Development of a Hydrogen Electrothermal Accelerator for Plasma Fueling.

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Abstract

We have developed a prototype high velocity pneumatic pellet injector which utilizes hydrogen plasma propellant generated in a high current arc discharge. A single barrel pneumatic pellet gun has been fitted with a cylindrical arc chamber interposed between the hydrogen propellant inlet valve and the gun breech. The chamber incorporates a ceramic insert for generating vortex flow in the incoming gas stream, which provides azimuthal arc stabilization. The arc is initiated after the propellant valve opens and the breech pressure starts to rise; a typical discharge lasts 150-300 microseconds with peak currents up to 2 kA. The gun has been operated with 4 mm diameter by 6-11 mm long deuterium and hydrogen pellets. At 100 bar breech pressure (hydrogen propellant), the arc characteristics are $\langle V \rangle = 350\text{-}800$ V, $\langle I \rangle = 600$ A, so that 60-150 joules of electrical power is dissipated. Pellet speeds increase by 300-500 m/s depending on the projectile mass, which typically represents a 10 joule increment in the pellet kinetic energy. Velocities up to 1.7 km/s for deuterium pellets and 2.0 km/s for hydrogen pellets have been achieved. Comparing these data to muzzle velocities calculated from lossless, one-dimensional compressible flow gun theory demonstrates that substantial propellant heating, resulting in increased propellant sound speed, has been achieved.

I. Introduction

Plasma fueling via. injection of solid hydrogenic pellets has expanded the operating range for tokamaks to higher densities[1,2] than attainable with gas puffing. Pellet injection has also resulted in improved plasma energy confinement[1-5] in tokamak discharges for which the pellet or pellets penetrate deep into the plasma core. Deep penetration ($\Delta \geq a/2$) can be achieved for moderate size ($\Delta n_e/n_e \sim 0.5$) pellets injected into ohmic discharges with $T_e \leq 3$ keV at pellet velocities attainable with present technology ($v \leq 1.6$ km/s). Deep penetration in hotter ohmic plasmas or in plasmas with suprathermal populations (e. g. fast ions from auxiliary heating, alpha particles from fusion reactions) may require higher injection velocities than attainable with single stage light gas guns or mechanical accelerators, however.

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We report here the development of a high velocity pneumatic accelerator for solid deuterium or hydrogen pellets. Dense hydrogen plasma is generated in a high current arc discharge initiated in the hydrogen propellant gas stream of a single-shot pneumatic gun. The increased gun breech pressure and propellant sound speed result in higher sustained projectile acceleration. Pellet velocity increases as large as 0.5 km/s at electrical dissipation to kinetic energy conversion efficiencies as high as 10% have been achieved at low electrical power levels without damage to the projectiles or to arc electrodes and gun components. Operation at higher power levels or with multi-stage plasma arc accelerators appears to be a promising means of attaining pellet velocities in the 2-5 km/s range.

II. Experimental Details

The accelerator consists of a single-shot "pipe gun" deuterium pellet injector, as described in Ref. 6, assembled together with the vortex-stabilized plasma jet generator, as shown in Fig. 1. Pellets are formed by condensing deuterium (or hydrogen) in the annular hole through the liquid-helium-cooled copper block. The 85 cm long gun barrel is attached to the cold block through a stainless steel flange, itself sealed to the copper block with indium wire. Another stainless tube, which admits propellant to the gun, penetrates the guard vacuum enclosure and connects to the plasma generator via an insulating break (not shown). High pressure hydrogen gas is delivered to the arc discharge enclosure from a fast valve of the type described in Ref. 6. Vortex flow is generated in the incoming hydrogen gas stream with a Macor insert machined to admit the hydrogen gas through eight 1/16" diameter holes canted at approximately 30^0 off the radial direction. Arc plasmas are initiated between the tungsten cathode and graphite anode by a 20 kV breakdown initiation pulse. The arc is powered from a single stage, ignitron-switched capacitor bank supply connected through an inductor and current limiting resistor network. The supply can deliver current pulses up to 2 kA of 200 microseconds duration; after breakdown the arc behaves as an 0.2-0.5 ohm resistive load. Arc currents are measured with a current transformer mounted around the cathode lead; arc voltages are measured differentially using a pair of high voltage probes connected across a 100 ohm safety resistor wired in parallel with the discharge assembly. The gun is fitted with piezoelectric pressure transducers at both the outlet of the hydrogen propellant valve and at the gun breech. Pellet velocities are determined by time-of-flight between an LED/phototransistor optical detector mounted at the gun muzzle and an accelerometer instrumented aluminum target located 1.2m downstream from the muzzle.

