PHYSICS OF WIRE-ARRAY Z-PINCH IMPLOSIONS

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Wire array Z-pinches are of great topical interest not only as an efficient intense source of soft X-rays for radiation-hydrodynamics but also, using a conical array, as a high Mach number jet for laboratory astro-physics experiments.

At early times, X-ray radiography of the liquid-vapour wire cores shows the development of uncorrelated m=0 instabilities, probably originating from MHD instabilities in the surrounding coronal plasma. There is a competition between an expanding plasma leading to merger of the wire plasmas and an inward jetting of plasma associated with the global magnetic field leading to a precursor plasma column on the axis. For aluminium there is a crossover of behaviour at an inter-wire gap of about 1 mm, while for tungsten even with half this gap, jetting is dominant. For most materials the magnetic Reynolds' number is less than one, and the precursor plasma column appears to be field-free, stable, under dynamic pressure balance with the inward flow, and shrinks due to radiation loss.

At later times the instabilities at the wires become correlated and as gaps appear in the cores the current appears to transfer to the neighbouring plasma which snowploughs to the axis with very little Rayleigh-Taylor instability leading to a fast rising X-ray pulse. Using these features and nested arrays in various modes it is possible to have control of the X-ray power pulse which will be useful for inertial confinement fusion.

1. Introduction

Wire-array Z-pinches are the most powerful and efficient soft X-ray sources; at Sandia National Laboratory[1] 1.8 MJ of soft X-rays have been emitted mainly in a 5 ns pulse with a peak power of 280 TW; this is from a stored energy of 11 MJ in the Z-accelerator and represents over 16% wall-plug conversion efficiency. Such a source has potential application to hohlraum physics, radiation hydrodynamics and indirect drive inertial confinement fusion. At Imperial College the MAGPIE generator[2] is ideally suited to studying the physics of the various processes because of its open access to diagnostic probing. We will examine these in temporal order.

2. Early phase

The current initially flows in the solid metal wires which heat and become more resistive. Melting and vaporisation occurs, and at some stage a plasma breakdown occurs on the surface of each. At Cornell[3] there has been X-ray radiography of single wires of many materials. Recently we have employed an X-pinch as a transient X-ray source to radiograph the wire array for the first time. This is shown in fig 1. Some materials e.g. Ti show a very ordered multi-layered structure in the liquid and vapour phase. The current switches to the plasma at breakdown which expands until the JxB pinching force is sufficient to overcome the plasma pressure. But then it is also unstable to m=0 (sausage) instabilities and inward jetting which is axially modulated is detected by laser probing both side-on, fig 2, and end-on, fig 3[4]. Three dimensional modelling[5], fig 4, is needed to describe this phase; a simplified analytic model[6] has been developed in which flux-limited heat flow from the joule-heated plasma in the m=0 necks leads to erosion and ablation of the molten core. The plasma flows to the m=0 lobes where the global JxB force diverts the flow towards the axis in the form of jets.

3. Merger or jets?

If the spacing of the wires is sufficiently small (~1 mm for A1 and <0.3 mm for W) then a radial merger of the expanding wire plasmas will occur[7]; the private magnetic flux around each wire will disappear, and the subsequent behaviour can be approximately described by a current carrying shell, which on accelerating to the axis under the action of the global JxB force is subject to magneto-Rayleigh-Taylor instabilities. In this case the heuristic model[8] predicts that the initial perturbations scale as $n^{-1/2}$ where n is the number of wires; this has been confirmed by experiment[9]. We have also shown that at the time of merger no further inward jetting takes place and the accumulated plasma on axis decays [7].

However, for wider spacing, no merger occurs and jetting to the axis continues until gaps appear in the molten wires at one or more m=0 necks. At this stage the m=0 modes are correlated as can be seen in an X-ray image (fig 5). The current then is conjectured to transfer to the surrounding plasma, and, remarkably, the process is almost simultaneous for the whole array. A current shell is thus formed which leads to a snow-plough-like one-dimensional compression of all the earlier ablated plasma, probably preceded by a shock. Such a dynamic pinch process is much more stable because the piston moves at almost constant velocity, as shown in the streak plots of fig 6.

Thus in contrast to earlier conjectures that early merger was necessary to obtain the most stable implosion (and later the sharpest rising soft X-ray pulse), it could instead be better to operate in the jetting mode, and, indeed for tungsten wires, probably all experiments have been in the jetting mode.

4. Precursor on axis

X-ray framing images (fig 5) show the accumulation of the jetting plasma on the axis[4]. The cylindrical column is remarkably stable, and it is conjectured that negligible current flows. Indeed the 3-D analytic model shows that the magnetic Reynolds number is less than one as the plasma jets inwards, confirming this conjecture. Pressure balance occurs because of the dynamic ρv^2 pressure of the jetting plasma of density ρ and radial velocity v. Accumulation of plasma on the axis will occur when the mean-free-path of the ions is less than some radius less than the wire array radius. In tungsten there is actually shrinkage of the radius of the plasma column due probably to radiation loss.

5. High Mach number axial jets

If a conical wire array is employed, the precursor plasma arriving on axis has an axial component of velocity. Fig 7 shows how this evolves through radiation cooling and contraction to a Mach 20 jet. Preliminary laboratory astrophysical experiments have been done in which the jet collides or is deflected by other plasmas.

