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Investigation of Radial Wire Arrays for Inertial Confinement Fusion and Radiation Effects Science

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Abstract

Radial wire arrays provide an alternative x-ray source for Z-pinch driven Inertial Confinement Fusion. These arrays, where wires are positioned radially outwards from a central cathode to a concentric anode, have the potential to drive a more compact ICF hohlraum. A number of experiments were performed on the 7MA Saturn Generator. These experiments studied a number of potential risks in scaling radial wire arrays up from the 1MA level, where they have been shown to provide similar x-ray outputs to larger diameter cylindrical arrays, to the higher current levels required for ICF. Data indicates that at 7MA radial arrays can obtain higher power densities than cylindrical wire arrays, so may be of use for x-ray driven ICF on future facilities. Even at the 7MA level, data using Saturn's short pulse mode indicates that a radial array should be able to drive a compact hohlraum to temperatures $\sim 92eV$, which may be of interest for opacity experiments. These arrays are also shown to have applications to jet production for laboratory astrophysics. MHD simulations require additional physics to match the observed behavior.

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Chapter 1

Introduction

Wire array z-pinches have been explored as an x-ray source for a number of years. Two of the primary motivations have been as a source to heat an Inertial Confinement Fusion (ICF) hohlraum [3, 4, 5, 6] and as a source of multi-keV photons for Radiation Effects experiments [7]. On the 1MA MAGPIE generator at Imperial College London a modification of the wire array z-pinch has been developed: the radial wire array (Fig. 1.1) consists of wires strung radially outwards from the central cathode to an outer anode. Initially this setup was developed for studying wire ablation in a magnetic field [8], and for laboratory astrophysics studies of a stellar jet launching through a magnetic tower geometry [1, 2]. During these MAGPIE experiments it was also discovered that radial wire arrays can emit similar x-ray powers and yields to those emitted by a typical MAGPIE cylindrical wire array (32 wires, 16mm diameter, 20mm tall) despite the source occupying a volume a factor of 25 smaller.

Figure 1.1. Radial array setup. Wires are strung radially outwards from a central cathode to a concentric anode [1]

In this report we discuss the outcome of experiments performed on the Saturn Generator at Sandia (7MA, 150ns or 50ns risetime). A total of 27 shots were performed in four discrete experimental series over two years. Most experiments used the Saturn long-pulse mode (150ns). The initial experiments were designed to address some of the possible issues with performing this type of experiment at the multi-MA level. For example one issue is how best to mount a high number of wires on a 6-12mm diameter electrode while maintaining a good wire contact. MHD simulations played a key role in designing experiments. Further experiments studied the optimal wire number, electrode diameter and wire diameter

in order to obtain high power density (and hence higher predicted hohlraum temperatures). Additional experiments explored the advantages of using the Saturn short-pulse mode and the effect of reversing the anode and cathode locations (i.e. central anode rather than central cathode). Throughout the project W wire arrays were used as a potential ICF source, however a smaller number of experiments were also performed using low-Z materials in configurations that were performing well in W to provide initial data on potential capabilities as a K-shell source. Further detailed work would be needed to optimize a K-shell source, as it is likely to be a considerably different configuration than for a compact W source, due to the high kinetic energy per ion required to ionize to the K-shell.

In the next chapter we discuss some background on radial wire arrays, specifically the motivation for using a compact wire x-ray source for ICF and previous work on radial wire array z-pinches performed at Imperial College. In Chapter 3 we then discuss details of the experimental setup, including the hardware used to field the radial wire arrays and the diagnostics used in the experiments. Chapter 4 describes data obtained in Saturn's long pulse mode, including general implosion dynamics and the effects of variations in electrode geometry, mass and wire number. In Chapter 5 we discuss simulations of the experiments. Details of the Gorgon code are presented, along with details specific to modeling radial wire arrays on Saturn and benchmarking the simulations to previous MAGPIE data. Comparisons between pre-shot simulations of radials using Saturn long-pulse and experimental data indicate a need to shift to experiments in Saturn's short pulse mode. Chapter 6 describes data obtained in Saturn's short pulse mode. We conclude in Chapter 7 with a discussion of the utility of the short pulse radial array setup to drive a compact hohlraum and some applications of the data presented to astrophysical jets.

Chapter 2

Background

Hohlraum scaling

A major driver for wire array z-pinch research over recent years has been for Inertial Confinement Fusion (ICF). On Z compact cylindrical tungsten wire arrays have achieved $> 200TW$, and much work has been performed utilizing these pinches to drive a secondary hohlraum. These compact cylindrical wire arrays are still multi-cm scale systems - typical array radii are $20mm$, surrounded by a $\sim 2mm$ feed gap, leading to a primary hohlraum diameter $\sim 24mm$ [3, 6]. Each pinch of a double ended configuration is $10mm$ tall, with a $\sim 15mm$ tall secondary, leading to a total system height of $\sim 35mm$ [6].

In ICF, one critical parameter, and often the most challenging to achieve, is the hohlraum temperature T . Hohlraum temperature scaling is strongly dependent on power density on the hohlraum wall ($P/A \propto \sigma T^4$) [9, 10].