III. Results and Discussion

Shadowgraphs of some of the pellets formed during gun operation at various temperatures and fill pressures are shown in Fig. 2. The pellet length is determined by the gas fill pressure and by the temperature differential maintained between the condensing region and two copper blocks brazed to the gun barrel and propellant tube. These are connected thermally to the main cooling block by short pieces of copper braid and are maintained at the desired temperatures by resistance heating. After pellet condensation, the barrel and breech tubes are evacuated and the breech fill line is sealed. The arc is triggered as propellant gas is admitted to the discharge chamber. A black and white photograph of a helium gas plasma jet obtained by firing the plasma generator directly into air is shown in Fig. 3. The spatial uniformity of the jet and the absence of hot particulate blowby as a result of electrode erosion are readily apparent from this figure. Individual arc electrodes have been subjected to hundreds of shots at this power level without replacement. Some anode erosion is evidenced by the deposition of very small amounts of graphite around O-rings and in the pressure transducer ducts over a period of several runs. No damage to either the cathode or to the anode is evident by visual inspection, however.

Transient gun diagnostic data from pellet shots with and without arc initiation are shown in Figures 4-6. In the data of Figure 4, which were obtained for fairly massive 4mm diameter by 11mm long deuterium pellets, the arc was triggered (Fig. 4a and 4b) at about 1200 microseconds as the hydrogen inlet pressure reached the 600 psi level (Fig. 4c). The high current portion of this discharge lasted for about 600 microseconds, during which time the arc voltage dropped to about -400 V. At approximately t = 1600 microseconds the arc current collapses to a level on the order of a few amps while the arc voltage rises, possibly as a result of parasitic breakdown, such as corona; all conduction ceases at around 2400 microseconds and the cathode potential rises to capacitor bank level. The breech pressure diagnostic shows a roughly two-fold increase over the no arc level during the high current portion of this discharge (Fig. 4d). We should note here that this pressure is measured well outside the arc radial boundary; the pressure at the arc center may be much higher. Approximately 60 J of energy was dissipated in the arc in this shot, resulting in the 1.0 km/s to 1.3 km/s increase in pellet speed (Fig. 5a and 5b). This represents a conversion efficiency of electrical power to projectile kinetic energy of 10%.

Data for a pair of shots with 4mm diameter by 10mm long hydrogen pellets are shown in Figure 6. As per the shot of Figure 4, the time at which the pellet exits the gun muzzle in the shot with the arc is about 0.6 ms earlier than the exit time for the comparison shot without the arc (Fig. 5c and 5d). The phototransistor signal trace is a single pulse approximately 4-8 microseconds wide, indicating a single intact pellet. The larger amplitude shock signal (Fig. 5d) generated by the impact of the plasma accelerated pellet further indicates the presence of a higher kinetic energy projectile which follows the line-of-sight trajectory to the target. For this shot, the anode section bore diameter was enlarged from 0.4 cm diameter to 1 cm diameter resulting in increased arc resistance and electrical dissipation, particularly as the propellant inlet pressure rises to its maximum value (Fig 6c). The arc in this shot was triggered slightly earlier in time with respect to the hydrogen gas inflow due to breakdown voltage limitations. The 6.4% conversion efficiency for this shot should be higher with optimization of the arc timing relative to the propellant gas inflow.

Pellet velocity data from several pairs of shots with and without arc initiation are plotted in Figure 7 versus the muzzle speed expected if the pellet base pressure were sustained at the maximum breech pressure value during the entire acceleration interval (the expected gun performance in the limit of infinite propellant sound speed). Also shown are hydrogen and deuterium pellet data obtained from the repeating pneumatic injector (Reference 10) and theoretical curves for the performance of finite sound speed pneumatic guns. These results are consistent with velocity increases observed in earlier work (Reference 7) in which hydrogen propellant was heated from room temperature to 400^{0} K via resistance heating. By comparing the theoretical curves with the plasma accelerated pellet data, we may infer (1) that the propellant heating has resulted substantially higher propellant sound speeds, and (2) that the effect of the heating is not offset by high levels of electrode ablation generated impurities.

We should make reference here to the efficient (10-20%) performance of single and multi-stage ablation fueled electrothermal guns designed for accelerating gram-size projectiles to 2-5 km/s speeds (Ref. 8). We should also note that theoretical calculations of electrothermal plasma gun performance indicate that hydrogen plasma will be the ultimate propellant in that it affords high propellant sound speeds at lower levels of power loss by radiation when compared to ablation plasmas produced from solid hydrocarbon materials (Ref. 9). Thus, the next efforts in this work will include modeling to determine the plasma power balance as dependent upon arc operating parameters, such as input power and arc geometry. In addition, a high energy pulsed power supply is under construction with the aim of obtaining plasma temperatures in the 1 ev range; development of multi-stage accelerator technology to sustain the high projectile base pressures over long acceleration paths is being considered. Speeds on the order of 7 km/s for 10 mm long deuterium pellets launched in a 5 m long accelerator might be attainable with 1 ev hydrogen plasma propellant at 100 bar supplied pressure.

