Effect of the global to local magnetic field ratio on the ablation modulations on X-pinches driven by 80 kA peak current

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Abstract. We report the results of experiments where a quantitative analysis of the behavior of ablation modulations in X-pinches (including wavelength and contrast between streams) was carried out as a function of distance from the cross-point, and consequently, as a function of the global to local magnetic field ratio. Experiments were performed using two tungsten wires of 10µm diameter in an X-pinch configuration on a pulsed power generator capable of producing an 80 kA current over a 50 ns rise time. We compare these findings directly to three-dimensional magneto-hydrodynamic (MHD) simulations using the MHD resistive code GORGON. Here, we demonstrate a dependence between the magnetic field ratio and ablation properties, suggesting a transition to a classical $m = 0$ instability far from the cross-point. Additionally, we examine the ablation properties of similar Z number nickel and copper wire X-pinches.

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1. Introduction

The pulsed power exploding wire experiments provide a versatile arena for studying high-energy density physics (HEDP), with applications in inertial confinement fusion [1], laboratory astrophysics [2] and point projection radiography [3, 4]. In these experiments, a fast-rising, high-current pulse (typically $>10^{11}$ A s$^{-1}$) passes through the fine metallic wires, generally measuring from sub-tens of µm to tens of µm in diameter. The wires ablate and expand, forming a heterogeneous structure consisting of a cold (approximately a few eV), dense wire core surrounded by a low-density, hot ($\sim$15 eV) coronal plasma, the latter of which carries the bulk of the current [5–8].

In a single wire system, the coronal plasma exhibits density modulations due to the development of magneto-hydrodynamic (MHD) instabilities caused by inherent non-uniformities in the coronal plasma. MHD instability growth timescales are determined by the Alfvén transit time, $V_A/r$, where $V_A = B/\sqrt{(\mu_0\rho)}$ and $r$ is the plasma radius. For exploding wires, timescales are of the order of 10 ns or less so systems undergo at least several growth periods over typical experimental durations of 50–300 ns. Observed $ka$ values are $\sim$5–20, and the dominant axial (parallel to the wire axis) wavelength initially increases as the plasma radius continues to expand as a result of ohmic heating [9]. In the ideal limit, the high $B$-field in the constricted region of the $m = 0$ instability prohibits radial mass flow entirely, whereas the flare regions expand essentially force-free, giving a large axial density contrast between constricted and flare positions. The conditions here yield an axially symmetric $m = 0$ instability.

When using multiple wires the private local magnetic fields surrounding each wire ($B_{\text{local}}$) are additionally encapsulated by a global magnetic field ($B_{\text{global}}$) enveloping the entire system. In a system with a dynamically significant $B_{\text{global}}$, the coronal plasma is accelerated from the wires by the $\mathbf{J} \times \mathbf{B}_{\text{global}}$ force at a rate well approximated by an analytical rocket model developed by Lebedev et al [10]. Independently, a similar numerical model was developed by Aleksandrov et al [11] of the compression of a plasma shell in a liner to achieve conditions for fairly compact and relatively stable radial compression.

Unlike the plasma in a classical $m = 0$ instability, the plasma accelerated from the wires here exhibits a quasi-periodic density modulation. A considerable number of previous studies indicate that the period of these modulations changes with wire element, but is insensitive to the initial wire diameter, current per wire or strong local perturbations such as features etched into the wire [12, 13]. Experiments with helical wires successfully altered the modulation wavelength, creating a period identical to that of the helix, indicating that the topography of the magnetic field plays a crucial role in the behavior of these flares [14].
Figure 1. Illustration of a scaled X-pinch with sample magnetic fields.

The X-pinch configuration, created by placing two or more wires between the electrodes of a pulsed power device and rotating one of the electrodes until the wires cross, provides an excellent opportunity to observe these modulations under varying $B_{\text{global}}$ (see figure 1). The calculations with a core width of 100 µm tungsten show that the $B_{\text{global}}$ exhibits relative dominance over the $B_{\text{local}}$, close to the cross-point, but then decreases rapidly moving toward the electrodes.

