Investigation of Carbon X-Pinches as a Source for Point-Projection Radiography

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***Abstract*—We report on the first investigations of the use of carbon fibers in an X-pinch load using a 250-kA linear transformer driver (LTD). Multiframe laser shadowgraphy is used to examine the evolution of the pinch and shows that carbon loads demonstrate wire expansion and cross-point pinch and gap formation as observed in X-pinches constructed from high Z materials. Radiographs taken using the carbon X-pinch as the source demonstrate both that sufficient flux is emitted to provide a good contrast image at source-to-image distances of > 10 cm and that the cross point produces a relatively small hot spot. Radiographs of a series of fine wires (5–30 μm) using X-rays > 500 eV demonstrated that 25-μm wires can be resolved in this energy range. Time-resolved X-ray emission measurements showed that, while emission in the $h\nu > 500$ eV range shows long (> 100 ns) timescales, emission in the $h\nu > 1$ keV range shows a multiple-peaked structure with durations as short as 20 ns.**

***Index Terms*—Carbon fiber, point-projection radiography, X-pinch.**

I. INTRODUCTION

THE X-PINCH is a high-energy-density plasma with properties which are ideal for application as a point-projection-radiography source. An X-pinch is produced by placing two or more wires between the electrodes as a load of a pulsed-power machine and by twisting these wires so they cross and touch at a single point, forming the shape of an "X." When a fast rising current is driven through the load, the wires expand and ablate, creating dense wire cores surrounded by low-density coronal plasma [1]–[4]. The self-generated magnetic field from the flow of current combines at the cross point to create a strong global field that compresses the plasma to near solid densities, forming a Z-pinch that is a few hundreds of micrometers in length, often referred to as a micro Z-pinch [5]. Magnetohydrodynamic instabilities lead to the pinching of the plasma at multiple points along the micro Z-pinch. Some of these pinching points develop into "hot spots" of high-density and -temperature plasma that emit intense bursts of soft X-ray radiation, typically in the 1–10-keV range for high Z materials, that can have subnanosecond duration [6], [7]. These hot spots, reliably reproduced in a predetermined location, are the sources used for point-projection radiography.

The photon energy emitted from the hot spots will determine the plasma structures that can be imaged, absorption being determined by both the material atomic number and the integral of the density over the path length. Previous studies of high Z source materials such as W, Mo, and Nichrome have used Ti radiation filters to image plasma objects in the 3–5-keV range, and this technique has been highly successful in providing both qualitative and quantitative measurements for densities $n_e > 10^{19}$ cm^{-3} [8]. However, for lower density plasmas, such as those accelerated to the system axis for both X-pinches and wire-array Z-pinches, the transmission of 3–5-keV X-ray can be very high. For example, in this range, the transmission of W plasmas with an areal density of 3×10^{-4} kg $\cdot$ m^{-2} (similar to ablated plasma) is $> 90\%$. At 1 keV, this is $< 70\%$, and at 0.5 keV, this is $< 50\%$. The use of either of these energy windows would greatly increase the contrast of images of these plasmas, expanding the range of tools available to researchers investigating systems with large density ranges.

A possible candidate for a lower energy radiography source is carbon. Studies of pulsed-power-driven carbon fibers have so far been restricted to Z-pinches, where a single fiber was the load of a pulsed-power machine due to similarities with the cryogenic deuterium fibers [9], [10]. The Z-pinch experiments focused on optical emission and low-density coronal dynamics, but did confirm that X-rays originated from the pinch regions of greatest radial compression, suggesting that even a low Z material may undergo a sufficiently high-quality radiatively driven collapse process to provide a useful point-projection source when used in an X-pinch configuration.

In this paper, we present the first investigations of carbon fiber X-pinches. Two wire loads were driven with a linear transformer driver (LTD) [11], generating 180 kA in 150 ns through X-pinch loads, and the gross system dynamics are investigated to assess possible application as a radiography source. The experimental setup is presented in Section II, followed by the results and discussion in Section III and the conclusion in Section IV.