IV. Acknowledgements

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Figure Captions

1. Single-shot pellet gun with plasma generator.

2. Shadowgraphs of pellets produced in pellet gun: (a) 11 mm long deuterium pellet, (b) 6 mm long deuterium pellet, (c) 9 mm long hydrogen pellet.

3. Helium plasma jet produced by vortex-stabilized arc discharge.

4. Diagnostic data for 11 mm long deuterium pellets; (a) arc voltage, (b) arc current, (c) propellant pressure at fast valve outlet, and (d) propellant pressure at gun breech. The dashed curves are for comparable no-arc shots.

5. Time-of-flight diagnostic data; (a) 11 mm long deuterium pellet launched with gas alone, and (b) with arc heating. Time-of-flight diagnostic data for 10 mm long hydrogen pellets launched (c) with gas alone, and (d) with arc heating.

6. Arc and propellant characteristics as in Figure 4 for 10 mm long hydrogen pellets, with (solid curves) and without (dashed curves) arc ignition.

7. Pellet velocity plotted versus the constant base pressure projectile speed calculated from the maximum breech pressure. The data labeled RPI were taken from Figures 3 and 7 of reference 10.

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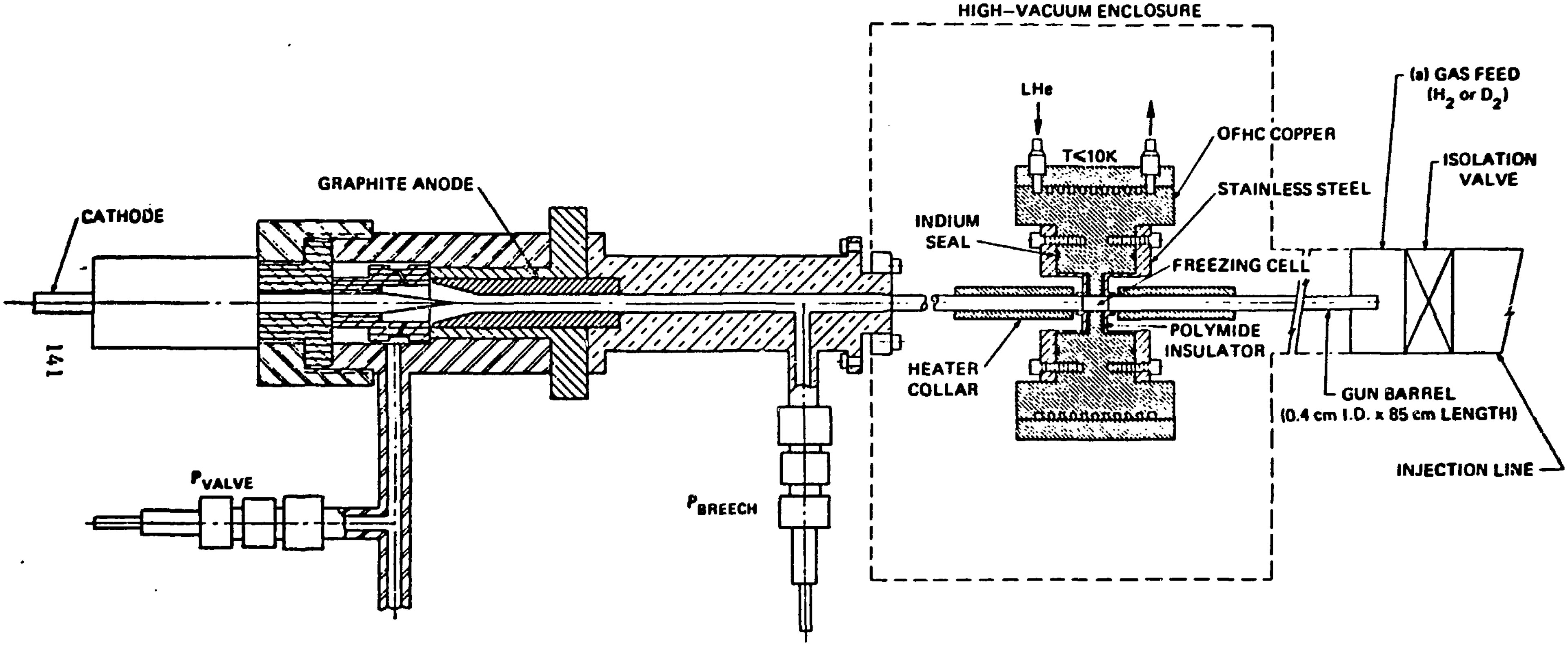