Predictions indicate that, using cylindrical wire arrays, in order to achieve the temperatures required for ignition would require two arrays, each driven by 60MA generator. This high current requirement is due to the large volumes required for z-pinch ICF - a double-ended z-pinch vacuum hohlraum typically requires an effective surface area $\sim 130cm^2$ [10] (~ 200 times a NIF-scale hohlraum) [9]. To make z-pinch hohlraums more feasible, with a lower current requirement, two approaches could be taken. The first of these is to improve the efficiency of the wire array z-pinch source, which much effort has gone into over the past decade [11, 12, 3, 5]. Alternatively a wire array z-pinch source could be developed which is compatible with a smaller hohlraum. Given the limited number and high costs of shots on the Z generator, the most appropriate approach to developing a more compact source is to study these objects on smaller-scale generators. A number of alternatives have been studied on IMA university generators, including radial arrays, planar/linear arrays and x-pinches. Each of these has been demonstrated to have high power densities at the IMA level.

Radial array dynamics and previous MAGPIE data

A radial wire array consists of a wheel spoke pattern of wires going from the tip of a cylindrical central cathode outwards to a concentric anode Fig. 1.1. Previous experiments on MAGPIE have studied the array dynamics of this configuration in detail. The combination of ohmic heating of the wires and the $J \times B$ Lorentz force leads to the steady ablation of material from the wire core axially, away from the power feed. Due to the radial dependence of the magnitude of the $J \times B$ force the wires ablate fastest near the cathode, resulting in mass depletion first at these locations, initiating an implosion from this point [1, 2]. The $J \times B$ force drives an implosion inwards and upwards until plasma stagnates on the array axis. The result is a magnetic bubble or cavity, surrounding a central pinch, as shown in Figure 2.1 [1]. This cavity grows axially and radially in time, producing a fast moving plasma propagating axially away from the array (Fig. 2.1). Within this bubble the inner edge implodes under the $J \times B$ force, stagnating on axis. One novel feature of radial wire arrays is that, due to the variation in direction of the $J \times B$ force between the ablation and implosion phases, there is separation between the mass profile and the implosion surface.

Experiments on MAGPIE indicate that radial arrays have an optimum implosion mass, in a similar manner to cylindrical arrays. A mass scan on MAGPIE is shown in Fig. 2.2. For a MAGPIE radial with a 6mm central cathode this is an array of 16 wires, each $7.5\mu\text{m}$ in diameter. With this configuration, the radial array is emitting a similar x-ray power to a 32 wire cylindrical wire array, however from a volume a factor of ~ 30 lower. There are a number of possible explanations for this higher power density achieved with radial arrays. For example, there is some indication in MAGPIE data that trailing mass and current are less problematic in radial wire arrays, the material ablated prior to wire breakage is directed away from the position of the final stagnation, hence not impeding the implosion of material onto the axis. The details of these are outside the scope of this report and will be discussed in future publications.

Figure 2.1. Dynamics of radial wire array implosions. (a) sketch showing general dynamics before wire breakage, during implosion and at stagnation as the bubble grows. (b) Experimental emission images from MAGPIE showing the growth of the magnetic bubble. (c) Simulated emission images from Gorgon MHD simulations showing bubble growth. [2]

Figure 2.2. Experiments on MAGPIE have studied the x-ray output from radial wire arrays. Peak radiated powers are similar to those from cylindrical wire arrays of significantly larger diameter.

Chapter 3

Saturn Experimental Setup

Hardware

For initial experiments on Saturn the long-pulse mode was chosen in order to keep experiments relevant to the current rise-time of the Z-generator. There is a significant cost benefit for x-ray sources that permit future generators with similar pulse lengths to Z or longer.

The radial wire array hardware fielded on Saturn is shown in Fig. 3.1. For initial experiments cathode diameters of 9 and 12mm were chosen. These are larger than those previously fielded on MAGPIE, however were chosen in order to facilitate mounting a higher number of wires, each of larger diameter than the MAGPIE experiments. Radial arrays made consisting of W, Ti and Al wire were fielded. The wire numbers were varied from 42 to 100 wires, and diameters were varied from $35\mu\text{m}$ to $55\mu\text{m}$. The setups for all shots performed are shown in Table 3.1.

Two different wire mounting techniques were fielded - for the first set of experiments the wires were laid across the cathode (which was either flat or rounded), however in the second set of experiments the wires were mounted in an EDM notched retainer ring which slotted into the cathode tip.

Experiments in Saturn's short pulse mode utilized a similar wire mounting technique, with 6.3mm and 12mm cathode diameters used.

Diagnostics

A standard set of x-ray diagnostics was fielded on these experiments. Two 5-channel heads were used for individual elements; one of these housed two Ni bolometers [13] and three X-ray Diodes (XRDs, filtered with $2\mu\text{m}$ or $5\mu\text{m}$ CH filters [14]) and the other housed Photo-Conducting Detectors (PCDs [15]) with a variety of filters. The Ni bolometers were used to diagnose the total radiated energy. The XRD's were used to determine the x-ray pulse shape, which when normalized to the bolometer yield gave the time-varying radiated power.

