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AUTHOR(S): P.H.Y. Lee, R.F. Benjamin, J.H. Brownell, D.J. Erickson, J.H. Goforth, A.E. Greene, J.S. McGurn, J.F. Pecos, R.H. Price, H. Oona, J.L. Reay, R.M. Stringfield, R.J. Trainor, L.R. Veeser, A.H. Williams

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Los Alamos Los Alamos National Laboratory
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DIAGNOSTICS FOR PIONEER I IMPLODING PLASMA EXPERIMENTS

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Abstract

The Pioneer I series of imploding plasma experiments are aimed at collapsing a thin aluminum foil with a multimegampere, submicrosecond electrical pulse produced by an explosive flux compression generator and fast plasma compression opening switch. Anticipated experimental conditions are bounded by implosion velocities of $2x10^7$ cm/s and maximum plasma temperatures of 100 eV. A comprehensive array of diagnostics have been deployed to measure implosion symmetry (gated microchannel plate array and other time-resolved imaging), temperature of the imploding plasma (visible/uv spectroscopy), stagnation geometry (x-ray pinhole imaging), radiation emission characteristics at pinch (XRD's, fast bolometry), and electrical drive history (Rogowski loops, Faraday rotation current detectors, and capacitive voltage probes). Diagnostic performance is discussed and preliminary results are presented.

Introduction

The Pioneer I series is a set of integrated experiments where an active inductive storage driver is used to implode an ultra-thin current carrying cylindrical metallic foil, which becomes heated into a plasma. The plasma is imploded toward the cylindrical axis by the JxB forces. The goal is to obtain an intense source of soft x-rays from the thermalization of plasma kinetic energy when pinch on axis occurs (Ref. 1, 2 and 3).

In order to characterize such an experiment, one needs to diagnose the driver performance and power flow as well as the imploding foil plasma. In this paper, we report on the various diagnostics which were fielded for the experiments.

Driver and Power Flow Diagnostics

The active inductive storage driver consists mainly of an explosive flux compression generator and a fast plasma compression opening switch, connected by an integral transmission line to the load. A circuit diagram of the system is shown in Fig. 1. The electrical performance of the system is obtained by measuring generator current I_G, the opening switch current I_S, the voltage across the opening switch V_S, the load current I_L and the voltage across the load V_L.

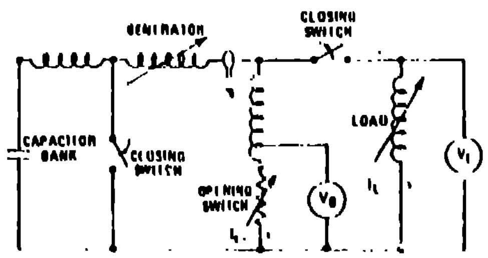

Fig. 1 Circuit diagram of the Pioneer I [illegible] storage driver and load

Currents I_G, I_S, I_L and their time derivative dI/dt were measured using Rogowski loops. Voltage V_S was obtained by means of current measurement through a 5.2 kΩ $CuSO_4$ resistor connected across the transmission plates. This voltage is also measured by using an integrated dV/dt probe with signal transmitted through a fiber optic data link. The opening switch resistance is calculated from $R_S = (V_S - L\, dI_S/dt)/I_S$. Faraday rotation current sensors were also used to measure I_L. The principle of operation of this current sensor is based on the Faraday effect in a single mode fiber. The Faraday effect is a magnetically induced rotation of the plane of polarization of linearly polarized light. This rotation is measured by placing the fiber between polarizers (which is typically oriented for minimum transmission at zero current). The transmitted light is then monitored by a photodiode.

