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TITLE: PROCYON EXPERIMENTS UTILIZING EXPLOSIVELY-FORMED FUSE OPENING SWITCHES

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PROCYON EXPERIMENTS UTILIZING EXPLOSIVELY-FORMED FUSE OPENING SWITCHES*

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Introduction

In this paper we describe results from tests of an explosive pulsed power system designed to deliver 15–16 MA to a plasma flow switch (PFS). The PFS,[1] in turn, has the goal of switching current to a z-pinch load to produce a 1-MJ implosion for x-ray generation experiments. The system consists of a MK-IX magnetic flux-compression generator,[2] a coaxial inductive store, an explosively formed fuse (EFF) opening switch,[3] and a vacuum power flow/PFS assembly. Figure 1 shows a completed assembly ready to test. Computational modeling of this system is described in another paper in this conference,[4] and important design considerations have been previously published.[5] Vacuum diagnostics are also discussed in a separate paper in this conference[6] as are results from a test in which a conventional foil-fuse opening switch replaced the EFF.[7]

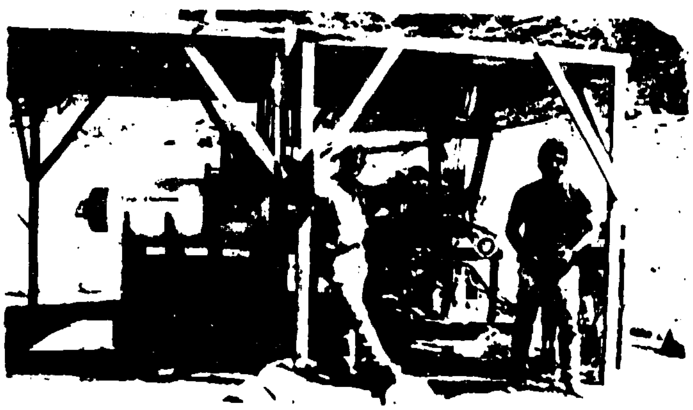

Fig. 1. A Procyon system ready to test. The three major sections are the MK-IX generator (left), the inductive store and opening switch (tri-axial center section), and the vacuum power flow section (right) seen with radiation diagnostic tubes attached.

We have performed two development tests of the Procyon system. A preliminary reduced energy test (Shot I) delivered ~13.6 MA to a 25-nH PFS load, and imposed a large voltage spike on the EFF at nominal pinch time without failure. In a full-energy test (Shot II), the system delivered 20 MA to the EFF without suffering unexpected losses, and demonstrated the proper onset of EFF opening. In the 20-MA test, mistiming between the EFF and the load isolation switches led to transmission line failure that disguised late time opening switch performance and diverted most of the current pulse away from the PFS load. These two tests have provided important system characterization information. In some cases design expectations are confirmed and in others adjustments to initial expectations are called for. Performance details are presented below.

Apparatus

A schematic of the Procyon system is given in Fig. 2 and the physical construction is illustrated in Fig. 3. The capacitor bank consists of two 600-kJ, 20-kV modules operated in series. These provide over 400-kA initial current to the 7.2-μH MK-IX generator and 57-nH storage inductor, L_s. The EFF, which is an initially low resistance (40 $\mu\Omega$), completes the circuit. The explosive action of the MK-IX closes the crowbar switch, S_c, trapping the initial magnetic flux in the circuit. The generator subsequently compresses the flux into L_s (~60% of the initial flux is lost to resistances) yielding a current gain of >40. At opening time, the EFF develops enough resistance to divert current through the detonator-actuated load isolation switch, S, to the remainder of the circuit in a time characteristic of PFS operation (~4 μs). L_T represents the inductance of the transmission line and radiation baffles. The PFS inductance increases as the plasma flows down the coaxial gun.

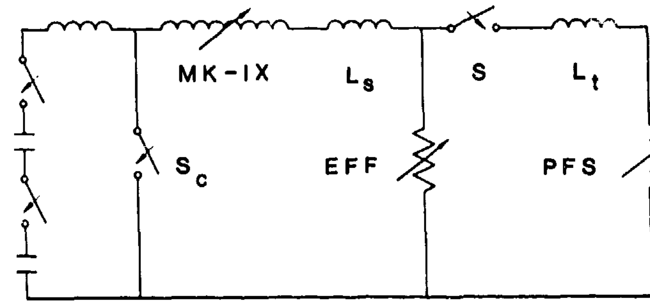

Fig. 2. Schematic of the Procyon system. The MK-IX model derives from experimental data and the EFF model was initially scaled from small-scale experiments. The PFS model is generated in a 2-D magnetohydrodynamic computer code.

