Experimental Analysis of the Acceleration Region in Tungsten Wire Arrays

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***Abstract*—We present the first analysis of the ablated plasma flow acceleration region in tungsten cylindrical wire arrays within 1 mm of the wire core. We apply a recently developed modification to the Lebedev rocket model to infer the 2-D distribution of effective velocities which redistribute the array mass as a function of time. From these data, it is possible to directly observe the acceleration region in a wire array. Analysis of radiography data from the 1-MA Cornell Beam Research Accelerator machine suggests a region of rapid acceleration extending up to 300μm from the wire core in 16 wire tungsten arrays.**

***Index Terms*—Precursor plasma, wire array Z-pinch.**

I. Introduction

WHILST the dynamical evolution of wire arrays is well understood [1]–[4] and multidimensional magnetohydrodynamic (MHD) modeling has demonstrated significant progress [5]–[8], a comprehensive predictive capability has not been realized to date. Experimental investigations have continued to highlight the need to more closely examine the ablation structure and its dependence on the initial parameters of the array. In particular, the range over which the ablated plasma is accelerated, and hence the extent to which magnetic flux is convected into the array, is often a disputed point in the comparison simulation and analytical work [9]–[11].

Recent work at the University of California at San Diego [12] examined interferometer data taken for nonimploding arrays on the 250-kA GenASIS device [13] for four-wire Al and W arrays. Two-dimensional areal electron density images allowed analysis of flare structures at various radial positions. The average density contrast, i.e., the average ratio of the peak flare density to the minimum density between flares, was $\sim$2 for W and $\sim$1.3 for Al, in line with previous studies [14], [15]. This work led to a modification of the standard rocket model [16] which uses an additional sinusoidal axial variation of the ablation velocity to describe both the axial and radial density variations. The form of the velocity is given in (1). Here, the y-offset is the density obtained from the standard rocket model calculated as the mean of $V_{\rm abl,1}$ and $V_{\rm abl,2}$, $\lambda_{\rm abl}$ is the average flare wavelength, and the amplitude is the range of effective ablation velocities needed to describe the data. This is then substituted into the standard rocket model for the radial density profile

$$V_{\rm abl}(z)=\left[\left(\frac{V_{\rm abl,1}-V_{\rm abl,2}}{2}\right)\sin\left(\frac{2\pi z}{\lambda_{\rm abl}}\right)\right] + \left(\frac{V_{\rm abl,1}+V_{\rm abl,2}}{2}\right) \quad (1)$$

$$\rho_{\rm mod}(r,z)=\left(\frac{\mu_0}{8\pi^2 R_0 r V_{\rm abl}^2(z)}\right)\left[I\left(t-\left(\frac{R_0-r}{V_{\rm abl}(z)}\right)\right)\right]^2 \quad (2)$$

where R_0 is the initial array radius. An advantage of this method is that an automated fit routine can be constructed using (1) and (2), which can then be used to assess the variations of the fit parameters required to match data from calibrated radiographs. The remainder of this paper presents the first results from such a process.

II. Analysis of the Flow Acceleration Region

A previous study at the MAGPIE facility examined inverse wire-array systems using interferometry [14]. Comparison of the experimental data to analytical theory and numerical simulations suggested that, in an aluminum array, the acceleration region extended $\sim$1.8 mm from the wire. Here, we examine 16×13 μm tungsten arrays on the 1-MA 100-ns Cornell Beam Research Accelerator (COBRA) generator [17] at Cornell University using X-pinch-based radiography. We make use of the COBRA-STAR [18] system which allows up to five calibrated radiograph frames per experiment with < 5-μm spatial resolution and $\sim$1-ns temporal resolution. An example image is shown in Fig. 1.

