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Investigation of the plasma jet formation in X-pinch plasmas using laser interferometry

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A two-frame Mach–Zender interferometer is used to investigate the dynamics of X pinches formed from two 10 μm aluminum wires at current levels of 100 kA. Particularly, the columns of plasma that form on the interelectrode axis of the X pinch are studied quantitatively. It is demonstrated that the plasma which forms these columns does not come solely from expansion of the corona from the limbs of the X pinch but rather predominantly from the crossing point region. The results suggest that the plasma column is indeed a jet which consists of several components. © *2000 American Institute of Physics.* [S1070-664X(00)03912-4]

I. INTRODUCTION

Hot, high density, pinch plasmas are potentially an excellent source of soft x-ray radiation. In general, the dominant sources of x rays in gas or single fiber Z-pinch plasmas are small, high density, high temperature regions[1] formed by the development of the $m=0$ magnetohydrodynamic (MHD) instability[2] perhaps assisted by radiative collapse in higher Z materials.[3] Typically several of these hot spots are formed in each pinch, emitting at different times and positions in the discharge. As a result the Z pinch is not suitable for applications that require a single pulse of x rays either from a small source and/or of short duration.

The X pinch, first studied by Zakharov *et al.*,[4] is of particular interest because it produces a brilliant source that has a highly reproducible intensity and time of emission as well as a predeterminable physical location. Furthermore the wavelength of the emitted x rays can be tuned to a certain extent by the choice of wire material and by the amplitude of the current pulse. The X pinch is formed by crossing two thin wires, normally metallic, so that they form the letter X and touch at the crossing point. Interest in the X pinch has recently been stimulated by its suitability as a backlighting source for the diagnosis of other dense plasmas, e.g., the single wire Z pinch,[5] or the plasmas produced in the wire array experiments on multi-mega-ampere pulsed power generators.[6,7] In order to resolve temporally and spatially the features in these experiments, the backlighting source must have a short duration ($\sim$1 ns), a small physical size, and a time of emission which can be predicted in advance. All these conditions are satisfied by the X pinch.

Previous experimental work has shown that the soft x-ray radiation produced by X pinches comes from one or two hot spots formed in the region of the crossing point of the wires. It has been demonstrated by Shelkovenko *et al.*[8] that the development of the plasma in the crossing point undergoes three distinct phases. First, the individual wires which form the limbs of the X pinch explode, as in conventional exploding wire experiments, resulting in a dense core (probably containing solid wire material) surrounded by a low density, higher temperature coronal plasma. Second, a small Z pinch forms at the crossing point on the interelectrode axis of the X pinch. This Z pinch is typically 100–500 μm long and is bounded at either end by virtual electrodes formed by the plasma from the X pinch limbs. Finally, in the third phase, a pulse, or pulses, of soft x rays are emitted from one or two hot spots located near the crossing point and then a gap rapidly opens up in the region where the Z pinch was.

Another common feature of X pinches is the development of plasma columns on the X-pinch axis which appear to start at the crossing point and increase in length toward both the anode and the cathode. The density of the plasma in these columns is much less than that of the solid core but similar to that of the limb corona. These columns of plasma have been observed in schlieren, shadowgraphy, and soft x-ray pinhole images of X pinches.[8–11] These columns of plasma on the diode axis are the main areas of investigation in this paper. The principal diagnostic used in this work is a two-frame interferometer that allows quantitative measurements of the electron density to be obtained in the regions where the interferogram shows fringes that can be followed. Furthermore, as two interferograms are obtained from a single shot the development of particular features can be followed without relying on shot to shot reproducibility. In particular the plasma columns which are formed on the X-pinch axis lend themselves well to examination by the interferometer as they have a relatively low density and density gradient allowing the electron density profiles to be calculated without significant errors. This quantitative analysis enables the issue or the source of the plasma column to be clarified. Such details have not been published to date.

II. EXPERIMENTAL DETAILS AND RESULTS

The experiments described in this paper were carried out on the Generador de Potencia Pulsada (Gepopu). Gepopu consists of a 4 kJ, 50 kV Marx bank coupled to a coaxial 1.5 Ω, 48 ns transmission line. After a self-break line switch a

