THE DECADE PERFORMANCE ASSESSMENT PROGRAM

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Abstract

Previous analyses of DECADE Module 1 experiments indicated significant current loss between the plasma opening switch (POS) and an electron-beam load. A program was initiated to diagnose and improve the power flow to assess the performance of a multi-module DECADE system. Power flow measurements between the POS and load indicate high vacuum flow, distributed current loss and azimuthal asymmetries. A decreased load impedance reduces the fraction of the load current flowing in vacuum. Improved plasma source symmetry reduces losses near the load for long conduction times. Increased POS impedance is required to significantly improve the power coupling to the load.

INTRODUCTION

DECADE is a high power generator designed and built for the Defense Nuclear Agency (DNA) by Physics International Company. The system consists of 4-16 modular generators that drive independent electron-beam diodes. Each generator consists of a Marx bank, a water capacitor, six triggered output switches, a water line to sharpen the current rise time, a ~ 4-m-long vacuum line, a plasma opening switch (POS) and a short vacuum line to the load. Previously, experiments [1] were performed on a single generator, DECADE Module 1 (DM1), to predict the characteristics of a multi-module system. The performance of the pulsed power components upstream of the POS are described in Refs. [1] and [2]. With a short circuit at the POS location, the current rises to 1.8 MA in 300 ns. Optimum system performance, as determined by bremsstrahlung output, was found at a POS conduction time of 220 ns, when the generator current was 1.4 MA. The load voltage was about 1.8 MV when the POS opened.

An analysis[3] of the results, using available data, circuit code modeling and radiation modeling indicated that a 700 ± 100 kA, 58 ± 8 kJ electron beam was producing the measured bremsstrahlung, and that about 80% of the load current consisted of vacuum flowing electrons. The difference between the load current and the generator current at the time of maximum x-ray emission, 550 kA, represents loss between the POS and the load. The POS was modeled in the circuit simulation using a flow impedance[4] rising to 1.4 Ω in 28 ns after the 220 ns conduction time, then decaying with a 1/e time of 55 ns. This flow impedance corresponds to a ~ 2 mm vacuum gap in the plasma at the cathode radius.

Based on these results, a research effort was initiated to understand and improve the power coupling from the POS to the load for the DECADE system. The power coupling problem consists of two related parts: decreasing the current losses between the POS and load, and increasing the POS impedance. Two POS techniques are being investigated in this program, the "standard" POS[5] that has been used on DM1 in the past, and the Magnetically Controlled POS (MCPOS) [6] developed at Sandia. The MCPOS will be tested on a second DECADE module, DM2, in the near future. This paper will describe measurements of the power flow between the POS and load for the standard POS on DM1.

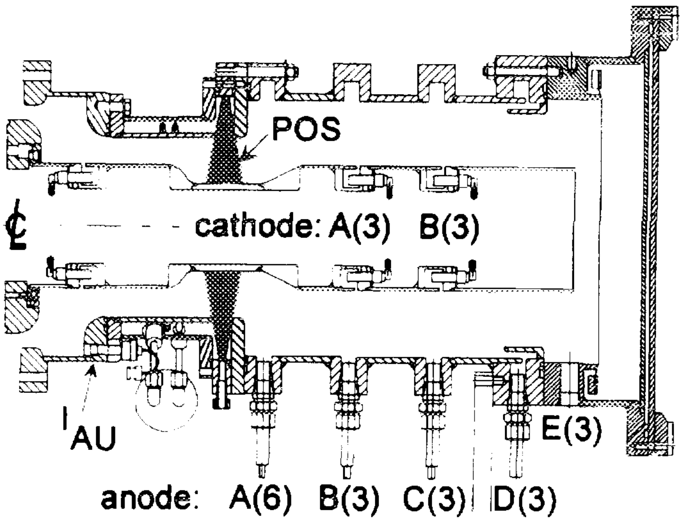


Figure 1. DM1 POS-load region instrumented with current probes.