Results

The purpose of the Shot I was to verify the performance at reduced energy and Shot II was to subject the system to full current and look for deterioration of performance due to increased currents and magnetic forces. The energy levels were determined by charging the capacitor bank to 16.3 and 18.4 kV, respectively, and Fig. 4 shows the current in L_s from the two tests. Both curves are ~10% lower than initially expected and we have examined the data for possible reasons. Figure 5 shows the voltage measured across the EFF on Shot II prior to the onset of opening. Also shown is an integration that curve, which gives the flux lost from the system due to the EFF resistance. Similar curves are available for Shot I. These losses are about what we expected and show that the reduced current is not due to unexpected losses in the EFF. We will present data below that suggest L_s is larger than intended, which can account for the reduced current.

The closing switches, S, illustrated in Fig. 6, consist of explosively driven annular jets that penetrate 1.25-mm Mylar insulation. The voltage measured across the closing switches on Shot I is shown in Fig. 7. The switches closed at the desired time and provided a very abrupt turn on. In addition, we measured current in each of the six switches and they turned on with good simultaneity as shown in Fig. 8. A baseline shift on one channel caused all but initial data to be lost. From an average of the five channels in the figure, we conclude that the sum of the six channels is between 13.3 and 13.8 MA.

Figure 9 shows the currents in L_s, I_s, and in the load, I_l, for Shot I. These are obtained from Faraday rotation and Rogowsky coil data. The 13.8-MA peak load current observed is at the high end of the range inferred from Fig. 8 data. Based on these two data sets we assume, for the following analyses, that 13.6 MA was transferred. For Shot I the PFS had a high mass wire array that moved very little before peak current, adding only 1 or 2 nH to the load. Using 18.3-MA (peak store current before flux compression in the EFF) for

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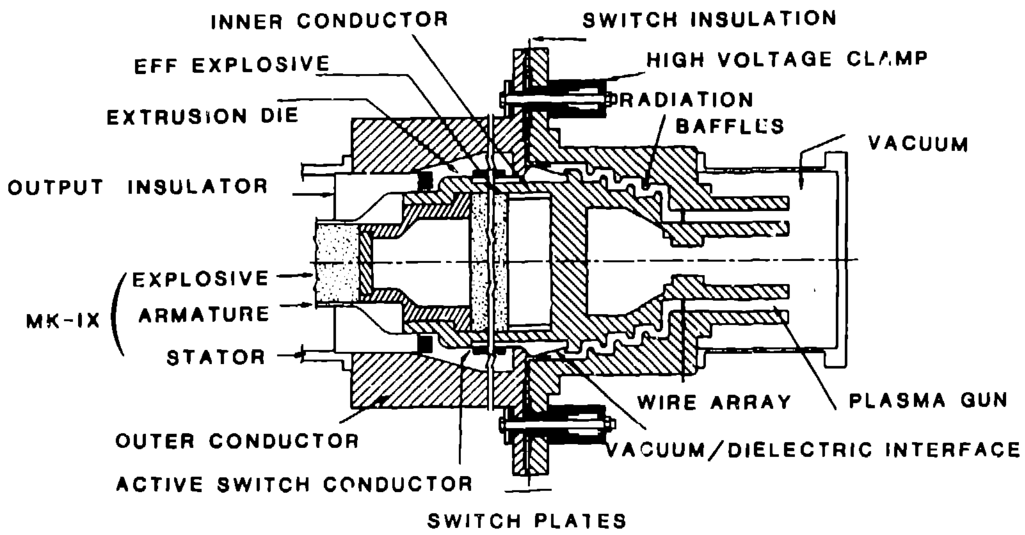

Fig. 3. Components of a Procyon system. The MK-IX stator (output only is shown) attaches to the outer conductor, and current returns to the armature through the 0.80-mm-thick active switch conductor. The volume thus enclosed, including any inductance remaining in the MK-IX, is the storage inductance, L_s. The active switch conductor is driven into the extrusion die by the EFF explosive. The opening switch voltage develops across switch plates that are held in position by high-voltage clamps. The closing switches (located between the high-voltage clamps) puncture the switch insulation on command. This allows current to flow along the outer radiation baffle, through the wire array and return to the armature along the inner radiation baffle and inner conductor. Plasma from the electrically exploded wire array is driven by magnetic pressure down the plasma gun and, in the version shown, pinches off the end of the gun. The cut line through the EFF foreshortens the appearance of the EFF. The EFF explosive is 28 cm in diameter and 76-cm long.