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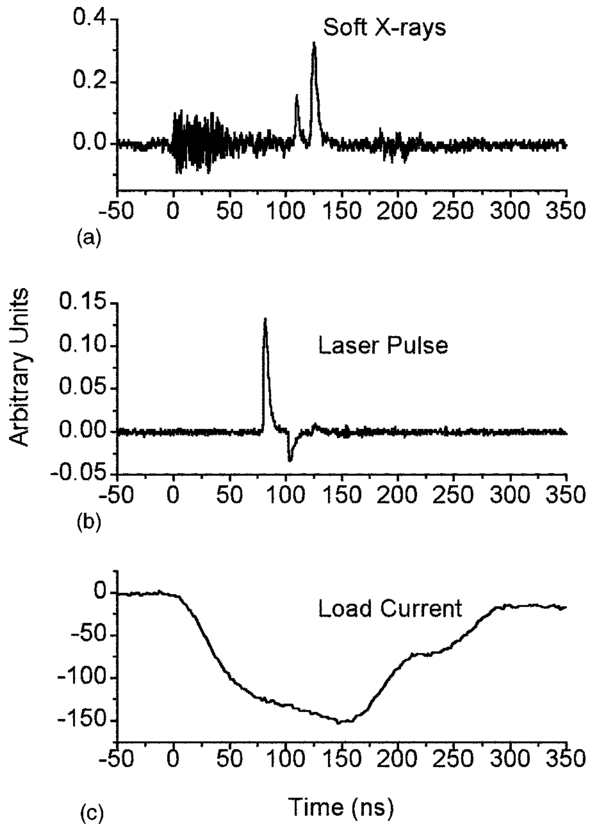

FIG. 1. Oscilloscope traces of a typical X pinch made from 10 μm aluminum wires.

short 1.5 Ω, 12 ns transfer line leads to the load chamber. Gepopu typically delivers 100 kA to the load with a rise time of 130 ns. The electrodes in the load were made of brass and separated by a distance of 1 cm. The X pinch was formed from two aluminum wires of diameter 10 μm. Each electrode had two holes along its diameter, with a separation of 8 mm (4 mm from center). The wires were loaded through these holes in such a way that they ran parallel across the anode–cathode gap. The X pinch was then formed by a half twist of one electrode relative to the other, thus forming a semblance of the letter X. The discharge chamber was evacuated to a pressure of $<10^{-4}$ mbar before each shot.

A set of traces from a typical shot is shown in Fig. 1. In this figure $t=0$ is coincident with the start of the current pulse. The timing of the traces has been corrected to account for the different transit times of the signals from the monitors to the oscilloscopes. The load current trace was obtained using a Rogowskii coil located in the return path of the current. The signal from the Rogowskii was then integrated just before the input of the oscilloscope and recorded with a temporal resolution of 1 ns.

A set of three uncollimated PIN (p-i-n) diodes was used to monitor the radiation emitted during the discharge from both the plasma and the electrodes. The diodes used were of the BPX 65 type (with the glass window removed) with a bias voltage of 27 V. The signals generated by the PIN diodes were recorded on a digital oscilloscope with a temporal resolution of 0.4 ns. A typical signal from the PIN diode filtered with 5 μm aluminum is shown in Fig. 1(a). This gives the timing of the x-ray emission and shows that two pulses of width 6 and 8 ns were emitted from the X pinch at $t=108$ and 123 ns, respectively. The pulse in Fig. 1(b) corresponds to the arrival at the pinch of the first of two laser pulses that are used in the interferometer described in the following. The second laser pulse arrives 22 ns later. It should be noted that the detected duration of the laser pulse is limited by the response time of the photodiode employed to monitor the signal.

To study the temporal evolution of the plasma in the X-pinch configuration a two frame Mach–Zender type interferometer was used. A frequency doubled, Q-switched Nd-YAG laser ($\lambda=532$ nm) with a stimulated Brillouin scattering (SBS) pulse compression scheme,[12] generating a pulse of 600 ps, was used as a light source. The laser beam was split into two collinear beams with linear, but perpendicular, polarizations and with a time separation of 22 ns. These beams were used to obtain the two individual interferograms in a single X-pinch shot. The two beams traveled along exactly the same path through the plasma providing two images with the same perspective, allowing the temporal evolution of the pinch to be studied. An image plane configuration, with a magnification of 1.3, was used in order to localize the interference fringes in the plane of the plasma. The images were recorded onto Ilford HP5 film using two 35 mm cameras, each one preceded by a polarizer to accept the desired image and to reject the other. The films were then optically scanned with a resolution of 2700 dpi. The laser pulse was monitored by a photodiode thus providing the timing of the laser pulse with respect to the other diagnostics, such as the electrical and x-ray signals, with a resolution of 1 ns. The sensitivity of the interferometer is a quarter of a fringe, which corresponds to a line integrated density of 1×10^{17} cm^{-3}cm. The optical arrangement used resulted in a spatial resolution of 50 μm.

Figure 2 shows a time sequence of interferograms taken from different shots. The first time written below each image is the time of the laser pulse relative to the start of the current pulse. The second time, in brackets, indicates the difference between the laser pulse and the time of the peak pulse of the x-ray emission detected by the diodes. A negative value indicates that the laser pulse is before the radiation pulse and a positive value indicates that it is after. Figure 2 shows the features mentioned in Sec. I, which are commonly found in X-pinch plasmas. First, the X-pinch limbs are seen to expand although the plasma density remains too high for the laser to penetrate. However, the slight fringe deviation that can be seen at the edges indicates the presence of a coronal plasma. This corresponds to the first phase of the three-phase development mentioned in Ref. 8. The velocity of expansion of this plasma is 0.5 cm/μs and is approximately constant throughout the discharge. Second, a column of plasma is seen to form on the axis of the pinch which increases in length with a velocity of typically 8 cm/μs until it reaches the electrodes after about 100 ns. The aspect ratio of the column is about 4, which suggests, although does not prove, that it is in fact a plasma jet. Other authors have also observed this column. As time proceeds, the expansion of the limbs continues and their density drops to the point where