A variety of pinhole cameras were fielded. The Multi-Layer Mirror (MLM) camera [16]

Table 3.1. Summary of all shots fielded on Saturn

Saturn Shot Number	Wire Material	Wire Diameter (μm)	Wire Number	Cathode Diameter (mm)	Cathode Description	Array Mass (mg/cm)
Radial 1 (Long pulse)						
3729	W	45.73	100	9	Curved (not at OD)	31.62
3730	W	39.86	100	12	Curved (not at OD)	24.02
3731	W	39.86	100	9.9	Modified (point)	24.02
3732	W	30.39	100	12	Square (h+1mm)	13.96
3733	W	35.54	100	12	Square (h+1mm)	19.10
Radial 2 (Long pulse)						
3757	W	35.54	100	12	Square	19.10
3758	W	55	42	12	Square	19.21
3759	W	45.73	60	12	Square	18.97
3760	W	35.54	100	12	Square	19.10
3761	W	35.54	100	12	Extended	19.10
3762	Ti	86.77	70	12	Square	18.65
3763	Ti	86.77	70	12	Square	18.65
3764	Ti	86.77	70	12	Square	18.65
7365	Ti	86.77	36	12	Square	9.59
3766	Ti	86.77	36	12	Extended	9.59
Radial 3 (Short pulse)						
3848	W	20.69	16	12	Square	1.04
3849	W	30.35	32	12	Square	4.46
3850	W	15	16	12	Square	0.54
3851	W	30	16	6.3	Square	2.18
3852	Al	38.35	16	12	Square	0.49
3853	W	25	16	6.3	Square	1.51
3854	W	35	16	6.3	Square	2.96
3855	W	20	32	12	Square	1.94
3856	Al	38.3	32	12	Square	0.97
Radial 4 (Long pulse)						
3867	W	35.54	100	12	Reverse	19.10
3868	W	35.54	100	12	Reverse	19.10

Figure 3.1. Hardware used on Saturn. (a) shows a photo of the array installed in Saturn, (b) shows a zoomed in view of the actual wires and (c) shows models of the entire system and of the diagnostic view.

consists of three discrete Micro-Channel Plates (MCPs). The imaging system for two of these MCPs consists of a set of pinholes followed by an MLM, which reflected monochromatically at 277eV (with the aid of a filter). The remaining MCP utilized a pinhole imaging system and an $8\mu\text{m}$ Be filter. On many shots an additional MCP was provided by Imperial College. This was configured with open pinholes, looking at the Extreme Ultraviolet (XUV) range [17]. To look at harder emission, a time-integrated camera was constructed with various filter cuts, and recorded on RAR 2497 film. For shots with low-Z materials (Al/Ti) a Time Integrated Crystal spectrometer (TIXTL [18]) was fielded.

The complete set of diagnostics fielded, along with some details of the setup are shown in Table 3.2

Table 3.2. Diagnostics fielded on Saturn shots

LOS	Position	Diagnostic	Filter	Details
A	0 ⁰	Time integrated PHC		
	90 ⁰	XUV camera	Open	Quadrant MCP from Imperial College
	180 ⁰	PCDs	2-5um kinfol,	
		PCDs	8 um Be, 12.5um Ti	
	270 ⁰	XUV camera	Open	Quadrant MCP from Imperial College
B	0 ⁰	XRDs	5 μ m Kinfol	
		Ni Bolometer	Open	
	90 ⁰	Au Bolometer	8um Be	Only fielded on Ti/Al shots
	180 ⁰	MLM centre camera	8um Be + Parylene N	> 1keV
		MLM side cameras		277eV (mirrored) [16]
C	270 ⁰	TIXTL	8um Be	Only fielded on Ti/Al shots

Chapter 4

Experimental data in Long pulse

In this chapter we will discuss the overall dynamics of radial arrays in long pulse on Saturn. The setup discussed is the optimal setup in long pulse, giving a good x-ray pulse shape and peak power. Later sections of this chapter will then look at some of the variations performed in order to achieve this optimal setup.

Radial array dynamics on Saturn

We begin our discussion of Saturn data by comparing the global implosion dynamics at 7MA to those of previous 1MA experiments, before looking at how these dynamics change with different array variations.

Figure 4.1 shows the x-ray pulse emitted by a radial wire array consisting of 100 tungsten wires, each $35.5\mu\text{m}$ diameter. The cathode is 12mm in diameter and a retaining ring with slots is used to hold the wires against the cathode. The anode diameter (as with all shots) is 24mm . The x-ray pulse emitted by this radial array is broadly similar to those radiated by cylindrical wire arrays, with a fast rise to peak power, and a lower energy foot post stagnation. Peak x-ray emission of 9TW is achieved around the time of peak load current, which is 7.3MA .

The dynamics of this implosion are diagnosed with self-emission imaging (Fig. 4.2). MLM imaging (Fig. 4.2a) was timed to study the dynamics around the time of this x-ray pulse (relative timing of the frames is shown in Fig. 4.2b). 277eV MLM images (Fig. 4.2a) show a bubble surrounding a bright column on axis beginning to form by -8ns (approximately the start of the rise of the x-ray pulse). This bubble continues to grow axially through all of the frames captured. In the time running up to peak x-rays (-8ns to $+1\text{ns}$) the extent of the bubble increases by $\sim 6.3\text{mm}$, indicating a velocity $\sim 7 \times 10^5\text{m/s}$. At peak x-ray emission (Fig. 4.2c) a tight pinch is seen on the axis, surrounded by the magnetic bubble.

These dynamics observed for experiments on Saturn are very similar dynamics to radial arrays on MAGPIE: prior to implosion precursor material is present above the wires, wire breakage then occurs, a bubble is formed and then the plasma stagnates onto the axis, followed by growth of the column and bubble.

