ELECTRICAL BREAKDOWN OF POWER RECTIFIERS FOR ELECTRIC GUN APPLICATIONS

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ABSTRACT

Experiments have been performed with a 100-kJ pulse-forming network (PFN) to characterize the transient behavior of semiconductor diodes serving as capacitor-protecting devices. In addition to the experiments, computer techniques are used to illustrate and predict the dynamic behavior of PFN diodes. From analyses of the data collected, it was determined that in a PFN under specific loading conditions, the diodes are subject to elevated transient high frequency voltage waveforms. In some experiments, the magnitude of the rate of change in voltage (dV/dt) across the devices was such that catastrophic failure was observed due to this phenomenon alone. This paper focuses on the determination of boundary conditions necessary for reliable device performance and the solutions that will circumvent diode operational failures. Our solutions include semiconductor device layout, choice of diode reverse recovery time, PFN switch timing, and selection of capacitive and inductive circuit parameters, all of which are presented in detail in this study. Information describing fundamental physics of semiconductor diodes under transient conditions and their role in electric gun propulsion technology is provided first to clarify the applicability of these areas of concern to the general field of very high power electronics.

INTRODUCTION

Power Diode Usage in Pulsed Power Systems

Diodes are successfully used as pulse power components in several facilities currently involved in electric gun research including the U.S. Army Research Laboratory (ARL)[1-3]. Since they shunt the capacitors during a voltage reversal, semiconductor diodes are referred to as "crowbar" diodes; i.e., they clamp the capacitor for the duration of the voltage reversal. Diodes will effectively extend the lifetime of the capacitors, which have been shown to fail under voltage reversal situations[4]. Diode failure occurs as a result of excessive junction temperature due to heating which leads to increased device conductivity; this results in additional current flow and further temperature increases. The conductivity is directly proportional to the concentration of mobile current carriers in the device, and is itself a function of operating temperature. The relationships between conductivity (σ) and mobile carrier concentrations for electrons (n) and holes (p) and carrier concentration and temperature are given, respectively, in Equations 1 through 3. Here q represents the charge of an electron, and μ_n and μ_p are the electron and hole mobilities:

$$\sigma = q\mu_n n + q\mu_p p. \tag{1}$$

For T > 30 K, the semiconductor becomes intrinsic with $n=p=n_i$ and:

$$\sigma = q(\mu_n + q\mu_p)n_i, \tag{2}$$

and n_i expressed as a function of temperature is given as:

$$n_i(T) = 3.88 \times 10^{16}\ T^{3/2} \exp(-7000/T)\ \mathrm{cm}^{-3} \text{ (for silicon above 30 K)}. \tag{3}$$

If a semiconductor is not allowed to dissipate heat quickly enough, this process will continue until the melting point of the device is reached and it is ultimately destroyed. This process is often referred to as "thermal runaway."

Diode Reverse Recovery Time (τ_{rr})

The reverse recovery time (τ_{rr}) is that time required for the diode to switch from an "on" or conducting state to an "off" or high impedance state. The τ_{rr} consists of the time associated with the minority carrier removal at the depletion edge, which is referred to as the "storage" time (τ_s), and a "fall" time component (τ_f) due to the junction depletion capacitance (C_j). This is expressed in Equation 4. The storage time (τ_s) depends upon the effective carrier lifetime (τ_{eff}) which is approximately the minority carrier lifetime (τ_p) of the semiconductor device (for long base diodes where the neutral base width, W_n > the diffusion length, L), or the transit time (τ_t)

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Experiments have been performed with a 100-kJ pulse-forming network (PFN) to characterize the transient behavior of semiconductor diodes serving as capacitor-protecting devices. In addition to the experiments, computer techniques are used to illustrate and predict the dynamic behavior ofPFN diodes. From analyses of the data collected, it was determined that in a PFN under specific loading conditions, the diodes are subject to elevated transient high frequency voltage waveforms. In some experiments, the magnitude of the rate of change in voltage (dV/dt) across the devices was such that catastrophic failure was observed due to this phenomenon alone. This paper focuses on the determination of boundary conditions necessary for reliable device performance and the solutions that will circumvent diode operational failures. Our solutions include semiconductor device layout, choice of diode reverse recovery time, PFN switch timing, and selection of capacitive and inductive circuit parameters, all of which are presented in detail in this study. Information describing fundamental physics of semiconductor diodes under transient conditions and their role in electric gun propulsion technology is provided first to clarify the applicability of these areas of concern to the general field of very high power electronics.

