The Formation of Precursor Structures in Cylindrical and "4 × 4" Wire Arrays

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(Invited Paper)

***Abstract*—This paper summarizes observations of precursor-column formation in cylindrical wire arrays on the 1-MA MAGPIE generator at Imperial College London. Direct experimental measurements of the diameter variation during the collapse and formation phase of the precursor column taken from gated soft X-ray images are presented. Three stages in precursor-column formation are identifiable from the data: broad initial density profile, rapid contraction to small diameter, and slow expansion after formation. The variation in the minimum diameter is measured for several materials, and data show good agreement with a pressure-balance model. Stability calculations suggest that the fraction of the drive current flowing the precursor column is $< 1\%$ for Al arrays and $\sim 2\%$ for W. "4 × 4" arrays show the formation of local precursor columns close to the wire position, which exhibit differences in stability depending on the wire separation. This may be related to deceleration of the plasma flow by the B-field or current convection in the flow.**

***Index Terms*—Precursor column, precursor plasma, wire-array Z-pinches.**

I. Introduction

A WIRE-ARRAY Z-pinch experiment displays several distinct phases, from wire initiation to implosion and X-ray generation. On longer current-drive (> 100 ns) machines, the processes occurring before the implosion of the main array mass comprise a significant proportion of the drive time, which presents an opportunity to study these in detail. During this period, a remarkably uniform and stable precursor plasma column forms on the axis of the array. Since its first identification [1], precursor-column structures have been observed in a large number of experiments and within a wide range of array parameters. The arrival of this mass fraction on the array axis, preimplosion, is due to the formation of a heterogeneous plasma structure from each wire caused by the passing of the drive current: Cold wire cores surrounded by a relatively low-density hot coronal plasma ($n_e \sim 10^{20}$ cm^{-3}, $T \sim 20$ eV) [2]. The radial $\mathbf{J} \times \mathbf{B}$ force accelerates the coronal plasma toward the axis, while the cold wire cores are continuously ablated. It is the stagnation of this flow at the axis which forms the observed precursor column.

This uniform and stable plasma object is interesting due to the combination of plasma-physics processes occurring during its formation. These include a transition from collisionless to collisional interaction of the plasma flow, the effect of radiation cooling on the dynamics of the plasma, and the development of ionization balance. In wire-array Z-pinches, the converging plasma flow is often sustained for a long time (> 100 ns) and in the precursor column these processes can develop in a quasi-stationary situation. The high degree of the azimuthal symmetry of the plasma flow in this system makes it an almost ideal test bed for 1-D radiation hydrodynamic codes, and offers parallels to other systems with converging plasma flows, e.g., of the plasma ablated from the walls of ICF hohlraums. The prefilling of the interior of an array with the plasma should be taken into account not only for understanding of X-ray pulse generation, where the accretion of mass during implosion may reduce instabilities at the accelerating plasma front but also in the design of different wire-array Z-pinch loads. This could be especially important for the concepts of dynamic [3] and static-wall [4] hohlraums, where the precursor flow can significantly change conditions of the foam targets installed on the array axis [5].

We present an experimental study of the dynamics of the precursor-column formation in wire-array Z-pinches at 1 MA using a range of imaging and X-ray power diagnostics. Data demonstrating formation times and column diameters for several different materials are presented and discussed, and an estimate of the current carried in the precursor column for Al and W is made. Results from "4 × 4" arrays are also presented.

II. Experimental Setup and Diagnostics

Experiments were carried out on the 1-MA 240-ns rise time MAGPIE generator at Imperial College London [6]. Wire arrays 16 mm in diameter and 23 mm long were used, which

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comprised 16 or 32 wires of Al or W wires of different diameters (10–50 μm Al, 4–13 μm W). Experiments with Ti, Fe, Ni, Cu, Mo, and Au wires were also investigated. Overmassed arrays (50 μm Al and 13 μm W) do not implode on the timescale of the experiment and are used to study the evolution of the precursor column on long time scales.

Diagnostics included laser probing, optical, and soft X-ray imaging, a range of filtered X-ray diodes, time- and space-resolved extreme ultra-violet (XUV) spectroscopy and X-ray radiography. Optical probing was performed using a frequency-doubled Nd-YAG laser (532 nm) with stimulated Brillioun scattering (SBS) pulse-compression (pulse duration ~0.4 ns), and images were recorded on charge-coupled-device cameras. Side-on optical diagnostics include laser probing with interferometer, shadow and Schlieren channels, and a streak camera with its slit oriented along the array radius. X-ray diagnostics include three gated (2-ns gate, spatial resolution of 100–200 μm) X-ray cameras, and photo-conducting detectors (PCD) with various filters.