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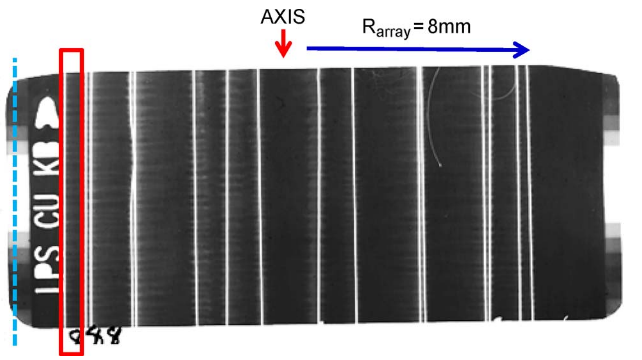

Fig. 1. Radiograph of a 16-mm-diameter 16×13 μm array on COBRA at 108 ns. Image shows the full array diameter and $\sim$8 mm of the 23-mm array height centered at the midplane. The box on the left is shown in more detail in Fig. 2, and the dotted line shows the step wedge used for calibration.

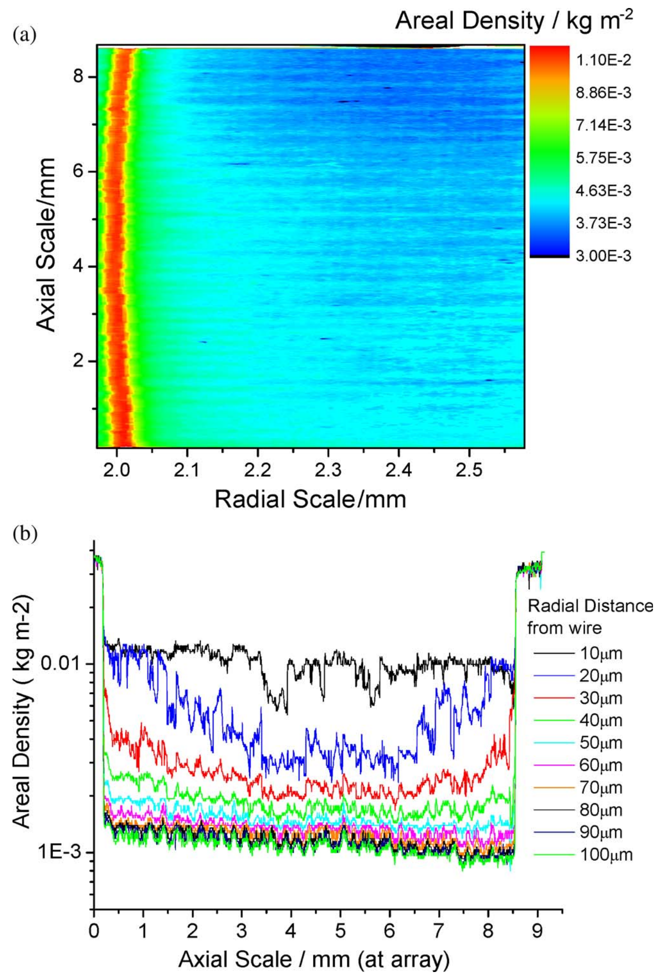

Fig. 2. (a) Calibrated radiograph data showing the expansion of a single wire on the edge of the array (red box in Fig. 1) and (b) lineouts at various radial distances from the center for the wire core.

Each radiographic film is filtered using a 25-μm Ti foil, passing photon energies of $\sim$3–5 keV. Additionally, a W step wedge is deposited in this filter via radio-frequency sputtering. Step-wedge thicknesses of 13.75, 27.5, 70.1, 163, 316.3, 555, and 1079 nm were applied giving calibrated exposure levels at W areal densities of 5.3×10^{-4} to 2.1×10^{-2} $\mathrm{kg \cdot m^{-2}}$.