Figure 4.1. X-ray power pulse and load current for Saturn shot 3760

Effect of electrode geometry

Initial experiments on Saturn used an array configuration where the wires were laid across a rounded electrode as shown in Fig. 4.3a. With this configuration multiple low power x-ray pulses were emitted, as shown in Fig. 4.3b. These x-ray pulses are at $\sim 15\text{ns}$ intervals spread over $> 50\text{ns}$. Examining x-ray emission imaging for such a shot (Fig. 4.4 indicates that these multiple pulses are the result of multiple implosions onto the array axis and the production of multiple jets of material away from the array. Similar dynamics have been observed on MAGPIE when a radial foil is used instead of wires [19] and where multiple current restrikes are observed at the edge of the cathode. In the case of the curved electrode on Saturn, it is likely with this shape of electrode that the large area over which the wire is close to the electrode facilitates a similar current restrike. While this electrode configuration is not advantageous to radial arrays as an ICF source, the production of multiple jets has significant relevance to laboratory astrophysics studies of protostellar jet production [19], and at these experiments with higher machine current than MAGPIE the densities and hence Reynolds numbers achieved will be higher making them more relevant.

Significantly narrower x-ray pulses were achieved using a square cathode, as shown in Fig. 4.3c. With this configuration peak powers of 9.5TW were achieved although still with a 6.5TW secondary x-ray pulse 30ns after the main pulse. Further modification to the hardware to mount the wires in a slotted retainer ring using the same wire array configuration were able to almost eliminate this secondary x-ray pulse to a late time foot of 2-3TW lasting $\sim 30\text{ns}$. The main pulse with this configuration is still 9.5TW, however now with a rise-time of 3.8ns and FWHM $< 10\text{ns}$. With this final hardware configuration good shot-to-shot reproducibility was achieved, as shown in Fig. 4.5.

Figure 4.2. Dynamics of Saturn shot 3760. (a) shows MLM self emission images at 277eV at six different times. (b) shows the x-ray pulse (on a shorter time window than Fig. 4.1), along with the timings of the MLM images. (c) shows a higher magnification view of one of the MLM images with various features labeled.

Mass variations

For the square electrode described above (i.e. without the slotted retainer) shots were performed at two different masses. Given that on MAGPIE radial arrays which imploded just before the peak of the current drive have performed well, for Saturn masses of 14mg/cm and 19mg/cm were chosen in order to implode at two different times just prior to the peak of the Saturn current pulse.

Fig. 4.6a shows the results of these two experiments. The heavier shot had $\sim 500kA$ more current coupled, but achieved approximately double the radiated power. This increase in power is likely the result of a more symmetric and more stable implosion, hence achieving higher temperature and density in the stagnated column. Now that a more reliable wire contact has been demonstrated further work is needed to optimize the mass and radius of these arrays.

Figure 4.3. Different style cathodes effect peak power and reproducibility. (a) is a curved cathode, (b) is a square cathode and (c) is a square cathode with the wires captured by a retainer ring. On the left is a diagram of the hardware and on the right is an example of the emitted power pulse from each.

Wire number variations

Following experiments that determined an effective array mounting technique and reasonable array masses, a set of shots were performed to understand which wire numbers and inter-wire gaps performed best on Saturn. The mass per unit length of all of the wires combined was kept constant, and the wire number was varied from 100 wires (as used in the discussion up to now) down to 60 and 42 wires (the diameter of the wires being $35.5\mu\text{m}$, $45.7\mu\text{m}$ and $55\mu\text{m}$ respectively, giving a fixed total mass of $19.1\pm 0.1\text{mg/cm}$).

It was found that the peak power did not vary significantly with varying wire number, however Figure 4.6b shows that the implosion time did change. The implosion time is reduced with increasing wire number, suggesting a higher rate of ablation at the cathode. This has also been seen in preliminary experiments on MAGPIE

Figure 4.4. Multiple episodes of a jet are produced by a radial wire array where bad contact is present between the cathode and the wires. The array cathode arrangement is similar to that shown in Fig. 4.3a, however the cathode diameter is smaller than in the previous figure and wire array is heavier (Saturn shot 3729).

Figure 4.5. Radial wire arrays consisting of $100 \times 35.5\mu\text{m}$ W wires with wires captured in slots by a retainer ring demonstrate good reproducibility

Experiments with an extended cathode

Radial wire arrays are very similar in their structure to the dense plasma focus. In a focus, the radial current path accelerates material axially until it reaches the end of the central conductor, at which point it collapses down toward the axis. The only difference that a radial array has is that there is no extended length for axial acceleration - the material is allowed to propagate towards the axis immediately as it begins to move axially. A few shots were performed on Saturn to investigate whether the use of an extended cathode would be beneficial to x-ray production. This setup is shown in Fig. 4.7a.

The x-ray pulse with the extended cathode (Fig. 4.7b) showed multiple peaks. These were below the peak power of a similar array without the extended cathode, despite the poten-

Figure 4.6. (a) Mass scan with fixed wire number. (b) Variation of implosion time with interwire gap at the cathode for fixed mass

tially higher kinetic energy in the system. Examining MLM imaging of this shot (Fig. 4.7c) shows that no pinch is formed on the axis of the system.

Figure 4.7. Experiments with an extended cathode. (a) shows the experimental setup, (b) x-ray pulse shape and (c) a series of XUV images of a shot with an extended electrode.

