Progress in Physics of Wire Array Z-pinch Implosions

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Abstract: Recent experiments show that the implosion dynamics of wire array Z-pinches is significantly different from that of a thin plasma shell. During the first ~80% of the implosion the interior of the array is gradually filled by the plasma ablated from the stationary wire cores. This phase ends with the formation of gaps in the wire cores, which occurs due to non-uniformity of the ablation along the wires. The final implosion phase occurs as a snowplough implosion of the radially distributed plasma, previously injected into the interior of the array. The axially peaked density distribution of the precursor plasma leads to a more stable implosion than previously thought, when the Rayleigh-Taylor was assumed to dominate. A hybrid ion Fokker-Planck code with radiation losses is used to describe the dynamics of the precursor plasma flow. The magnetic Reynolds number of the coronal plasma around each wire can be shown in a 3-D model to be less than one, thus explaining the current-less inward precursor plasma flow. 2-D and 3-D simulations of wire arrays model the switching of current from the wire plasma to the snowplough implosion.

1. Introduction

The wire array Z-pinch not only yields record X-ray powers (270TW) [1] in a fast rising pulse, but it is also very reproducible. Furthermore it is difficult to account for this high performance and the detailed profile in terms of a computational model of a collapsing cylindrical shell of plasma subject to Rayleigh-Taylor instabilities. A careful analysis of experimental data from the smaller MAGPIE experiment at Imperial College reveals that the physical phenomena at work may be rather different; namely that there are inward jets of a precursor plasma followed by a snowplough like implosion when the wire cores have gaps. We have also made advances into mechanisms that control the shape of the X-ray pulse, an important consideration for ICF.

2. The wire plasma and inward jetting

Early work [2] showed the occurrence of a precursor plasma, and this has been explored in detail by us [3]. It would appear from its stability, that the plasma that accumulates early on axis, as a straight and usually very stable column, is not carrying a current. The reasons for this are probably due to the occurrence of a low magnetic Reynolds number in the plasma surrounding each wire, and the confinement of the axial electric field to the outer plasma due to the fast rising magnetic field. A phenomenological model [4] was developed, which gives the ablation rate of wire cores, the radial profile of the plasma distributed in the array interior, and suggests modified initial conditions for use in 2-D MHD simulations of wire array implosions. In a recent 3-D analytical model [5] in which the joule heating in the plasma surrounding each wire is conducted by flux-limited heat flow to the core.

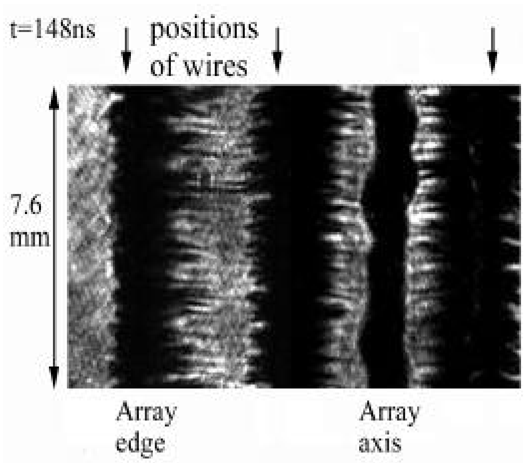


FIG. 1. Inward jetting of the coronal plasma from wire cores.

This then ablates with an expansion velocity approaching the speed of sound (similar to ICF capsule behaviour) leads to a magnetic Reynolds number below 1 and indeed a Hall parameter less than 1. The plasma however is unstable to a local m=0 instability, and indeed the model assumes that the joule heating is dominantly in the necks of this instability while the inward jetting from the lobes each side (see fig 1) can be described by a rocket equation using the calculated mean ablation rate. The nature of the instability is an issue since it is unlikely to be an MHD mode if the magnetic Reynolds number is so small. A strong candidate is the heat flow drives electrothermal instability [6] which requires that the mean-free-path is less than the collisionless skin depth, a condition which is also satisfied in the model.