III. Precursor-Column Formation

A. Collapse and X-ray Output

As the drive current is applied to the array, wire cores initially remain stationary and slowly ablate, generating coronal plasma which is continuously injected into the array. The rocket model [7] defines an "ablation velocity" as a constant relating force and the mass-ablation rate of the wire cores and sets this equal to the observed plasma stream-flow velocity. In experiments, measurements of the inwards radial velocity of plasma streams in aluminum arrays gives $\sim 1.5 \times 10^5$ ms^{-1}, with wire arrays made of other materials yielding comparable values [2]. The apparent universality of this "ablation velocity" suggests that the ion kinetic energies for different materials vary due to their atomic masses, and calculated values are ~3 keV for Al and ~21 keV for W. The mean free path (mfp) for ion collisions varies as the kinetic energy squared, and this determines the stream interaction and resulting density distribution at early times.

Plasma streams ablated from the wire cores first reach the axis at ~105 ns, which is a combination of a ~50 ns "dwell time" (during which the core-corona structure is formed) and the time-of-flight from the array radius to the axis assuming fixed velocity. The rocket model gives ion number densities of $\sim 10^{17}$ cm^{-3} for aluminum and 10^{16} cm^{-3} for tungsten, and the calculated mfp values are then ~0.5 mm for Al ions (assuming $z \sim 6$) and ~10 mm for W ions (assuming $z \sim 14$). The ablated plasma streams for aluminum are, therefore, collisional on the scale of the array radius (8 mm), and tungsten streams should be far less collisional.

The variation of the precursor-column diameter (gated XUV imaging) and typical PCD traces (filtered with 2-μm polycarbonate film transmitting 150–280 eV) taken over a series of experiments are given in Fig. 1 for both Al and W. The variation in diameter occurs similarly for both materials, and three distinct stages in the diameter evolution can be identified: 1) broad initial density profile; 2) rapid contraction to small

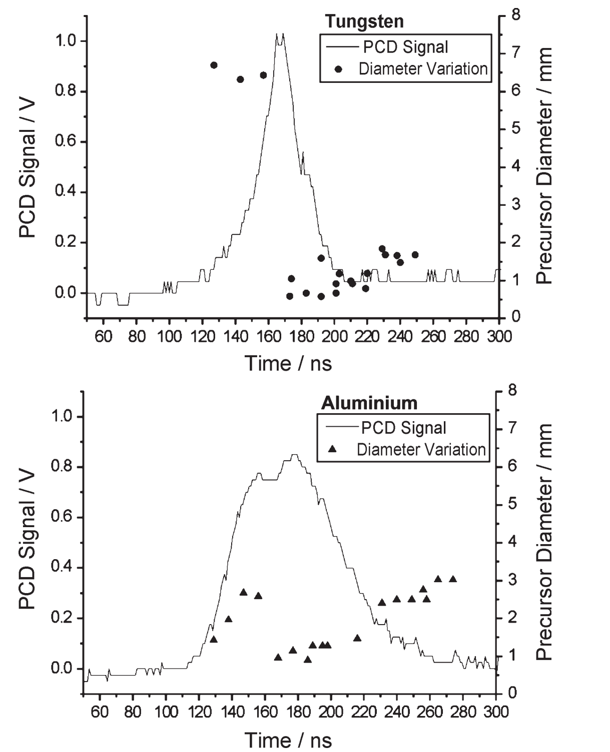

Fig. 1. Variation of precursor-column diameter and soft X-ray emission during column formation for W and Al.

diameter; and 3) expansion of column following formation. The initial diameters are significantly different for aluminum and tungsten. Aluminum shows an increasing diameter from ~110 ns and reaches a maximum of ~3 mm before the rapid contraction phase. Tungsten, however, shows a diameter of ~7 mm from early times, which remains relatively constant until collapse occurs. This is a direct result of the collisionality differences discussed above. Tungsten ions counter-stream for some time, and so, a broader emission region is observed, whereas aluminum ions essentially stagnate at the axis, forming a more confined emission region. The contraction phase and appearance of the precursor column occurs noticeably earlier in the current drive for aluminum (150–160 ns) than for tungsten (160–175 ns). This process occurs over approximately 10–15 ns for both materials and is associated with an X-ray output. The initial broad-density profile collapses immediately following the first X-ray peak, and the fully formed precursor-column results. An extended investigation of the precursor column is presented in [8].