Chapter 5

Validating Simulation results against previous radial wire array experiments

Radial wire arrays were initially investigated at the 1MA level on the MAGPIE generator of Imperial College where they have established themselves as a high power, fast rise time x-ray source, and a platform relevant to laboratory Astrophysics. MHD simulations were conducted to investigate the scaling of these sources to the multi-MA Saturn generator of Sandia National Laboratories in an attempt to understand the powers achievable, and to aid in the design of experiments.

This chapter is organized as follows. The first section briefly describes the Gorgon resistive MHD code used to model radial arrays on both the MAGPIE and Saturn generators. This is followed by a discussion of validating the MHD model through the comparison of simulation and experimental results for a mass scan conducted at the 1MA level on MAGPIE. The third section describes results from simulated radial arrays on Saturn. Finally we discuss where some of the discrepancies between simulation and experiment may arise.

The Gorgon resistive MHD code

The modeling we describe here was performed using the 3D resistive MHD code Gorgon [20, 2]. This is a finite volume, fixed grid, Eulerian code using directionally split Van-Leer advection to update the hydrodynamic variables. The plasma is modeled as a single fluid, with separate ion and electron energy densities and temperatures. Ionization states are calculated using a Thomas-Fermi average atom model, with the ionization potential energy stored as a component of the electron internal energy. Braginskii transport coefficients are used to calculate separate ion and electron thermal diffusivity and the equilibration between these species. Discrete wires are initiated as regions of cold dense vapor, enabling the use of a simple ideal gas equation of state throughout the calculation. Ionization in the initial cold, dense wire cores is suppressed above a density of 10Kg/m^{-3} to prevent the Thomas-Fermi model from overestimating the initial ionization state in this material. This technique has been successfully employed in cylindrical wire array calculations where it has proven capable of reproducing the wire ablation dynamics experimentally observed. Since we are primarily interested in x-ray emission as the array implodes and stagnates on the central

axis we are prevented from exploiting this axis of symmetry in reducing the computational volume to a pie-slice, or a 2 dimensional, azimuthally symmetric representation of the array. To do so allows the computational geometry to force the convergence of the imploding plasma onto the central axis, artificially enhancing the convergence achievable, and resulting in anomalously high densities and x-ray powers. In reality the discrete nature of the initial wires and irregularities in their ablation result in a poorly defined central axis. Different parts of the imploding plasma are able to implode slightly off axis, limiting the convergence ratio and ultimately generating the significant $m=1$ instabilities that have been experimentally observed to follow stagnation. To accurately capture these effects we are required to model the full circumference of the array. Simulations discussed in this report typically utilize $\sim 10^7$ computational cells. Given the computationally intensive nature of these full volume calculations radiation transport is neglected in favor of a simple radiative recombination loss model, locally limited to prevent emission exceeding the black body limit.

Radial arrays on MAGPIE

Simulations were initially validated against a mass scan performed on MAGPIE in which the initial wire diameter of a 16 wire radial array imploded on a 6.3mm diameter cathode was varied to change the total mass. Figure 5.1a shows a comparison between simulated total x-ray emission and the PCD signal measured through a $6\mu\text{m}$ plastic filter, for initial wire diameters of $5\mu\text{m}$, $7.5\mu\text{m}$ and $10\mu\text{m}$. PCD signals have been normalized to bolometry indicating a total yield of 5.2kJ for the $7.5\mu\text{m}$ shot, assuming the PCD response remained constant for the other shots. Simulation results are in good agreement with measurements, recovering the correct powers and yields for the first two shots of the mass scan, and correctly identifying the optimum array mass. Figure 5.1b compares the measured XUV ($> 40\text{eV}$) emission with a simulated synthetic emission profile for the $10\mu\text{m}$ wire shot, indicating we are also able to adequately reproduce the observed implosion dynamics.

While agreement in the x-ray powers is very good for the first two shots of this mass scan, the simulation of the heaviest array significantly overestimates the peak power. It is possible that increasing the wire core size affects either the way in which the wires ablate, or the quality of the electrical connection between the wires and the central cathode. Either effect may be potentially detrimental to the symmetry of the implosion, but since the wire initiation in our simulation requires pre-expanding the wire core up to a vapor that is computationally resolvable, we are unable to effectively account for finite wire core size effects in these calculations. Such issues may be relevant to the higher masses and higher wire diameters used to scale these arrays to Saturn.

Figure 5.1. Comparison of (a) power pulses and (b) dynamics from Gorgon simulations and MAGPIE experiments.

Radial arrays on Saturn

We developed a transmission line equivalent circuit of the Saturn generator (Fig. 5.2). Simulations for 100 wire radial arrays on Saturn were initialized in the same way to those used to model MAGPIE. The dynamics of a typical wire array implosion are demonstrated in Fig. 5.3(a), which shows logarithmic density distributions of a section cut through the center of a 100 wire tungsten array. For reference Fig. 5.3(b) indicates the times of each of these density distributions overlaid against current flowing through the load, and indicating the x-ray power produced by this simulated implosion.

By 100ns the wires are seen to be ablating, with the $J \times B$ force from the radial current flowing in the wires directing the ablated material upwards. The force exerted by some current diffusing through into the ablating plasma redirects some of the material towards the axis forming a kinetically confined jet. This jet is seen to form between $\sim 200ns$ and $\sim 250ns$, approximately half way up the current rise. Since regions of the wire core at small radius (next to cathode) experience the highest magnetic field, they ablate the fastest. This region is therefore the first to run out of mass, launching a magnetic bubble which expands upwards.