I_s, 13.6 MA for peak load current, and 25 nH for total load inductance ($L_T + L_{PFS}$) at peak, the calculated value of L_S is 72 nH. This is larger than the design value by 15 nH. System calculations have been performed using 72 nH and the results give a very good match, not only to current transfer data, but also to the curves in Fig. 4. We conclude that this is the correct interpretation of the data and we are examining our MK-IX inductance model where we believe the inconsistency occurs.

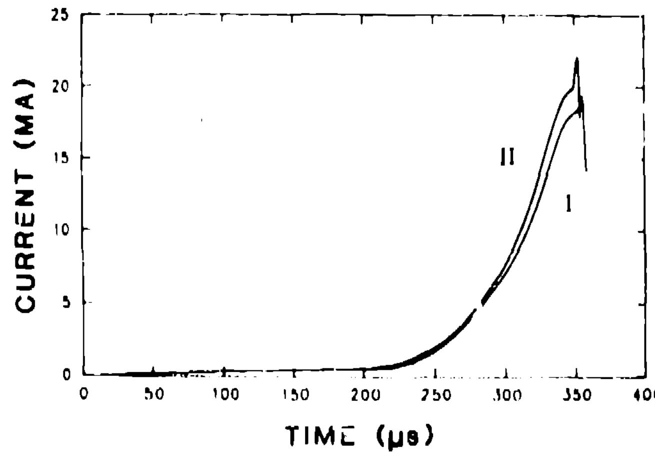

Fig. 4. Storage inductor current profiles from Shots I and II. Initial current from the capacitor bank occurs at ~16 μs, and generator crowbar occurs at ~155 μs. The spike on the peak of each waveform is due to flux compression in the EFF.

Figure 10 shows dI/dt measured in the load. The width of the positive pulse shows that most of the current was delivered in ~3 μs. The negative spike was produced by a rapid inductance increase that occurred when the PFS plasma pinched off the open end of the gun. This imposed a >250-kV spike at the vacuum/dielectric interface and a >200-kV spike at the EFF. Because the negative dI/dt measured in the storage inductor is of equal magnitude, we conclude that no reconduction occurred in the EFF.

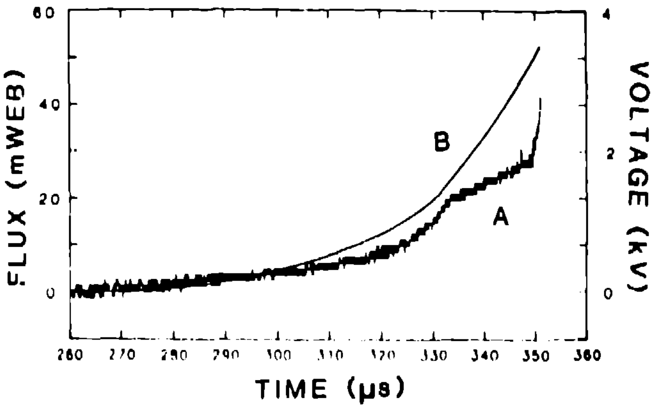

Fig. 5. (A) Voltage measured across EFF prior to actuation on Shot II. (B) Integral of (A), giving the flux lost from the circuit due to EFF resistance during the conducting phase. In 60-nH, 53-mWeb represents ~880 kA, which is close to the initially predicted loss.

On Shot II, the EFF opened relatively early compared to Shot I. We have subsequently discovered sources for the timing difference, but as a result, the high voltage shown in Fig. 11 developed across the opening and closing switches. The voltage peaked at 72 kV when a breakdown occurred near the vacuum/dielectric interface. This not only bypassed the detonator switches, which are seen to close at 355.2 μs as planned, but also caused a failure to occur across the vacuum/dielectric interface that diverted most of the current away from the load.