3. A Monte Carlo Fokker-Planck ions hybrid model

The mean-free-path of the inward jetting ions can, especially for high Z materials such as tungsten, be larger than the interwire separation or the final precursor column radius. Thus a fluid representation is inadequate and a Fokker-Planck code has been developed employing a

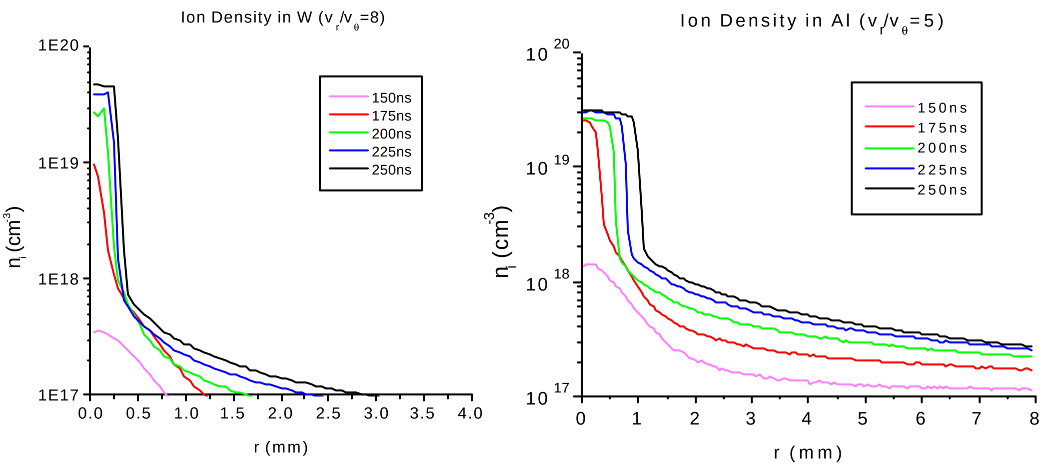


FIG.2. The calculated radial profiles of the precursor plasma.

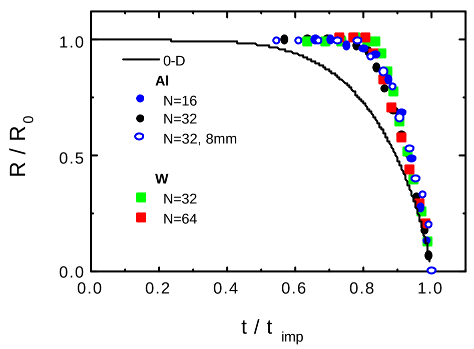
Monte Carlo approach and ignoring any current or magnetic field. The electrons are treated as a neutralising fluid with a finite temperature. At first the streams interpenetrate at the axis due to the high initial mean-free-path. But the density peaks on axis due to the convergent flow and gradually the plasma on axis becomes collisional and accumulates. Fig 2 shows the radial profiles of the precursor plasma at consecutive times for aluminium and tungsten. More focused jets and radiation cooling of the latter led to a narrower column as observed and in both cases the stagnation pressure of the column was balanced by the ρV^2 kinetic pressure of the incoming streams.

4. Effect of current pre-pulse

Experiments with a current prepulse were performed, in which a ~30kA, 500ns current ramp was applied to a 32 wire aluminum array before the start of the main current pulse. It was found that this small level of prepulse current (<1kA per wire) was sufficient to modify significantly the results of the implosion. The x-ray pulse became much smaller, and there is evidence that some current fraction is transported to the precursor plasma column, which demonstrated the development of an m=1 instability. This could be due to the penetration of the applied axial electric field since now the magnetic field associated with the current is rising only very slowly. Experiments were performed to study the effect of wire material on the implosion dynamics of both single and nested wire arrays [7]. It was found that in nested wire arrays made of Ni wires in the outer array and Al wires in the inner (or vice versa), the current fraction flowing through Al wires is larger than that expected from mutual inductance. Such a division of current between the arrays is different from the case of purely Al nested arrays. Similar effects of material on current distribution between the wires were observed in single wire arrays made with alternating W and Al wires. The use of wire arrays with mixed materials opens a possibility to reduce the amount of material left behind by the imploding current sheath and provide an additional control over the X-ray pulse-shape.