6. Nested arrays

When an inner array of wires is added to the system, the X-ray pulse is sharpened up significantly. At least three possible modes have been identified. In the first mode, as numerically modelled at Sandia[10] and Los Alamos[11], it is assumed that the outer merged shell carrying current impinges on the inner (merged) shell; the resulting level of Rayleigh-Taylor instabilities is greatly reduced and the eventual X-ray pulse is sharper.

At Imperial College we have found[12] that when a (standard) low inductance inner array is employed, some current flows in this and the incoming outer array compresses this magnetic field, which, acting as a cushion, leads to the inward acceleration of the inner array to the axis. On the other hand if a high inductance (three times the length of wires) inner array is used, negligible current flows in it, and the outer array current shell on arriving at the inner array allows the plasma to flow through the gaps between the wires, but the current transfers to the inner array (which is now the outer plasma). It then, being of lesser mass, rapidly accelerates to the axis, compressing the outer array plasma that, in this case, had arrived first. In both cases the resulting X-radiation pulse at stagnation is higher in power and is faster rising.

7. Conclusions

Nested wire arrays allow control of X-ray pulse shaping, which is useful for inertial confinement fusion. We have also found that wire spacing can also control the mode of implosion and it would appear that prevention of early merger of wire plasmas can lead to a faster and more stable implosion.

References

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Figures

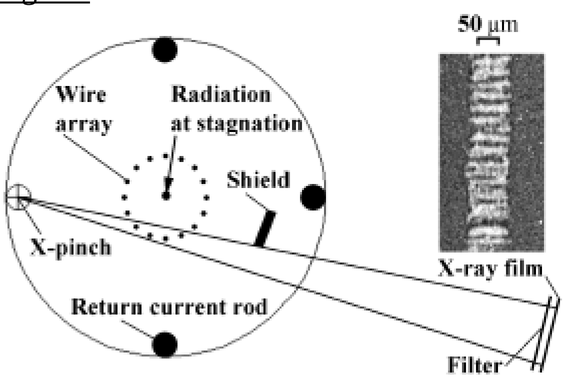

Fig 1. Schematic of the Xpinch backlighter

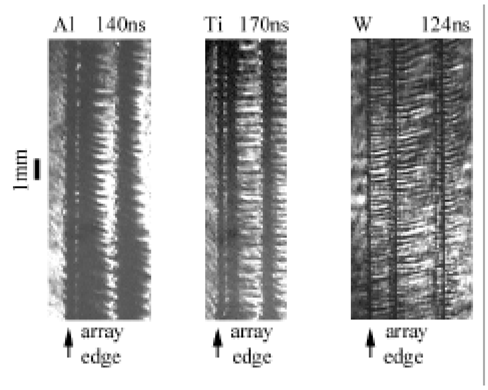

Fig 2. Side-on laser schlieren images

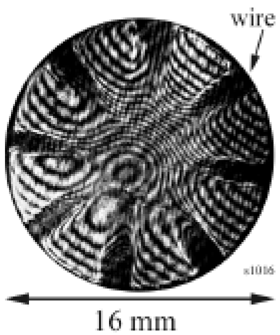

Fig3. End-on laser interferometry

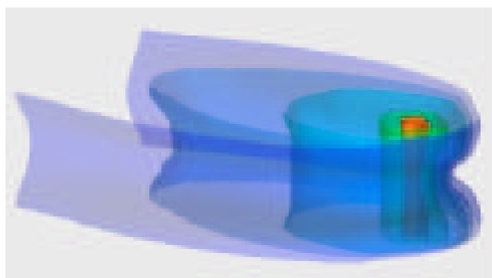

Fig. 4. Density surfaces from a 3D MHD simulation of a wire in an array during the breaking phase.

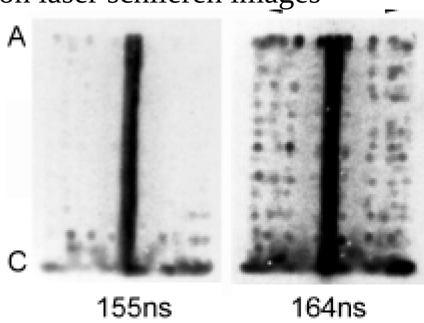

Fig. 5. Gated X-ray image of precursor and global m=0 mode

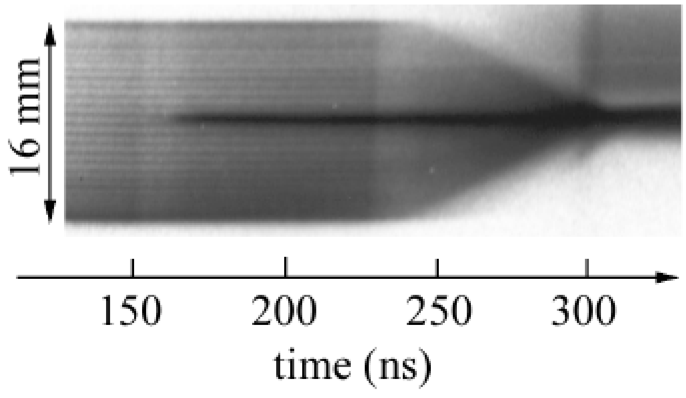

Fig 6. Optical radial streak image.

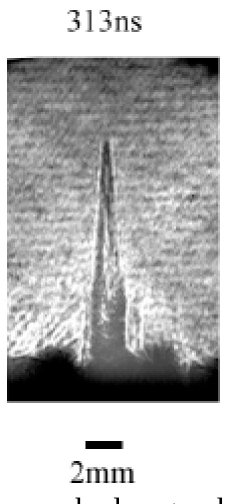

Fig. 7. Laser shadowgraph of jet