One of the most important purposes for Shot I was to ascertain the resistance profile of the EFF in this configuration. Pretest calculations were based on an extrapolation of small-scale data.[8] Figure 12 compares the extrapolated data with the data curves from Shot I. In addition, data obtained from Shot II prior to breakdown are shown. The portion of Shot II shown is a valuable addition to our knowledge that cannot be

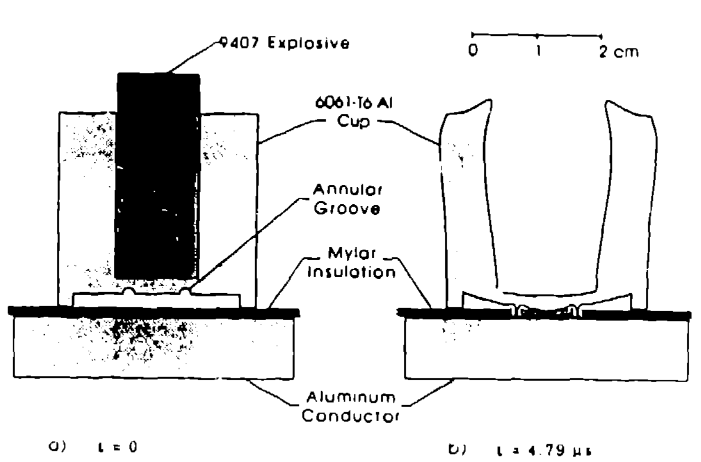

Fig. 6. Explosive-actuated closing switches used on Procyon tests. (a) cross-section of the initial configuration. (b) 2-D hydrodynamic code calculation showing the annular jet penetrating the Mylar insulation 4.79 μs after the explosive is detonated. Each test has six switches in parallel to provide symmetric current flow to the PFS.

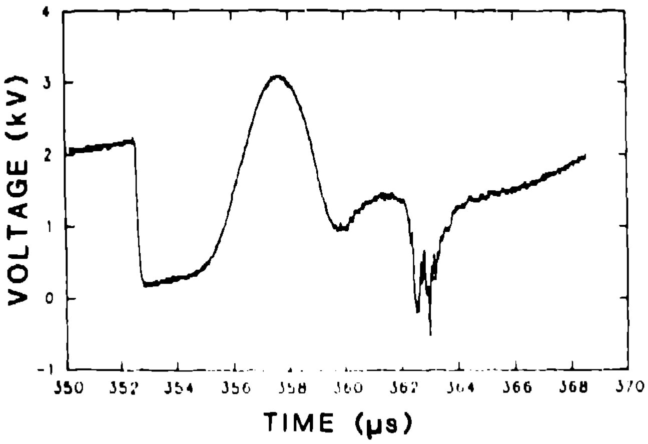

Fig. 7. Voltage across closing switches on Shot I. The abrupt break at 352.2 occurs when the switches close. The 3-kV positive spike at 358 and the negative spikes at 363 are features due to dI/dt and ~0.6-nH circuit inductance inside the voltage probe loop. The resistance of the switches at 360 μs is ~0.08 mΩ.

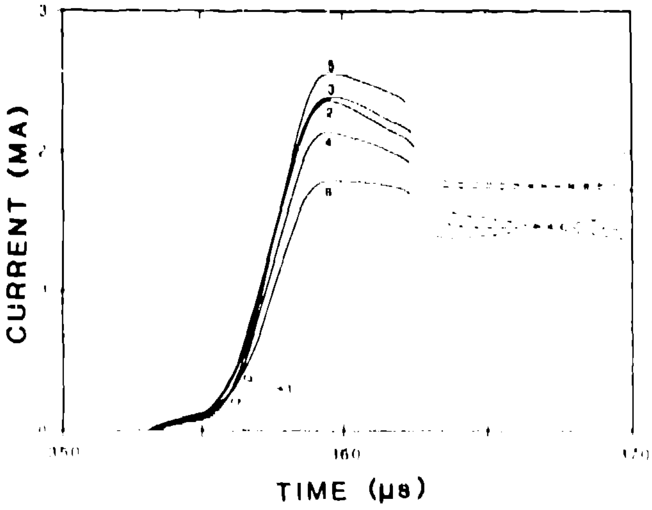

Fig. 8. Current in five of the six closing switches on Shot I. The signal from Channel 1 went offscale due to a ground loop. The two points given show the signal strength on Channel 1 before it was lost.