POWER FLOW BETWEEN THE POS AND LOAD

A sketch of the POS-load region on DM1 is shown in Fig. 1. This is an instrumented version of the configuration used for the experiments cited above. Plasma is injected between the inner and outer conductors a few μs prior to firing the generator using 12 plasma guns. Two gun configurations have been used: direct injection as shown in Fig. 1 and "manifold" injection, where the plasma flows through a 90° bend. The electron density is about 10^{15} cm^{-3} in the electrode gap. The plasma is generated by a surface flashover on Teflon, producing ions of F, C, and possibly H and O impurities. The center conductor radius in the POS region is 4.4 cm, increasing to 6.3 cm downstream. The plasma is injected through a 2-cm long aperture. The distance between the plasma guns and the load anode is 40 cm. The electron-beam diode in Fig. 1 has an anode-cathode (AK) gap of 2.5 cm, resulting in a relatively high load impedance (30 D/r = 12 Ω).

The power flow between the manifold-gun POS and load was diagnosed using dB/dt current monitors at various locations along the anode and cathode as shown in Fig. 1. At most axial locations, three monitors were positioned 120° apart. At the location closest to the POS on the anode, 6 monitors were positioned 60° apart. The monitors were recorded individually to analyze the symmetry of the current flow. Radiation diagnostics were used to supplement the electrical measurements: A filtered pin diode array[7] was used to determine the time-dependent load voltage, a calibrated pin diode was used to determine the electron current and

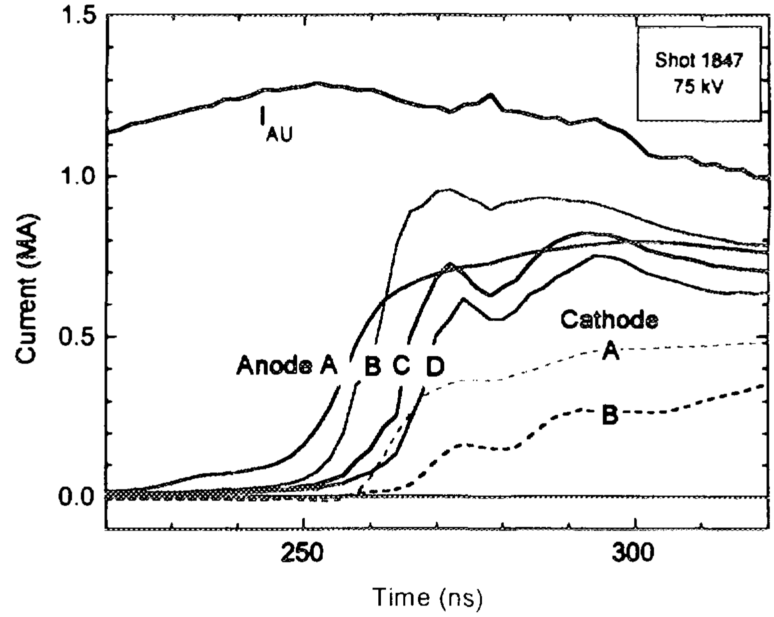


Figure 2. Current waveforms for a typical shot with a high impedance load (30 D/r = 12 Ω).