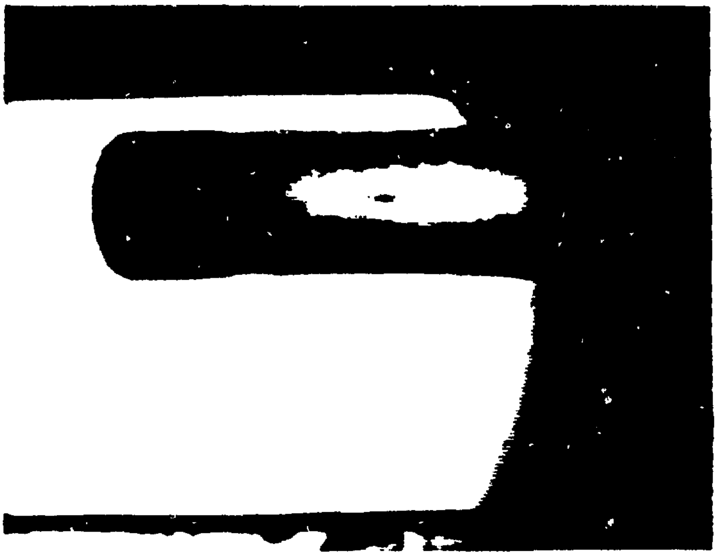

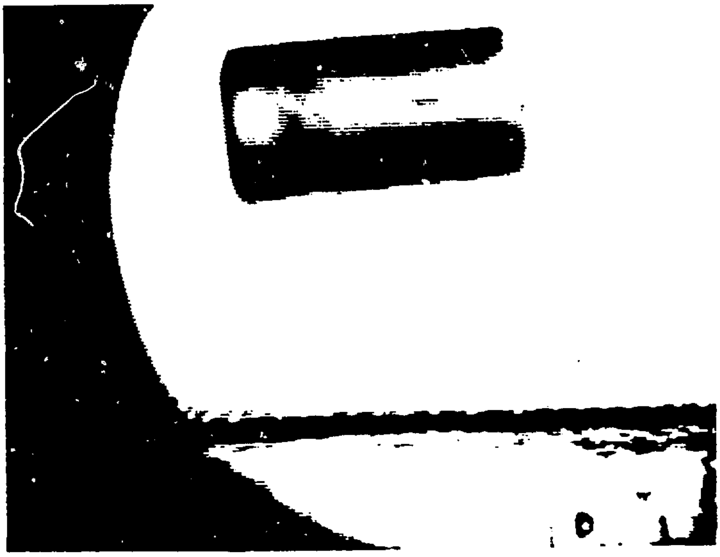

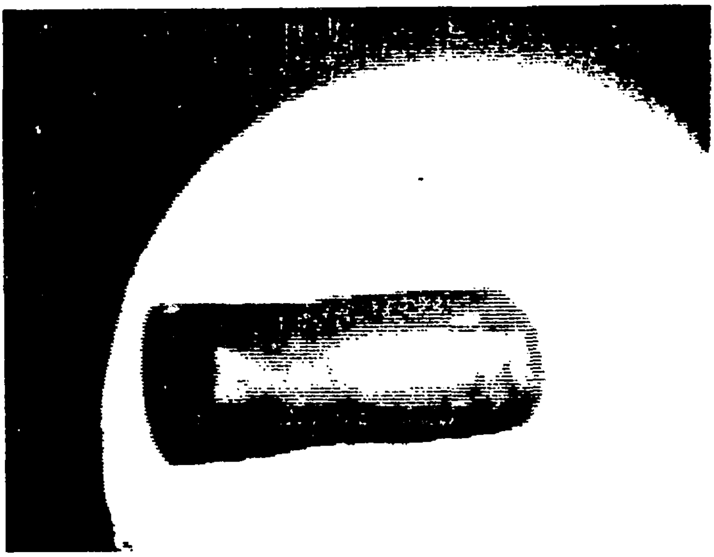

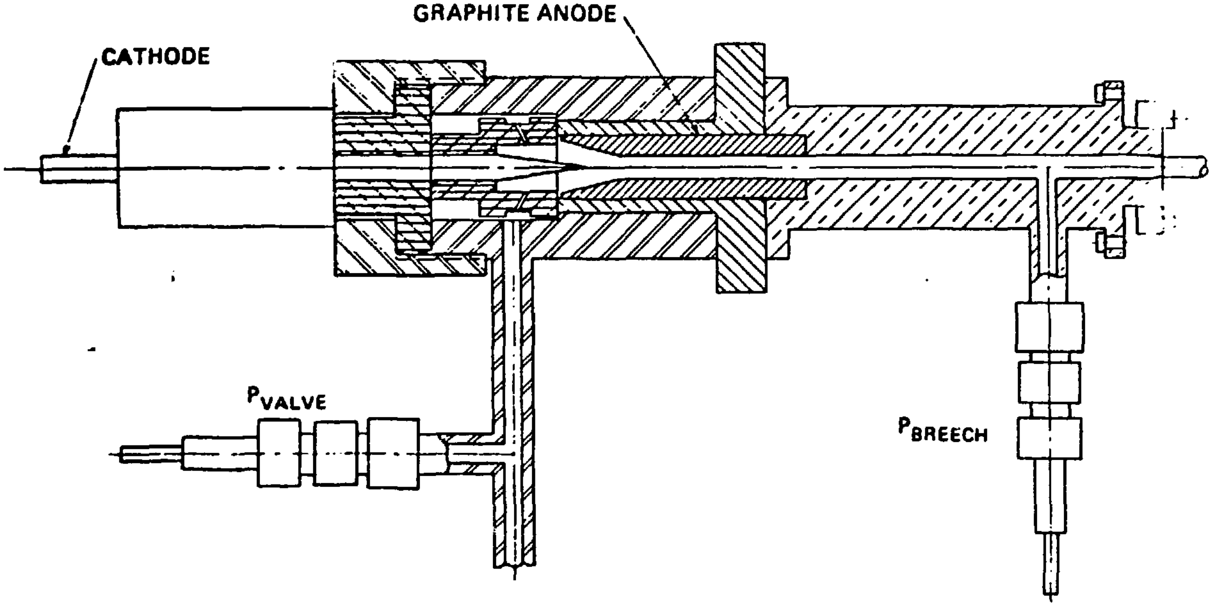

