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Laboratory investigation of magnetic bow shocks in radiatively cooled plasmas

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Overview

- Magnetized and radiatively cooled shocks are present in many astrophysical systems.
- The early stage of a wire array z-pinch implosion consists of the steady ablation of material from fine metallic wires.
- Ablated material is accelerated toward the array axis by the JxB force.
- This flow is highly supersonic (M>5) and becomes super-Afvenic (M_A>2).
- Radiative cooling is significant in this flow, and can be controlled by varying the material in the ablated plasma.
- The introduction of a wire as an obstruction in this steady flow leads to the formation of bow shocks.
- The magnetic field associated with this obstruction wire can be controlled by varying the current through it.
- Differences in the shock for different cooling rates and different magnetic fields associated with the obstruction will be discussed.

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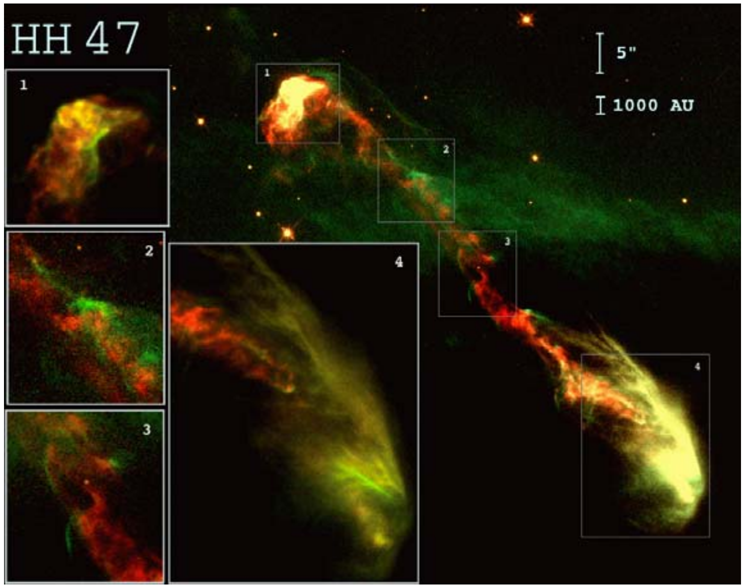
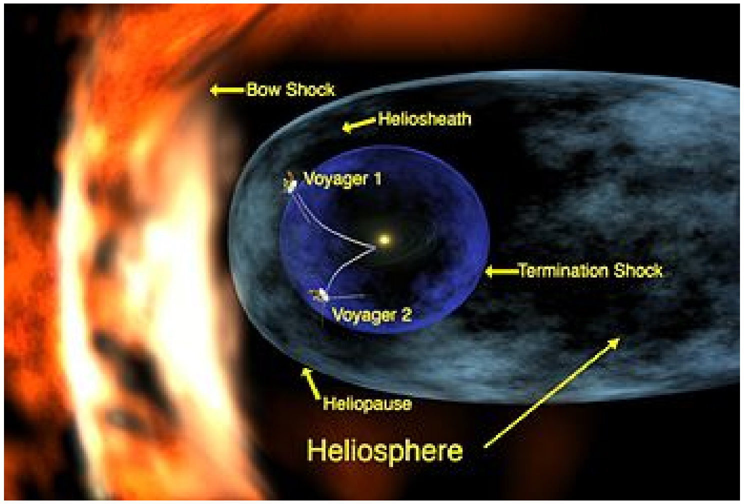
Radiatively cooled and magnetically dominated shocks exist in various astrophysical plasmas

- Shocks occur in various astrophysical objects
- The energy balance of a subset of these shocks are dominated by radiation loss
- Magnetic fields can also play a critical role in the shock dynamics





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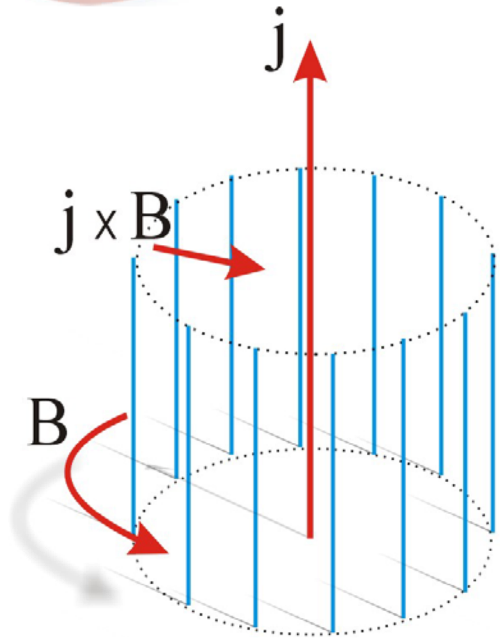
Wire array z-pinches provide a steady flow of material ablated from the wires.