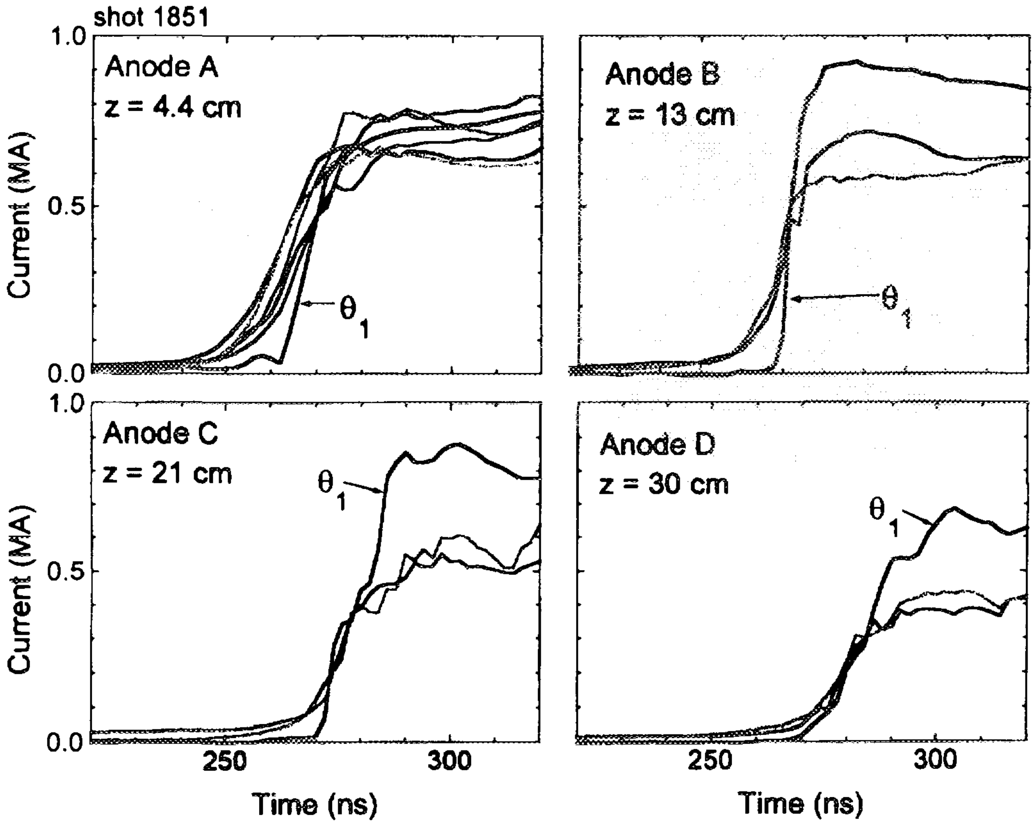
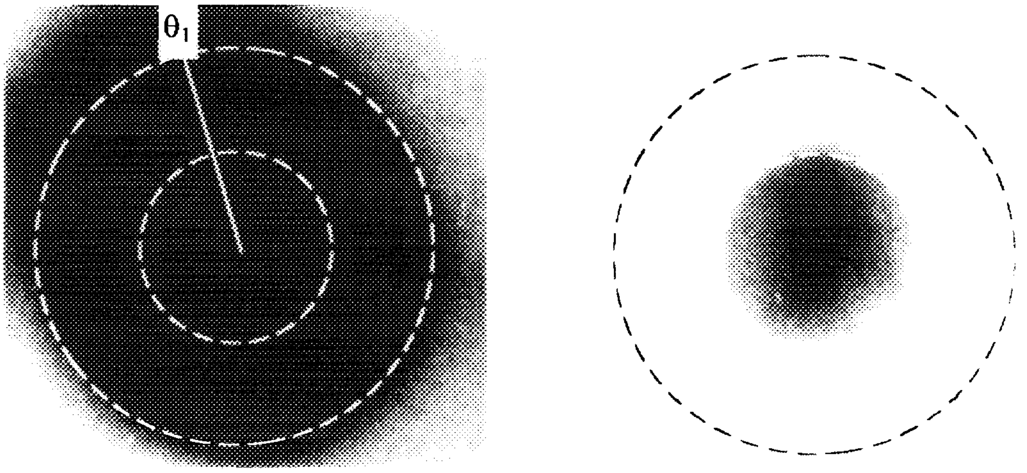


Figure 3. Azimuthal asymmetry of current propagation between POS and load (shot 1851).

radiated energy, and to calculate the load power, energy, and impedance. The measurements could be combined to estimate the POS flow impedance. A time-integrated pinhole camera recorded the end-on x-ray image.