II. EXPERIMENTAL SET UP

Experiments were carried out on the GenASIS machine, an LTD recently installed at UCSD. Current is delivered to the load *via* a conical magnetically insulated transmission line (MITL) which both raises the load to provide excellent diagnostic access and reduces the electrode diameter to ensure efficient coupling of the generator to the load. The X-pinch

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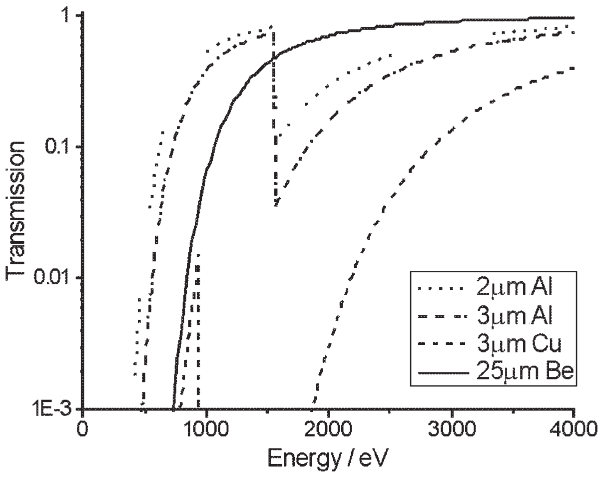

Fig. 1. X-ray transmission curves for 25-μm Be, 3-μm Cu, and 3-μm Al.

is loaded between two brass electrodes separated by 10 mm. The electrode and MITL structure is contained inside a small vacuum chamber held below 6×10^{-4} mbar for each shot. Measurements of dI/dt were taken by a Bdot probe mounted in the generator return path and by the use of a Rogowski coil placed around one of four return current posts which measured the load current directly. The signals from both were then numerically integrated to obtain the current. All loads in this work were constructed of two wires of 30-μm carbon fiber.

Information on the dynamics of the coronal plasma was obtained by optical probing with a frequency doubled Nd-YAG laser (532 nm) with a pulselength of 5 ns and a spatial resolution of < 30 μm. All shots used two-frame shadowgraphy. This was accomplished by splitting the laser beam into two beams before the chamber and optically delaying one of the beams by 6 ns prior to passing through the chamber.

Time-resolved X-ray signals were acquired with the use of filtered silicon PIN diodes and recorded using an HP 16500B Logic Analysis System. The diodes were filtered with 25-μm Be, 3-μm Cu, and 3-μm Al for a qualitative comparison of the energy radiated from the pinch. The transmission curves for the filters used are shown in Fig. 1.

The radiation source was tested for flux and source size by taking radiographic images of a copper mesh (250-μm wire and 380-μm cells) and an array of wires of various diameters (30, 25, 15, 10, 7.5, and 5 μm). The X-pinch radiation was filtered with 2-μm aluminum, and images were recorded on a Kodak BioMax MS film [12]. The mesh was placed 11 cm from the X-pinch and 3.2 cm from the film, providing a magnification of 1.3. The wire array was 12 cm from the X-pinch and 17.5 cm from the film, giving a magnification of about 2.5. A schematic of the setup is shown in Fig. 2.

III. RESULTS

Fig. 3 shows the drive current for both a short circuit and a typical carbon X-pinch load on the LTD generator. The typical load current was 140–180 kA with a rise time of 150 ns. Note that the load current trace has a small pulse approximately 30 ns in duration before the main pulse. This is most likely related to the voltage buildup and breakdown across the wire and is more pronounced than in metallic loads since carbon is an insulator. The generator has a relatively low impedance (~ 0.3 Ω), and this means that a change in the load inductance has measureable effect of the drive current. For each X-pinch load, a dip in the current trace is observed shortly after peak current, and this is likely to be due to the rapid change in inductance as the X-pinch cross point is compressed to a small radius.

