2D study of current distribution evolution in exploding wires with the FLASH code

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Motivation

The main goal of this work is to better understand the proton radiographs obtained from x-pinch experiments conducted at Cornell University on the XP generator (current rise time $\tau_{\mathrm{XP}} = 70\,\mathrm{ns}$, peak current $I_{\mathrm{peak,XP}} = 480\,\mathrm{kA}$) and at the University of Michigan on the MAIZE facility ($\tau_{\mathrm{MAIZE}} = 140\,\mathrm{ns}$, $I_{\mathrm{peak,MAIZE}} = 370\,\mathrm{kA}$) (see [1]). The resistive MHD simulations served as the cornerstone of this work.

The hybrid x-pinch emits protons, which then traverse the scanned exploding wire plasma under investigation. They lose part of their energy depending on the plasma density, and then deposit the energy inside the CR-39 detectors. Their trajectory is bent by the magnetic field of the x-pinch and exploding wire. The schematic of the experiment is shown in Fig. 1.

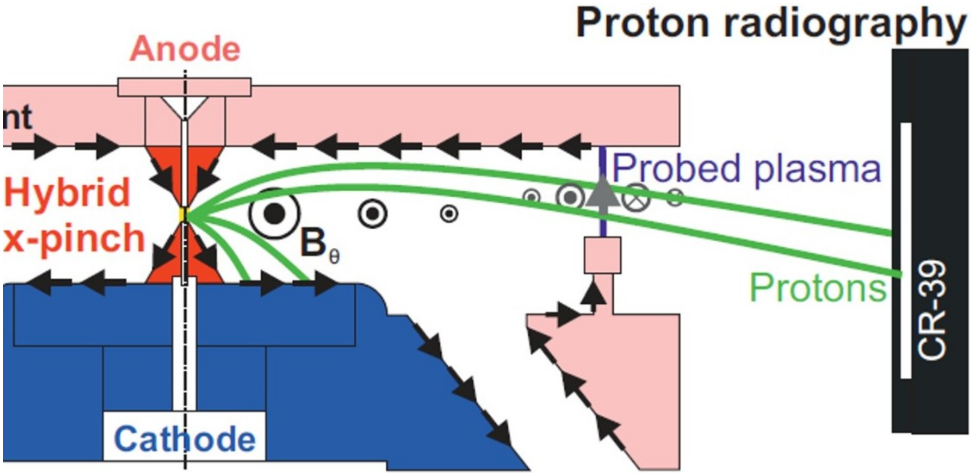


Figure 1: Schematic of hybrid x-pinch facility on MAIZE, with proton radiography. [1]

Measuring the currents in the low density corona of exploding wire plasma remains experimentally challenging. Therefore, MHD simulations are utilized to analyse the corona of the exploding wire and compare the results with proton radiographs. The investigated temporal window primarily covers the expansion phase of the wire.

The study focus especially on the expansion dynamics, instabilities, current and density profile. Another motivation for this work is to gain deeper insight into effects of current rise time, influences of skin effect, anomalous resistivity and magnetic diffusion.

Radiographs

Due to the distortion caused by strong magnetic fields, a direct quantitative comparison between the proton radiographs and simulations is inherently limited, the exact magnitude of which has not yet been quantified. Nevertheless, this comparison still provides valuable insights, although the absolute values should be interpreted with caution. Accordingly, the $m = 0$ instabilities with their wavelengths are identified. The extracted wavelengths, with density profiles are then compared with numerical simulations. The proton exposure time of the radiographs is evaluated by correlating the shadow of the bolt head on the radiograph with the hard X-ray emission pulse and the distinct dips in the current waveform.