Current waveforms for a typical shot with a high impedance load are shown in Fig. 2. Each waveform is identified by a letter corresponding to those in Fig. 1. Anode currents are indicated by the solid lines and cathode currents by dashed lines. Note that cathode monitor A is at the same axial location as anode monitor B. The POS voltage (not shown in Fig. 2) has a maximum value of 1.8 MV at t = 290 ns. At this time, the generator current is 1.2 MA, the anode monitor closest to the load (D) indicates 700 kA, and 250 kA is indicated by the cathode monitor closest to the load (B). The decreasing trend of current with distance from the POS indicates that these values are probably upper limits to the actual load currents. These measured values agree with the conclusions cited above based on circuit simulations and radiation modeling[3]. About 500 kA is "lost' in the POS-load region, and of the 700 kA total current reaching the load anode, about 450 kA (or more) is flowing in vacuum. The high vacuum current is not unexpected considering the high load impedance.

The anode current waveforms in Fig. 2 show that the current propagates from the POS to the load with a velocity of about 2 cm/ns, ten times slower than vacuum flow in a MITL. If this current propagation corresponds to a current-carrying plasma, the speed is approximately the Alfven speed, implying a plasma density of 10^{12} - 10^{13} cm^{-3}, small compared with the injected plasma density but high enough to have dramatic effects on the power flow. The current propagates slower along the cathode, indicating slanted current streamlines. At the time of peak voltage (t = 290 ns) the current loss is distributed along the length of both the anode and cathode. The POS flow impedance for this shot at peak POS voltage is 1.5 Ω.



shot 1851 (30 D/r = 12 Ω)

shot 2001 (30 D/r = 3 Ω)

Figure 4. End-on x-ray pinhole images for a shot with a high impedance diode and asymmetric current flow (1851) and one with a low impedance diode and symmetric current flow (2001). The broken circles indicate the center conductor and outer conductors. The solid line indicates the angle θ_1.

Variations between the individual current monitors at a given axial location indicate the azimuthal symmetry of the current. An illustrative example of a shot with asymmetric current flow is shown in Fig. 3. The current asymmetry is localized at one azimuth, (denoted θ_1 in Fig 3) where at location A on the anode, one probe out of six rises later than the others indicative of late opening at that location which corresponds to a local high density in the POS. The asymmetry propagates downstream past the B, C, and D probes and has the appearance of a localized current channel, indicating a higher current after the channel passes the probe location because of field lines looping around the localized current channel.

The end-on pinhole camera shows asymmetric radiation patterns when the current is asymmetric, with intense emission from the walls at the same azimuth as the propagating current channel, as shown on the left in Fig. 4. The azimuthal asymmetry is fairly random, but occurs more frequently at longer conduction times. The asymmetry is important for load coupling because it can be related to losses near the load.

The vacuum flow current can be reduced dramatically by using a lower impedance diode load. Current waveforms from a shot using a 6.4 mm AK gap (30 D/r = 3 Ω) are shown in Fig. 5, and the corresponding radiation pattern is shown on the right in Fig. 4. After a ~ 20 ns propagation time, the anode and cathode currents all agree, indicating negligible vacuum flow. There