Fig. 2 shows the electrical characteristics of the shot Pioneer I-2. Of the 5.6 MA from the generator, about 1.9 MA was transferred to the load

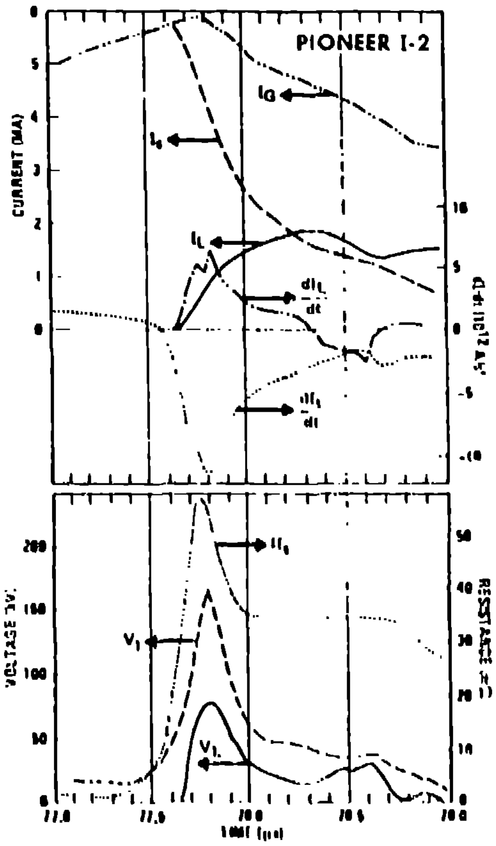

Fig. 2 Electrical characteristics for Pioneer I-2. Opening switch reaches maximum resistance at ~77.7 μs, pinch occurs at ~78.6 μs.

in 0.8 µs, which was sufficient to implode the Al foil load. The load voltage and current traces were used to obtain the inductance as a function of time, which in turn provides an estimate of the time history of the plasma radius and therefore gives implosion velocity and peak compression ratio.

Plasma Diagnostics

Since the generator and the opening switch are both driven by high explosives, the target chamber and most of the diagnostics bolted on to the target (load) chamber do not survive the blast. Consequently, some of the diagnostics are of the "disposable" type.

The load is a thin Al foil mounted in the target chamber. Typical foil dimensions are 2 cm high, 6 cm in diameter and ~200 nm thick. There are three phases of the foil implosion process, namely, initiation, run-in and thermalization. Diagnostics for these phases consist of a filtered x-ray diode array, a bolometer, visible or uv photodiodes, a visible/uv spectrometer, time-resolved visible imaging, and x-ray pinhole imaging.

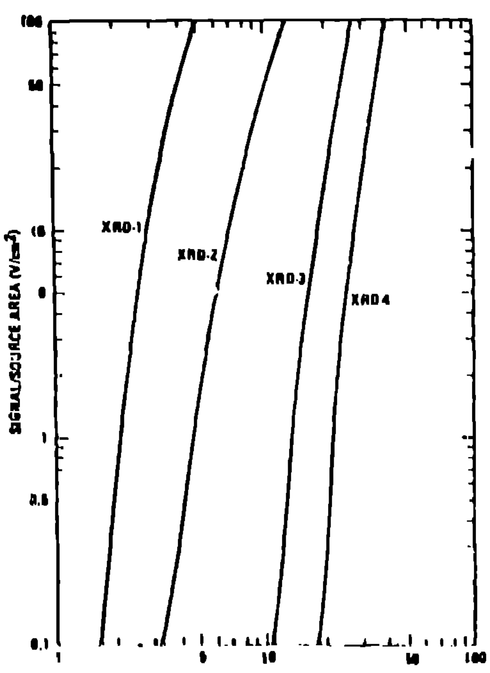

Fig. 1 Expected XRD signals divided by the estimated emitting source area as a function of source temperature.

The XRD array consisted of four uv/x-ray diodes, each diode with a 71 mm² Al cathode and a 90 percent-transmitting mesh anode, some covered with a filter. The channel filters and energy ranges are: 1) no filter, 1.7 – 4.6 eV, 2) 200 µg/cm² of Al, 3.3 – 12 eV, 3) 19.7 µg/cm² of Al on a 71.4 µg/cm² polypropylene substrate, 11 – 26 eV, and 4) 16 µg/cm² of Al on a 431 µg/cm² Mylar substrate, 18 – 30 eV. An applied voltage of 1 kV was used across a 1.27 mm gap. Responses for the diodes are shown in Fig. 1. A typical signal of a channel response is shown in Fig. 4.