Instability development in cylindrical wire arrays typically arises from redistribution of the mass during wire ablation, resulting in the irregular break up of the wire cores [21]. Since the point of wire breakage for a radial array is fixed at the cathode contact point, and the ablation rate is enhanced at this location by the convergent geometry, these arrays are less susceptible to ablation instabilities that typically disrupt the implosion of cylindrical

Figure 5.2. Vacuum section of Saturn generator, modeled by circuit model driving simulations

arrays. The time of wire breakage is highly correlated around the azimuth resulting in a high degree of symmetry in the expanding bubble. The axial component of the current in the rising bubble is now able to rapidly implode on axis. Since the majority of the precursor plasma was directed upwards, relatively little plasma must be accreted during the radial implosion. The high degree of azimuthal uniformity and the relatively tenuous material acting to decelerate the implosion, results in a short rise time, high intensity x-ray pulse (peak $\sim 275\text{ns}$). Following peak power, the bubble continues to expand, moving up the axis, compressing more material and launching a jet at the head of the bubble, while the base of the pinched column is driven rapidly unstable (shown at 285ns). It is the magnetic launch mechanism of this jet that is relevant to astrophysics, providing a laboratory representation of the formation of magnetic tower jets [1].

Figure 5.4 looks in more detail at the energetics of the x-ray power pulse through stagnation. Separating out the proportion of radiated power resulting from the thermalization of kinetic energy we see that this accounts for only 25% of the total radiated energy. The remainder comes from additional energy that must be delivered by the generator to the pinch during stagnation. As such the power radiated is heavily dependant on effective current delivery to the pinched column. This requires the small length over which the wires break to be able to remain clear as the bubble expands, and prevent significant reconnection of the current across this opening. While this is readily achievable in simulation it is more difficult to realize in experiment.

Figure 5.3. Time history of (a) radial wire array implosion and (b) x-ray power pulses for two different masses.

Where simulation and experiment diverge

Directly comparing simulation results with experimental measurements for a 60 wire radial array made up of 45.7 micron tungsten wires over a 12mm diameter cathode (Fig. 5.5) we see a significant discrepancy between model predictions and experiment.

Simulations indicate powers for this array in excess of 26TW with pulse widths of 10ns should be available from this configuration, however soft x-ray power of 8TW with a pulse width of 12ns was obtained from the experiment. Furthermore the experiment imploded 75ns earlier than predicted from simulation. The high simulated powers proved insensitive to temperature and mass perturbations typically used to seed instabilities and reduce x-ray power in cylindrical wire array experiments. The radial array configuration is very robust to the development of such ablation seeded instabilities due wire breakage already being highly localized at the cathode contact point. The geometry determines the position of wire breakage far more effectively than wire perturbations observed in cylindrical wire arrays do. It is possible to dramatically reduce x-ray power output by allowing current reconnection across the initial wire break, as shown in Fig. 5.6.

This reduces current delivered to the imploding pinch but typically does not affect the implosion time, so cannot be reconciled with the early implosion observed. The combination

Figure 5.4. X-ray power (black) compared to the rate of decrease in kinetic energy (red).

of early implosion and low powers possibly indicate that only a fraction of the predicted mass is participating. It is possible that azimuthal variation in the initial wire breakdown for high wire number arrays prevents the effective initiation of some fraction of the wires removing them from the implosion. Figure 5.7 indicates this random removal of wires can recover the low powers and early implosion times more consistent with those observed.

Alternatively the ablation of the wires at the cathode contact point could be anomalously high in the experiment, resulting in rapid breakthrough of the wires, as demonstrated in Fig. 5.8. A high ablation rate has previously been observed when thick wires are fielded on MAGPIE.

While all these approaches effectively reduce the peak power, they have difficulty recovering the early implosion time. It is possible that some combination of these potential issues is at work. Simulations of low wire number arrays at the 1MA level did not require additional mechanisms to agree with the x-ray power and implosion time. Comparable wire number arrays with comparable wire sizes may be fired at the multi-MA level on Saturn in short pulse mode where high powers should be obtainable from this proven configuration.

Figure 5.5. Currents and x-ray powers compared between simulation and experiment.

Figure 5.6. Reduction in x-ray power resulting from conduction across vacuum gaps (decrease in vacuum resistivity).

Figure 5.7. Effect of random removal of wires on the simulated x-ray pulse.

Figure 5.8. Effect of hot-spot at wire connection point on simulated x-ray powers.

Chapter 6

Experimental data in short pulse

Motivated by the MHD modeling described above, a series of experiments was performed in Saturn short pulse mode. Two cathode diameters (6mm and 12mm) were used. At 12mm 32 and 16 wire configurations were fielded, with two different masses used on each. At 6mm cathode diameters three shots at different masses were fielded, all with 16 wires. Additionally two Al arrays at 12mm diameter were fielded in short pulse.

Short pulse experiments with 12mm cathode diameter

A total of five shots were performed with a 12mm cathode in short pulse mode. Figure 6.1a shows x-ray power pulses for the two shots that utilized 32 wires, along with a current pulse for one of them for reference. These shots were massed to approximately be implosion time matched to peak current of the machine, which was achieved. Peak powers of $\sim 8TW$ were achieved, which are similar to those found in Saturn's long pulse mode (e.g. Fig. 4.5). Notably, the FWHM of the pulse is similar to that found in long pulse, hence temporal compression plays a much less significant role than in long pulse (the FWHM of the x-ray pulse is now similar to the FWHM of the current pulse). In Figure 6.1 the peak x-ray powers for the two cases are very similar.