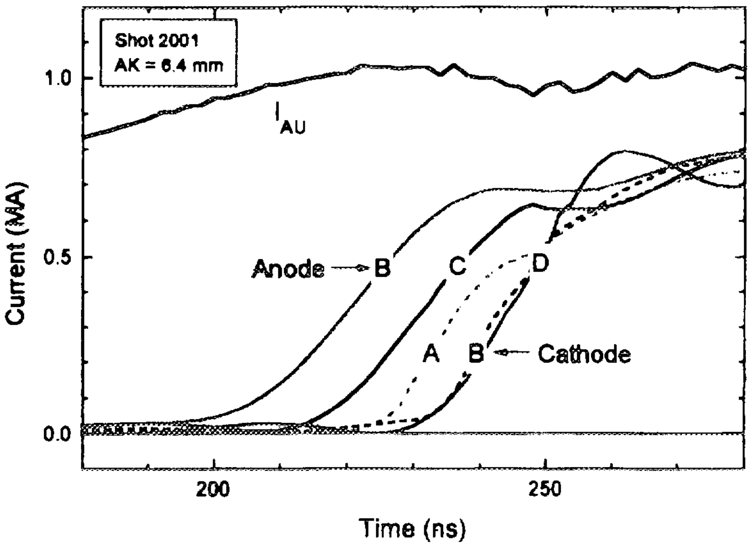


Figure 5. Current waveforms with a low impedance load (30 D/r = 3 Ω) showing negligible vacuum electron flow.

still is substantial current loss, about 300 kA for this shot, but it is now localized near the POS instead of being distributed throughout the entire POS-load region.

In general, low impedance diodes result in increased load energy (80-90 kJ) but longer pulse widths (50-100 ns). Ion currents are inferred in these diodes that constitute 10-30% of the diode energy. This unwanted ion current can be reduced with appropriate diode design. Centered, symmetric radiation patterns are possible with these diodes which is desired for a multi-module system, however, at long conduction times (> 250 ns) the load coupling often deteriorates as the result of asymmetries described above.

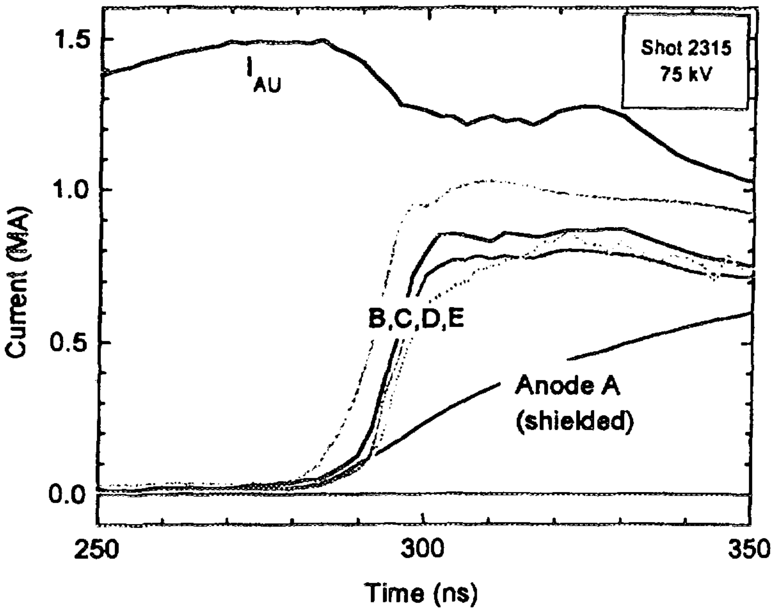


Figure 6. Current waveforms showing reduced downstream plasma effects by improving the POS plasma symmetry.

The downstream plasma effects responsible for the slow current propagation can be ameliorated by changing the plasma sources. For example, using direct-injection plasma guns, doubling the number of guns to 24 and doubling the current and dI/dt in each gun results in the current waveforms shown in Fig. 6. The anode monitors at locations A, B, C, D, and E indicate very rapid current propagation after the C location. The individual monitors at different azimuths indicate very good symmetry. The particular shot in Fig 6 has a 290 ns conduction time, close to optimum for storing the available energy in the vacuum inductance. This plasma gun configuration results in reduced current loss near the load at the longest conduction times on DM1. Current losses are still observed, with 400 kA loss localized upstream of the C location. Improving the power coupling to the load requires increasing the POS flow impedance (increasing the ratio of gap size to radius).