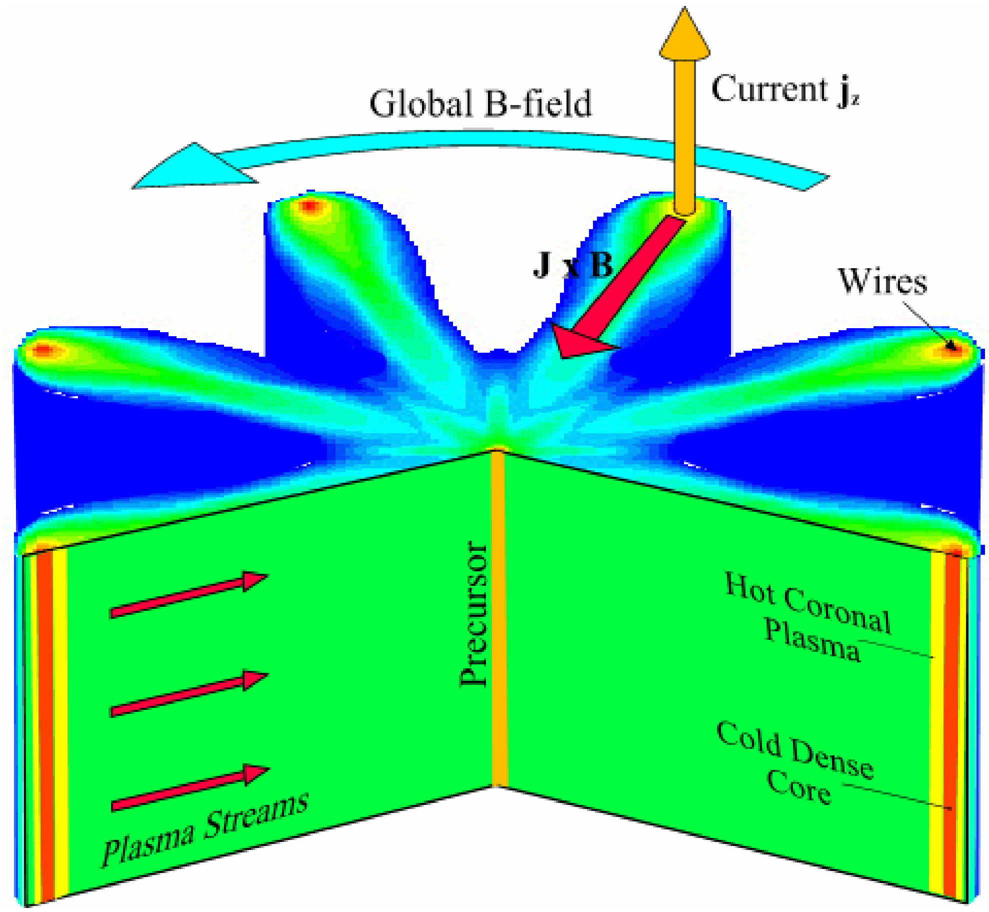
Current 1 MA (rise-time240 ns)

Wire Material: W, Al, Fe, Cu, etc

Wire Ø: 7–30 μm

Array Ø: 16 mm

Array Height: 23 mm



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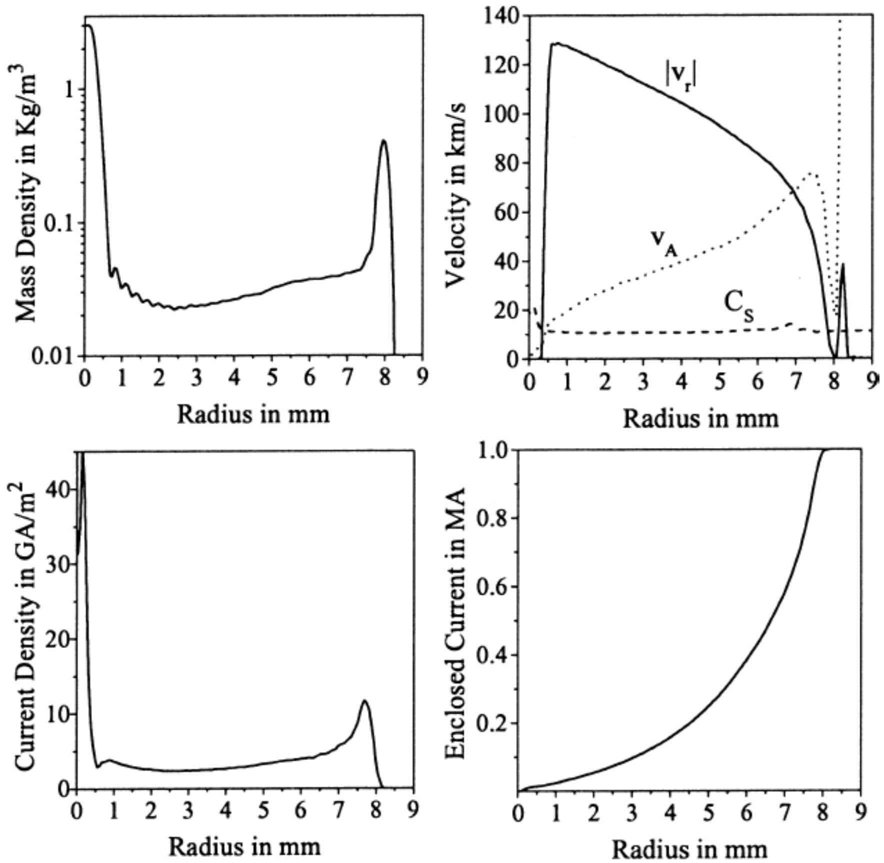
The early stage of a wire array z-pinch implosion consists of a radiatively cooled, super-sonic, super-Alfvenic flow

Averaged radial profiles from simulations of MAGPIE
From Chittenden *et al.*, Phys. Plasmas, 11, 1118 (2004)



Typically the ablated streams from the wires are:

- **Supersonic (M>5)**
- **Super-Afvenic (M_A>2)**
- **Collisional**

Simulations indicate some field is entrained in the flow

The rate of radiative cooling can be adjust by changing the wire material

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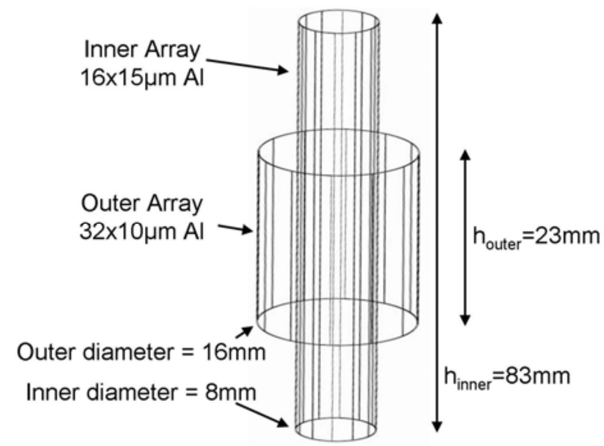
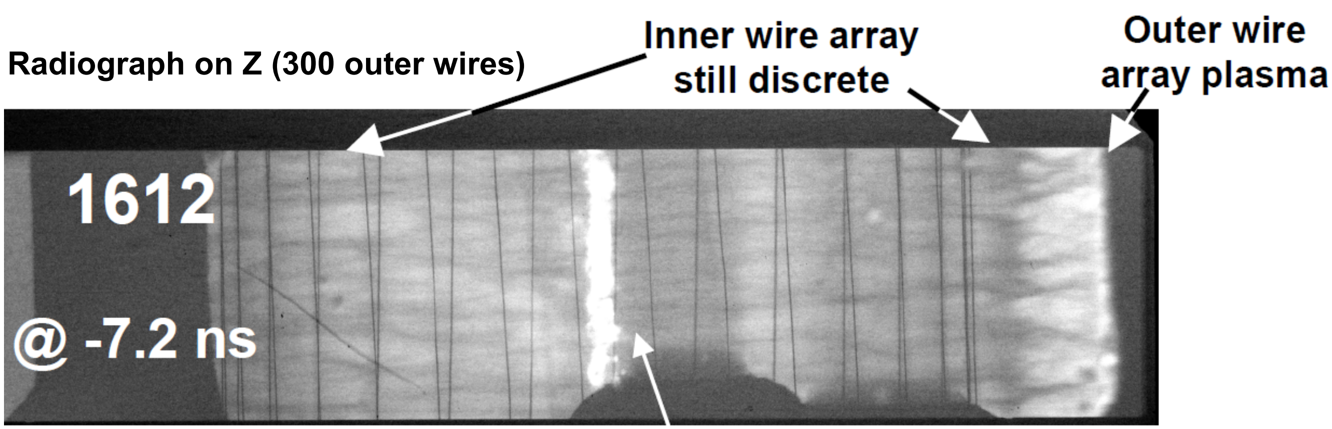
In nested wire arrays the inner array remains current free while the outer array ablates

- **Inductive current division between inner and outer arrays with high outer wire number leads to a negligible current through the inner array**
- **With smaller number of outer wires (16-32) a similar current division is achieved by lengthening the inner array**
- **Small current through the inner array leads to minimal expansion of the inner wires (less than radiograph resolution)**

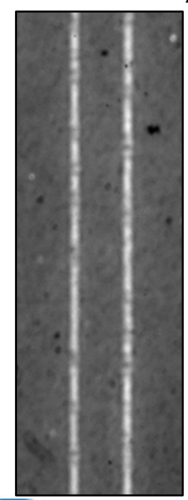
High inner inductance setup on MAGPIE (32 outer wires)



Radiograph on Z (300 outer wires)



Radiograph of inner on MAGPIE (32 outer wires)



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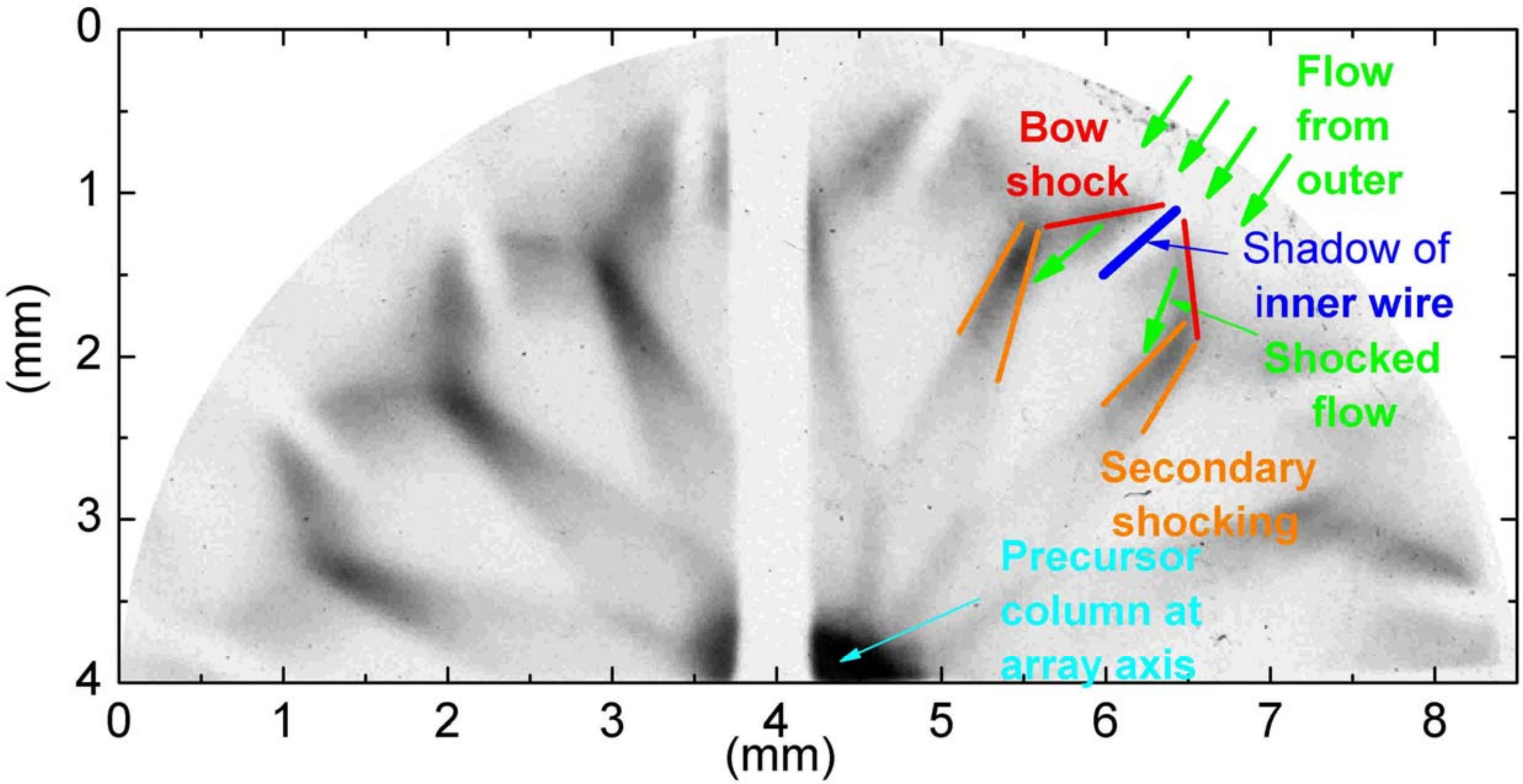
Inner array wires act as an obstruction to the plasma flow, producing bow-shocks