The bolometer consisted of a 1 µm thick aluminum resistive element mounted on a vacuum pipe 2 m from the imploding load foil. The bolometer is to be

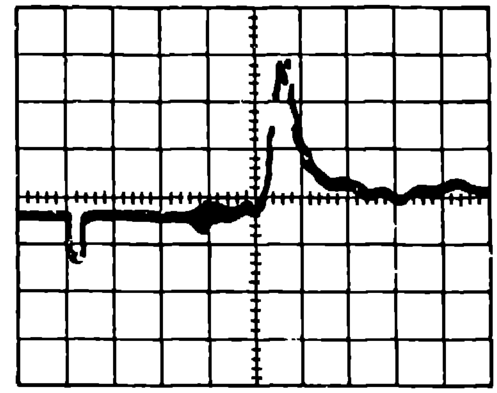
Fig. 4 Signal from XRD channel 4, for Pioneer I-2. Vertical axis: 5 V/div, horizontal axis: 500 ns/div. The negative fiducial began at a reference time of 76.32 µs.

biased with 42 A about 50 µs before critical events in the shot so that when the Al element was heated by source radiation its temperature and resistance would change in a predictable way. The bolometer integrates over all photon energies from 6 eV to 1 keV, with reduced responses above 1 keV. Its response time is about 3 ns and the energy sensitivity at 2 m is ~0.18 V/kJ sphere. No data are yet available for this diagnostic.

The visible photodiode detector was used to look at the center of the chamber for light associated with the initiation or implosion of the load foil and obtain shot-to-shot light intensity levels to aid us in developing the imaging diagnostic films. Photodetectors with S-20 response, filtered with ND filters, are placed ~60 cm from the center of the load chamber so that it views the entire foil. A typical signal shown in Fig. 5, is obtained by using an FW-128 (EG&G) photodiode with an ND-2 filter.

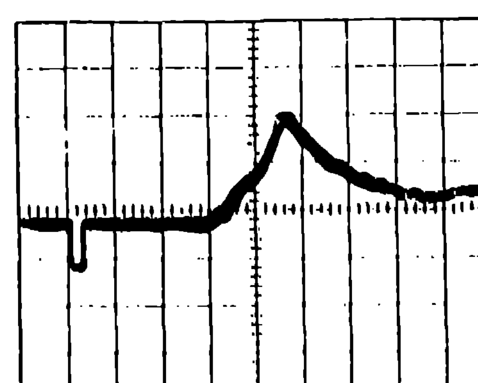
Fig. 5 Signal from the visible diode, for Pioneer I-2. Vertical axis: 5 V/div, horizontal axis: 500 ns/div. The negative fiducial began at a reference time of 76.32 µs.

Visible spectroscopy can reveal the nature of the plasma from the charge state of the Al ions. In addition it can provide a rough estimate of the plasma temperature from measurements of line ratio and from the continuum spectrum. The present configuration uses a 600 line per millimeter grating set to observe emission in the 200 to 500 nm region with a resolution of 1 nm. The foil was focused by means of a 15.2 cm telescope mirror (with 1.22 m focal length) and a second flat mirror on to a slit (10 μm wide and 0.75 cm long). The foil was focused along the entire length so that 1-D imaging was possible. A light tight tube filled with helium connects the experiment to the spectrometer. Data obtained so far indicate that insufficient spectral resolution and copious background radiation made the identification of exact atomic transitions quite difficult. Also, curve-fitting a blackbody spectrum to the measured continuum would require absolute calibrations of the spectrometer and film response. Work on all these aspects are still in progress. Fig. 6 shows the spectrum recorded on Pioneer 1-2.