5. Main implosion

Cylindrical wire array experiments were carried out on the MAGPIE facility at Imperial College. Parameters of the plasma formed from the Al, W, Ni and Cu wires were measured using laser probing and X-ray radiography using an X-pinch in the return current path. Implosion trajectories of wire arrays with different wire numbers were measured using optical radial streak imaging. The data show that 3-D effects, associated with the formation of a core-corona plasma structure in wire array z pinches, play a very important role in the implosion dynamics [4]. The precursor flow of the coronal plasma provides a gradual redistribution of the mass prior to the implosion. As a result, the implosion trajectory (see Fig.3) deviates strongly from the calculated trajectory of a thin plasma shell. The wire cores remain stationary at their initial positions for ~80% of the implosion time, until the formation of gaps in the wire cores occurring due to the non-uniformity of ablation rate along the wires.



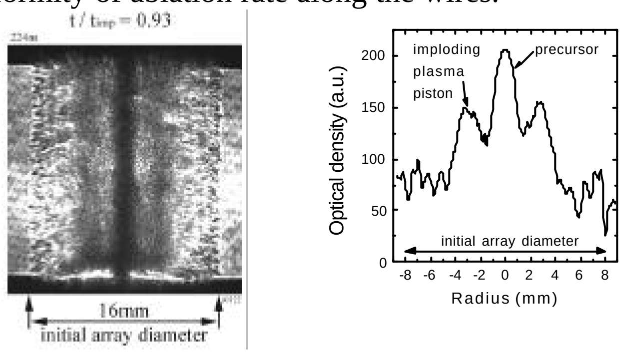


FIG.3. Normalized implosion trajectories for several Al and W arrays

FIG.4. Laser schlieren image of an imploding W wire array showing precursor and a snowplough implosion

From this moment the final stage of the implosion starts as shown in Fig.4, occurring as a fast snowplough-like implosion of the pre-fill plasma driven by a piston, which contains a relatively small fraction of the array mass. The x-ray power generated during the snowplough implosion phase is quite considerable (translating into a few TW for Z conditions) and might account for the early preheat of hohlraums observed e.g. in Ref. [8]. Stabilization of the snowplough implosion phase by the density profile, which is peaked on axis, could be a key factor responsible for the remarkable performance of wire array z-pinches. The present work suggests that for wire arrays operating in the regime of discrete wires the development of the Rayleigh-Taylor instability during the implosion phase could be less important than it is usually thought.

6. MHD simulations

A new approach to modelling high wire number single and nested wire array implosions on

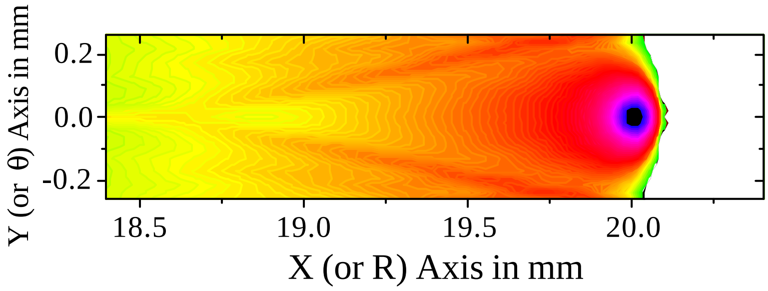


FIG.5. Mass density contours from a 2D simulation of one of 240 tungsten wires in an array on 'Z'

'Z' has been developed which breaks up the sequence of events. A 2D(x,y) high resolution simulation of a single wire in the array, is used to model the gradual ablation of the cold dense wire core and the subsequent injection of the ablated material into the interior of the array. The fluxes of density, internal energy, momentum and magnetic field through the left-hand boundary of the 2D(x,y) calculation can then be used as boundary conditions for 1D(r) or 2D(r,z) simulations which track the flow of material to the axis. This two stage simulation process then gives excellent agreement between the position of the outside edge of the plasma and the experimental optical streak data. For nested arrays a further simulation is included to model the impact of outer array material on the inner array.

