

Effect of wire number on x-pinch discharges

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An investigation has been carried out into the x-ray emission and plasma dynamics of a “tabletop” x-pinch plasma generated by passing a 40 ns, 35 kA current pulse through two or four 5 μm thick tungsten wires. It was found that a four-wire x pinch consistently resulted in an order of magnitude higher energy hard x-ray yield (>3.5 keV) than a two-wire pinch. The total x-ray emission from a four-wire pinch also had a shorter pulse length such that the total x-ray power was increased by more than a factor of 2. Observations of x-pinch discharges driven by a higher energy 160 kA, 80 ns generator are also presented. In this case x pinches with two, four, and six wires were made using thicker aluminum and molybdenum wires and the number of wires is shown to play a significant role in the plasma dynamics. Increasing the number of wires enhanced the reproducibility of the discharge and the x-ray pulse. © 2006 American Institute of Physics. [DOI: 10.1063/1.2216110]

One of the most important applications of plasma physics is the use of discharges for the production of x-ray radiation. Clearly, x rays have a wide range of applications for lithography, biomedicine, material science, and for the diagnosis of dense plasmas.

In z-pinch discharges, in which a large current passes through a single wire, a series of bright x-ray emission regions located along the wire is typically observed and is associated with the growth of magnetohydrodynamic instabilities. The random spatial and temporal behavior of these bright spots often makes use of this source problematic. x pinches, however, which are typically formed by two wires placed between the electrodes making shape of the letter “x” are much more reproducible.^{1–8} A localized x-ray source is produced at the cross point which can have an x-ray pulse duration less than 1 ns, a spot size less than 1 μm , and x-ray energies in the 1–10 keV range. These parameters make x pinches particularly attractive for many applications.^{4,5}

In this letter, we report measurements of the effect of wire number on x-ray emission and jet formation. Experiments were performed using x pinches formed from two, four, and six wires and measurements of the optical and x-ray emission were made. The use of more than two wires during these discharges resulted in higher x-ray emission and more consistent performance of the discharge.

In the initial experiments a small four capacitor Marx bank was used to pulse charge a coaxial water dielectric line, which was then switched by a self-breaking gas spark gap into an x pinch load located in an evacuated chamber.⁷ The total footprint of the generator and x pinch chamber was about 1.2×0.4 m². The x pinch was formed with 5 μm thick tungsten wires between electrodes separated by a distance of 20 mm. The current pulse peaked at 35 kA with a 10%–90% rise time of 30 ns. The current crowbarred at about 100 ns as a result of a breakdown across the insulator at the high voltage feedthrough in the discharge chamber.

Time integrated optical images of the pinch were obtained using a charge coupled device (CCD) camera (see Fig. 1). It is apparent from these images that there is a significant qualitative difference between two- and four-wire discharges. There is less emission from the “legs” of the four-wire x pinch than the two-wire pinch, while there is significantly more emission from the cross point of the four-wire pinch. The jets propagating to the anode and cathode from the x point are more prominent in the four-wire pinch. An unusual aspect of the four-wire x-pinch image is the appearance of fine “streamers” of plasma emitted from the plasma legs, which seem to travel away from the central jet.

The main diagnostics for detecting x-ray emission from the x pinch were photoconducting diamond diodes (PCDs). A variety of filters was used with the PCDs to characterize the range of x-ray energies emitted by the x pinch. For a typical shot two PCDs were used, mounted onto one of the chamber ports at a distance of 30 cm from the x pinch. A 6 μm thick aluminum filter was used on the first PCD for measurements of the “harder” x rays (>3.5 keV). 1.5 μm polycarbonate was used on the second PCD to detect softer x rays (which had a lower range of about 1 keV). To provide time integrated images of x-ray emission a pinhole camera was

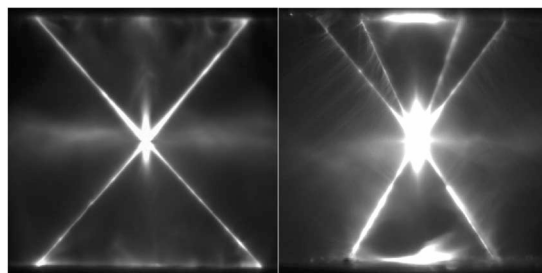


FIG. 1. (Color online) Two- and four-wire x-pinch CCD images of time integrated optical emission using similar contrast to highlight emission from the “legs” and from the plasma jet interaction with the electrodes. Anode and cathode are situated at the top and bottom of the image, respectively (vertical scale is 20 mm).