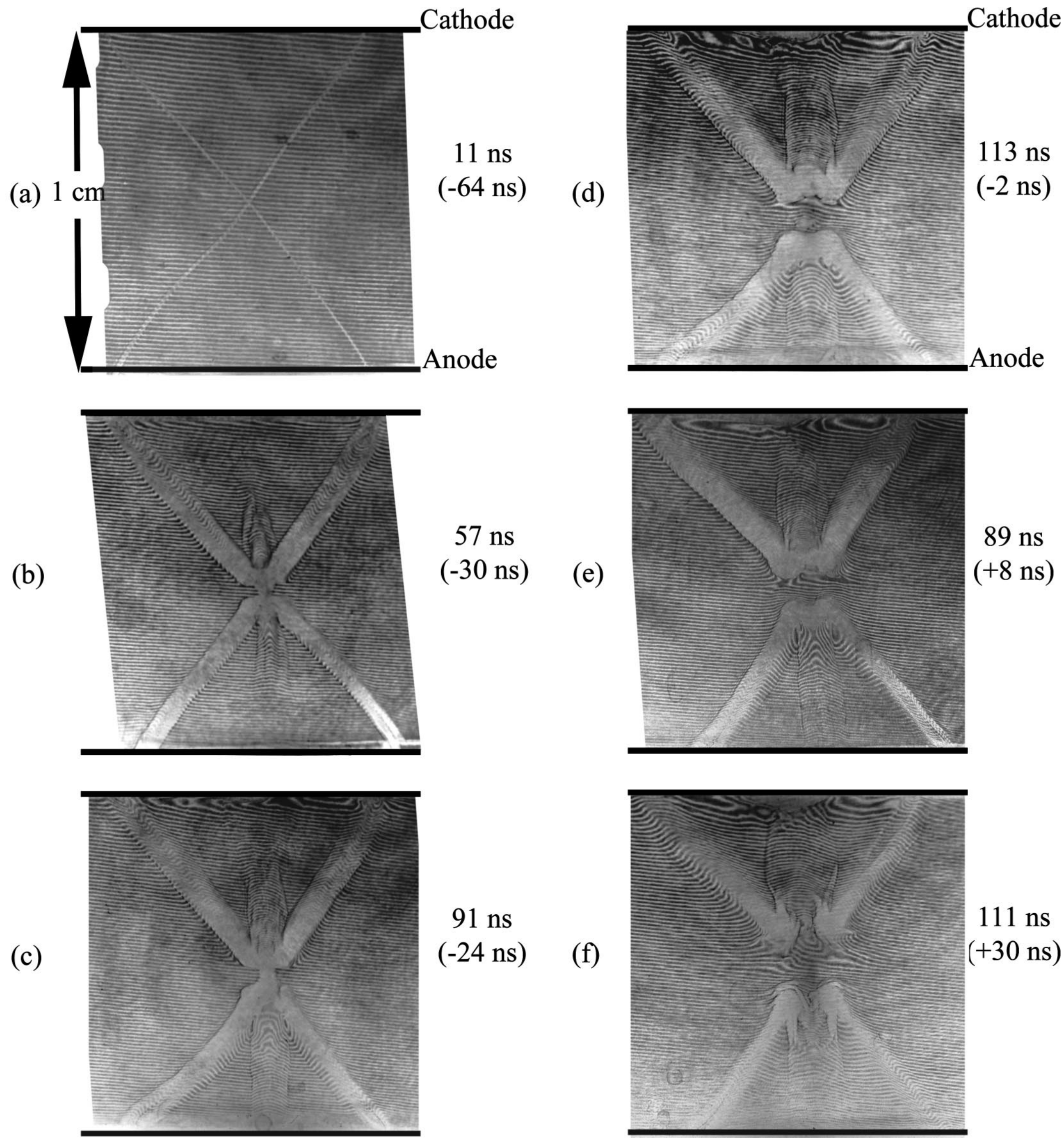

FIG. 2. A sequence of interferograms taken at different times in the X-pinch development. The time of each frame relative to the start of the current pulse is given and the time relative to the emission of the x-ray pulse is given in brackets. Interferograms (c) and (d) are from the same shot, as are (e) and (f).

the laser is able to penetrate the plasma and continuous interferometeric fringes start to appear across the limbs.