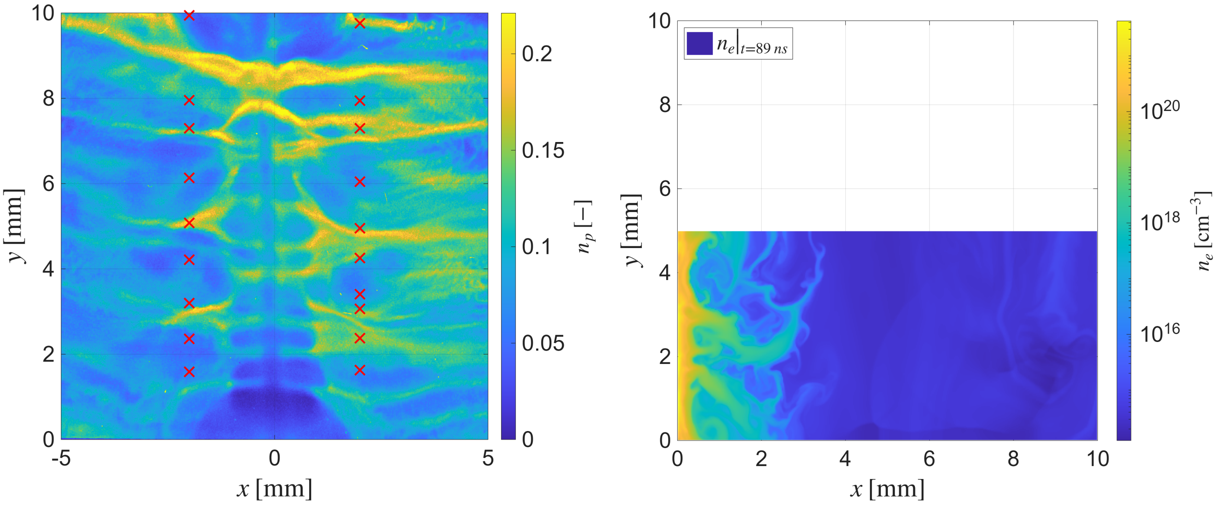
Simulation

The simulations in this work are performed using the multi-physics FLASH code (version 4.8). The resistive MHD simulation incorporated artificial viscosity [2], perpendicular resistivity, IONMIX tabulated values for the equation of state, unsplit staggered mesh scheme, hybrid Riemann solver and implicit diffusion. The AMR grid was established using 2D cylindrical geometry, spanning 1.0 cm radially and 0.5 cm axially with the peak resolution of 6.5 μm to 26.0 μm the same along both axes. Because both experimental setups utilized three return current posts alongside a single exploding wire, the drive current through the wire was approximated as one quarter of the total current (using data from shot 9622 for XP and shot 3369 for MAIZE). The resulting wire current peaked at 120 kA for XP and 93 kA for MAIZE. The radial density profile of the wire was initialized with a uniform core superimposed with white noise, smoothly transitioning into the vacuum via a Gaussian profile to avoid sharp gradients while remaining independent of the axial coordinate. In both experiments, an aluminium wire with a diameter of 25 μm was used. The initial temperatures of the wire and the vacuum were set to 2.0 eV and 0.5 eV, respectively.