While X-pinches are often studied for their cross-point dynamics or axial plasma jets, we utilize them in this paper to study the transition from a regime with a dynamically significant $B_{\text{global}}$ to a $B_{\text{local}}$-dominated system and the effect this has on the behavior and properties of the ablation modulations. The experimental data are then compared to three-dimensional (3D) MHD simulations produced with the GORGON code. Additional comparisons are made between the ablation properties of nickel and copper X-pinches.

The rest of this paper is organized as follows. Section 2 describes the experimental setup. Section 3 gives the details of the computational code GORGON. Section 4 presents the experimental and computational results and a detailed comparison of the different wire materials, while section 5 provides a discussion of the results and a summary of the work.

2. Experimental setup

The X-pinch pulser at UCSD delivers a current pulse with a peak amplitude of 80 kA and a rise time of 50 ns as shown in figure 2. The X-pinch pulser consists of a Marx bank comprising $4 \times 0.2 \mu F$, 50 kV capacitors, a 1.5 $\Omega$ water-filled pulse forming line (PFL) and a self-breaking SF$_6$ switch, which operates at 15 psi. Loads in this experiment comprised two wires of either 10 µm tungsten, 10 µm copper or 10 µm nickel placed between two brass electrodes spaced ~12 mm apart. This experiment utilized electrodes with large openings at their centers to prevent stagnation of the axial plasma column and the resulting current transfer between the plasma and electrodes that might alter the behavior of the ablation flaring. The opening angle of the X measured 42.5° from vertical.
Figure 2. Current waveform from a 10 µm W shot with a peak current of \( \sim 80 \) kA.

Optical probing using a 532 nm frequency-doubled Nd-YAG laser with a pulse width of 5 ns provided the primary diagnostics. Two charge-coupled device (CCD) cameras captured either simultaneous dark-field Schlieren and Mach–Zehnder interferogram or a two-frame Mach–Zehnder interferometer with a 20 ns inter-frame delay. All images view the half of the X from the cathode to the cross-point. The resolution of the cameras exceeds the spatial resolution of the optical system, previously measured at \(< 30 \) µm \([15]\). A Si photo-conducting diode captures the laser pulse along the beam path to determine the laser timing, and a Rogowski coil mounted on one of the four anode return posts records the \( dI/dt \) information to obtain the shape and amplitude of the current rise. For the experiments presented below the variability measured in the current was \( \pm 5\% \) and that in the rise time measured \(< 2\% \).

All interferograms were unfolded using the analysis software IDEA \([16]\) to obtain 2D areal electron density mappings. Immediately prior to each shot, after the chamber was loaded and had reached appropriate vacuum levels \((10^{-3} \) mtorr\), a background interferogram was taken to use as the reference for the plasma interferogram. After the plasma discharge, both the background and the plasma interferograms were imported into IDEA and processed identically. IDEA first performs a fast-Fourier transform (FFT), producing a zero frequency. This zero frequency is selected, and the program then performs a reverse FFT to recreate the image, which then allows IDEA to determine the phase shift of the fringes relative to a point selected near the center of the image. The contours of the phase-shift data are then smoothed to create a continuous profile. At this point, we subtract the background phase-shift image from the phase-shift image of the X-pinch discharge, giving a difference profile. The areal electron density mapping is produced via a simple rescaling that sets the minimum value in the image to zero and then multiplies by a constant specific to the wavelength of the laser used. A complete description of the methodologies and algorithms used in IDEA can be found in Hipp et al \([17]\). The error for the electron density mappings is \( \sim 1/6 \) fringe shift \((7 \times 10^{16} e \) cm\(^{-2}\)), determined by subtracting two unfolded background images from each other, taking lineouts and measuring.
the amplitude of the peaks caused by the natural shifting of the fringe profile. The results from the areal electron density mappings are used directly, requiring no further assumption such as the ionization state, $Z$ or symmetry to perform an Abel inversion.