B. Column Characteristics

Once the collapse process has begun, compression then continues until the final precursor diameter is reached, and this shows a dependence on array material. Several array materials have been investigated on MAGPIE, and the observed minimum column diameters are plotted in Fig. 2. Values range from 3 mm for carbon arrays to 0.25 mm for gold arrays. Values decrease almost monotonically with increasing atomic number, suggesting that radiative cooling plays an important role. Previous analysis [9] leads to a description of how the

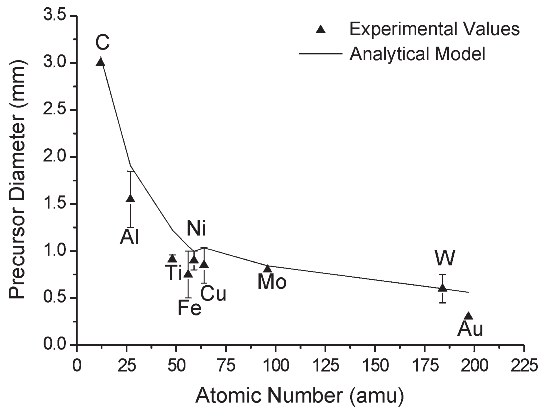

Fig. 2. Variation of precursor-column diameter with atomic number. Data (▲) with analytical model estimations (line).

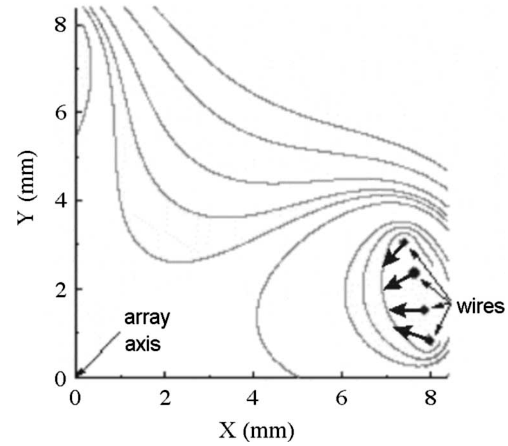

Fig. 3. Magnetic-field topology from magnetostatic calculations for 4 × 4 wire arrays. Arrows indicate flow direction for plasma in field configuration.

precursor diameter varies with atomic number. The method is derived from the rocket-ablation model and equates the kinetic pressure of the incoming plasma streams to the thermal pressure of the column itself. It is assumed that all kinetic energy from the streams is radiated away. This leads to a ratio of the column radii for Al and W as

$$\frac{R_{\mathrm{W}}}{R_{\mathrm{Al}}} = \frac{(Z_{\mathrm{W}}+1)T_{\mathrm{W}}A_{\mathrm{Al}}}{(Z_{\mathrm{Al}}+1)T_{\mathrm{Al}}A_{\mathrm{W}}}. \quad (1)$$

For $Z_{\mathrm{W}} = 14$, $Z_{\mathrm{Al}} = 6$, and $T_{\mathrm{W}} = T_{\mathrm{Al}} = 60$ eV (T_{Al} from XUV spectra in [9]), a ratio of 0.31 is calculated. This compares well with the value from experiments of 0.37 (using the minimum radius values of $R_W \sim 0.3$ mm and $R_{\mathrm{Al}} \sim 0.8$ mm). This simple analysis can be extended to include all the array materials investigated on MAGPIE, and this allows comparison to the experimental data. The calculated variation with atomic number is given by the solid line in Fig. 2. The values for charge states used for the comparison (assuming $T \sim 60$ eV in all cases) are $Z_{\mathrm{C}} = 4$, $Z_{\mathrm{Al}} = 6$, $Z_{\mathrm{Ti,Fe,Ni}} = 7$, $Z_{\mathrm{Cu}} = 8$, $Z_{\mathrm{Mo}} = 10$, and $Z_{\mathrm{W,Au}} = 14$, which are consistent with corona-equilibrium ionization values. Note that the model is normalized to tungsten, and so, the ratio in (1) equates to unity for this material. The experimental column diameter observed immediately after formation compares very well to the diameters expected from this analysis, and this suggests that the precursor column is in approximate pressure balance immediately after formation.