Results and Discussion

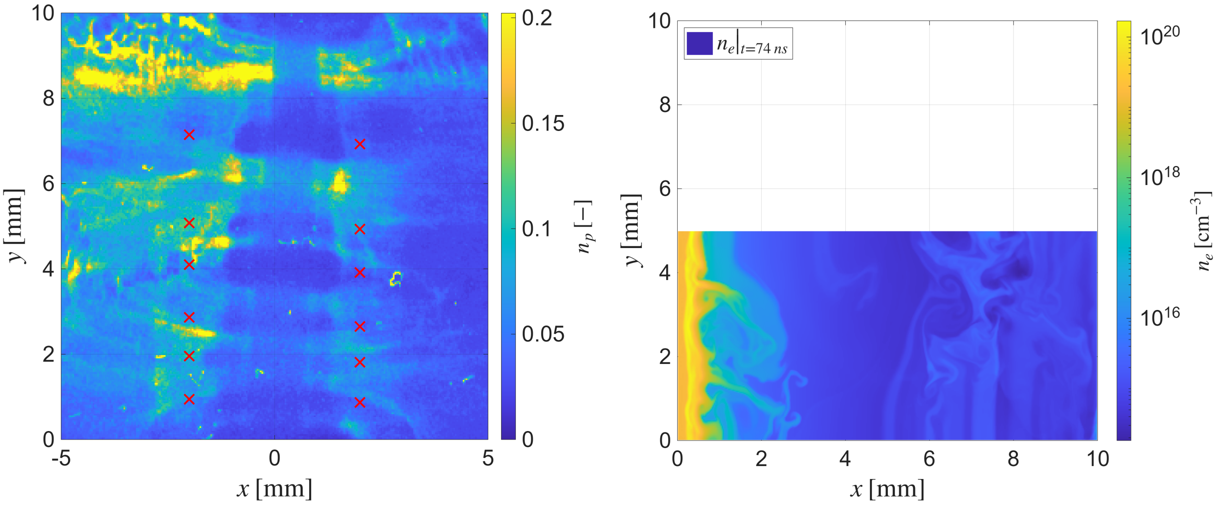
The main comparison of the simulation with experiments is done by their $m = 0$ instability wavelengths. Considering a reasonable manual measurement error of 0.5 mm, four out of five shots on MAIZE and two out of five shots on XP fall within the experimental error margin.

Although the $m = 0$ instability wavelength is expected to grow monotonically over time [3], the radiograph from Shot 9627 reveals an unexpectedly large initial wavelength. This discrepancy could point to either an inaccurate estimation of the radiograph exposure time or an error in extracting the wavelength from the radiograph.



(a) XP proton radiograph: shot 9626 at $t = 89\,\text{ns}$, utilizing 3.3 MeV protons.

(b) XP simulation: electron density profile n_e at $t = 89\,\text{ns}$.



(c) MAIZE proton radiograph: shot 3369 at $t = 74\,\text{ns}$, utilizing 1.3 MeV protons.

(d) MAIZE simulation: electron density profile n_e at $t = 74\,\text{ns}$.

Figure 2: Comparison of density profiles between the experimental proton radiographs and numerical simulations: (a), (c) proton radiographs showing relative proton density n_p for XP and MAIZE, respectively, and (b), (d) simulations showing electron density n_e for XP and MAIZE, respectively. The red crosses indicate the $m = 0$ instability peaks.

From Fig. 2, we observe that only the longer $m = 0$ instability wavelengths are comparable. A distinguishing feature clearly visible in both the radiographs and simulations is the plasma core radius, which is larger for the MAIZE configuration.

Further inspection reveals a greater radial plasma expansion for the MAIZE configuration, characterized by comparable expansion velocities but different overall plasma dynamics.

Conclusion

A closer look at the density profiles (Fig. 2) reveals a significantly larger plasma core radius in the MAIZE case, which is well captured by both the proton radiographs and the simulations.

The slower rise time of the MAIZE configuration not only leads to a more erratic evolution of the distant corona radius, but it also drives greater overall plasma expansion. Consequently, the specific impacts on radial velocity dynamics remain to be investigated in greater depth.

Due to the distortion of the proton radiographs and discrepancies in the $m = 0$ instability wavelengths, it cannot be definitively concluded that the simulation accurately reproduces the experimental data.

Although the simulation does not fully replicate the experiment, this study demonstrates that further investigation is required regarding the radiographs exposure time, overall magnetic field induced distortions and the more precise current estimation through the exploding wire. Additionally, incorporating a particle code analysis (see [1]) would provide more precise insights into the characteristics of the exploding wire plasma, thereby yielding more robust data to better constrain the simulation.

Further analysis of the current distribution and plasma dynamics remains a subject of ongoing research.

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