Fitting these discrete points into an exponential function allows calibration of the continuous exposure levels observed on the film in each case. An example calibrated radiograph is shown in Fig. 2 which shows the expansion of a single wire on the edge of the array (red box in Fig. 1). Calibrated lineouts can be taken at any point to examine the density variation (Fig. 2). Each lineout can then be compared to the modified rocket model, and the fit routine is applied to optimize the velocity and wavelength parameters to provide a best fit. In general, the density range of the experimental data, i.e., the amplitude of the density variations in the axial direction, is well described by the model using two limits on the ablation velocity (Fig. 3). The wavelength parameter fit is less convincing, although several cases do show good periodicity over several millimeters (e.g., the 400-μm lineout in Fig. 3). At positions > 100 μm from the wire core, a single wavelength provides the best fit, but closer to the wire core, the fit becomes far less good, and in some cases, a two-component wavelength appears more appropriate.

Estimates of the error on the fits shown in Fig. 3 can be carried out using residual analysis, and the goodness of fit varies considerably. For the full 2 mm of axial extent at 600 μm from the wire core [Fig. 3(a)], the standard error is $\sim$10%. For the $r = 400$ μm plot [Fig. 3(b)], it can be seen that the goodness of fit at either end of the plot is very poor and the standard error is $>$100% of the experimental measurement. In the section between 4.5 and 5.5 mm, however, the fit is rather better and gives an error of $\sim$5%. Similar tends occur in the $r = 30$ μm plot [Fig. 3(c)]. We show this variation in fit quality as a demonstration of the difficulty of comparing model data to experimental data in these ablating wire experiments. For the remaining analysis, we will focus on the data between axial positions of 4.5 and 5.5 mm, where the fit is reasonable (and therefore meaningful) and also where the wire core is relatively straight relative to the z-axis.

The trends in the fitted ablation velocities and wavelength with radial position are shown in Fig. 4. This shows that a rapid increase is observed over the first 300 μm, before reaching some asymptotic value $\sim 5.5 \times 10^5$ $\mathrm{m \cdot s^{-1}}$. This region of acceleration likely describes the extent to which the drive current profile extends into the array interior for this array configuration. It should be noted that the velocity 600 μm from the core is much higher than the ablation velocity used to describe the general ablation rate from this array, as determined *via* precursor column formation times and mass density evolution [19], [20]. This previous work examined similar arrays on MAGPIE [21] and COBRA to compare the effect of current risetime on wire ablation at fixed peak current. It was found that the precursor column formation time and temperature on COBRA could be well predicted from the standard (i.e., single velocity) rocket model developed from MAGPIE data under the assumption of $R_{\mathrm{eM}} \leq 1$ (i.e., the plasma flows are diffusive with respect to the accelerating B-field) and a simple pressure balance model. Use of a similar velocity also predicts the wire breakage time and the start of the implosion on MAGPIE [16] and COBRA [2], under the assumption that the implosion is triggered after $\sim$50% of the initial wire mass has been ablated. When comparing precursor column formation times with implosion start times for wire