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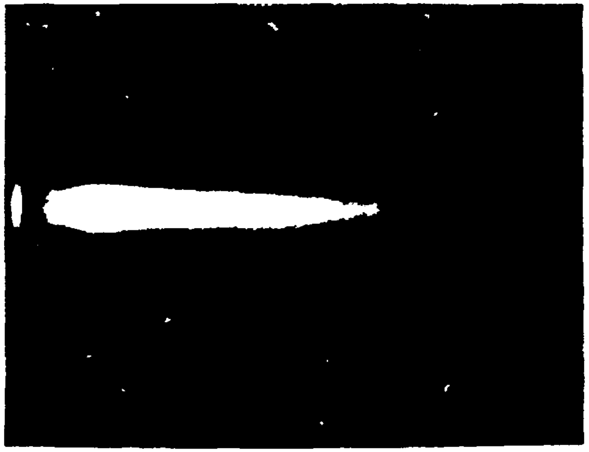

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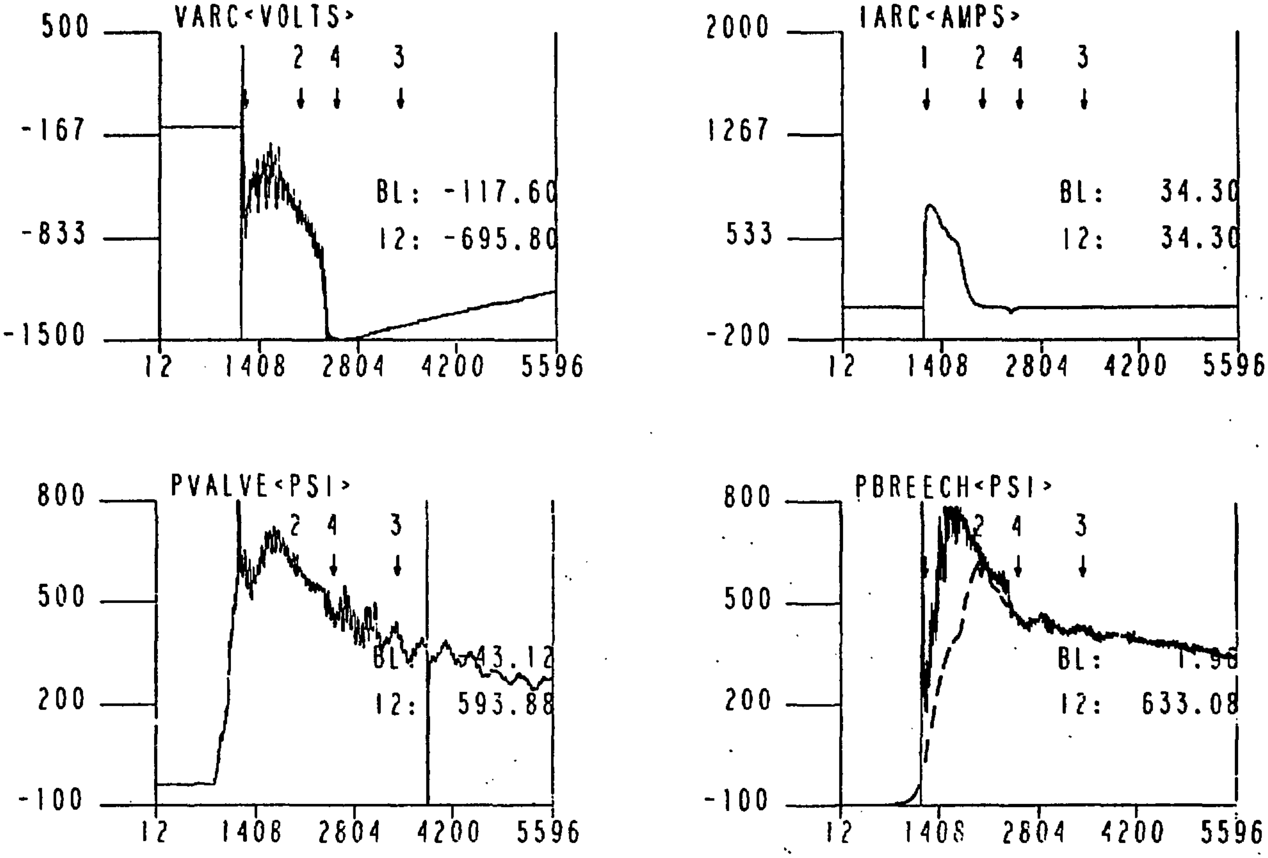