C. Current in the Precursor Column

After formation, the precursor column shows remarkable stability over the duration of the experiment. Data from laser probing show that $M = 0, 1$ magneto-hydrodynamics (MHD) structures are seen only at very late time W arrays (> 100 ns after formation) and are not seen for Al arrays even 300 ns after column formation. This information can be used to obtain an upper estimate of the current, which might flow through this plasma, assuming that the growth time of the classical MHD instabilities would be given by these time scales. Characteristic growth rate γ of $m = 0, 1$ instabilities in a Z-pinch can be written as a function of the Alfven speed c_A as [10]

$$\gamma = \left[\frac{c_A}{r_0}\right]\Gamma = \left[\frac{I}{2r_0}\sqrt{\frac{\mu}{\pi m_{\mathrm{pr}}}}\right]\Gamma. \quad (2)$$

The upper estimate of the current (I) which might flow through the aluminum precursor column could be obtained using $1/\gamma > 300$ ns, column radius $(r) = 1$ mm, and the precursor-column mass $(m_{\mathrm{pr}}) \sim 1 \times 10^{-6}$ kg/m, which is ~10% of the initial mass of a 16×15 μm Al wire array. Taking the wavelength of any instabilities in the precursor to be determined by the coronal streams as 0.5 mm, the minimum value of Γ is ~0.9 (corresponding to a $m = 1$ mode with uniform current distribution). Hence, maximum current through the precursor column is less than ~10 kA or < 1% of the total current through the array. For tungsten, if we take the growth time to be 100 ns, $r_0 = 0.3$ mm, and again, using 10% of the array mass, we obtain ~2% of the drive current. These current estimations are not sufficient to provide containment of the column, which is consistent with the assumptions in the pressure-balance condition used in the previous section.

The situation, however, could be different for some other materials, resulting in a higher current fraction. This follows from our preliminary experiments with Ni wire arrays composed of eight wires [11], in which development of $m = 1$ instabilities with characteristic growth time of ~50 ns was observed in the precursor. This indicates that as much as ~30% of the total current could flow through the column in this case.

IV. "4 × 4" ARRAYS

In this configuration, the wires are positioned in four groups with four closely spaced wires in each group (Fig. 3). This affords greater side-on diagnostic access to plasma ablated from the wires, while maintaining a global magnetic field to accelerate plasma to the array axis [2]. Arrays with two different interwire separations were used, equivalent to interwire separations in 32 and 64 wire arrays ($\delta\theta = 2\pi/32$ and $\delta\theta = 2\pi/64$). Formation of the core-corona plasma structure occurs

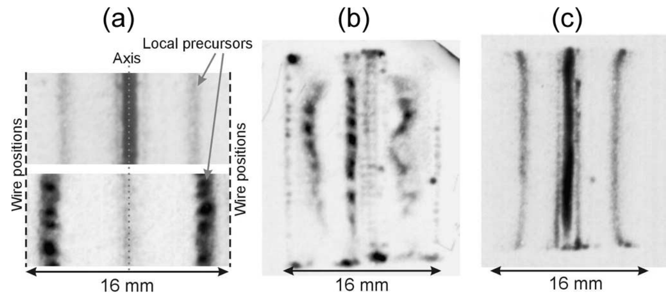

Fig. 4. Soft X-ray images of Al "4 × 4" arrays showing. (a) Difference in separation of wires and local precursors for (top) $2\pi/32$ and (bottom) $2\pi/64$ arrays and late time stability for (b) $2\pi/64$ at 171 ns and (c) $2\pi/32$ at 159 ns.

in the same way as in standard cylindrical wire arrays, and the $\mathbf{J} \times \mathbf{B}$ force sweeps the coronal plasma from the cores. The radial component of the force in this configuration is the same as in a standard cylindrical array, but in addition, there is a large azimuthal component of the $\mathbf{J} \times \mathbf{B}$ force. On the edge wires, this azimuthal component exceeds the radial force by a factor of four or seven for the interwire separations of $\delta\theta = 2\pi/32$ and $\delta\theta = 2\pi/64$, respectively. The first collision of the coronal plasma streams from the different wires (within each group), therefore, occurs close to the initial array radius, forming a "local" precursor in aluminum arrays. This is analogous to previous observations in linear-array experiments [12]. The characteristic diameter of the emitting region observed for Al arrays in the soft X-ray range is $\sim$1 mm, which is comparable with the estimated ion mfp of $\sim$1 mm. For tungsten arrays, this is not seen due to the low collisionality of the ablated plasma streams.