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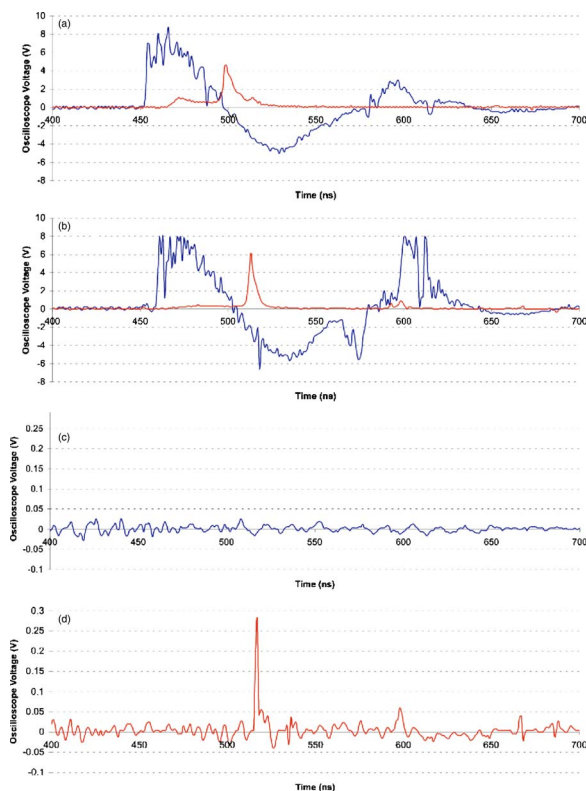


FIG. 2. (Color online) (A) Two-wire x -pinch PCD signal using 1.5 μm polycarbonate filter—the pinch occurred 2 ns after the peak current, (B) four-wire x -pinch PCD signal using 1.5 μm polycarbonate filter—the pinch occurred 10 ns after peak current, (C) two-wire x -pinch PCD signal using 6 μm aluminum filter—no signal observed above noise level, and (D) four-wire x -pinch PCD signal using 6 μm aluminum filter—no signal occurred 10 ns after peak current. Note that the dI/dt trace for these shots is shown in (A) and (B).

mounted on a chamber port at a distance of 220 mm from the x pinch. A range of filters was used for the pinholes, similar to those used for the PCDs. The PCDs and the pinhole camera provided a consistent way of comparing two- and four-wire x pinches. To observe the plasma dynamics of the x pinch over the duration of a shot, a framing camera was used which was able to image the plasma in the soft x-ray region in 5 ns exposures spaced by around 9 ns. By combining images from multiple shots an image of the plasma dynamics over the duration of a typical shot could be built up.

Figure 2 shows some typical PCD traces for a two- and four-wire x pinch, taken using 1.5 μm polycarbonate and 6 μm aluminum filters. The two sets of traces show that the four-wire x pinch emitted more x rays in both wavelength ranges in a narrower pulse and hence with a larger power. The average 1.5 μm polycarbonate filtered PCD peak voltage for the four-wire x pinch was 5.0 ± 0.6 V compared to 4.0 ± 0.6 V for the two-wire shots.