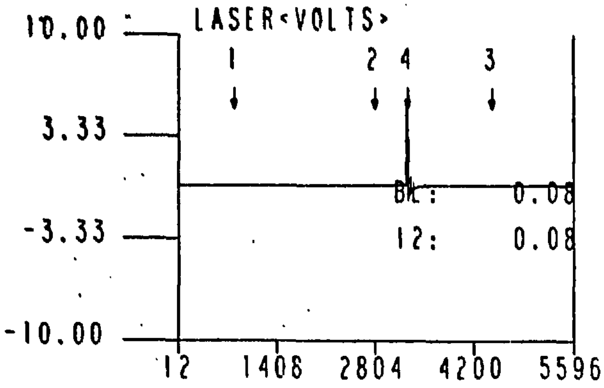
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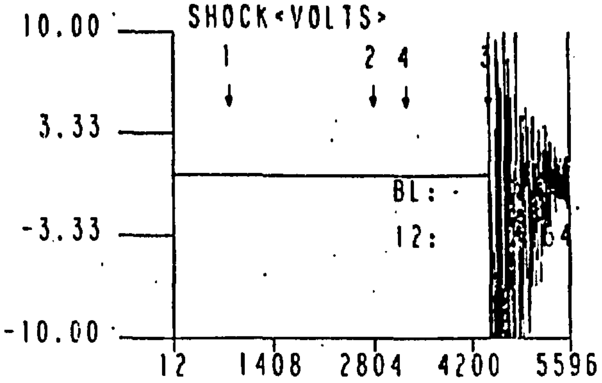
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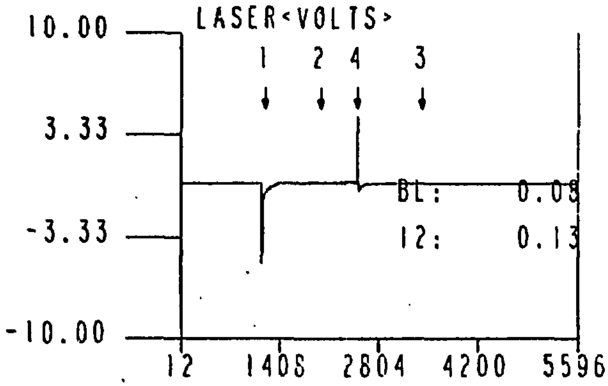
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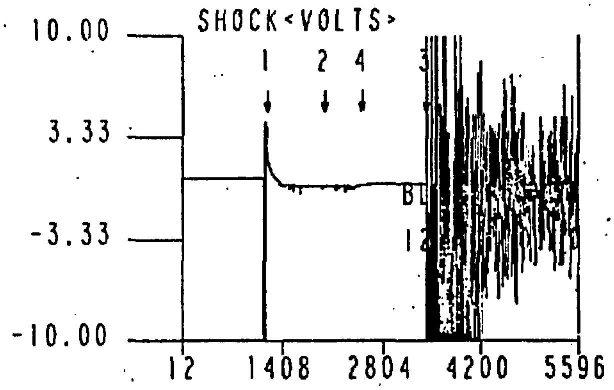
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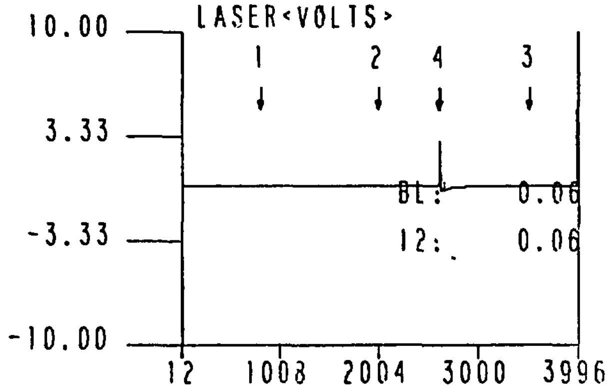