- **Bow shocks observed by self emission (>30eV)**
- **Secondary bow shocks seen between inner wires**
- **Third shock seen just before the flow meets the axis**

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Factors that will effect the shock shape/structure in experiments

- Magnetic field advected with flow (function of R_m)
- Magnetic field associated with current in the inner array
- Plasma β in flow (whether sonic or magnetic shocks more important)
- Flow temperature (sound speed)
- Ablation (flow) velocity from the outer wires
- Size of the inner wires (obstruction size if shock is sonic)
- Rate of radiative energy dissipation from the shock
- Opacity of material upstream of shock (radiative precursor??)

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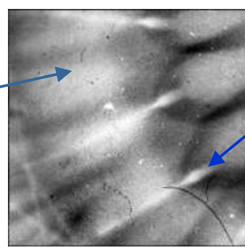
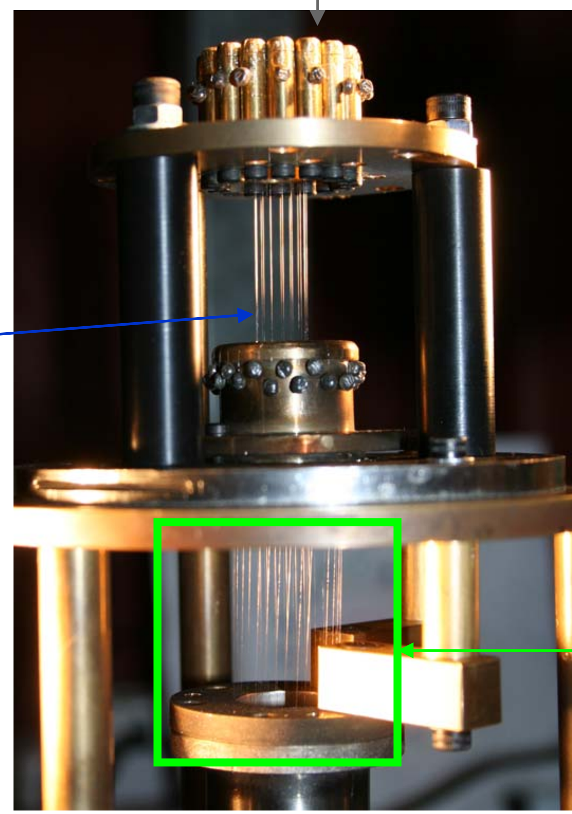
Modified setup allows better diagnosis of flows

Spider web of wires is used to position the inner array, allowing diagnosis of streams before and after the bow shock



Good view prior to streams reaching inner (with some wires obstructing)