Similarly massed arrays were fielded with 16 wires in short pulse. Figure 6.1b shows data with two different masses for 16 wires. Here we see lower peak powers emitted from the pinch, likely indicating that pinch quality was worse than in Fig 6.1. A comparison of time integrated image through three different filters for these two wire numbers is shown in Fig. 6.2. The images show that for the 16 wire case, no discernible column is formed on the axis of the array even through the Be filter ($h\nu > 1keV$), however for the 32 wire case a well established column is seen through this Be filter, along with both the Ti and Ni filters (indicating $h\nu > 2.5keV$ and $h\nu > 4keV$ respectively). It is likely that the large inter-wire gaps are the cause for this drastic change in pinch quality.

Again, as with the long pulse experiments, the implosion and resulting x-ray power pulse came earlier in short pulse than simulations indicate. This implies that rather than an effect associated with large initial wire diameters, the discrepancy between simulation and experiment arises, either from not all of the array wires participating (which is unlikely given

Figure 6.1. (a) X-ray pulses for two 32 wire shots performed on 12mm cathode. The current is shown for one of these. (b) X-ray pulses from 16 wire arrays with a 12mm cathode.

the very low wire number now used) or from an additional heating mechanism increasing energy deposition into the point where the wires contact the cathode. If problems with the implosion do arise from additional heating leading to early wire breakage at the wire contact point, then experiments in which anode and cathode are reversed may help to determine, or eliminate the cause of this extra energy deposition. It is known that magnetically insulated electrons, emitted from the cathode are confined to the electrode surface and flow up towards the load. This magnetic insulation of the transmission lines allows electrical power to reach the load region, but may be modifying the way in which energy is delivered to the array wires as they contact the cathode. Reversing the electrode configuration will remove this affect to the outside end of the wires, which do not participate in the implosion. Such experiments have been performed as part of this work, but the data has not yet been fully analyzed.

Figure 6.2. Comparison of pinch quality 16-32 wires short pulse.

Short pulse experiments with 6mm cathode diameter

Experiments were also performed in short pulse on a smaller 6mm diameter cathode. Power pulses from these are shown in Fig 6.3a. Here we see similar pulse widths to the 32 wire shots on 12mm cathodes (another indication that large inter-wire gaps were the cause of the bad pinch quality for the 16 wire 12mm case).

The peak powers achieved at 6mm are higher than those at 12mm. All three shots demonstrate peak powers $> 8TW$, with Shot 3854 ($16 \times 35\mu m$ W wires) achieving $9.5TW$ peak power.

Figure 6.3. (a) Mass scan with 6mm cathode in short pulse. (b) comparison of one of the shots, Saturn 3854, with the Saturn short pulse current waveform

Figure 6.3b shows a comparison of the current pulse and radiated power for shot 3854. Again, as with the 12mm shots, no significant temporal compression is achieved.

The time-integrated emission from the pinch in this 6mm cathode configuration is shown in Fig 6.4. The harder filtered image demonstrates that a dense hot pinch is formed on the axis. The softer image ($h\nu > 1keV$) demonstrates that all of the emission, and hence the majority of the mass at peak x-rays is originating from a volume of similar diameter to the cathode, and of height similar to the radius of the cathode (i.e. from a hemisphere of with the same radius as the cathode).

Emission $\sim 9.5TW$ from a source of mm scales is a significant gain in power density over a $40TW$ source which occupies a volume defined by multiple cm in each dimension. In the Discussion chapter of this report we will take Saturn shot 3854 as an example of the output from a radial array and make quantitative comparisons to cylindrical wire arrays and discuss possible applications of this source.

Figure 6.4. Saturn 3854 - 6mm short pulse

Chapter 7

Discussion

In this chapter we discuss two of the most likely applications of the work presented thus far. Firstly we discuss the utility of this source to drive a hohlraum. This could be for ICF or (more likely) to drive an opacity experiment. Secondly we discuss briefly the applicability of the data to the physics of astrophysical jets. Laboratory astrophysics was not the primary driver for the work performed, since radial wire arrays have previously been used extensively to study these jets. Minimal effort has gone into this application of the data, however much of the data obtained can be applied to this problem.

Hohlraum calculations

In the previous chapter we demonstrated a compact source capable of radiation $\sim 9.5TW$ from a $\sim 3mm$ long column above a $6mm$ diameter cathode. It is assumed that placing a primary hohlraum around this column would not adversely affect the pinch performance. Additionally, we assume that only the inner 2mm of the wires (nearest the cathode) participate in the implosion process, hence the remainder of the wire can be removed. Both of these assumptions are consistent with experimental data to date, however could easily be tested if further experiments are performed.

Figure 7.1 shows two hohlraum schemes that we are proposing to utilize radial wire arrays, one with single sided drive (Fig. 7.1a) and one with double sided drive (Fig. 7.1b). These two schemes are analogous to the single- and double-ended configurations previously developed for cylindrical wire arrays [10]. One advantage that has been utilized in these radial wire array schemes is their ability to depart from a cylindrical primary hohlraum. This has the advantage of reducing the primary hohlraum wall area by 50% over a cylindrical primary hohlraum of similar diameter and height.