SUMMARY

Previous experiments on DM1 and analyses indicated significant (>40%) current loss between the POS and load. These losses have been diagnosed using current monitors and x-ray diagnostics. With a high impedance diode load, the current losses are distributed between the POS and load, and much of the load current consists of vacuum flowing electrons. The current propagates from the POS to the load with a ~ cm/ns velocity (faster along the anode than along the cathode), indicating a low density current-carrying plasma. At increased conduction times, the current tends to become azimuthally asymmetric, forming a localized current channel that propagates to the load. X-ray images indicate asymmetries that correspond to the asymmetry in the current flow.

The power flow can be changed using a lower impedance load to virtually eliminate the vacuum flow. If this is the only change, however, the current propagation, total current loss and current flow symmetry are unchanged. Changing the plasma sources to direct injection, doubling the number of guns from 12 to 24 and doubling the gun current results in reduced losses near the load at long conduction times, probably because of improved symmetry in the POS plasma. Current losses still persist in this configuration, but they are now localized close to the POS. Improved power coupling to the load requires increasing the effective flow impedance of the POS.

DM1 experiments are planned to investigate methods to increase the POS flow impedance at long conduction times by varying the POS geometry and the plasma sources. POS experiments on DPM1[8] with similar I×t (conduction current times conduction time) products have demonstrated that anode geometry affects performance. Experiments on Hawk [9] and DPM1 [8] have demonstrated improved POS impedance depending on cathode shape and radius. These experiments have achieved POS flow impedances higher than those yet achieved on DM1, indicating the possibility for improvement. Other variations include increasing the plasma length and using "transparent" conductors consisting of wire arrays to reduce secondary plasmas from electrode surfaces. Plasma source variations have included increasing the number of sources and their driving current (as described above), and varying the radial location of the guns. These changes have already indicated improved power coupling.

The best combination of the above POS variations will be compared with the results of the MCPOS tests. This information will allow an assessment of the DECADE performance.

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[1] P. Sincerny, S. Ashby, K. Childers, J. Goyer, D. Kortbawi, I. Roth, C. Stallings, J. Dempsey, *Proc.10th IEEE International Pulsed Power Conf.* (Albuquerque, 1995).

[2] P. Sincerny, C. Stallings, K. Childers, J. Goyer, D. Kortbawi, I. Roth, J. Dempsey, L. Schlitt, these proceedings.

[3] R. J. Commisso, J. R. Boller, D. V. Rose, S. B. Swanekamp, J. M. Grossmann, P. F. Ottinger, B. V. Weber, F. C. Young, and G. Cooperstein, *Proc.10th IEEE International Pulsed Power Conf.* (Albuquerque, 1995).

[4] C. W. Mendel, Jr., M. E. Savage, D. M. Zagar, W. W. Simpson, T. W. Grasser, and J. P. Quintenz, J. Appl. Phys. **71**, 3731 (1992).

[5] J. R. Goyer, D. Kortbawi, F. K. Childers, J. A. Dempsey, I. S. Roth, and P. S. Sincerny, *Proc. 10th International Conf. High Power Particle Beams*, (San Diego, 1994), p. 1.

[6] M. E. Savage, E. R. Hong, W. W. Simpson, M. A. Usher, *Proc. 10th International Conf. High Power Particle Beams*, (San Diego, 1994), p. 41.

[7] J. C. Riordan, J. E. Faulkner, D. Kortbawi, J. S. Meachum, R. S. Mendenhall, I. S. Roth, and B. A. Whitton, *Proc. 8th IEEE International Pulsed Power Conf.*, (San Diego, 1991), p. 390.

[8] J. R. Goyer, D. Kortbawi, P. S. Sincerny, D. Parks and E. Waisman, J. Appl. Phys. **77**, 2309 (1995).

[9] P. J. Goodrich, R. J. Commisso, J. M. Grossmann, D. D. Hinshelwood, R. A. Riley, S. B. Swanekamp, and B. V. Weber, *Proc. 10th International Conf. High Power Particle Beams*, (San Diego, 1994), p. 299.