Whereas the two-wire x pinch produced very little hard x-ray emission (through the 6 μm aluminum filter) the four-wire x pinch gave a sharp peak corresponding to the higher energy x rays. The harder pulse of x rays from the four-wire x pinch had an average peak voltage of 190 ± 30 mV and a full width at half maximum (FWHM) time duration of 1–2 ns. However, due to the oscilloscope resolution (1 ns), it is likely that the duration of the hard x-ray signal was less than this. Unfiltered PCD measurements were also made for some two-wire x pinches (seven shots in total), with an average peak voltage of 5.1 ± 0.6 V. This equated to an emitted

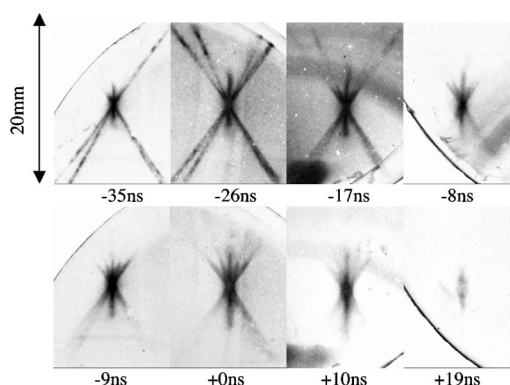


FIG. 3. (Color online) Four-wire x -pinch x-ray framing camera images showing dynamics of the pinch (no filters are used). Timing is given relative to the “pinch time.” Note the development of a “kink” instability in the jet indicating current transfer to the jet at early times.

power of 7.1 ± 0.8 MW. Multiplied by the typical FWHM of the unfiltered x-ray peak (4 ± 1 ns) a typical energy for the x-ray burst for a two-wire x pinch of 30 ± 10 mJ was found. The total x-ray energy for four-wire pinches (over a sequence of 12 shots) was roughly similar to that of the two-wire x pinches (although the hard x-ray emission >3.5 keV was enhanced by about an order of magnitude). We estimate that the increase in total x-ray power for four-wire pinches was about a factor of 2 because of the shorter pulse duration.

Less than 10% of shots showed any detectable hard x-ray emission with a two-wire x pinch during this experiment whereas they were easily detected on every four-wire shot. It was also clear that there was a difference in the timing of the x-ray burst for each configuration between the two- and four-wire pinches. A clear pattern was observed, with the four-wire x pinches consistently producing a later x-ray burst than the two-wire shots. The average times of the two- and four-wire x-ray emissions (after peak current) were 2 ± 1 and 10 ± 1 ns, respectively.

The reason for this marked difference in pinch timing may be due to the process that occurs just before the discharge “pinches” to its minimum radius, where a large amount of plasma material is squeezed out of the central crossing point. With four wires there is twice the mass present in that region, so in order for the pinch to take place a longer time is required to eject the necessary mass. Hence it would be expected that not only would more mass be ejected from the central region (as evident in Fig. 1) but the peak x-ray emission would take place at a later time for a particular current pulse. Shown in Fig. 3 are x-ray gated images of the four-wire pinch. The anode and cathode are situated at the top and bottom of the image, respectively.

When two- and four-wire pinhole images are compared several differences can consistently be observed. For a two-wire x pinch observed through an open pinhole (no filter) several hot spots were seen along the legs, corresponding to smaller scale instabilities. For a four-wire x pinch these hot spots not only disappeared, but a much brighter emission from the x point was observed (particularly through the 6 μm aluminum filtered pinhole). This result supported the observations made with the PCDs that the four-wire x pinch produced a significantly higher amount of hard x rays.

With a four-wire x pinch the current is divided between four legs instead of two, which may mean that less energy would be deposited and lost in each leg (in the form of soft x-ray emission along the legs). The result of this may be a

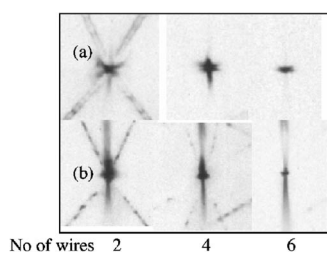


FIG. 4. (Color online) Time integrated x-ray pinhole images for (a) aluminum and (b) molybdenum x pinches. x pinches consisted of two, four, and six wires driven by the IMP generator. Images were recorded through a $1.5\ \mu\text{m}$ thick aluminized Mylar filter ($h\nu > 100\ \text{eV}$) and a $100\ \mu\text{m}$ pinhole (the vertical scale is 20 mm).

hotter, denser plasma at the central crossing region that could then produce the harder x rays observed with the pinhole images and PCDs. It may also be possible that the current path is more complex for pinches with more than two wires and that this can affect the x -ray emission.