Figure 3 shows several enlargements of the interferograms in the region of the crossing point, before and after the radiation pulse. In the earlier of the two frames in Fig. 3(a) a dense pinch of radius 250 μm and length 500 μm bridges the gap between a virtual anode and cathode which are formed by the dense plasma at either end of the crossing point region. This region has been referred to as the minidiode gap[8,9] because of the evidence for electron beams accelerated in this gap. There is little or no deviation of the fringes at radii greater than that of the pinch in the minidiode gap, which suggests that the pinch is very efficient in sweeping up the material as it collapses. In the later frame of Fig. 3(a), which is taken 22 ns later in the same shot, at about the time of emission, a spot of plasma of diameter 400 μm and of high density is observed in an otherwise tenuous gap. Interference fringes cannot be seen in this spot suggesting that the laser is refracted from the optical system implying a density greater than $\sim 5\times 10^{19}\ \mathrm{cm}^{-3}$. After radiation has been emitted from the crossing point the interferograms show only a tenuous gap as in Fig. 3(c). Frequently interference fringes can be seen to traverse this gap undeviated, indicating that the electron density is less than $\sim 10^{18}\ \mathrm{cm}^{-3}$ assuming a path length equal to the size of the dense spot which was visible before the emission. This is the third of the three phases.

Figure 4 shows two interferograms of X pinches which are taken side-on, i.e., in the same plane as the X-pinch wires. In image (a) a soft x-ray pulse was detected 4 ns after the laser and a pinch is clearly seen at the crossing point. Image (b) is taken 11 ns after the emission of a radiation pulse and it can be seen that a gap traversed by an almost undeviated fringe has now opened up in the crossing point region. Another feature which can be noted from these interferograms, particularly image (b), is that the diameter across which the fringes are deviated is about 1.2 mm, which is the same as the diameter of the wires and of the plasma column

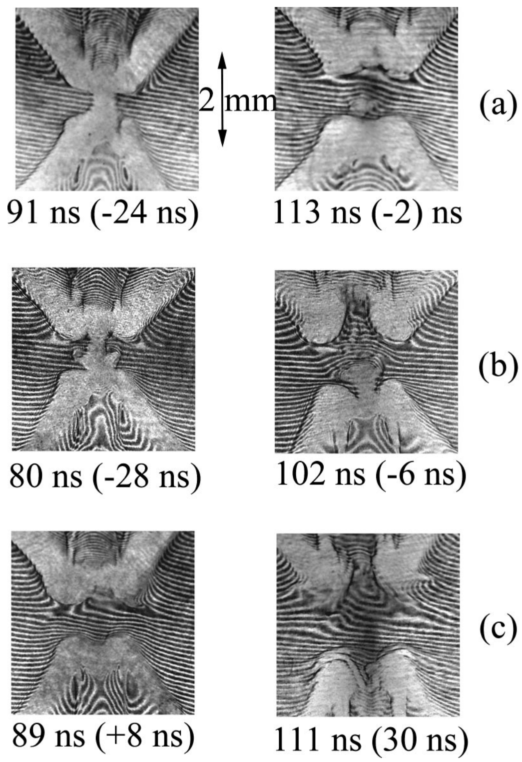

FIG. 3. Enlargement of the crossing point at various times relative to the radiation pulse. Each pair of interferograms is from the same shot.

measured in the interferograms of Fig. 2 taken at the same time but in the plane perpendicular to the wires of the X pinch. This shows that neither the plasma column nor the limbs have a significantly bigger diameter in this plane. This partly justifies the assumption of cylindrical symmetry that is used in the calculations of the electron densities from the interferograms.

The soft x-ray emission from the X pinch was temporally and spatially resolved using a gated two frame microchannel plate (MCP) x-ray pinhole camera with exposure time of 2 ns and a variable frame separation. Pinholes and filters were arranged such that each frame supplied multiple images of the pinch in different spectral ranges. The timing of the x-ray frames relative to the other diagnostics was known to within 1 ns. Two sets of images of a 10 μm aluminum wire X pinch obtained using the gated MCP camera at two different times separated by 10 ns are shown in Fig. 5. A 100-μm-diam pinhole was used for each image. The filter associated with each image is also indicated in Fig. 5 and the spectral transmission of each filter is shown in Fig. 6. Emission from the coronal plasma of the X-pinch limbs can clearly be seen through the 0.75 and 1.5 μm Al filters but this does not appear through the 1 μm titanium filter. Inspection of Fig. 6 reveals that the radiation is transmitted by a window in the aluminum filters between 15 and 70 eV but it is not sufficiently energetic to be transmitted by the titanium window which starts at about 200 eV. This indicates that the emission from the limbs is UV from the *L* shell of the aluminum inferring that the temperature of the limbs is below about 50 eV.

Figure 7 shows two interferograms taken from another X pinch shot. In this shot the crossing point did not pinch, nevertheless well-collimated plasma columns are still observed on the X-pinch axis. These results show that the plasma columns do not appear solely as a result of the pinching at the crossing point.