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of the minority carriers (for short base diodes where the neutral base width, W_n < the diffusion length, L). The fall time (τ_f) is a function of the depletion capacitance (C_j) and the diode circuit resistance (R) during reverse biasing.

$$\tau_{rr} = \tau_s + \tau_f \tag{4}$$

The expressions for the storage and fall times are given, respectively, in Equations 5 and 7.

$$\tau_s = \tau_{eff} (\ln[1 + I_f/I_r] - \ln[1 + I_f/(I_f+I_r)]) \tag{5}$$

$$\tau_{eff}^{-1} = \tau_p^{-1} + \tau_t^{-1} \tag{6}$$

where I_f and I_r are the peak forward and reverse current magnitudes, respectively, and τ_t is the hole transit time through the n region. Also, $\tau_{eff} \approx \tau_p$ for long base diodes and $\tau_{eff} \approx \tau_t$ for short base diodes.

$$\tau_f \approx 2.3 (RC_j) \tag{7}$$

In general, the minority carrier lifetime can be decreased by increasing the carrier traps or defects in the semiconductor crystal (accomplished through electron bombardment), but an increase in the reverse saturation current of the device results[5]. Higher reverse current is a disadvantage in PFN operation since energy storage capacitors will discharge faster, because they have diodes of higher reverse saturation current.

The transit time of the carriers may be smaller than the carrier lifetime. This is true for "short base" diodes that have a narrow base width and which are much faster in terms of recovery time. For short base, the transit time is given by:

$$\tau_t = 1/2 (W_n^2/D), \tag{8}$$

where τ_t is referred to as the transit time of the device. Note that τ_t can be made smaller than the carrier lifetime of the bulk material (τ_p) by adjusting the base width and diffusion coefficient. For example, for short base diodes it is generally required that the base width be much less than the diffusion length (L), which is the square root of the diffusion coefficient (D) multiplied by the carrier lifetime. Assuming that the base width in Equation 8 is equal to the diffusion length, the resulting transit time through the base is twice as fast as that of the carrier lifetime. The diffusion coefficient is a function of carrier mobility, a basic property of semiconductors, and to obtain a fast device it is desirable to have a large mobility material, such as GaAs. It should be stressed that the trade-off in using a fast recovery device is that of lower breakdown voltage and increased risk from damaging inductive over-voltages during rapid diode turnoff[6]. As an alternative, the blocking voltage can be increased by the use of multiple diodes in series; however, this is a solution that tends to increase the bulk and expense of the pulsed power system.The reverse recovery time of commercially available diodes is a limiting factor in many power electronic circuits, and it has been shown that electrical breakdown of power diodes as a result of rapid diode turnoff is possible during PFN operation[7]. Other researchers have shown that novel diode doping profiles resulting in lower carrier concentrations at the *pn* junction can provide an earlier start of reverse blocking and hence a smaller peak reverse current[8]. These recovery characteristics are referred to as "soft" recovery and they result in reduced inductive over-voltages on semiconductor diodes. It should be noted that the turnoff characteristics imposed on power diodes in an electric gun PFN are variable, by design, so the diode reverse recovery time may be appropriate for one set of switch- timing conditions and marginal or even inadequate (as is shown later in the report) for others. It is recommended that care be exercised when selecting semiconductor diodes for pulsed power applications of this nature.

EXPERIMENTAL APPROACH

Electric Gun Experiments

A schematic diagram of the PFN under consideration is given in Figure 1. This PFN consists of five triggerable submodules of capacitor banks, labeled C1 through C5 in the figure, which can be independently discharged through ignitron closing switches, S1through S5, and inductors, L1 through L5, into the load resistance R. A multiple capacitor bank and switching system of this type provides a high level of flexibility to the electric gun researcher in that it allows the capability of delivering various pulsed power profiles to an electric gun[9]. The diode failure problems we experienced during laboratory gun firings were found to occur in only one PFN capacitor submodule (submodule C1 with diode D1 in Figure 1), indicating a repeatable power dissipation pattern with severe values on the D1 diode. Semiconductor diode failure was observed subsequent to gun firings and in 100-mΩ fixed resistance dis‹ › rges. The diodes (D1 through D5) that were used in the PFN during these experiments are model C03-1123 power rectifier assemblies made by International Rectifiers of Marcum Ontario, Canada. They are designed with a peak current surge rating of 60,000 amperes (8-ms duration) and a 15,000-V reverse blocking limit. The series parasitic inductance of the complete diode circuit after installation into the PFN was measured at 1 μH (± 0.2 μH) for each circuit submodule.