3. Three-dimensional magneto-hydrodynamic simulations

An explicit, parallel version of the 3D resistive MHD code GORGON [18] provided comparisons to the experimental results. This code has been successfully used for various wire array [19] and x-pinch [20] geometries and provides a well-benchmarked platform for comparisons to experiments. GORGON solves the MHD equations on a 3D grid in Cartesian geometry using the single-fluid approximation. The MHD equations can be modeled as a single fluid to good approximation in the experimental plasma parameter space. The ion and electron components of the plasma are allowed to be out of thermodynamic equilibrium with respect to each other and their relative energy equations are solved separately. An equation of state relates the pressure and internal energy, and the average ionization state of the plasma, $Z$, is calculated using an average-ion Thomas–Fermi model. Radiation effects are included through an optically thin loss model. High-resolution 3D calculations using the GORGON code recently demonstrated the growth of the ablation flaring structure by seeding small-scale thermal noise in the wire core, which compares well with experimental observations [21]. A similar setup is used in this work with a cubic cell size of 20 $\mu$m. While the 20 $\mu$m cell size is larger than the initial 10 $\mu$m wires used in these experiments, the diameter of the wire core exceeds 20 $\mu$m within a few nanoseconds of current start. Simulations include the full electrode configuration coupled to a circuit model of the generator, along with a range of simulated diagnostics (extreme ultraviolet framing images, radiography and radiated power). For this work, GORGON integrated the electron density data through the computational grid, providing areal electron density maps as a function of time. There is no upper limit of plasma density in simulations; however, there is a lower limit on plasma density that is typically set to $10^{-4}$ kg m$^{-3}$. Any density below this value is considered as vacuum by the code.

4. Experimental and simulation results

Tungsten wires are commonly used in pulsed power exploding wire experiments, particularly those designed to produce high-power soft x-ray pulses. Recent wire array experiments demonstrated that the ablation wavelength increases considerably during the first 60% of the current rise before saturating at the typically observed value [22], and as a function of distance from the wire [23]. Additionally, the materials used in these experiments pinch at the cross-point near peak current, presenting another factor potentially affecting the ablation flaring. To minimize these effects, the results presented here will draw from data collected only in the upper 40% of the current rise ($\sim$30–50 ns) and use lineouts taken close ($\sim$0.3 mm) to the wire. Figure 3 shows a time-sequenced sampling of experimental areal electron density mappings using 10 $\mu$m W, and comparable times from the simulations.

After unfolding the interferograms, a linear profile plot of the unfolding is made parallel to the wire to record the wavelength and position of the ablation flares. Near the wire we assume that the streams propagate orthogonally, so their position is obtained by adding an offset value measured along the wire to the projected intersect of the stream and the original wire core, as demonstrated in figure 4(a). Wavelengths were measured peak to peak.
Figure 3. (a) Time-sequenced areal electron density mappings of 10 µm W experimental X-pinches, overlapping their source interferograms, at the top 40% of the current rise. (b) Time-sequenced areal electron density mappings of 10 µm W simulation X-pinches at the top 40% of the current rise.

Figure 4. (a) Lineouts taken parallel to the wires at ∼0.3 mm from the center of the wire cores give areal electron density waveforms (b), which are used to measure wavelength and relative contrast between ablation flares. Lineout is from a 10 µm W experiment at 48 ns.

The contrast of the areal electron density between streaming and non-streaming regions may provide further insight into the mechanisms driving the ablation. These data were obtained by dividing the electron density at the peaks by the average electron density of their adjacent troughs (see figure 4(b)), and again recorded as a function of position along the wire. If a transition to an $m = 0$ instability occurs as $B_{global}$ decreases away from the cross-point, we would expect to observe an increase in both the statistical variation of the wavelength and inter-stream contrast.