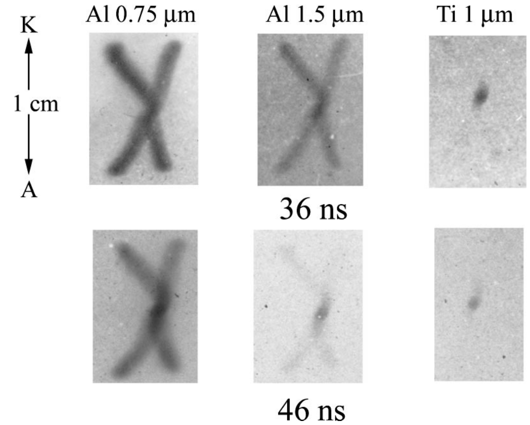

FIG. 5. X-ray framing images of a 10 μm Al wire X pinch taken at 36 and 46 ns after the start of the current pulse. The transmission of the filters is shown in Fig. 6. The images have a 5 ns exposure time.

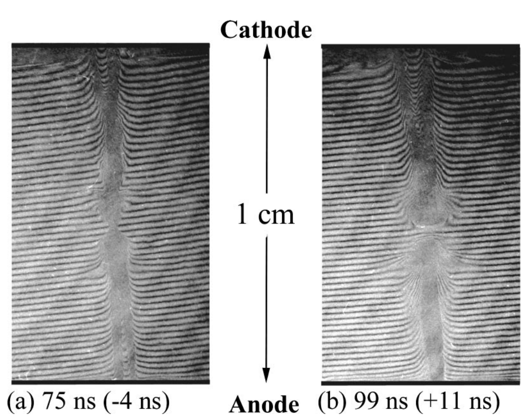

FIG. 4. Side-on interferograms of X pinches with radiation taken 4 ns before and 11 ns after the emission of radiation. These interferograms are from different shots.

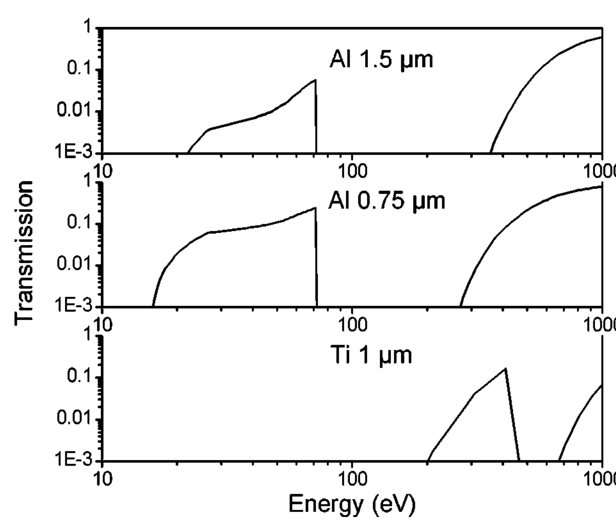

FIG. 6. Spectral transmission of the filters used with the MCP camera.

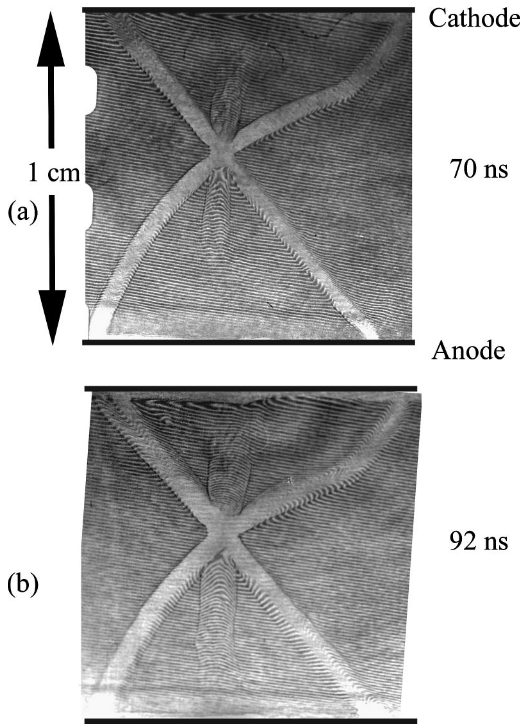

FIG. 7. Two interferograms from a single X-pinch shot where no pinching was observed at the crossing point. The time of the interferogram relative to the start of the current rise is given.

III. ANALYSIS

The question of the source of the plasma column that forms on the axis of the X pinch remains unanswered. Although the aspect ratio of the plasma column suggests that it is a jet, it is also feasible that the column is in fact formed from the coalescing on the axis of a low density expansion from the corona plasma of the X-pinch limbs, similar to the formation of the precursor in wire array Z pinches.[13] As the limbs are closer together toward the crossing point, expanding plasma from the limbs meets on the axis first near the crossing point and then, as time progresses, at axial positions toward the electrodes. This would give the appearance of the plasma moving axially from the crossing point toward the electrodes. Such a feature, called a snake, has been observed[10] in x-ray pinhole pictures in X-pinch discharges in aluminum and other materials. The following analysis sets out to test the hypothesis that the plasma column is composed of plasma which streams in from the limbs.