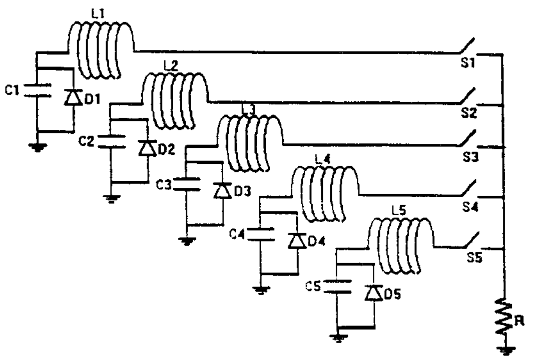


Figure 1. The circuit diagram for a 100-kJ PFN used for electric gun applications.

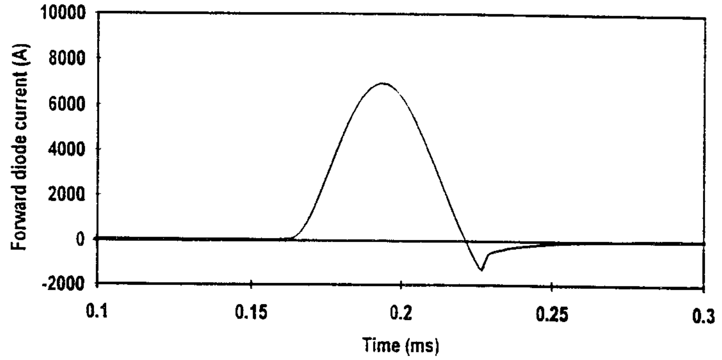


Figure 2. Diode current measurements for 100 mΩ load at a reduced system energy.

Our experiments were carried out with fixed resistive load discharges and verified using computer techniques. Experiments were performed with PFN discharges into 35-, 100-, and 200-mΩ load resistors. Experimental measurements of diode current and voltage determined that only for the case of the 100-mΩ load did a large dI/dt and dV/dt occur across D1. Experimental current and voltage waveforms for this case are given in Figures 2 and 3 and the transient waveforms can be seen at 226 μs, as indicated by the arrow. These results were corroborated with resistive load computer simulations, and it was also demonstrated that significantly large transients (dI/dt, dV/dt) were experienced on D1 with a current-dependent plasma load simulation. The plasma resistance varies from 30 mΩ to hundreds of milliohms during the discharge and the simulation results are given in Figure 4. The transient voltage waveform on D1 occurs at 280 μs. These computer simulation studies demonstrated that the rate of change in diode current (dI/dt) is smaller for the plasma case compared with the 100-mΩ case, but the overall diode current magnitude is larger with the plasma load. A large dV/dt is evident across D1 in the simulations and is a possible cause of diode failure in experimental gun firings where plasma loads are used.
For the 100-mΩ load case in Figure 2, the current waveform exhibits a small pulse of current over a 50-μs period which begins at 160 μs, and the rate at which the current decreased through the device was extremely large. In one experiment, the maximum rate of change (dI/dt) for D1 was calculated at 124.6 A/μs, which is the largest dI/dt observed for any PFN diode. This is pointed out since large dI/dts can lead to overheating in semiconductors and they are associated with dV/dts which are also harmful to diodes. The reverse recovery time of these diodes, estimated at 25 to 50 μs, could produce inductive over-voltages as current flow is abruptly interrupted[10]. The diode turns off rapidly and produces an inductive voltage (LdI/dt) which is applied across the diode's semiconductor junction. In fact, our measurements of diode reverse voltage (see Figure 3) provide definite evidence that a fast pulse of reverse voltage occurs across the diode as it is switching from the forward to reverse mode. This transient voltage occurs in spite of the parallel 400-μf energy storage capacitor (C1 in Figure 1) which generally behaves as a low pass filter provided there is minimal series inductance in the capacitor-diode circuit loop. As seen in Figure 1, a rapidly rising diode reverse voltage is applied to D1 as current conduction ceases at 226 μs. The maximum dV/dt in Figure 3 is calculated at 127 V/μs.

dV/dt Dependence on Initial Capacitor Voltage

It was determined that the relationship between the magnitude of dV/dt on D1 was a linear function with respect to the initial capacitor voltage of the PFN. This relationship was established by experiments with different voltages as shown in Figure 5. The data of Figure 5 can be used to predict the dV/dt expected for a given initial voltage and make it possible to determine the maximum initial (stored) capacitor voltage to be used.