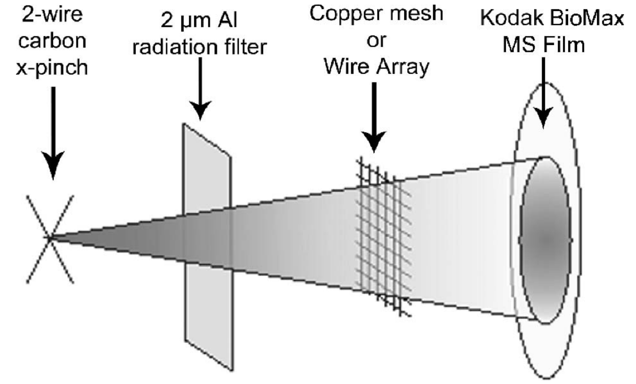

Fig. 2. Schematic of setup for taking radiographs of copper mesh and array of wires of various sizes.

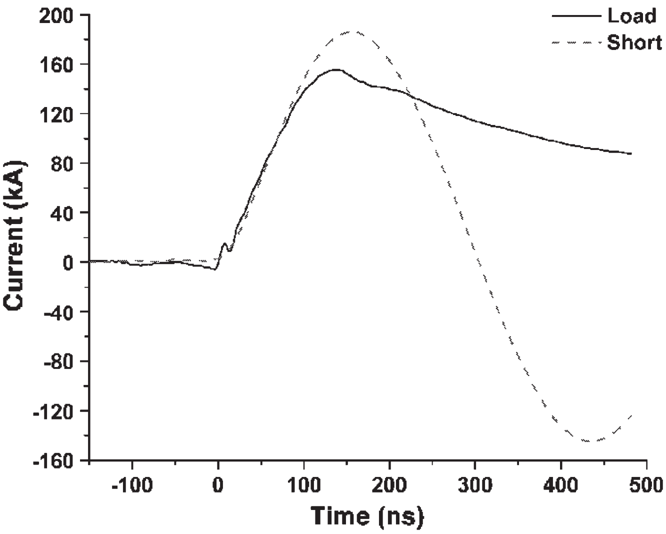

Fig. 3. Rogowski current traces for a short circuit and a carbon fiber X-pinch load.

Shadowgraphs allowed an examination of the carbon X-pinch dynamics. A selected sequence of images that shows the different stages of an X-pinch before and after maximum current can be found in Fig. 4. The time below each image refers to the amount of time after the beginning of the current the image was taken, and each image came from a different shot. The first image in the sequence [Fig. 4(a)] was taken at half the current rise. At this point, the wire cores have expanded to approximately double in width, and a small flaring structure is developing along the legs. In the region where the two wires cross, a small vertical column has begun to form, which denotes the beginning of the high compression phase to form the micro Z-pinch. In all the images, there is a high degree of top to bottom asymmetry in the plasma structure on the

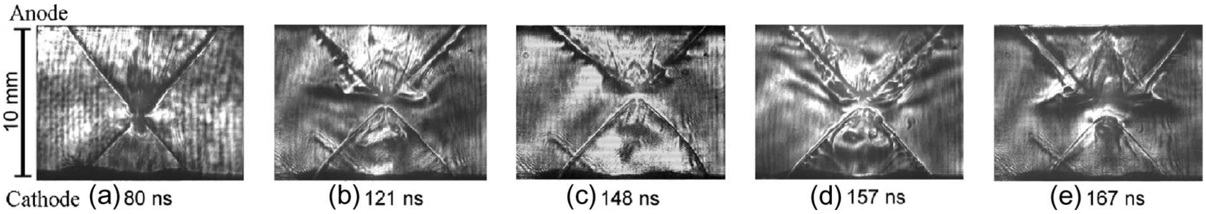

Fig. 4. (a)–(e) Shadowgraph images of two-wire 30-μm C X-pinches with times relative to the start of the current drive.

central vertical axis. The plasma on the anode side of the cross point reaches further toward the electrode and contains a greater mass. The height-to-width ratio is greater than that of most jetlike structures seen in X-pinches such as those described by Mitchell *et al.* [13], most likely due to the low radiative loss rate for carbon relative to typical X-pinch loads. Fig. 4(b) shows the continued expansion of the legs and growth of instabilities in the low-density coronal plasma along their length. At the cross point, a micro Z-pinch that is several hundreds of micrometers in length has formed.