Inner wires



Main nested array

Setup by G.N. Hall

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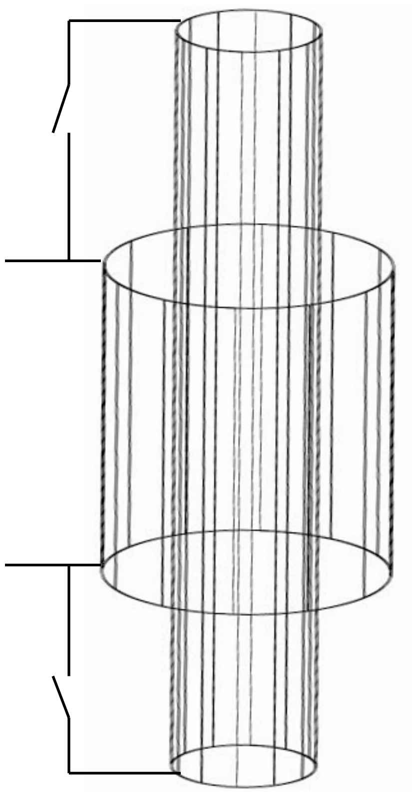
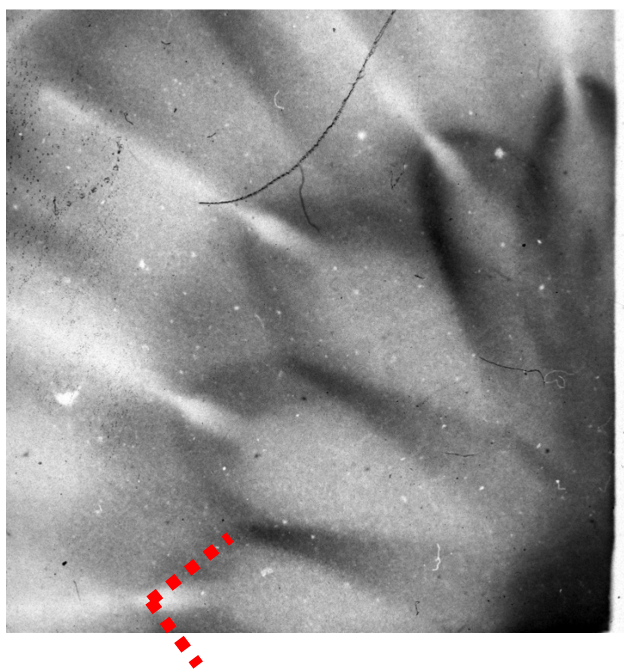
Magnetic field around obstacle alters shock, giving it a larger opening angle

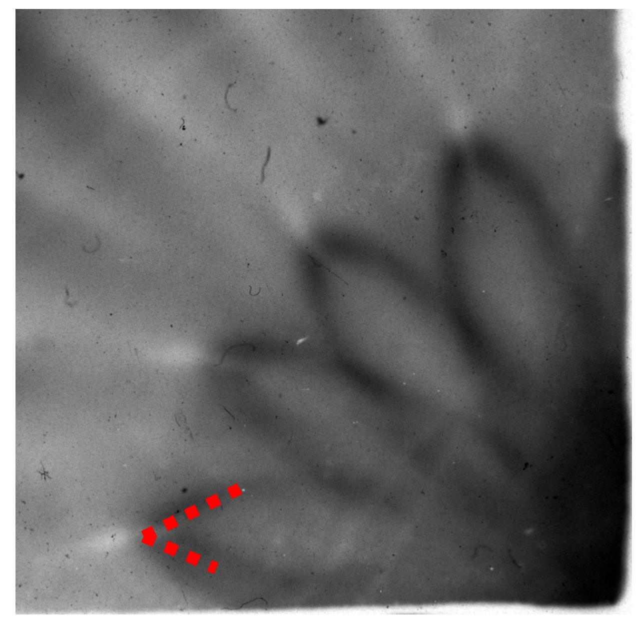
- By altering the current contact of the inner array, the weak magnetic field around each of the inner wires can be turned off
- Data shows that with this magnetic field present the opening angle of the shock is larger (~10degrees)



With field



Without field



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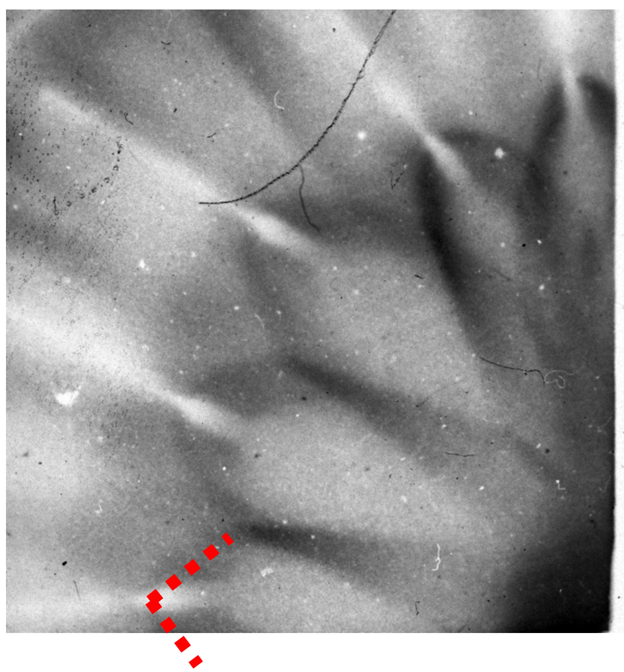
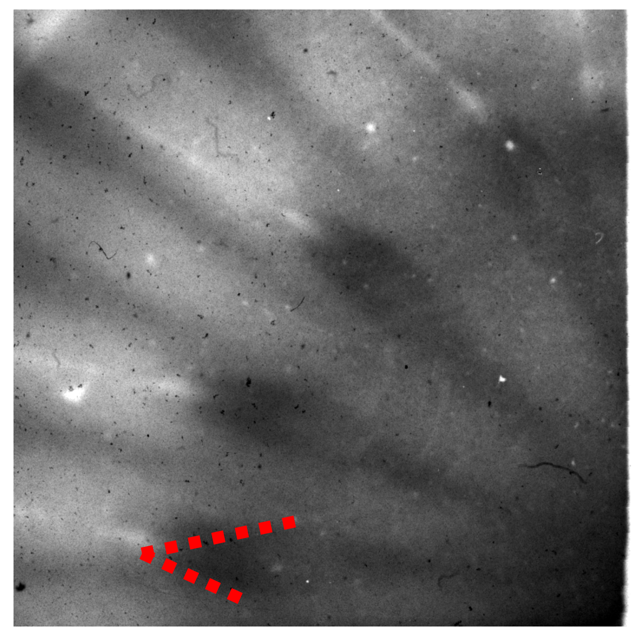
Changing the flow material significantly alters the shock configuration, likely due to radiative cooling