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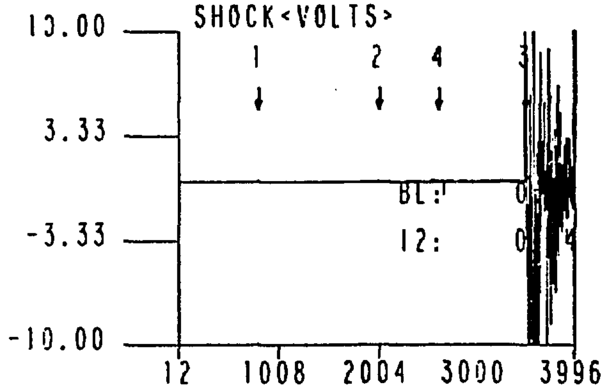
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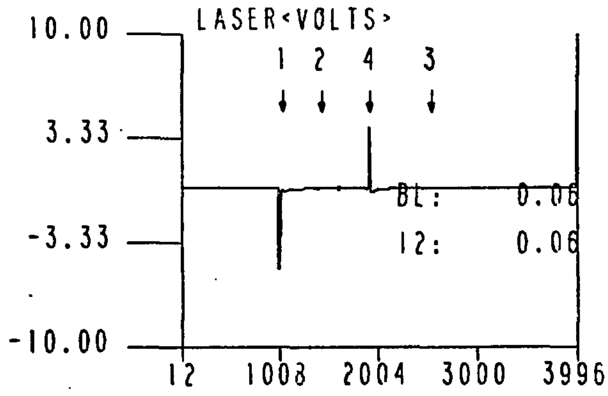
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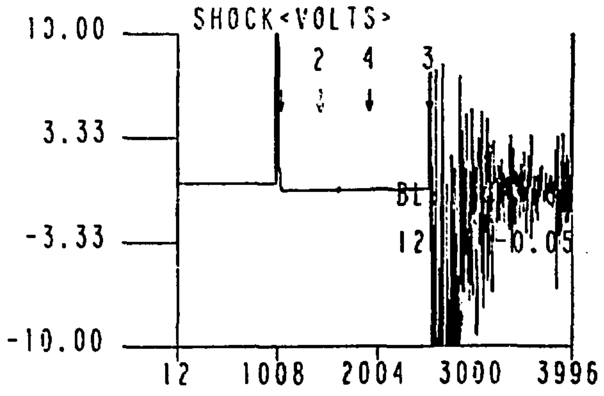
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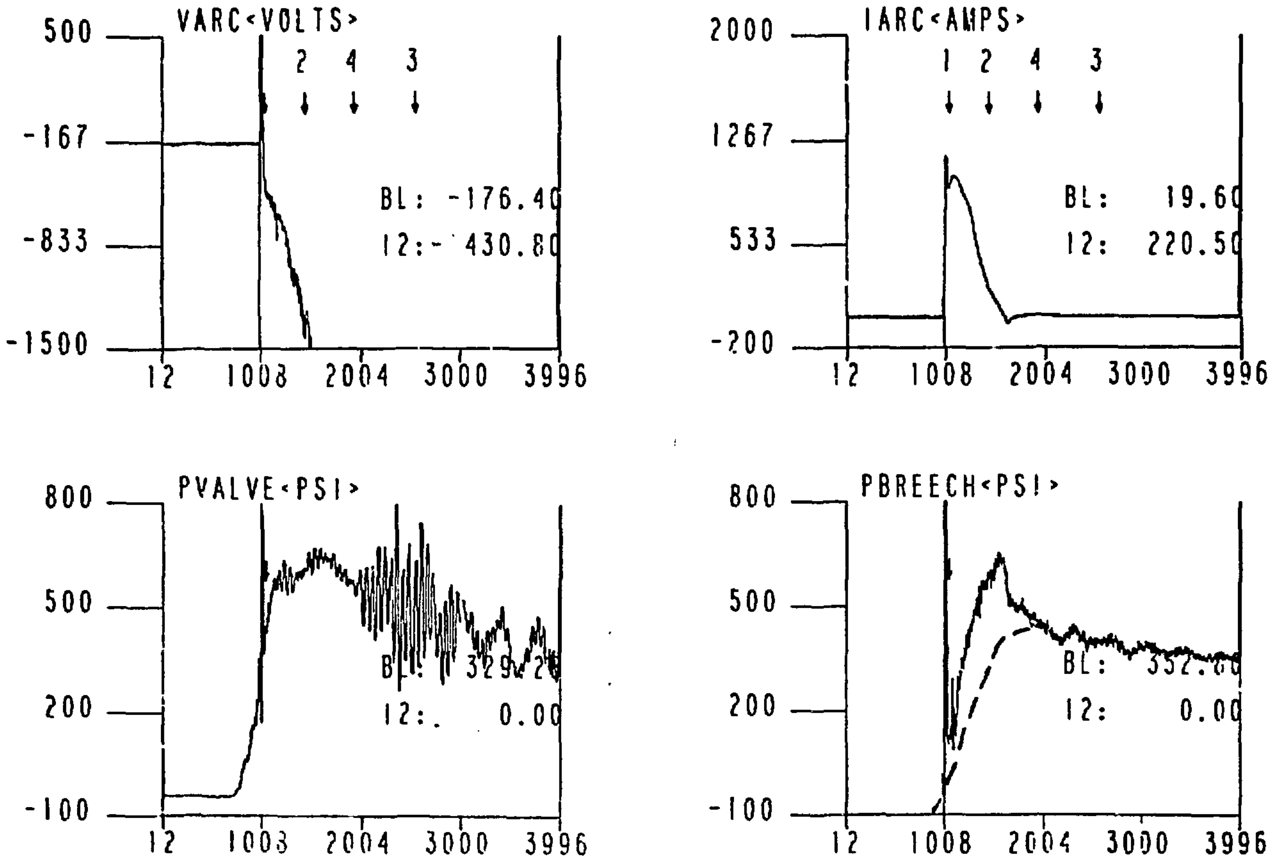