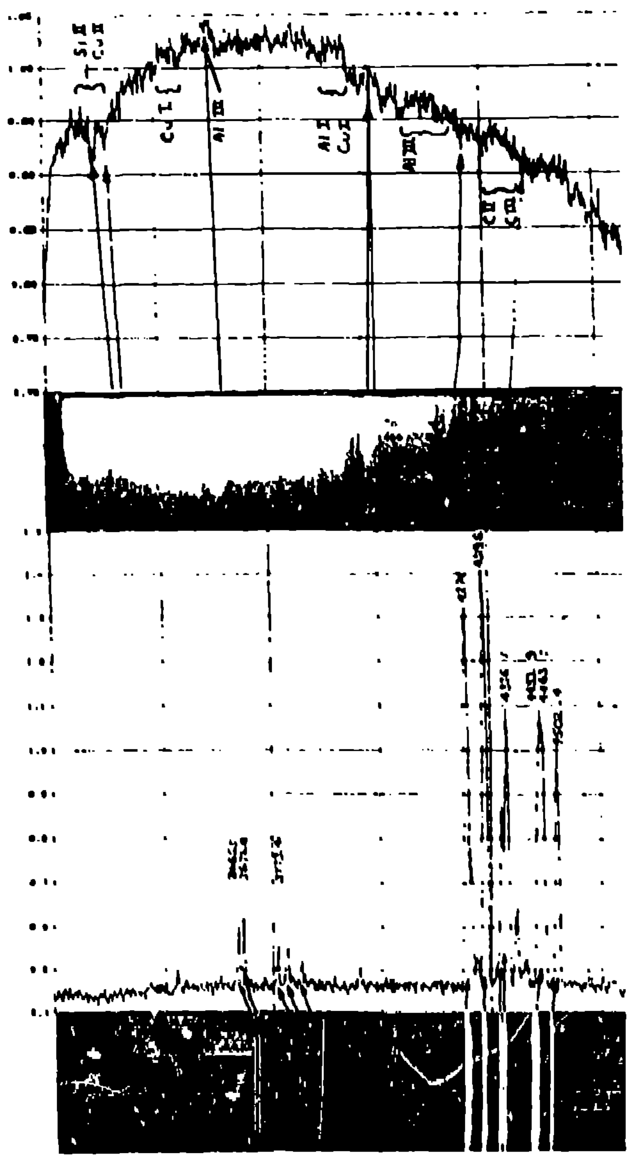

Fig. 6 The spectrum recorded by the visible spectrometer on Pioneer 1-2. The upper portion shows the spectrum and the corresponding densitometer trace. The lower portion shows the krypton calibration spectrum and its densitometer trace. Vertical axis gives the specular density, horizontal axis gives the wavelength in Angstroms.

Axial and radial time-resolved visible images were obtained by using an Imacon camera and a four-channel gated microchannel-plate camera.

A schematic for the Imacon framing camera setup is shown in Fig. 7. The camera views the foil along its axis. An 89 mm aperture f/12 Questar telescope collected the light reflected from two mirrors outside and one inside the diagnostics bunker. The view was partly obscured by the 13-hole screen which formed the upper electrode, a similar plate below the foil allowed the camera to look down into the chamber. A framing record is shown in Fig. 3, where

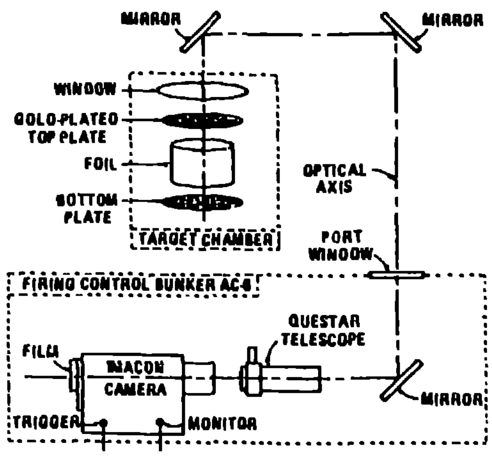

Fig. 7 Imacon framing camera setup for axial view of imploding foil.

10 frames were shot, each lasting 40 ns with an inter-frame time of 170 ns. The objective of this measurement was to observe early emission from the initiation, this is seen beginning from frame 2. No optical filtering was used in this example, so when the light intensity increased significantly, the excessive light intensity caused distortion and shrinking of the image (frames 4 to 10). This distortion can be eliminated by more optical attenuation.

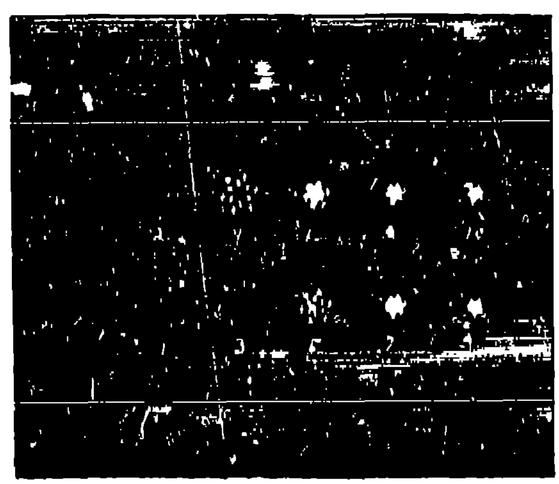

Fig. 9 A framing record obtained by the Imacon framing camera for Pioneer 1-1.