Preliminary results showing the evolution of a single wire in the array in 3D [9] show that with a perturbation applied to the mass per unit length of each wire, the regions of lower mass per unit length begin imploding towards the array axis first, thus effectively breaking through the wire core. Rather than attempt to flow across the breaks, the current flows along the first straight axial path which is now inside the array. The process of "wire breaking" then allows the full generator current to bypass the wire cores and be switched directly onto the outside of the radial plasmas streams. The ensuing implosion is then similar to the snowplow of a uniform fill Z-pinch, with debris from the broken wires left behind by the implosion.

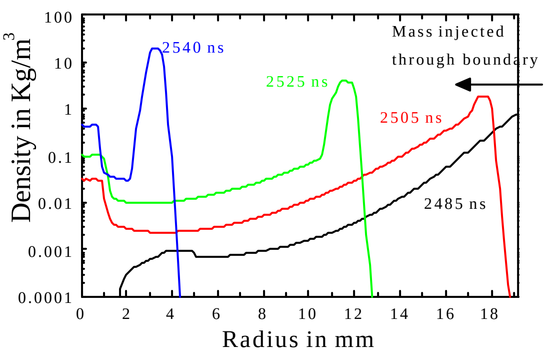


FIG.6. Radial densiy profiles showing structure of imploding snowplough

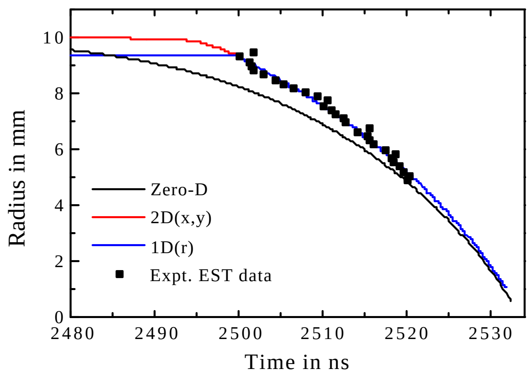


FIG.7. Comparison of simulated implosion trajectory with experimental optical streak data

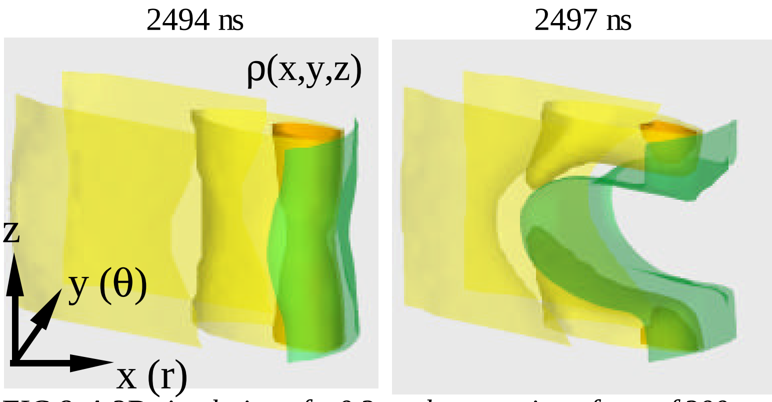


FIG.8. A 3D simulation of a 0.3mm long section of one of 300 11.5mm tungsten wires in a 20mm diameter array on 'Z', (the array axis is far away, to the left of the picture).

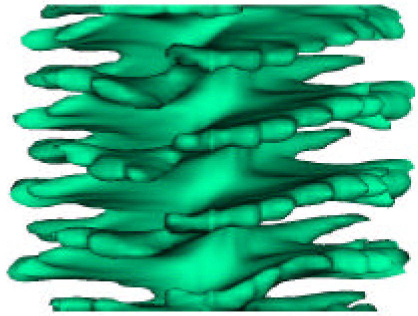


FIG.9. Density surface from a 3D simulation of a 32 wire array on MAGPIE

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