- Changing the wire material to tungsten drastically increases the radiation loss rate, leading to a much narrower shock angle.
- Higher cooling rate leads to lower temperature, and hence pressure behind shock, therefore smaller opening angle

Al (lower cooling rate)



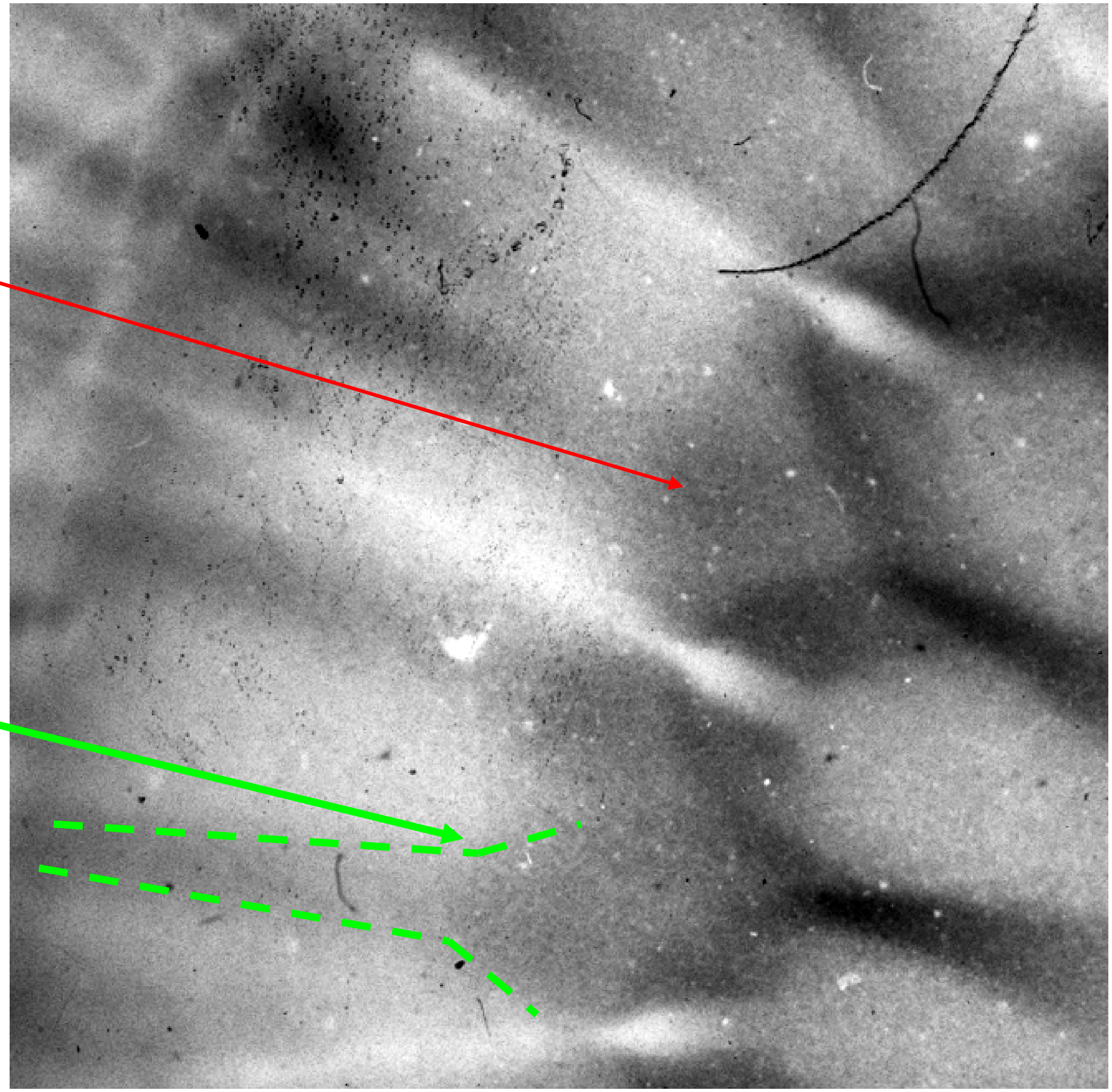
W (higher cooling rate)



Setup with good diagnostic access demonstrates a possible radiative precursor ahead of the shock

- **Region of emission upstream of the shock could be a radiative precursor**

- **Divergence of incoming stream consistent with preheat**



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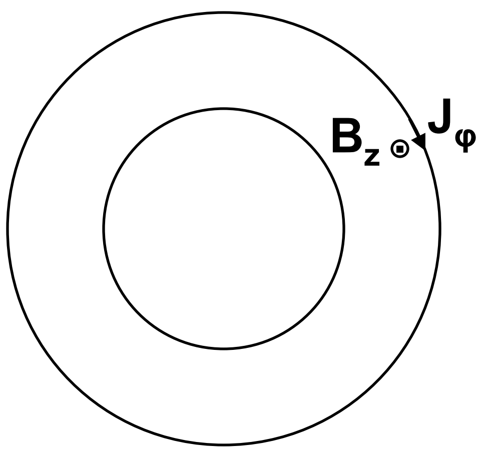
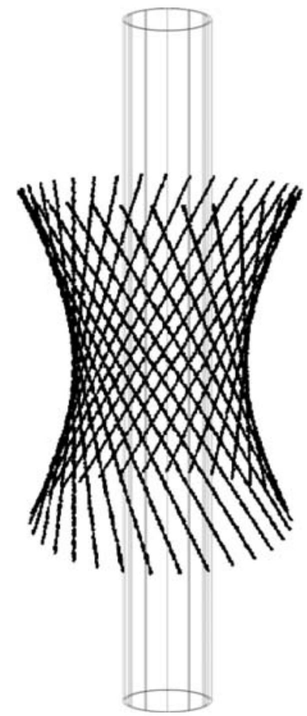
Twisting the outer array should change the jump conditions