Figure 8 shows enlargements of the cathode plasma column for the two interferograms obtained from the shot whose traces are shown in Fig. 1. Two pulses of x-ray emission were detected from this shot and the interferograms were taken 28 and 6 ns before the first pulse. In these interferograms the interference fringes can be followed through the limbs of the X pinch enabling the ''zero'' (i.e., the unshifted) position of the fringes to be obtained from the position of the fringes at the extremities of the interferograms, where the plasma density is zero. The horizontal white lines in Figs. 8(a) and 8(b) are these zero levels of the bottom of each fringe. These lines are numbered consecutively with fringe 1 being the fringe closest to the crossing point. By following the fringes through the plasma limbs in the first interferogram, it can be seen that the fringes between the X-pinch limbs and the plasma column return to the zero position from fringe number 24 upwards and consequently there is no detectable interaction between the limb corona and the plasma column at axial positions above fringe 24. (Due to the radial expansion of both the column and the corona, the area of interaction increases up until fringe 26 by the time of the second interferogram.) As the density profiles of the plasma column can be measured at these two different times, and hence the number of particles per unit length calculated, it is possible to ascertain whether, for a given velocity, the electron flux required to account for the increase in density in the column would be detected by the interferometer if the material was coming in from the X-pinch limbs.

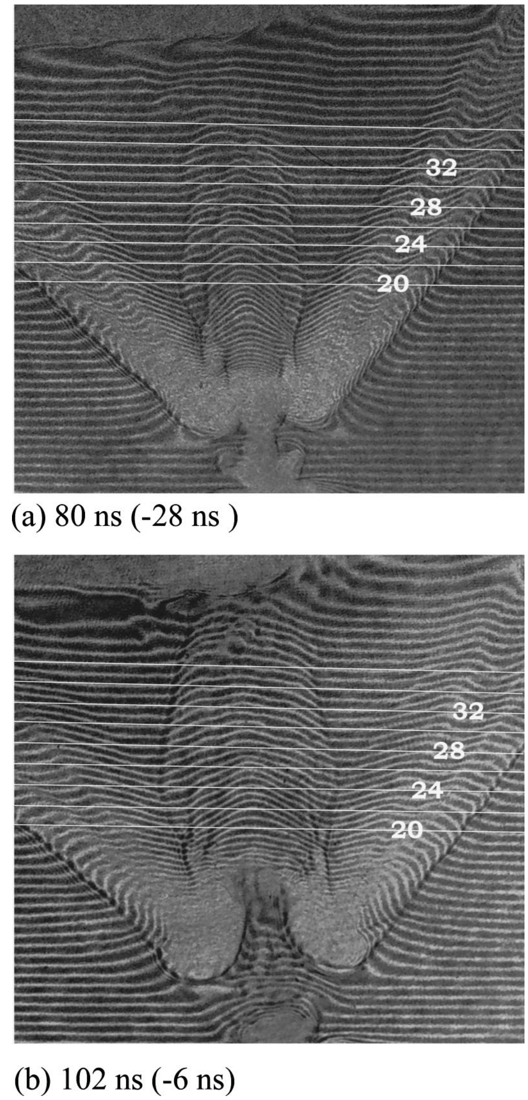

FIG. 8. Enlargements of the cathode jet in two interferograms from the same shot at 80 and 102 ns after the current start, which was 28 and 6 ns before the emission of a soft x-ray pulse.

Assuming cylindrical symmetry, density profiles of the plasma columns on the cathode side were obtained from both interferograms. The profiles were then integrated to obtain the particles per unit length in the column, Ne, at that axial

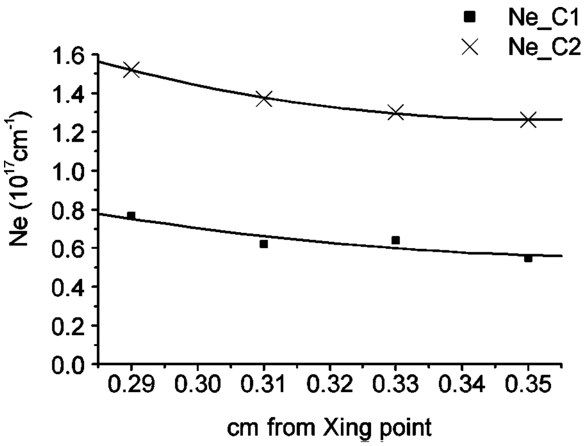

FIG. 9. Line density, Ne, of particles in the jet at $t=80$ ns (-28 ns) and $t=102$ ns (-6 ns) from interferograms of Fig. 8.