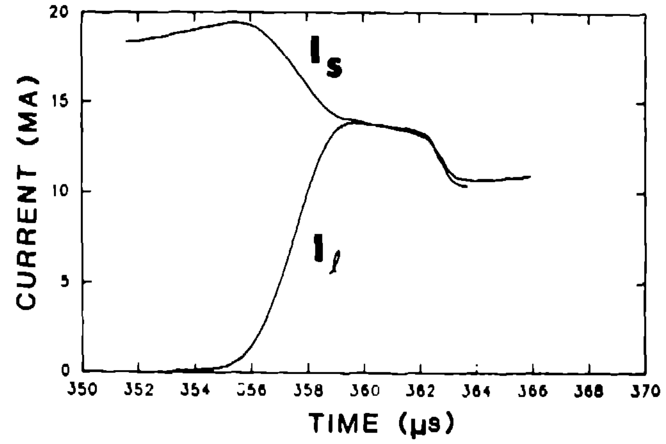

Fig. 9. I_s and I_l for Shot I, demonstrating total current transfer with a 10–90% risetime of <3 μs. In addition, the current drop at ~362 is due to the change in inductance as the plasma exits the gun and shows that the vacuum/dielectric interface and EFF have not failed.

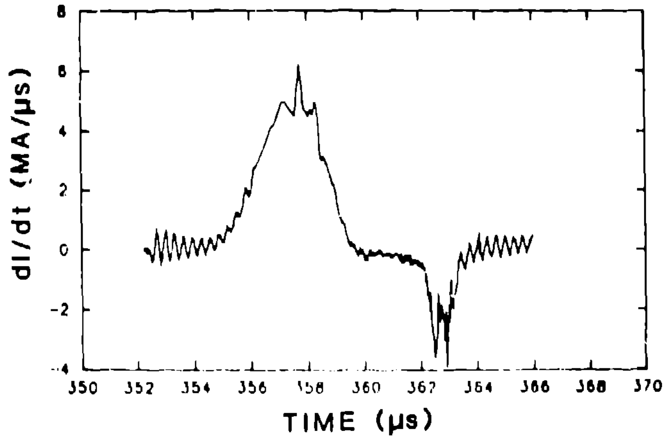

Fig. 10. Composite Faraday rotation and Rogowsky coil measurement of dI/dt in the vacuum region on Shot I. The positive spike indicates the rate of current transfer to the load, and the negative spike the effects of the pinch of gun plasma off the open end of the gun.

Among the reasons for the early EFF opening on Shot II is a more uniform actuation of the EFF. We infer the improved performance from the curves shown in Fig. 13. These curves show dI/dt measured in the storage inductor during the early phases of EFF operation and reflect the rate of flux compression occurring as the EFF is actuated. The more abrupt increase to a higher value shown at 349.5 μs indicates a more simultaneous expansion of the EFF. We have modeled the system to determine how assembly misalignment contributes to asimultaneity and we have found sources for such errors in the hardware specifications. These errors were found and corrected by assembly technicians in Shot II, but were never found prior to Shot I. The shorter duration of the positive signal on Shot II is due to the EFF passing more quickly through the regime where $(dL/dt + R)$ is negative. There are several factors that contribute to this. A thorough analysis of the effect of the asymmetry is extremely complicated and has not been performed. However, a simple model suggests that the asymmetry accounts for some of the difference. In addition, we expect a slightly faster switching due to the higher current density of Shot II, due to both long and short-term I^2R heating effects. Coupling the I^2R heating and asymmetry effects will further add to the difference. For now we are concentrating on reproducing the high-quality, high-current Shot II.

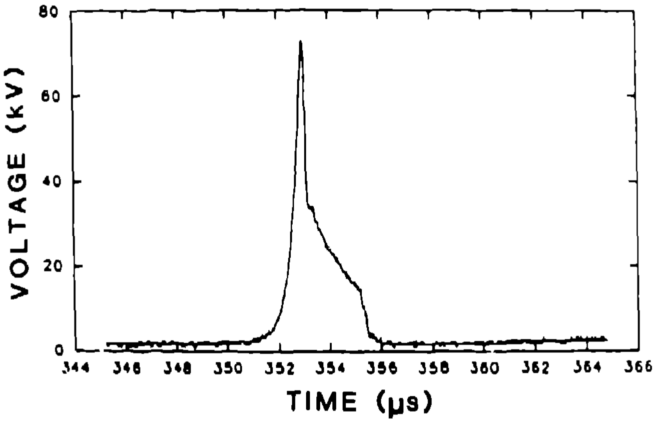

Fig. 11. Voltage measured across the switch plates on Shot II. This is the voltage developed across the EFF until the time of the 72-kV peak when a breakdown occurred near the vacuum/dielectric interface. From that time until ~355.2 μs, when the closing switches closed as commanded, this is the voltage across the breakdown channel.