The more prominent four-wire jet emission could be due to the increased temperature, or the extra mass that is expelled from the crossing point during the pinch. The pinhole images (not shown)⁹ also showed an apparent asymmetry in the plasma jetting axially outwards from the central crossing point, with more x -ray emission from the plasma jetting downwards towards the cathode than upwards to the anode. Previous investigations into the central jetting of the x pinch using laser probing have generally shown symmetry in the electron density of the plasma jets emitted.⁶ This suggests that the asymmetry observed in x -ray emission for the jets here is likely due to the jet propagating towards the cathode having a higher temperature. It is clear from other measurements during these experiments (radiochromic film measurements)⁹ that the energy of the ions in the cathode directed jet was much higher than in the other jet.

To summarize these low current experiments it was found that, unlike the two-wire x pinch, four-wire x pinches consistently produced harder x -ray bursts of a duration of $< 2\ \text{ns}$. The four-wire x pinch was also found to occur around 7 ns later than a two-wire x pinch (with respect to the peak current flowing through the system), which suggests that more time is required to eject the additional plasma at the central crossing point of the four-wire x pinch before the pinch can occur. Pinhole images of the two configurations confirmed the harder x -ray emission from the four-wire x pinch, with greater soft x -ray emission along the limbs measured for the two-wire x pinch. An observed asymmetry in the soft x -ray emission from the central plasma jetting may indicate a difference in the plasma temperature for the anode and cathode directed jetting.

To confirm this behavior, experiments were also carried out on the much higher current “IMP” generator at Imperial College. The generator used to drive the x pinch is discussed in detail in Ref. 8. It consists of a Marx bank (eight stages, each stage having a $0.7\ \mu\text{F}$ capacitor charged to a maximum of 100 kV in parallel and discharged in series). The Marx generator pulse charges a water dielectric coaxial pulse forming line ($4\ \omega$, 40 ns transit time). A self-breaking SF₆ gas pressurized switch connects the line to the z -pinch load via a transfer line with a matched impedance and similar transit time. The x pinch was positioned between electrodes, 20 mm separation, at the axis of a metal (aluminum) evacuated

chamber of 300 mm diameter. In most shots, a surface breakdown occurred late in time along the Lucite (polymethylmethacrylate) insulator in the vacuum on the x -pinch side. This crowbarred the current in the pinch at about 200 ns. The peak current was 160 kA, which occurred at 80 ns after the beginning of the discharge. The x pinch was formed using either aluminum or molybdenum wires. The diagnostics included a time integrated x -ray pinhole camera with a variety of x -ray filters and pinhole sizes.

A significant difference was observed between aluminum and molybdenum x pinches as shown in Fig. 4. Time integrated x -ray images were recorded for x pinches consisting of two, four, and six wires. In Fig. 4(a), x -ray emission from wires and at the cross point can be seen. X -ray emission from individual wires and jets was not observed for four- and six-wire aluminum x pinches. However, emission from the central pinch was most intense for aluminum x pinches consisting of four wires. In contrast to aluminum results, extended jets were observed for all molybdenum x pinches with different wire numbers, which was consistent with x -ray framing images. Emission from the individual wires was not observed for x pinches consisting of six wires. Another striking difference is the observed size of the pinch plasma, which was at least a factor of 2 larger in the case of aluminum x pinches and it is likely due to radiative effects. This clearly shows that the wire material plays a significant role in jet formation.

These higher current experiments confirm the observations of pinch dynamics made on the “tabletop” x pinch. It is clear that the number of wires plays a significant role in the dynamics of x pinches and the x -ray production processes, throughout a wide range of plasma conditions and currents. The use of more than two wires results in more stable discharges, increased reproducibility, and the emission of harder x rays with a shorter pulse duration. The use of four- and six-wire pinches also enhances the emission of energetic plasma jets in some cases.

The general conclusion from these experiments is that it is advantageous to use more than two wires for x -ray production, but that the optimum number of wires (and wire diameter) used for the x pinch depends on the parameters of the generator used.

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