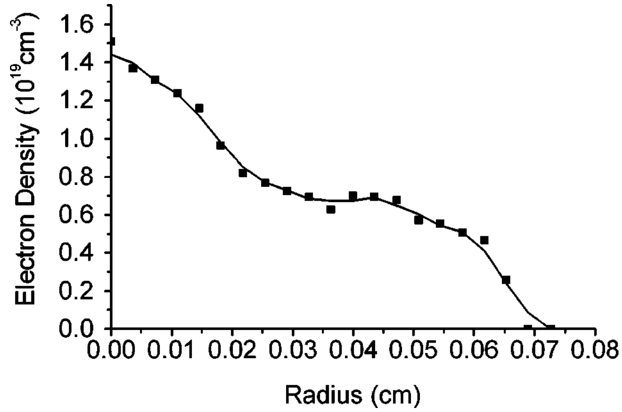

FIG. 10. Radial density profile of fringe 24 in Fig. 8(a) showing the centrally peaked component.

position. This calculation was then repeated for fringes at axial positions that did not exhibit any interaction between the limbs and the column in either of the interferograms. The results are plotted in Fig. 9 as a function of distance from the crossing point. The average difference in Ne between the two interferograms, which are separated by $\Delta t=22$ ns, is 7.2×10^{16} cm^{-1}. If the plasma in the column is assumed to come only from an expansion of the corona plasma from the X-pinch limbs (the idea here is to test this hypothesis), then the flux per unit length of electrons which is required to account for the difference in lineal density between the two frames can be calculated by

$$\phi/l_z=\Delta N_e/\Delta t=3.2\times10^{24}\ \text{electrons s}^{-1}\,\text{cm}^{-1}$$

$$(l_z \text{ is unit length in } z \text{ direction}).$$

Each limb of the X pinch must therefore supply 1.6×10^{24} electron s^{-1} cm^{-1}. If the plasma expanding from the limbs has a radial component of velocity, v_r, then the flux of electrons at the column is given by

$$\phi=n_e l_z l_y v_x, \tag{1}$$

where $v_x=v_r\cos(\alpha/2)$, and α is the angle between the limbs, in this case $=77°$. x and z are the horizontal and vertical axes in the interferograms and y is the axis perpendicular to the interferogram plane.

l_y is in fact the path length of the laser through the expanding plasma and therefore the fringe shift is proportional to $n_e l_y$. A fringe shift of one complete fringe is obtained for a line integrated density ($n_e l_y$) of 4×10^{17} cm^{-2}. As no fringe shift is observed, and the sensitivity of the interferometer is one-quarter of a fringe shift, an upper limit on the value of $n_e l_y$ of 1×10^{17} cm^{-2} can be set. Using this value in Eq. (1) along with the calculated value of $ø/l_z$ results in a lower limit of 32 cm/μs for the incoming velocity, v_x. This implies a radial expansion of low density plasma from the wires at a velocity of at least Mach 7.

Interferograms in which the plasma column had not yet reached the electrode were used to calculate the axial velocity, v_z, of the plasma jet. The distance the plasma column extended from the crossing point was measured using the shift of the interference fringes on the axis to indicate the presence of the column. As the time of each interferogram is known then the axial velocity can be calculated. In this way an average value of 8 cm/μs was obtained for v_z. This is the velocity with which the plasma column extends into the plasma free region on the axis. This value of v_z is in good agreement with that obtained from schlieren pictures of identical X pinches on the Gepopu generator[14] in another set of experiments.

If the plasma column is formed from low density material coming from the wires it would be expected that its axial velocity would be equal to the axial velocity of the incoming material. From the previous analysis, the radial velocity of this incoming plasma, v_r, must be greater than 40 cm/μs. The z component of the velocity would then be given by $v_z=v_r\sin(\alpha/2)$, which gives a minimum value of 25 cm/μs. This is obviously inconsistent with the measured value of v_z of 8 cm/μs, which suggests that the plasma column is not totally composed of plasma coming in from the wires. It is noted, however, that the axial velocity of the plasma column is about equal to the sound speed of the plasma corona.

In Fig. 7, once again, the fringes appear undeviated between the X-pinch limbs and the plasma column on the axis. In this shot no pinching was observed at the crossing point. A similar analysis to that previously carried out on the two interferograms in Fig. 7 gave a value for $\Delta N_e/\Delta t$ of 2.5×10^{24} cm^{-3} s^{-1}. This results in a minimum incoming radial velocity of 30 cm/μs if the column is composed solely of undetected, incoming material from the limbs. The axial velocity of the plasma column in this shot is close to the average of 8 cm/μs and is again much lower than that of the incoming material.

Further investigation of the fringes in Fig. 8(a) suggests that the plasma column is highly structured and, judging by the sudden change in the slope of the fringes about half way to the edge of the column, it appears to be made of at least two separate components. A radial density profile obtained from fringe number 24 of Fig. 8(a) is shown in Fig. 10. The profile clearly shows a narrow centrally peaked component superimposed on a broader component. This structure can also be observed in Fig. 2(b) in which the crossing point is in the process of pinching.