Work by Cuneo et al. [10] has developed 0D energy balance for a single- or double-ended hohlraum for cylindrical arrays. Here we apply this methodology to the compact radial array radiation source demonstrated in Saturn short pulse. We will assume a single ended hohlraum using this source, as shown in Fig 7.1a. While this setup is unlikely to be relevant to Inertial Confinement Fusion due to the stringent symmetry requirements, it may be an efficient method of driving radiation physics experiments, such as opacity measurements.

Figure 7.1. Two hohlraum schemes based on radial wire arrays. (a) shows a single ended concept and (b) shows a double-ended concept.

The configuration in Fig. 7.1a has a primary hohlraum wall area of $\sim 1.6\text{cm}^2$ and secondary hohlraum wall area $\sim 1.4\text{cm}^2$. The coupling area between these two hohlraums is $\sim 0.3\text{cm}^2$.

Assuming a hohlraum wall albedo of 0.75 and feed gap albedo of 0.34 (as used by [10]), we find a 9.5TW source drives the primary hohlraum to $\sim 100\text{eV}$, and this in turn is able to drive the secondary hohlraum to a temperature $\sim 92\text{eV}$ (assuming no additional diagnostic exit holes on the hohlraums). 40mm diameter cylindrical wire arrays have previously been shown to emit $\sim 40\text{TW}$ [22]. Applying the same methodology to these we predict primary and secondary hohlraum temperatures $\sim 62\text{eV}$ and $\sim 57\text{eV}$ respectively, hence radial wire arrays have the potential to drive significantly higher hohlraum temperatures than cylindrical wire arrays (we note that the 20mm compact cylindrical wire arrays more recently fielded on Z have not been thoroughly explored, hence no direct comparisons can be made).

This source might additionally have application for opacity experiments on Saturn. Previous work has used the dynamic hohlraums on Z [23] for opacity measurements, however it is possible may provide a tool for more cost effective, lower temperature opacity experiments on the Saturn generator. Further work is needed to determine what brightness temperatures are achievable and also to create the pulse shape needed for certain opacity experiments.

As a source for Inertial Confinement Fusion, experiments in Saturns long pulse mode are more appropriate (the cost of building higher current 40 – 50ns risetime generator is prohibitive with current technology).

Astrophysical relevance

Previous experiments with radial wire arrays and foils have shown significant relevance to astrophysical jets [1, 2, 19]. The magnetic launch mechanism in a radial array is thought to have analogies to the magnetic field produced by rotation of accretion disk in stellar jets [1]. Furthermore, the propagation of jets and their interaction with the Interstellar Medium, whether magnetically or hydrodynamically launched, is also a topic of current interest to the astrophysical community, and laboratory experiments which can help in these studies are of interest to the community (e.g. [24]).

The data presented in the previous chapters shows reasonably similar dynamics to previous 1MA radial wire array jet experiments [1, 2, 19]. Specifically, at the 7MA level we have demonstrated the ability to drive single- and multi-episode jets.

For a magnetically launched laboratory jet, the density of the jet is directly related to the magnetic field and hence the current driving the system. It is anticipated that the jet densities in the current experiments are ~ 50 times more dense than in previous MAGPIE experiments. This density change will act to increase the Reynolds and Magnetic Reynolds number, moving the experiments into a more astrophysically relevant regime.

Similarly, the typical time and length scales of z-pinch system are dictated by the current rise time of the generator and the distance traveled during the implosion [25]. The experiment in Fig 4.2 had a larger cathode and shorter current rise time than the MAGPIE experiments, hence the jet produced achieved a higher propagation velocity than for MAGPIE experiments. This higher velocity will likely lead to higher Mach and Alfvén Mach numbers, broadening the range of parameters achievable in magnetically driven laboratory jet experiments.

Further analysis of the data presented in this report from a laboratory-astrophysics perspective is likely to yield much useful information relevant to the understanding of protostellar jets, however is outside the scope of the present report.

One significant contribution these experiments make to astrophysically relevant magnetic jet experiments is by establishing good configurations for radial wire arrays at multi-MA current levels. A recently funded proposal is planning to explore conical and radial wire arrays on the Z generator for laboratory astrophysics applications [26]. Experiments on Z will have many advantages for laboratory astrophysics over Saturn, including higher current levels, improved diagnostic access and a radiography capability provided by the ZBL laser.

Conclusions

Radial wire array z-pinches have been explored for the first time at multi-MA current levels. Dynamics appear very similar to those previously observed at 1MA [1, 2, 19].

Experiments have demonstrated a compact x-ray source using Saturn short pulse which radiates 9.5TW from a $\sim 0.5\text{cm}^3$ volume. This could drive a primary hohlraum with surface area 1.6cm^2 to $\sim 100\text{eV}$, and in turn drive a secondary hohlraum to $\sim 90\text{eV}$.

The demonstration of single and multi episode jets at 7MA current levels aid in planning future magnetic driven jet experiments at higher currents, or better diagnosed experiments at this current level.

A number of other variations were performed in the experiments including lower atomic number wire materials (Al & Ti), reversed polarity on the array and extending the cathode a few mm beyond the wire locations. Each of these showed interesting data which it is hoped will be discussed in more detail in the future.

Comparisons of 3D MHD simulations with detailed experimental data indicate a number of non-ideal phenomenon are likely occurring in the experiments, possibly associated with current restrike. More experimental and theoretical work is required to address these issues.

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