In Fig. 4(c), which is near peak current, a gap has appeared at the cross point, suggesting that the high compression phase which produces the radiative hot spot has already occurred. The coronal plasma in Fig. 4(d) has become highly dominated by instabilities, and plasma appears to have re-entered the cross-point area. By the time of Fig. 4(e), plasma has cleared far from the cross-point region. These dynamics are consistent with those observed for metallic loads (e.g., [6], [14], and [15]) and the expansion of the "legs," compression of the plasma at the cross point, and formation and expansion of a mini-diode gap are well recognized phases of an X-pinch.

To assess application to radiography, the spatial and temporal characteristics of the carbon X-pinch need to be investigated. For radiographic imaging, a 2-μm aluminum filter was employed to cutoff energies below 500 eV. Initial testing used a fine copper mesh at a magnification of 1.3, as described previously, to examine whether, at typical source-to-image plane distances, often greater than a few centimeters, sufficient flux was emitted to enable good contrast imaging. An example radiograph is shown in Fig. 5.

This image indicates that good contrast radiography is possible at least at the system distances used here. In addition, the clear imaging of the 250-μm wires suggests that the image is generated either by a single source with a size less than $\sim$200 μm or by more than one smaller sources which are closely separated. In order to examine the limits of the spatial resolution, radiographs of a series of fine wires were taken to provide a simple estimate of the resolving power of the hot spot produced. The wire diameters were 5, 7.5, and 10 μm for W, 15 μm for Mo, 25 μm for Al, and 30 μm for C arranged in descending order from left to right as shown in Fig. 6(a). Fig. 6(b) shows a radiograph of this setup using a 2-μm aluminum filter.

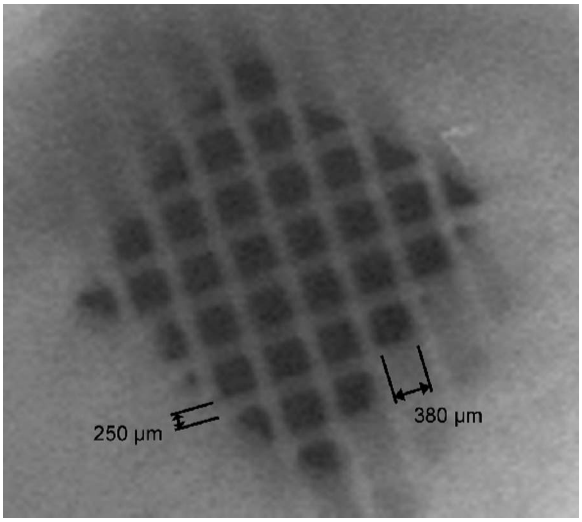

Fig. 5. Radiographic image ($h\nu > 500$ eV) of a copper mesh (250-μm wire and 380-μm cells) at a magnification of 1.3.

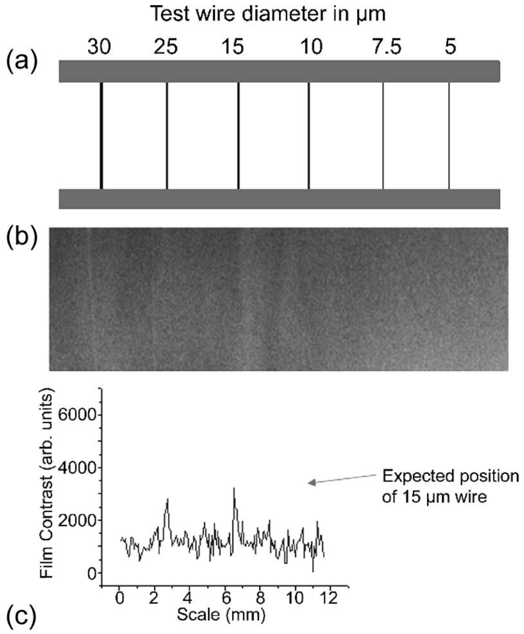

Fig. 6. (a) Illustration of linear wire array with wires of varying diameter. (b) Radiographic image of a wire array at a magnification of 2.5. The film was filtered with 2-μm Al. (c) Line out taken horizontally along radiograph.