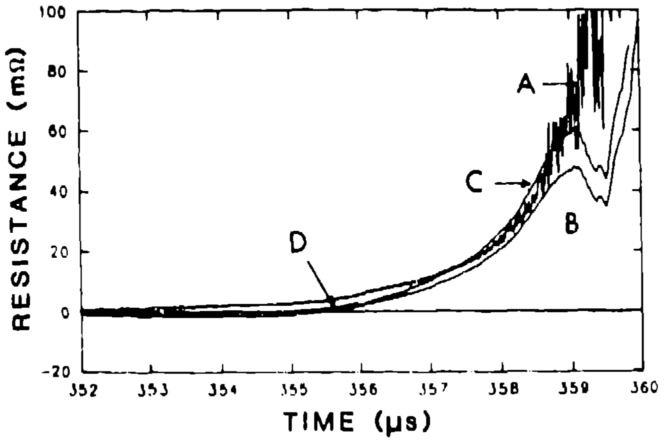

Fig. 12. (A) Resistance from small-scale tests multiplied by 1.7 to correct for geometric differences between small and large tests. (B) R_{eff} from Shot I, assuming nominal storage inductance of L_s = 57 nH. (C) R_{eff} from Shot I, assuming L_s = 72 nH, which is self-consistent with other data. (D) R_{eff} from valid portion of Shot II. The time scale of (D) is shifted arbitrarily for better display. The negative region of (B) and (C) are due to the fact that we cannot accurately calculate the dL/dt produced in the EFF, and ignore it in calculating $R_{eff} = L_s \dot{I}_s/(I_s - I_{load})$. Both (A) and (D) have accurate early time resistance curves determined by $R_{eff} = V_{eff}/I_s$.

Conclusions

From our initial tests of the Procyon system we are able to reach important conclusions. The most important is that the EFF will actuate as predicted in a circuit that has generated 14.4 MJ in an inductive store. We, therefore, have the capability of transferring current to a 25-nH load in less than 3 μs. The EFF will not only sustain the current transfer, but also a voltage spike generated at the load after current transfer is complete. Of the 12 MJ generated in our reduced energy test, 9 MJ was still available when the PFS plasma reached the end of the gun. Based on these numbers, we should have ~11 MJ available to drive an implosion on a full-energy test. Assuming a 10-nH inductance increase in the implosion, we would generate a 900-kJ implosion, which is very close to our 1-MJ goal. We believe other improvements will allow us to meet, or exceed, that goal.

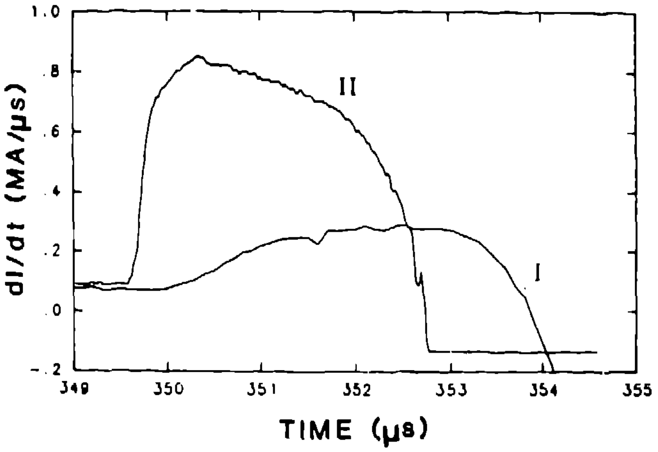

Fig. 13. dI_s/dt from Shots I and II. The Shot I data are shifted earlier by 1 μs to account for the difference in the time the EFF explosive was detonated on the two tests. The time scale is that for Shot II.

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