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Advantages of a soft protective layer for good signal-to-noise ratio proton radiographs in high debris environments

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Proton radiography is a very powerful diagnostic but in some high debris environments it may be challenging to get a good signal-to-noise ratio radiograph to gain insights into the electric and magnetic field topology, and thus the basic physics. Such environments are produced for example on z-pinches and also on lasers such as the National Ignition Facility. We demonstrate here the feasibility of clean, very high signal-to-noise ratio proton radiographs in extremely hostile environments.

1. Introduction

Proton radiography is a relatively new technique that uses charged particle beams, namely protons, to gain a deeper understanding of the electric and magnetic fields present in plasmas [1–4]. This technique allows a better characterization of the physics associated with high-energy density plasmas and extremes states of matter of relevance for inertial fusion [5], laboratory astrophysics, shocks, laser plasma interactions, or equation of states. This technique has been applied to laser-driven implosion [6,7] and more recently to holraums [8–10]. Yet it has not been done on z-pinches where it holds the same promises for a better understanding of the physics at play [11]. Z-pinches are one of the most hostile laboratory environments due to the high electromagnetic pulse (EMP), mechanical shock, and destruction zone associated with a copious production of debris [12] during a shot. Such a hostile environment is also found for example on the National Ignition Facility [13], and is expected on the Laser Megajoule [14]. NIF can produce about 180 kJ of X-rays during a shot and possibly more in specific conditions [15]. Several wire arrays z-pinch facilities have produced X-rays in the range 0.2–1.8 MJ [16–20]. Both NIF and the z-pinch facilities generate a large EMP signal [21] as well as high velocity debris. Debris and shrapnel have been measured in the context of damage to and survival of debris shields in facilities such as NIF [13,22], Omega [23], and Pharos at NRL [13]. The debris also damage the diagnostics thus drastically reducing the signal-to-noise ratio and the ability to extract precise, useable information. We present in this paper a technique that demonstrates the feasibility of proton radiography in such hostile environments by protecting the detectors from debris damage while obtaining a good signal-to-noise ratio for radiography.

2. A high debris environment

At the Nevada Terawatt Facility the Zebra z-pinch (1 MA, 2 MV, 80 ns) was used to shoot single planar wire arrays [24–26] to assess the level of debris present and background proton noise that threaten clean proton radiography. The detector of choice was CR39 due to its quasi insensitivity to X-rays, electron and gamma rays [27,28]. The same detector is also widely used for example on

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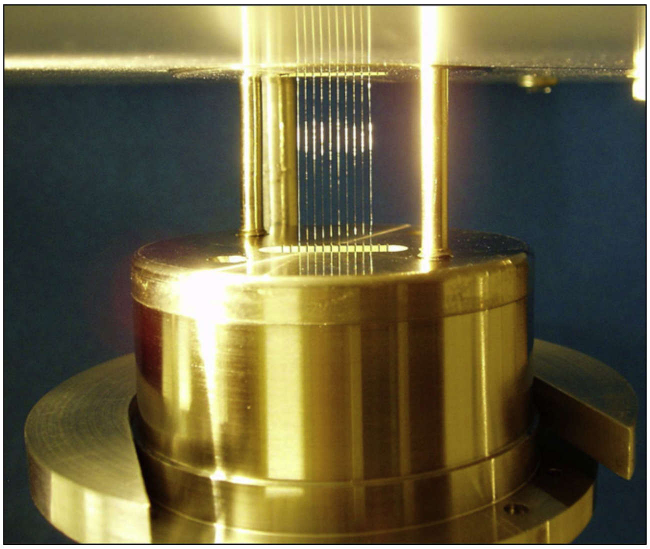

Fig. 1. Typical single planar wire array load.

Omega [29,30]. Fig. 1 shows a typical planar or linear wire array (single planar wire array or SPWA). In this case, the array was built with alumel wires. Fig. 2 shows the z-pinch current associated with such a load (solid black curve, scale to the right) as well as the electron beam current measured (dotted curve, scale to the left) directly above the load at a distance of approximately 9 cm. For this type of load the X-ray emission has been measured to be 20 kJ, which at 9 cm gives us a fluence of 19 J/cm^2. For a comparison, recent data from NIF [31] give us relevant information. Debris from NIF shots were collected at several points including a distance of 50 cm from TCC for shot energies from 568 kJ to 836 kJ. Corresponding X-ray fluence with a 90% conversion efficiency [15] at 50 cm are: 16 J/cm^2 and 24 J/cm^2. In that later reference [15] the soft X-ray radiation drive is measured with DANTE [32]. The X-ray fluence on DANTE's front filter, about 5 m from Target Chamber Center (TCC), is 0.2 J/cm^2. These references and our data indicate an optimized distance as a function of load type and geometries. Ref. [30] also points out that particle impact craters and molten splat are found 7 m from TCC but in fewer number than closer to TCC