The radiograph clearly shows that both the 30- and 25-μm wires can be imaged using a carbon X-pinch at a magnification of 2.5. Fig. 6(c) shows a line out taken horizontally along the radiograph showing both these wires and also that the 15-μm wire is below the resolution capability of the source. This simple approach does not place exact limits on the source size and is certainly not as complete as the determination of this from diffraction profiles as in [16], but it does demonstrate that a suitably small source does indeed occur in carbon X-pinches and provides spatial resolution on the order of a few tens of

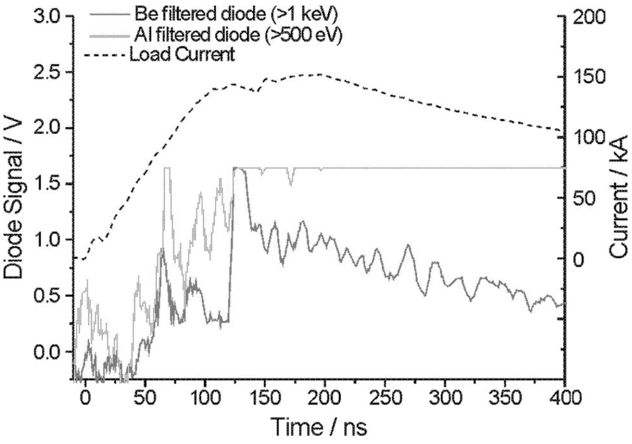

Fig. 7. Time-resolved X-ray emission > 1 keV from a carbon X-pinch with current trace for the same shot.

micrometers. It is interesting to note that this limit is in the same range observed for low Z materials from vacuum spark gap investigations [17].

For some applications where high time resolution is not critical, such as the offline characterization of inertial confinement fusion capsules [18], a radiography source may be considered acceptable, provided that exposure is less than a few microseconds (depending on the radiation window utilized). However, much of the application of X-pinch radiography is in the analysis of exploding wire systems, including both X-pinches and wire-array Z-pinches, and for this, temporal resolution at least on the order of a few nanoseconds is required.

To investigate this, time-resolved X-ray emission was recorded on the filtered Si diodes. The radiation recorded on the softest channel (Al, $h\nu > 500$ eV) has a peak prior to the inductive dip in the current for the shot in Fig. 7. At the time of pinching, indicated by the dip in current, emission can last for a few hundred nanoseconds for this energy range. The signal was cut off by the measurement device at approximately 1.6 V. The beryllium filter $(h\nu > 1$ keV$)$ recorded three peaks in the radiation output before the dip and a large well-defined peak at the time of pinching.

The first peaks occur on the current rise, and the large single peak coincides with the inductive dip and with the large broad emission of lower energy Al filtered diode. Peaks during the current rise are most likely due to the load being undermassed for the current or are the result of hot spot formation along the X-pinch "legs," similar to single-wire experiments, with pinching at the cross point occurring close to current maximum. The peak at pinching had a full width at half maximum (FWHM) in the range of 15–20 ns. The Al channel shows greater emission than the Be channel at all points, and no emission was observed with harder filters transmitting energies > 3 keV. This indicates that emission is likely to be from a thermal plasma source, the X-pinch hot spot, and not as a result of other mechanisms, such as an electron beam impacting the electrodes. This is supported by the fact that the FWHM of the peaks is relatively short, whereas electron beam sources generally last for a greater period and would be expected to be observed in harder emission channels.

IV. CONCLUSION

The use of laser imaging demonstrates that carbon X-pinches evolve in a similar manner to those constructed from high Z metallic wires typically used, such as tungsten. Radiographs of a fine Cu mesh and a range of fine wires demonstrated that the hot spot formed in carbon X-pinches is sufficiently small to resolve a 25-μm wire at a magnification of 2.5 with X-rays > 500 eV but that 15-μm-wire images at the same time cannot be distinguished. The diode signals for the same energy cutoff showed that emission lasts for hundreds of nanoseconds, and this is too long for use in a radiographic source for imaging dynamic objects. Diode signals recording energies > 1 keV, however, showed promise to give some time resolution for use on plasma experiments. These also typically showed multiple peaks. Subsequent studies will examine if it is possible to improve performance by varying the mass of the X-pinch to change the pinch time relative to the peak current or by further investigating suitable filter arrangements.

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