII process itself, and the additional power dissipation associated with charging the power cable, feedthrough, and plasma.

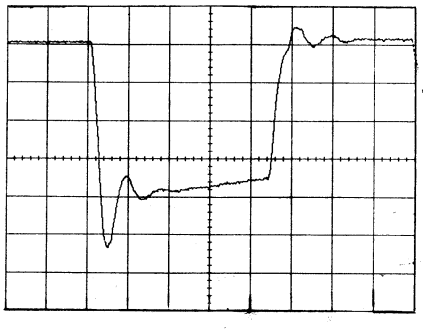

Figure 18: Sample Uncompensated Pulse Transformer Pulse (80kV, 5µ/cm into Capacitive Load

Discussion

We have seen that there are two obstacles to the efficient application of constant voltage-accelerating pulses in PIII applications. First, the peripheral passive circuitry plays a significant role in pulse shaping and power loss. Second, the non-ideal characteristics of the modulator switching elements can also significantly degrade pulse shape, power efficiency, or system complexity and cost.

Regardless of switch characteristics, passive elements of the discharge circuit should be optimized:

- minimize cable and feedthrough capacitance
- minimize inductance(especially for high current systems)
- design for large peak currents (many times the average pulse current)

Furthermore, the use of a solid state switch element for PIII pulse modulation produces several advantages:

- short pulse to DC flexibility
- high power efficiency and lower costs for DC power and cooling
- fast risetime, and fast opening for arc protection
- a scalable, modular design which can be scaled to the specific PIII system and processes
- very high reliability
- small footprint
- no x-rays