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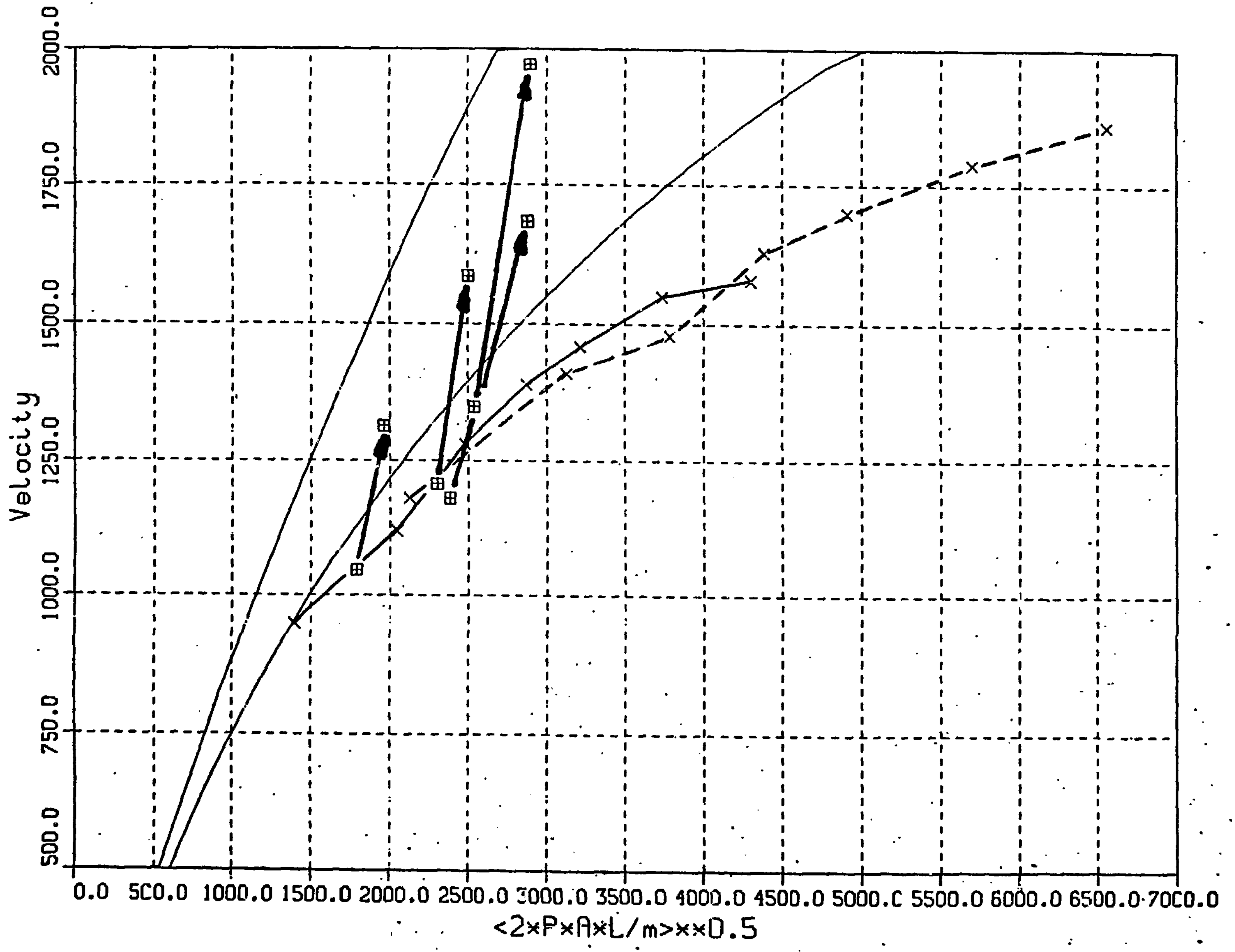

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