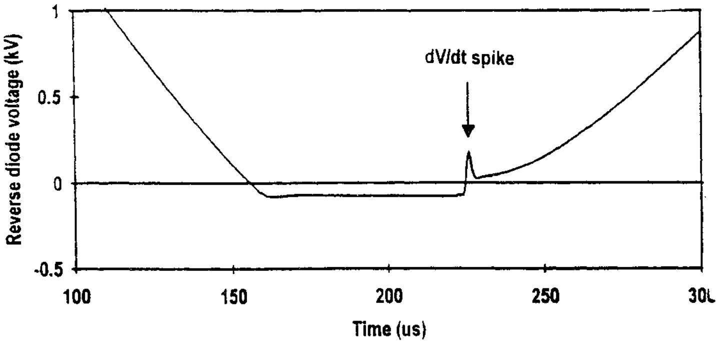


Figure 3. Measured diode reverse voltage with 100-mΩ load.

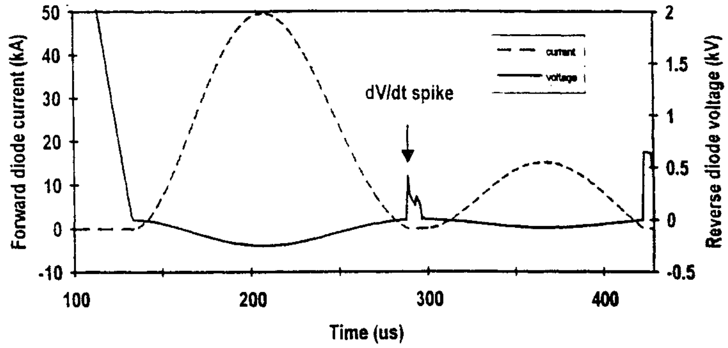


Figure 4. Simulation of D1 current for a current-dependent plasma load.

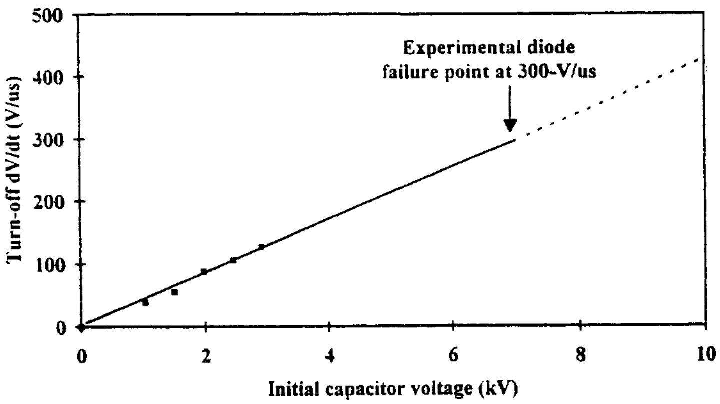


Figure 5. The rate of change in diode voltage (dV/dt) verses PFN system voltage with 100-mΩ fixed load resistance.

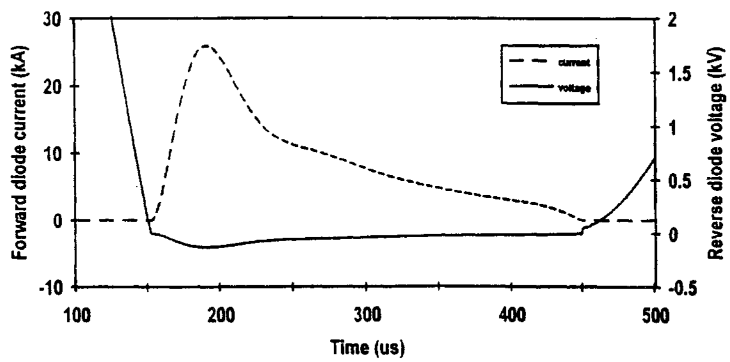
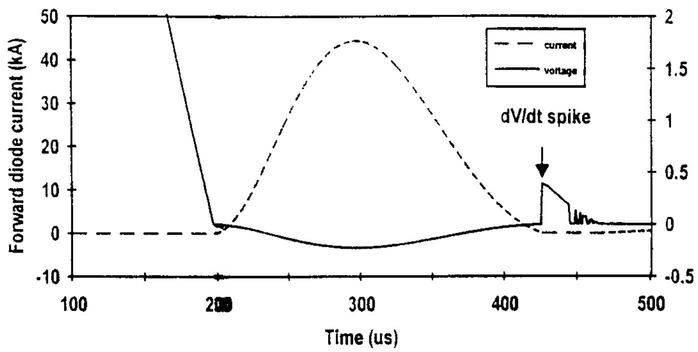