- Twisting one or both of the arrays can enhance the magnetic field by introducing an axial component

- This additional magnetic pressure should alter the shock structure
  - » Increase in field would increase v_a
  - » Reduction in M_a would lead to smaller jump across shock
  - » Lower pressure jump would open shock angle





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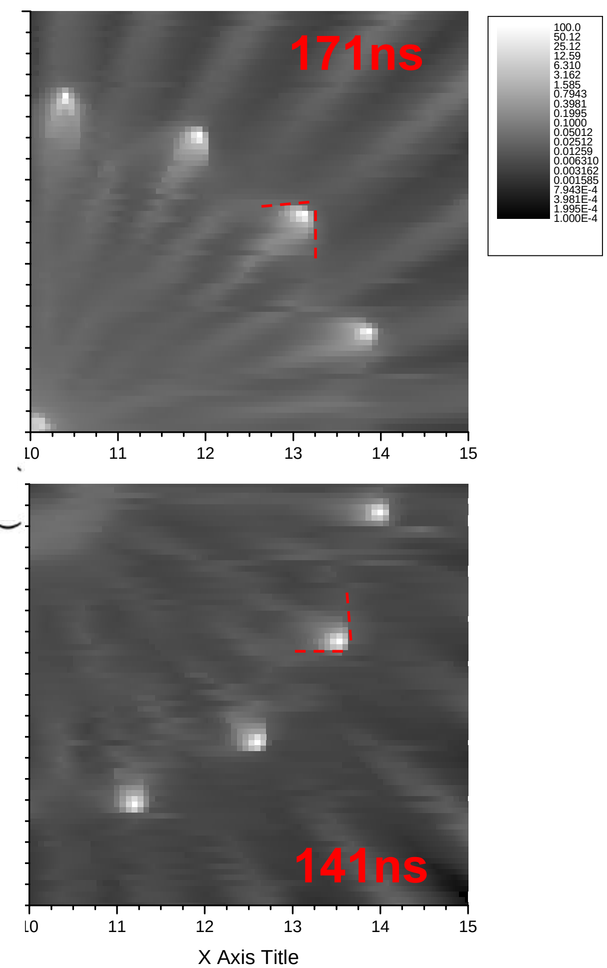
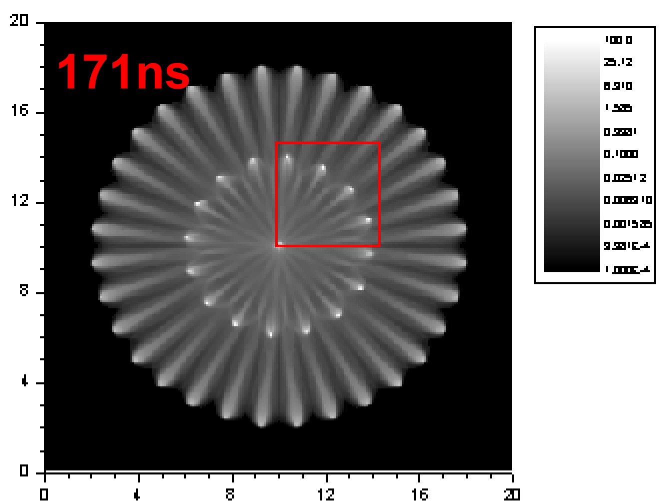
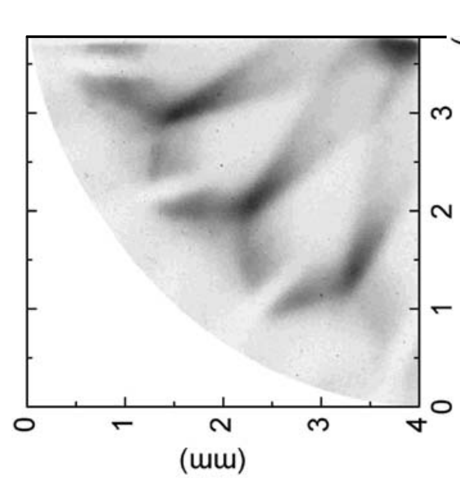
Simulations give additional insight into flow and shock parameters

- **Simulations can recreate the shock structures observed in experiments**
- **Simulations are in agreement with experimental data that the shock angle is approximately static in time**
- **Simulation angle is similar to experiment**







