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3D MHD simulations of radial wire arrays

Evaluating Radial Arrays at the multi-MA level

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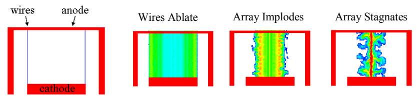
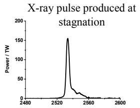
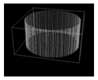
We present 3D resistive MHD simulations evaluating radial wire arrays at multi-MA as a potential compact, high intensity source for inertial confinement fusion and for laboratory astrophysics applications. A radial wire array consists of wires running radially outwards from a central electrode, and were first investigated at the 1 MA level on the MAGPIE generator at Imperial College. Originally used as a method of producing magnetic tower laboratory jets relevant to astrophysics [1], they have also shown potential as a high power x-ray source [2]. Able to produce x-ray pulses with a rise time and peak power comparable to cylindrical wire arrays, radial arrays occupy a smaller volume and may consequently be able to access higher power densities. We discuss simulation results reproducing radial array experiments performed on the MAGPIE facility as a means of benchmarking our model. This model is then used to evaluate radial wire arrays in the multi-MA regime for planned experiments on the Saturn generator of Sandia National Laboratories.

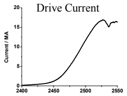
Wire Arrays for ICF



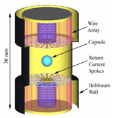




Wire Array Z-pinch

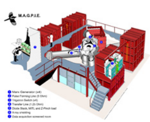


Large current ~20MA passed through cylindrical array of fine metallic wires

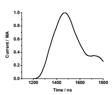


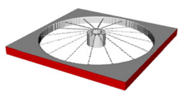
ICF design using wire array x-ray source requires large hohlraum size dictated by large volume occupied by arrays (~20mm diameter / 10mm tall). Efficiency could be improved if we decrease source size

Radial Wire Array on MAGPIE

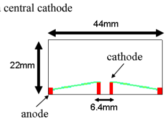


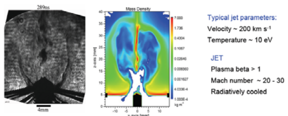
MAGPIE generator at Imperial College





Radial Array – Wires arranged as spokes on a wheel around a central cathode

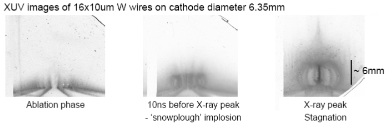




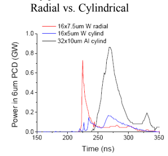
Radial Arrays first investigated on MAGPIE for laboratory astrophysics as a way of creating magnetic tower jets. However they have also shown promise as an x-ray source

Implosion of a Radial Array
Wires are seen to ablate. A bubble forms at the cathode. The bubble expands and pinches on axis.

XUV images of 16x10um W wires on cathode diameter 6.35mm

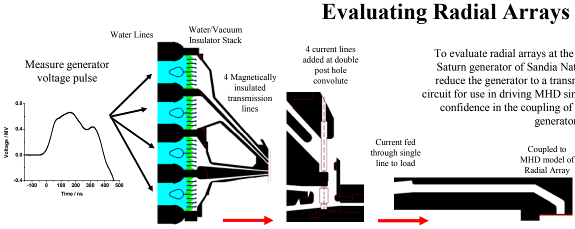


X-ray powers on MAGPIE
Radial vs. Cylindrical

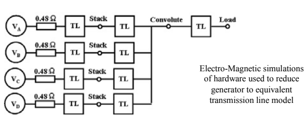


Radial arrays on MAGPIE are seen to produce comparable x-ray powers to cylindrical arrays. However pulse widths are narrower, rise times are shorter and volume of array is reduced. All of which is good news for ICF source

Evaluating Radial Arrays on Saturn

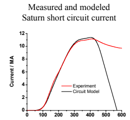


To evaluate radial arrays at the multi-MA level on the Saturn generator of Sandia National Laboratories we reduce the generator to a transmission line equivalent circuit for use in driving MHD simulations, so we can have confidence in the coupling of the radial array to the generator



Electro-Magnetic simulations of hardware used to reduce generator to equivalent transmission line model

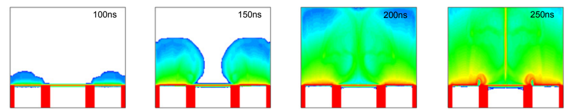
Measured and modeled Saturn short circuit current

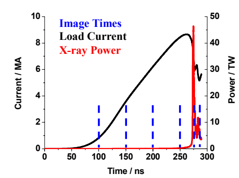


Simulated Radial Array Implosion

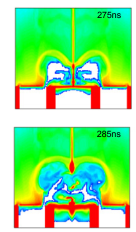
Wires ablate – the jxB force from the radial current flowing in the wires directs the ablated material upwards

Some material is directed towards the axis forming a kinetically confined jet. Regions of the wire core at small radius (next to cathode) experience highest magnetic field so ablate fastest. This region runs out of mass soonest, launching a magnetic bubble which expands upwards.