Radial imaging was obtained by using a four-channel gated microchannel-plate camera. A 28 cm aperture, f/10 telescope focused at the foil from ~25 m by using two mirrors outside the bunker. Only 10 cm of the 28 cm aperture of the telescope was used as a result of the 15 cm diameter reflecting mirror being tilted at ~45° to relay the image through an 18 cm diameter porthole. Fig. 9 shows a schematic of the setup. The output beam from the telescope is split five ways, four into the "4-eyes" (four gated micro-channel plates) via pellicle beam splitters. The fifth channel was a time-integrated channel which usec a 35 mm SLR camera without a lens. The gains of all channels were set by in situ calibration, and neutral density filters were then used to match and balance the gains of all channels.

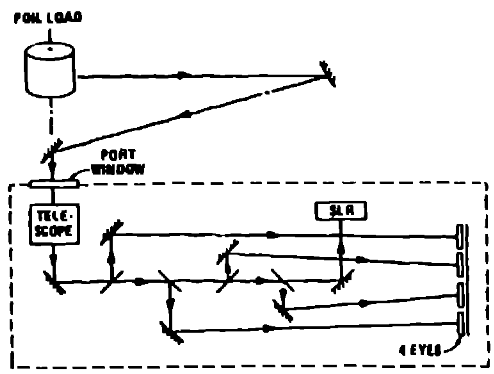

Fig. 9 Schematic of the "4-eyes" (4 gated micro-channel-plate camera) setup for radial view of imploding foil.

Fig.10a An implosion record of the foil load obtained by "4-eyes", for Pioneer I-2. Frame 1 to 4 begins with lower left image, progressing clockwise. Bright patches on frames 1 and 4 are damage spots on micro-channel-plates. The axis of the foil load is parallel to the conductor vanes, seen in each frame as dark stripes.

The gate-open times as well as the interframe times could be set to any desired values. An example of a framing record is shown in Fig.10. In this case, the gate open times were all set to be 12 ns. An implosion of the foil can be seen from the visible emission in the first three frames; the 4th frame triggered before the pinch occurred (the implosion velocity was slower than expected), but since this channel was set at a higher (~20 eV) threshold, nothing was recorded. This situation will be remedied by using an x-ray diode signal to trigger the 4th channel which will record the implosion. The parallel lines, 8.7 mm apart, are the conducter vanes. Some structures can be seen on the surface of the plasma in frame 2 and these may be the beginnings of hydro-instabilities. This will be further investigated. Also, the time-integrated channel recorded no bright emission line on the center axis; this could mean that during the implosion some colder plasma may have been left behind that is opague to visible light. This suggests that x-ray imaging is strongly desirable.

Fig.10b A record of the fifth (time integrated) channel of "4-eyes", obtained for Pioneer I-2. This channel records visible emission from the foil for all phases: initiation, run in and implosion. Dark lines are conductor vanes, spaced 8.7 mm apart.

X-ray imaging diagnostics consist of using three time integrated x-ray pinhole cameras, both for radial and axis view of the foil, filtered differently to obtain hard uv or Al K-line at ~1.56 keV. The foil implosions are at present too cold to produce measurable x-rays in the few hundred eV (soft x-ray) region. A time-integrated uv/x-ray imaging diagnostics was made by using a filtered pinhole and an x-ray-to-light converter where the images are formed, and then using the "4-eyes" as the recording device. This diagnostic has been completed and is ready for testing.

Conclusions

In the Pioneer I series of experiments we have demonstrated that almost all the diagnostics required for measuring driver characteristics and plasma implosion have been successfully fielded, some yielding better data than others. Work is in progress to sharpen the resolution and improve the performance of each diagnostic, and implement new diagnostics as the parameter range of the experiment increases.

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