The quasi-periodic ablation modulations have generally accepted wavelengths (∼250 µm for W and ∼500 µm for Al), although there is considerable standard deviation from these values [24]. Figure 5(a) shows wavelength data collected from 12 shots with 10 µm W between
30 and 50 ns, plotted as a function of their projected point of origin along the wire. There is a visible increase in wavelength down the wire, accompanied by a considerable increase in standard deviation. The average wavelength within 1.5 mm of the cross-point measures $\lambda = 289 \mu m$, with $\sigma = 71 \mu m$ (24%). Beyond 4.5 mm, the average wavelength increases to $414 \mu m$ with $\sigma = 128 \mu m$ (31%), an increase in standard deviation of $\sim 80\%$. A linear fit applied to the data yields a $Y$-intercept at $263 \mu m$ with $\sigma = 33 \mu m$ and a non-zero gradient measuring $42 \mu m \ mm^{-1}$ with $\sigma = 11 \mu m \ mm^{-1}$.

Identical processing of the simulations, with lineouts taken at 5 ns intervals from 30 to 50 ns, yields a wavelength distribution similar to the experimental data. An initial comparison of the data from the cathode and the anode halves of the X yielded no considerable differences in the results, so data from all four legs of the simulated X is used. Figure 5(b) shows a statistical trend toward larger wavelengths and simultaneously greater standard deviation down the wire. For the simulation, ablation flares within 1.5 mm of the cross-point averaged $260 \mu m$, $\sigma = 62 \mu m$ (24%), whereas those beyond 4.5 mm averaged $1040 \mu m$, with $\sigma = 608 \mu m$ (58%). A linear fit applied to the simulation data plot produces a $Y$-intercept at $197 \mu m$ with $\sigma = 67 \mu m$, overlapping that of the experimental data. The gradient for the simulations is also non-zero, measuring $148 \mu m \ mm^{-1}$ with $\sigma = 20 \mu m \ mm^{-1}$.

The simultaneous increase in wavelength and standard deviation in both the experiments and simulations suggests a transition into a realm where the $B_{\text{global}}$ plays little or no effective role in the ablation. Using the same experimental and simulation datasets as for the wavelength plots, the intra-stream contrast may be plotted again as a function of position along the wire. Figure 6(d) shows a plot of the contrast values as a function of position along the wire for the W simulations. There is relative uniformity in inter-flare contrast close to the cross-point. Between 2 and 3 mm, the contrast increases dramatically. Values measured ranged from $\sim 1$ to 600 (for visual purposes, the higher values were removed from figure 6(d)). When looking at a lineout waveform from the simulations, displayed in figure 6(c), the point of contrast increase...
Figure 6. (a). Lineout waveform of 10 μm W experiment at 48 ns. (b) Inter-stream contrast versus position along the wire for 10 μm W experiments. (c) Lineout waveform of 10 μm W simulation at 45 ns. (d) Contrast versus position along the wire for 10 μm W simulations.

is visible as well, as the electron density in the non-streaming regions beyond 2–3 mm from the cross-point drops several orders of magnitude.

A plot of the experimental inter-flare contrast (figure 6(b)) reveals no rapid spike in contrast as observed in the simulation plot, but a statistical increase is demonstrated when applying a linear fit to the data, yielding a non-zero gradient. The areal electron density in the ‘troughs’ decreases with increasing distance from the cross-point, and reaches a lower limit at large separation, as seen in figure 6(a). The instrument sensitivity limits the measurable contrast in the experiment, and thus the effective dynamic range in the simulations is much greater than that achievable in experiments.

In order to understand the effect of the local to global magnetic field ratio on flare structure with wire materials of different resistivities, experiments were conducted using copper and nickel wires. Both materials lie adjacent to each other on the periodic table with atomic numbers 29 and 28, respectively, but despite their proximity to each other, they exhibit considerably different behavior during pulsed power experiments [25], attributed to a difference in their
resistivities (factor of 4 difference). Here we show a quantitative comparison of their ablation behavior in X-pinches.

The coronal plasma surrounding the Cu wire cores is noticeably larger than that of W (figure 7(a)). Plotted as a function of position along the wire in figure 7(b), the wavelength at 2.5 mm and closer to the cross-point measured 387 µm with σ = 30%, while the wavelength beyond 2.5 mm measured 510 µm with σ = 42%. The wavelength demonstrates a statistical increase with a gradient of 62 µm mm⁻¹ with σ = 23 for a linear fit.