In order to explain these results the plasma column must consist of several components at least one of which does not depend on the pinching at the crossing point. One component may come from the corona plasma of the X-pinch limbs. The previously analysis shows that this material must be highly supersonic (greater than Mach 7) if it is to account for the influx of plasma into the plasma column. Such incoming material may explain the highly collimated jets which are present even when there is no pinching at the crossing point of the X pinch as the column may be confined by the bombardment by this highly energetic plasma. This idea is also consistent with the radial expansion of the plasma column observed between successive interferograms. The average expansion velocity is 0.7 cm/μs. If this were a thermal velocity then the plasma column would be expected to diverge with an angle of 5°. In fact angles of 1° or 2° are observed in many cases. Rather than being due to a thermal radial velocity, the expansion between frames may be due to the accretion of material streaming in from the limbs. However, as demonstrated previously, this model is not consistent with the assumption that the axial velocity of the plasma column is equal to the axial velocity of the incoming plasma.

Another possible source of plasma is the corona plasma in the region of the crossing point. As the higher density region (i.e., that which can be detected by the interferometer) expands radially from the limbs, it forms an overlap region close to the crossing point. In this overlap region the density will be greater than the density of the individual coronas. The expansion velocity of the limbs is such that this overlap region is limited to within about 0.5 mm of the crossing point. This plasma would see the low field region near the axis and could therefore stream axially toward the electrodes at its ion sound speed, thus providing another component of the column structure. This explanation is more consistent with the measured axial velocity of the column. It is of course possible that both of the above-mentioned components are present in the plasma column. If the assumption that the axial velocity of the plasma column is equal to the axial velocity of the incoming material is made, then a maximum value of the incoming flux per unit length that is consistent with a fringe shift below the sensitivity of the interferometer can be obtained. In the case of the interferograms in Fig. 7 where no pinching is observed, this maximum flux per unit length amounts to 40% of that required to account for the observed increase in the plasma column. In this case the confinement of the plasma column can still be explained by the bombardment of the incoming material. Current flow in the plasma column may also contribute to the observed confinement. The presence of an azimuthal B field has been shown to be a good confinement mechanism for plasma jets[15] and simulations of wire array Z pinches have shown that a combination of supersonic bombardment and an azimuthal *B* field confines the precusor plasma.[16] (However, the increased symmetry in the case of the wire array Z pinch would make the confinement due to bombardment more effective than in the X pinch.) Current flow could also explain the slight kinks observed in some of the columns which may be due to MHD instabilities.

The results show that another component of the plasma column is the axial ejection of material from the crossing point caused by the pinching of the plasma there. This component could provide the centrally peaked density profile observed in Fig. 10. The transport of mass away from this region is obvious when the sequence of interferograms in Fig. 2 is considered. In Fig. 2(c) a dense pinch can be seen at the crossing point which refracts the laser light from the system, whereas in part (d), 22 ns later in the same shot, interference fringes can be followed here. This indicates a sudden decrease of mass in this region. Comparison of Figs. 8(a) and 8(b) shows that between the two frames there is again a striking drop in the density, this time at the central part of the virtual electrode formed by the plasma limb. Figures 2(e) and 2(f) also show the same feature although at a more developed level. Here the formation of an axial channel linking the crossing point and each of the columns through the virtual electrodes is seen. The crossing points in these interferograms are shown enlarged in Fig. 3. These observations strongly suggest that the plasma has been forced axially away from the crossing point and has pushed the high density plasma ahead of it into the plasma column and left behind a low density region. These observations are consistent with the backlighting images and conclusions obtained in Ref. 8.

IV. CONCLUSIONS

A quantitative examination of the electron density in aluminum wire X pinches has been carried out using two-frame, time resolved interferometry. The development of the X pinch was demonstrated to follow the familiar sequence of events. Initially the wires of the X pinch expanded and were surrounded by coronal plasma. Plasma columns were then seen to form on the axis of the pinch between the crossing point and the electrodes. A pinching was observed at the crossing point and a short Z pinch was formed. Some tens of nanoseconds later all that remained at the crossing point was a hot spot and a pulse of soft x rays was emitted. After emission, the crossing point region contained only low density plasma, sometimes less than the detection level of the interferometer.

Analysis of the interferograms showed that although the corona plasma and the plasma column had expanded to the extent that they interacted only in the region close to the crossing point, there was a definite separation of the two at distances further away from the crossing point where the interference fringes returned to their zero position. The issue of the source of the plasma column was addressed in a quantitative way and demonstrated that the results were not consistent with the column being produced solely by plasma coming in from the X-pinch limbs. It is believed that the plasma in the column comes from several different sources. One source is a low density, supersonic component expanding from the limbs which is not detected by the interferometer. The authors suggest that another component of the plasma may come from the corona plasma in the parts of the limbs close to the crossing point. This plasma is seen to expand and reach the axis where it can stream at the sound speed into the low field region. The final source of the column plasma is the axial expulsion of material from the crossing point due to the pinching process. This explains the transfer of mass out of the crossing point region which is observed in the interferograms.

Given the above-mentioned information and the high aspect ratio of the dimensions of the plasma columns, it is concluded that the plasma columns are indeed jets which originate from the crossing point of the X pinch. It is hoped that these experimental results will stimulate numerical simulations in order to provide a clearer picture of the physics involved in the plasma jet formation.

ACKNOWLEDGMENTS

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