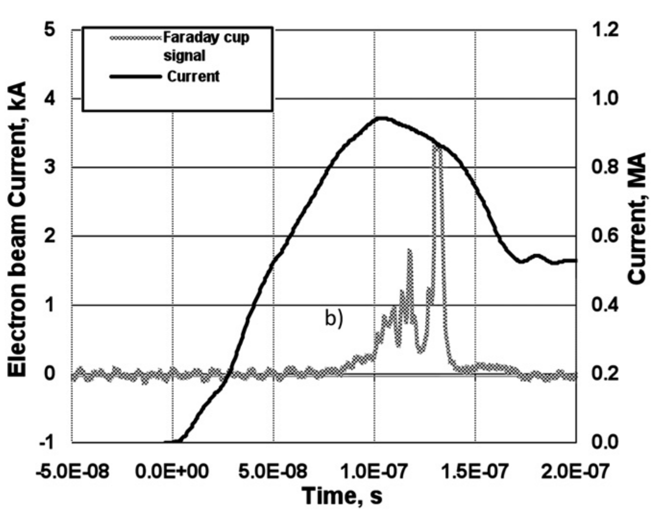

Fig. 2. Typical z-pinch current (solid grey line) and Faraday cup signal (dotted line) for the array of Fig. 1 (shot # 1954, wire material is alumel, wires number $N = 12$, wire diameter $\Phi = 10.16$ μm, inter-wire gap is 0.7 mm).

though. Seven meters away from TCC the X-ray fluence drops to 0.12 J/cm^2 but the potential for breakage remains.

A future publication including a more in depth study of debris collection similar to NIF in our Zebra z-pinch is in progress [20].

In our measurements, the Faraday cup, filtered with a 10 μm Cu filter (electron cutoff of 63 keV) measured a maximum electron current of 3.4 kA. Along with the electron beam, vaporized material, ions, and macroscopic pieces of material land on the filter in front of the Faraday cup. This is the location we choose to assess the level of debris in a worst-case scenario, but also a reasonable choice for on-axis proton radiography [11]. Prior to a shot, a single piece of clear CR39 was taped in the front of the Faraday cup and the Cu filter. At first, our attempts resulted in shattered CR39, and quickly progressed to quasi-intact (unbroken) CR39 covered with debris (Fig. 3a) by putting the CR39 on a flat support and not a ring shaped one like the edge of the Faraday cup. Fig. 3b shows that same piece of CR39 after etching it for 60 min in 6.0-N NaOH solution at 70 ± 1 °C. Details on the etching process and the response of CR39 can be found in Ref. [27]. The etched CR39 clearly shows remaining debris covering the detector. Fig. 3c is a microscopic picture of this etched CR39. It shows dark areas where remaining material still covers the detector, a background of proton/ion tracks and areas that have been broken or impacted as if by bullets of flying material. These are similar to the impact of a small stone in your windshield, and like those, sometimes cracks can be seen spreading from the impact location. It is clear from these typical results that a clear, high signal-to-noise ratio result is a challenging task, especially with the goal of obtaining clear 2D radiographs similar to those in laser plasmas interaction [1–4]. Note that of course we choose an on-axis location and that a radial location is possibly less challenging.

3. Obtaining a clean high signal-to-noise ratio

A different approach successfully eliminated debris, cracks and breakage of the detector. We covered another piece of CR39 with a thin layer of transparent glycerol soap and taped it to the front of the Faraday cup. We used a similar SPWA load with the same drive current from the z-pinch as showed in Fig. 2. Fig. 4a shows the CR39 immediately after the shot with the layer of soap covered in debris. Fig. 4b shows the same CR39 after a simple rinse with water. We then processed this CR39 in precisely the same way as the one before. Fig. 4c shows tracks left by the protons in the CR39 after etching. The CR39 is transparent, unbroken and holds data with excellent contrast – a high signal-to-noise situation. In our case the protective layer used is soft enough to absorb and diffuse the momentum and thus allows the CR39 to not crack or break. This technique is reproducible and the results showed here are typical results. It clearly demonstrates the feasibility of clear, high signal-to-noise proton radiography in very hostile environments such as z-pinches, and high-power lasers such as NIF and Laser Megajoule. Note that another well-known technique from the laser target interaction community consists of placing a solid filter in front of the detector layers. This solid detector is very often a 12 μm thick aluminum foil in standard laser target proton radiography. Being solid, it does not absorb and diffuse the momentum of the debris landing on the detector pack. In our case, where bullet-like debris land on the detector, a solid filter transmits the momentum and this results in breakage of the CR39 detector. Also, Al witness plates were fielded on NIF [31] 25–50 cm from TCC. Each plate was of a thickness included between 1.18 mm and 1.22 mm. Evidence of aluminum surface melt was observed, as well as debris splats and particle impact craters. Impact craters were also detected as far as 7 m away from TCC. A soft material such as a glycerol layer will stop the debris and diffuse their momentum resulting in an unbroken