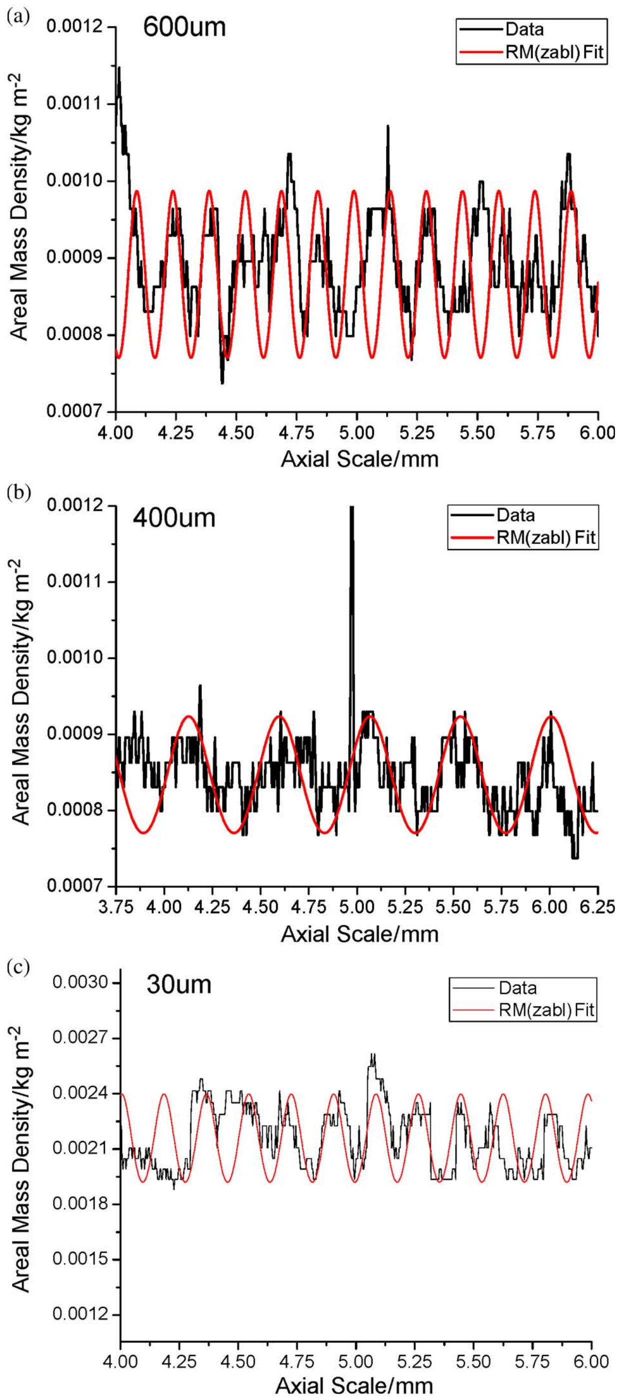

Fig. 3. Comparison of experimental lineouts to best fits using the modified rocket model at (a) 600, (b) 400, and (c) 30 μm radially inward from the wire core.

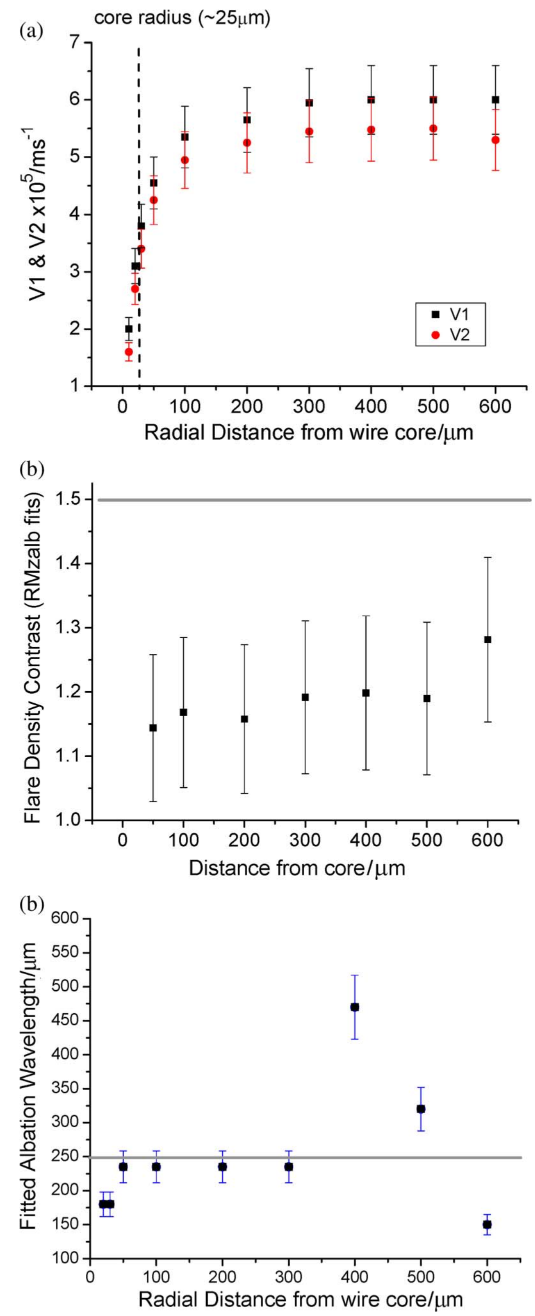

Fig. 4. Plot of (a) fitted ablation velocities, (b) flare mass density contrast ratio, where the solid horizontal line is the average value from previous work (e.g., [12]), and (c) fitted axial wavelength as a function of radial position from the wire core, where the solid horizontal line is a typical value for the wavelength from previous studies (e.g., [16]).