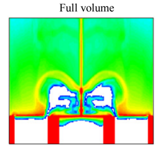


Axial current as bubble rises now able to rapidly implode on axis producing x-ray pulse (peak ~275ns). Bubble continues to expand, moving up axis compressing more material and launching a jet, as the base of the pinched column is driven rapidly unstable.

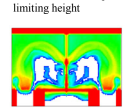


Potential benefits over wire arrays

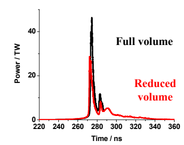
The active area producing x-rays is a small part of the volume. So can reduce the size of the load to approximately encompass this volume whist maintaining high x-ray powers



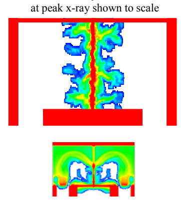
Full volume



Reduced electrode gap at base, electrode plate limiting height



Comparison of radial array to wire array

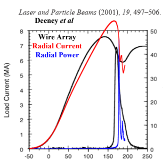


Saturn wire array and radial loads at peak x-ray shown to scale

Pinch performance compared to 180 wire, 25mm diameter, 21mm tall tungsten array imploded on Saturn. Radial power is comparable although pulse width is narrower. Radial load is initially higher inductance although inductance change through implosion is less, so higher load currents are obtained.

Radial has >4 reduction in volume / increase in power density

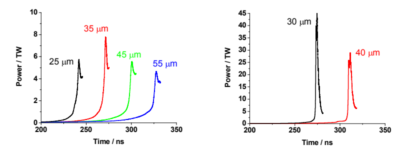
X-ray power and load current



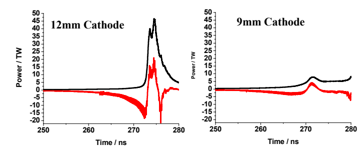
Simulated mass scan for different cathode diameters

Keeping wire number fixed (100 wires) we change initial wire diameter to vary the initial mass. We also vary initial cathode diameter. Variation in power exhibits optimum for 9mm diameter cathode with 35μm wires. Dramatic increase in total power seen as cathode diameter increased

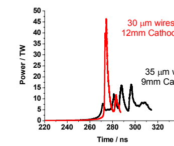
Total X-ray Power for different initial wire diameters



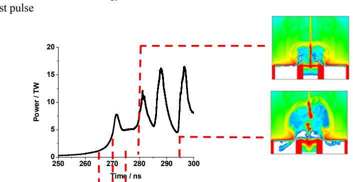
Power delivered from Kinetic Energy Compared to X-ray Power



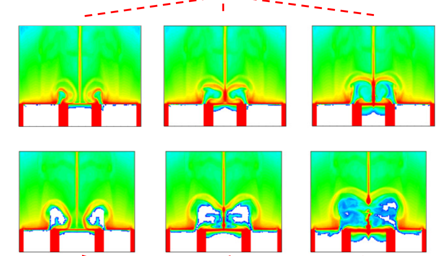
Smaller cathode diameter results in initially low first x-ray pulse as bubble hits axis, after which lots of energy is radiated in multiple peaks as stagnated column is driven unstable. For larger diameter cathode a larger bubble hits the axis at a higher velocity, and then rapidly goes unstable resulting in a greater concentration of energy in the first pulse



Comparing x-ray power to the power delivered from the thermalization of kinetic energy we see that this source accounts for nearly half the measured x-ray power. It is interesting to note that the smaller cathode diameter does not drive the bubble as hard, developing only a small fraction of the total kinetic energy obtained from the larger cathode diameter

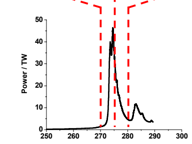


Comparison of mass density profiles for 9mm and 12mm diameter cathodes indicate that for the large diameter cathode the bubble forming the implosion is able to more effectively open up after wire breakage. As the implosion proceeds the bubble is able to expand to a greater height before reaching the axis allowing for a greater pinch length during x-ray production. Furthermore the open bubble tightly confines current to the stagnating column providing further gains in x-ray power. For the smaller diameter cathode the bubble never effectively opens, driving an initially weak implosion. Following stagnation the bubble slowley creeps up the axis producing multiple x-ray peaks as the column is driven unstable.



Conclusions

- Radial arrays are capable in the simulations of producing comparable powers to cylindrical arrays with reduced load volume at the multi-MA level on Saturn
- Radial arrays seem to favour larger cathode diameters to allow the imploding bubble to more effectively open, and implode with a greater kinetic energy.
- If the magnetic bubble does not effectively open then initial x-ray burst is dramatically reduced and energy is released in multiple, instability driven bursts post stagnation
- Need to validate these results against initial experiments on Saturn



National Nuclear Security Administration

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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