The greater azimuthal force in the $2\pi/64$ case means that the local precursor is formed closer to the wire position than in the $2\pi/32$ case. The measured distances from the wires to the local precursors are 1 and 2.5 mm, respectively [Fig. 4(a)]. In addition, the stability of these objects is markedly different. For the $2\pi/32$ case, the local precursor is formed at $\sim$130 ns and appears aligned vertically, with some curvature close to each electrode. This object remains stationary and stable until the main array implosion begins at $\sim$200 ns. The local precursor in the $2\pi/64$ case, however, shows large instabilities immediately following formation [Fig. 4(c)]. Regions of bright emission are observed with an axial wavelength of $\sim$2 mm, and a longer $\sim$10-mm wavelength modulation of the local precursor is also evident. Following the formation of the local precursor, the behavior of the plasma flow is again different for the two cases. In the $2\pi/32$ case, the plasma flow is not significantly hindered in its progress to the global array axis, and indeed, the global precursor is seen to form at a similar time to a cylindrical array. The $2\pi/64$ case shows no global precursor, suggesting that the plasma streams do not reach the axis in sufficient densities to allow its formation.

Once the local precursor has formed, it may provide an alternative current path, and carry a portion of the drive current. The magnetic field generated by this current may affect the plasma-flow conditions downstream (toward axis) of the local precursor position. The axial modulation of the local precursor in the $2\pi/64$ array configuration, along with the lack of a global precursor suggest that the observed instabilities are current driven. Inductance calculations were performed at a current of 500 kA (i.e., half way through the current drive) using the experimental wire-to-local-precursor separations and local precursor diameters. These calculations yield 21 kA ($\sim$4% of the drive current) in each local precursor for the $2\pi/32$ case, and 36 kA ($\sim$7% of the drive current) for the $2\pi/64$. These current values can be used to calculate the timescale for instability growth with the density taken to be the global precursor density after formation divided into the four local precursors. This gives $1/\gamma \sim 80$ ns and $\sim$50 ns for the $2\pi/32$ and $2\pi/64$ configurations, respectively. The density used is likely to be an overestimate for each local precursor, especially for the $2\pi/32$ case where the global precursor is also formed, and so this represents an upper limit to this timescale.

The experimentally observed difference between the two configurations appears significantly larger than these calculations suggest. In the $2\pi/32$ case, the local precursor is observed for $\sim$70 ns but probably contains significantly less mass than used in the calculations, since the global precursor forms only slightly after the expected time for a cylindrical array. A lower mass would reduce the instability timescale, and the growth of instabilities would be expected. This is not observed, and the level of current in the local precursor may be less than the inductive calculations suggest. Similarly, the $2\pi/64$ configuration shows instabilities immediately after formation in the experiment, which is considerably more rapid than the 50-ns timescale from calculations. In this case, the density used is likely to be much closer, since the global precursor is not formed and mass flow to the axis is hindered. The current level inferred from experimental observations may be higher than from inductance calculations.

It is possible that the difference in stability is related to the deceleration of the plasma flow by the magnetic field. The local field configuration around the wires and local precursor in each group requires the plasma flow to penetrate through the field to travel to the array axis. The stronger field in the more closely spaced $2\pi/64$ case may generate Raleigh–Taylor-like structures due to strong flow deceleration, but the lower field in the $2\pi/32$ case means these are not present. It is also possible that the extent of current convection toward the axis by the plasma plays a role. If current remains within $\sim$1 mm of the wire cores, it may be expected that the local precursors would carry different amounts of current, since $2\pi/64$ configuration forms a local precursor closer to the wire position than the $2\pi/32$, and hence, display different stabilities.

V. Conclusion

The phenomenon of the compact precursor column in wire-array Z-pinches occurs due to an intrinsic feature of the plasma-formation process from the initially solid wires. The precursor-column-formation process shows three distinct stages: 1) broad initial density profile; 2) rapid (10–15ns) contraction to small diameter; and 3) slow expansion following formation. The timing of these stages is a result of the collisionality of the ablated streaming plasma. This leads to a delay between the first arrival of the plasma to the axis and the formation of a dense precursor column for higher Z materials, as well as a variation in the diameter of the on–axis plasma at early times. A simple model for scaling of the precursor radius immediately after formation with atomic number developed from pressure balance shows good agreement with the experimental data for wire arrays of several materials. The precursor column remains stable and analysis suggests $< 1\%$ of the drive current flows in the column for Al arrays and $\sim 2\%$ for W arrays.

“4 $\times$ 4” arrays show the formation of local precursor columns close to the wire position, the position, and stability of which depends on the wire separation. The difference in stability may be related to the deceleration of flow by the magnetic field or current convection by the ablated plasma streams.

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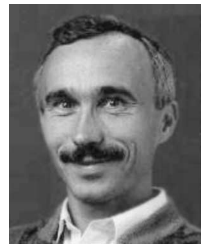

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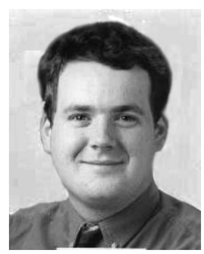

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