arrays on the 20-MA Z generator at Sandia [22], however, the standard rocket model cannot simultaneously correctly predict both [20]. The use of more than one velocity in the rocket model was developed in an attempt to better describe the Z experiments. In this case, a two-velocity rocket model approach required velocities of $3.5 \times 10^5\ \mathrm{m \cdot s^{-1}}$ and $0.9 \times 10^5\ \mathrm{m \cdot s^{-1}}$ to describe the precursor column and implosion start times, respectively, which differ by a factor of approximately four. Note that, in Fig. 4, the maximum difference in the velocities used is only $\sim$10%, which is generally consistent with the previous use of a single-velocity model, albeit with the details of the axial variation in the ablated plasma flow now included. It is still unclear whether the requirement for a rocket model with greatly different velocities required to match results for wire arrays on Z is due to the significantly greater magnetic pressures involved or some other physical mechanism. Unfortunately, ablation data to compare predictions too are extremely limited.

The plasma flow beyond 600 μm from the wire core is obscured by other wires in the array, but it is possible that the flow velocity decelerates after this point, for example, *via* interaction with the B-field local to the wire, which remains significant relative to the global B-field in these relatively low-number wire arrays. It is also possible that the plasma remains at these high velocities or accelerates toward the axis reaching the axis at much earlier times than precursor column formation times in these arrays suggest. Inconsistency in the precursor formation time is perhaps confusing, since these data are taken from the same set used in [19] to examine the scaling of ablation physics with current risetime. Given that the velocities in Fig. 4 are higher by about a factor of $\sim$3.5, this may be explained by a reduction in the collisionality of the flows, leading to a delay in the appearance of the precursor column, and is the case for W flows at early time [20]. More experimental data are required to determine which of these scenarios is appropriate. This examination of the flare contrast and wavelengths suggests that these parameters have not yet evolved to the expected values typically observed far from the wire core (indicated by the solid lines on the plots in Fig. 4) and it is possible that the flare structure is still evolving in the radial direction.

It should also be noted that, while there are "accepted" values of the flare wavelength and contrast, detailed examination of the temporal evolution of these remains to be investigated for all array parameters. The most detailed experimental work to date regarding the flare evolution is presented by Knapp *et al.* [11], who plot the growth and saturation of the flare wavelength as a function of time in the early phases of the current drive. Furthermore, the saturation of the wavelength growth is shown to be coincident with a change in the magnetic topology which leaves open field lines between the wire position and the array axis, thereby disrupting the MHD-instability positive-feedback loop which initially drives the growth. In this work, data are taken later in the current drive than for data in [11], and so, the flare wavelength is expected to be relatively constant in time. Indeed, this is confirmed in recent work by Douglass *et al.* [23], who provide further detailed radiographic data on ablating wire arrays.

III. Conclusion

This work has represented the first experimental investigation of the acceleration region (< 1 mm from the wire core) during the ablation phase of wire arrays which have a convergent magnetic geometry. While analysis of more data is required, present data indicate a rapid increase in velocity within 300 μm of the wire core. Future studies will focus on the evolution of this region over time at higher drive current. Since the mass that ablated from the wires is proportional to the square of the drive current, the increased mass will provide greater absorption on radiography relative to both the present results and the lower detection limit, improving signal/noise ratio at comparable times to this study and extending the timescale over which measurements can be effectively made. In addition, using fewer wires, e.g., eight-wire arrays, would provide an extended radial view due to the larger wire spacing. These data can be then directly compared to existing computational models.

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