Figure 6. Simulated current and voltage waveforms for D1 in a delayed discharge experiment illustrating the reduced transient.

For instance, it was noted that when the system voltage was at 7 kV, with the 100-mΩ load, diodes failed repeatedly. This initial voltage corresponds to the 300-V/μs point on the curve in Figure 5, which is highlighted with an arrow. The diode reverse recovery time can now be chosen such that the maximum dV/dt is not exceeded during PFN operation. A reliable design method to determine an adequate PFN configuration uses a circuit analysis computer code to characterize dynamic diode behavior. This approach has been taken on the PFN of Figure 1 and is discussed in the following section.

Circuit Parameter Effects

The switching transients applied to the diodes in the PFN were studied with respect to switch closing times, submodule capacitance, and diode series inductance using an electronic circuit analysis code[11]. It was determined for the PFN considered in Figure 1, that the rapid decrease in diode current of the first submodule was caused by the relatively small value of submodule capacitance, 400 μf, coupled with the other submodules discharging relatively quickly after the first.



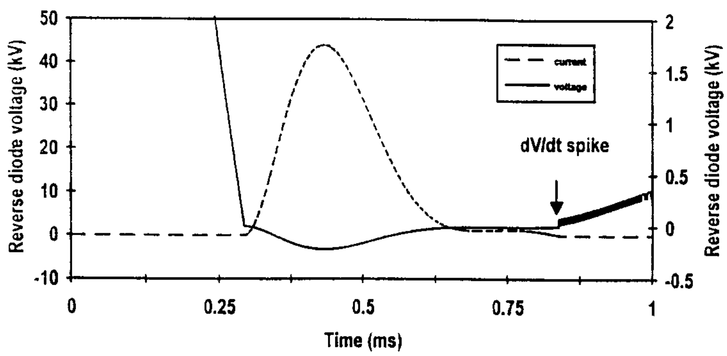


Figure 7. Current and voltage calculations of the first submodule diode with 800-μf of parallel capacitance.

Figure 8. Current and voltage calculations of the first submodule diode with 1600-μf of parallel capacitance.

This resulted in a large dI/dt and subsequent large dV/dt once D1 conduction ceased. Submodules 1 through 5 begin discharging at 0, 40, 80, 120, and 180 μs, respectively. The combination of the 400-μf capacitance (C1) with submodule inductance (L1) and load resistance (R) produce an effective capacitor discharge time of 165 μs for the first submodule. When the diode stops conducting, the series inductance in the buswork surrounding the diode immediately produces a transient voltage (dV/dt) responsible for D1 destruction as described in the previous section. The simulations of D1 forward current and reverse terminal voltage are given in Figure 4, where an initial voltage of 10 kV (maximum system voltage) is assumed for the PFN. The simulations reliably predict the transient voltage waveform; specifically the dV/dt across the diode terminals at approximately 280 μs into the discharge cycle is accurately predicted. Other computer simulations determined that the submodules beginning to discharge at 80, 120, and 180 μs are responsible for the abrupt current turnoff and the magnitude of dV/dt on the first submodule's diode. As the diode current decays exponentially, the final three submodules are switched into the network and substantially increase the voltage across the load. This additional current forces an increased dI/dt through the inductor and diode of the first submodule that drives the current to zero[12]. A solution to the excessive dV/dt problem by expanding the overall pulse width by discharging the last three submodules after the completion of D1 conduction, which is successful in reducing the magnitude of dV/dt on D1, is discussed next. This solution will be referred to as the "delayed" discharge technique and its computer simulation is provided in Figure 6.