Inter-stream contrast measurements for Cu also demonstrate an increase in magnitude and standard deviation moving away from the cross-point, as seen in figure 7(c). The low number of data points beyond 3 mm from the cross-point in the Cu data is partly caused by the frequent breaking of fringes by higher electron densities in the ablation flaring beyond this point. The Ni experiments presented a similar difficulty.
Figure 8. (a) Areal electron density map of a 10 µm Ni X-pinch at 40 ns, overlapping its source interferogram. (b) Plot of wavelength as a function of position along the wire for 10 µm Ni. (c) Plot of inter-stream contrast as a function of position along the wire for 10 µm Ni. Both plots contain data collected from seven shots collected in the top 40% of the current rise.

Nickel exhibits a coronal plasma diameter different from closely massed Cu (figure 8(a)). Its wavelength (see figure 8(b)) within 2.5 mm of the cross-point measured 373 µm with σ = 27%, whereas the wavelength over the remainder of the wire measured 553 µm with σ = ~30%. A linear fit applied to the wavelength plot yielded a gradient of 91 µm mm\(^{-1}\) with σ = 24. Inter-stream contrast measurements for Ni again increase with distance from the cross-point, in agreement with the other elements examined.

5. Discussion and summary

The initial quantitative analysis of the ablation modulations for 10 µm W experiments yields a wavelength of 289 µm in a region with large \(B_{\text{global}}\) contribution, comparing well with published values [10]. In the same region, the simulations yield an average wavelength of 260 µm. The
simulation data show a marked increase in contrast starting from approximately 2 mm from the cross-point and continuing to the electrode. Prior to this increase, inter-stream contrast values remain effectively uniform, with the non-streaming regions not dropping below 2/3 the areal electron density of the streams. This is in good agreement with previous investigations of the inter-stream contrast carried out close to the cross-point in X-pinches, and on MegaAmpere (MA)-scale wire array Z-pinches [25].

The 10 µm Cu X-pinches exhibited large-diameter coronal plasmas and an average wavelength near the cross-point (387 µm) supporting the generally accepted increase in wavelength as a function of decreasing atomic mass. Ni exhibited a coronal plasma noticeably smaller than that observed in Cu, but only a slightly smaller wavelength (373 µm) in the same region near the cross-point. At room temperature the resistivity of Ni is ~4 times higher than that of Cu, and during the initial breakdown of the wire, experiences a greater ohmic heating power \( P_{\Omega} = j^2 \eta \). The coronal plasma is formed more rapidly and the current is transferred to this at an earlier time than for Cu. This shunt of current effectively stops the expansion of the dense wire core at an earlier time in Ni than in Cu, and the core and corona sizes are significantly smaller as a result. Previous experiments with Ni also demonstrated that the ablated plasma in Ni convects a considerable fraction of the drive current to the axis [26], and other research works using two-wire X-pinches suggested that the ablation flaring from lower Z wires carry current to the axis more markedly than higher Z wires [27]. Nickel’s modulation wavelength and coronal plasma behave as expected from an element heavier than Cu, while the transmission of current in its ablation flaring is characteristic of a lighter element. Despite their observed disparities, Cu and Ni both exhibit increases in wavelength and contrast similar to those demonstrated in W.

Over a variety of elements and 3D MHD simulations, all data collected here follow similar trends. The increase in the average wavelength of the ablation flares moving away from the cross-point indicates that the relative magnetic field strengths play a dynamic role in the ablation structure. The simultaneous increase in standard deviation suggests that the modulations are moving toward a more random distribution of wavelengths, and no longer confined to a quasi-periodic average, indicative of a changeover from the commonly observed wire array ablation to a \( B_{\text{local}} \)-driven regime. The increase in contrast moving away from the cross-point further supports this transition, and more specifically suggests an evolution into a classical \( m = 0 \) instability.