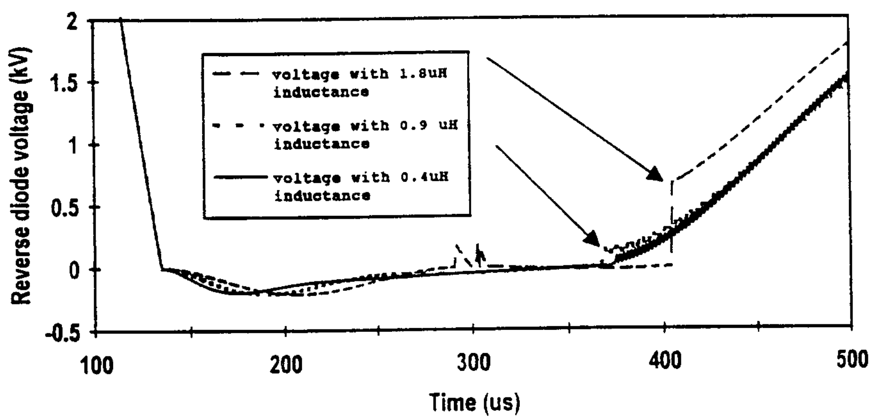


Figure 9. The effect of varied series inductances in the diode circuit. The calculations show the resulting diode voltage as the diode is switched off for the cases of 1.8, 0.9, and 0.4 μH of series inductance.

The result of the delayed discharge simulation, shown in Figure 6 with two submodules discharging 400 μs after the first, is a reduction in D1 dV/dt magnitude by a factor of five compared to the undelayed discharge sequence of Figure 3. To completely avoid an increased diode dI/dt of any submodule, no subsequent submodule should be discharging while a preceding submodule diode is conducting. The main difficulty here is that the system is now limited as to the length of the power pulse width that can be produced by the PFN. This is an extremely confining solution to the dV/dt problem in terms of pulse power flexibility and is not a very attractive solution if pulse shaping is a necessity. Further simulations were performed with PFN discharges in which the total capacitance in the first submodule was varied to minimize the magnitude of the D1 dV/dt. These results are shown in Figures 7 and 8 where the capacitance of the first submodule is increased from 400 μf in Figure 4 to 800 μf in Figure 7 and 1600 μf in Figure 8. The simulations in Figure 8 illustrate that an increase in submodule capacitance (C1) is quite effective in reducing the dV/dt magnitude on the first submodule diode (D1). While the dV/dt in Figure 7 is only slightly reduced compared to that in Figure 4 with the standard 400 μf capacitance, the dV/dt in Figure 8 having a capacitance of 1600 μf is reduced by a factor of five compared to that in Figure 4. The problem with the approach of increasing C1 capacitance, say from 400 μf to1600 μf, is that the total energy of the first submodule is now increased by a factor of four, the PFN output power is increased by 30%, and the total pulse width of the first submodule is now twice as large as in the initial (400 μf) case.

The final investigation was the study of the effects of series inductance in the first submodule diode conduction path. The results of computer simulations where this inductance was varied from 1.8 μH to 0.4 μH are given in Figure 9. The figure shows that the simulation having a diode series inductance of 0.4 μH results in a D1 dV/dt magnitude that is four times less than that of the 1.8-μH case. The dV/dt waveforms are highlighted by the arrows in Figure 9. Minimizing inductance in practice by keeping buswork lengths to a minimum will have a very large impact on the reduction of diode dV/dt magnitudes.

SUMMARY AND CONCLUSIONS

It has been shown through a variety of experimental measurements and computer simulations of a PFN currently used for electric gun applications that crowbar power diodes are subject to rapidly changing voltage signals (dV/dts) which produce catastrophic diode failures for experiments involving both plasma and resistive loads. It was determined that series inductance can produce rapidly changing voltage transients that can exceed the reverse recovery time and voltage limits (dV/dt) of the semiconductor diodes. Our solution to limit the dV/dt problem is to consider diodes that have "softer" recovery characteristics and produce minimal inductive over voltages. Alternatively, the PFN pulse width can be increased such that subsequent submodules discharge only after diode conduction has ceased in the preceding submodules; although this technique will limit the minimum pulse width obtainable for a given PFN. It has been demonstrated that further protection of diodes from excessive dV/dts is possible by increasing the capacitance surrounding each crowbar diode or decreasing series inductance.

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