Time integrated soft x-ray imaging using 7.5 µm W X-pinches at 80 kA from previous experiments further support the suggestion that an \( m = 0 \) instability arises far from the cross-point. A pinhole camera image with a magnification of 2.4 and an unfiltered pinhole 25 µm in diameter, giving a spatial resolution of ~35 µm for \( h\nu > 120 \text{eV} \), is shown in figure 9. The image shows pinching along the wire near the electrodes. While experiments involving wire arrays show that the wire cores pinch and break at the non-streaming regions along the wires, there are no visible hard emission signals from the wires close to the cross-point in these films. The pinching regions captured in the image suggest higher levels of emission than the areas that invariably pinch and break closer to the cross-point. There are also faint plasma streams visible near the cross-point, indicative of the stationary flare structure commonly observed in wire arrays, since individual flares exhibiting considerable temporal evolution are not likely to be resolved in a time integrated film. The coinciding lack of visible streaming near the electrode suggests the presence of temporally evolving ablation modulations in this region, characteristic of \( m = 0 \) plasmas.
The broad range of $B_{\text{global}}/B_{\text{local}}$ contained in the X-pinch configuration envelopes the relative magnetic field conditions found in most pulsed power wire array experiments. At $\sim 0.15 \text{ mm}$ along the wire from the cross-point, the magnetic fields are approximately equal in strength. The first resolvable ablation flares in these experiments were measured at approximately $0.7 \text{ mm}$ from the cross-point, where the magnetic field ratio measured just above 0.2, comparable to the 8-wire, 10 mm diameter Al arrays on the COBRA generator at Cornell University [22]. A 16-wire W array with 16 mm diameter, commonly found on MAGPIE, has a $B_{\text{global}}/B_{\text{local}}$ of 0.1, comparable to the ratio found at $1.5 \text{ mm}$ from the cross-point in this experiment.

While cylindrical arrays do not contain a changing $B_{\text{global}}/B_{\text{local}}$ with which to observe the results found in this experiment, conical arrays do. Figure 10 shows the wavelength for $10 \mu\text{m}$ W X-pinch experiments and matching simulations as a function of $B_{\text{global}}/B_{\text{local}}$. The box on the left contains the domain where ablation flares were resolved in these X-pinch experiments. The short segment highlighted inside this box denotes the $B_{\text{global}}/B_{\text{local}}$ domain found in 16-wire conical arrays used at MAGPIE with an 8 mm radius base, $25^\circ$ opening angle and 15 mm height [28]. The range of wavelengths ($\sim 55 \mu\text{m}$) found in the conical experiments is likely insufficient to be noticed over the standard deviation found in pulsed power experiments.

The existence of a sharp increase in contrast visible in the simulations’ lineout waveform near $2.5 \text{ mm}$ from the cross-point (figure 6(d)) suggests that there might exist a transition point, i.e. a critical value of the $B_{\text{global}}/B_{\text{local}}$ field ratio, rather than a steady progression from the $B_{\text{global}}$ to the $B_{\text{local}}$ dominated regime. The experimental data, such as that for Cu (figure 7(c)), are not conclusive, but may support the results found in the simulation data. $2.5 \text{ mm}$ down the wire from the cross-point of a 2-wire X-pinch with a $42.5^\circ$ opening angle and $100 \mu\text{m}$ diameter wire cores corresponds to a region where the $B_{\text{global}}/B_{\text{local}}$ measures approximately 0.06. If a critical transition point does exist, 6% $B_{\text{global}}/B_{\text{local}}$ lies below the ratio found in most cylindrical array setups used, and at the lower end of ratios found in conical array setups previously used.
To summarize, the work described in this paper demonstrates that the global to the local magnetic field ratio at the wire determines the wavelength and standard deviation of the ablation flares at a given position in X-pinch experiments. Along with the associated increase in the inter-stream contrast, this suggests a transition from a ‘wire array-like’ regime, where the global field is dynamically significant, to a classical MHD $m = 0$ instability where the local field is dominant. 3D numerical simulations closely reproduce the data, and identical processing of the experiment and simulation data shows good agreement both qualitatively and quantitatively. Simulations suggest that the contribution of the global field becomes negligible at a critical value of the field ratio, $\sim 0.06$, which is indicated by the sharp increase in the inter-stream contrast. Some experimental results support this, although the primary trend is a continuous increase in the contrast with decreasing $B_{\text{global}}/B_{\text{local}}$.

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