Simulations by C.A. Jennings

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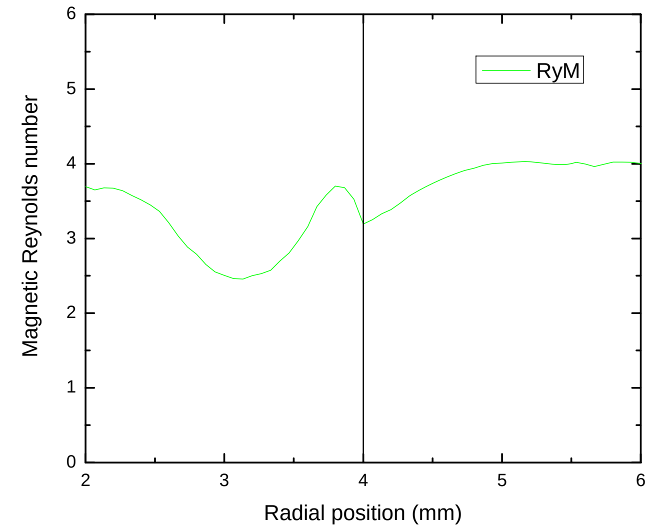
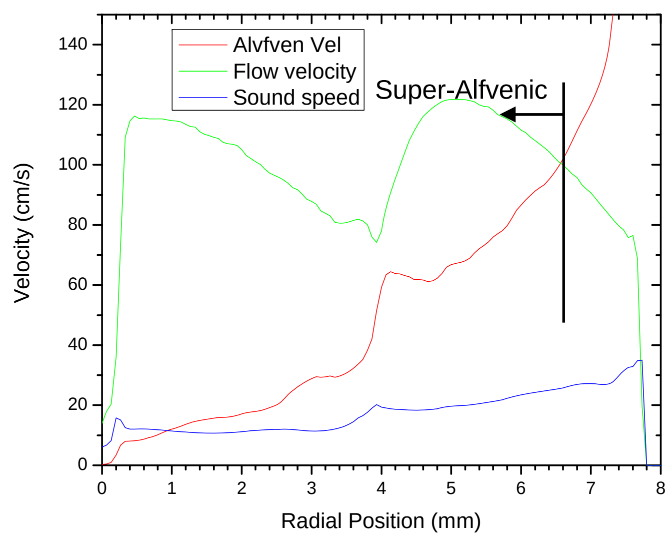
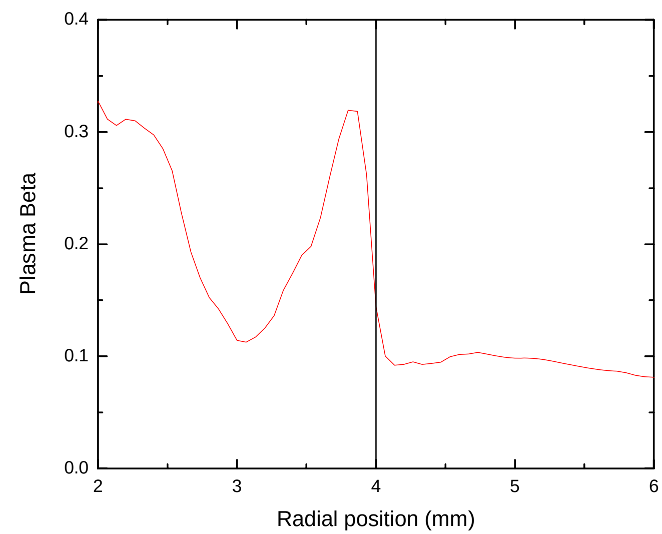
Radiative cooling and magnetic field have significant effects in these lab-experiments

- **Magnetic Reynolds number is >1, indicating magnetic field is advected with the flow**
- **Upstream of shock plasma Beta is ~0.1, indicating that the flow is dominated by magnetic pressure, rather than thermal effects**
- **At the shock the Beta increases, however remains <1**







Simulations by C.A. Jennings

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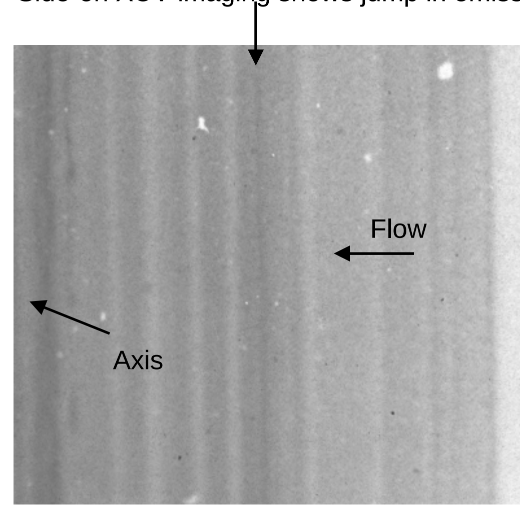
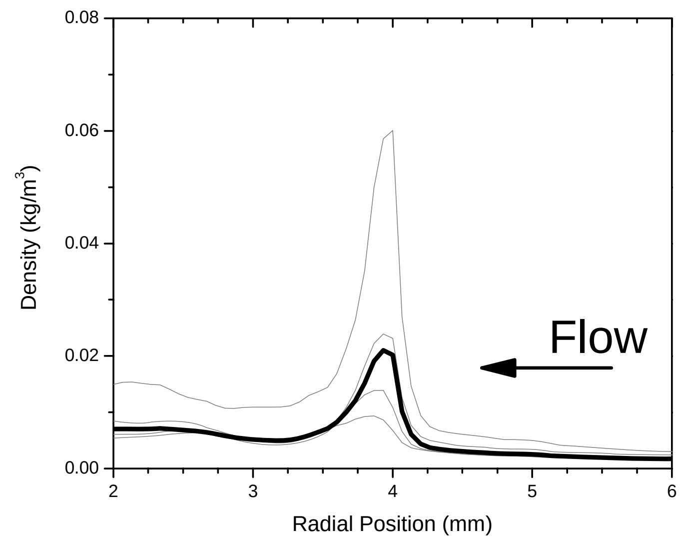
Jump conditions in shock can be recovered from simulations

- **Density profile and jump changes with azimuthal location, but a jump is seen at all locations**
- **Average jump in density is ~x4, as would be expected for a strong shock**
- **Varying the radial location of the inner would vary the Alfven number upstream of the shock**

Side-on XUV imaging shows jump in emission





Simulations by C.A. Jennings

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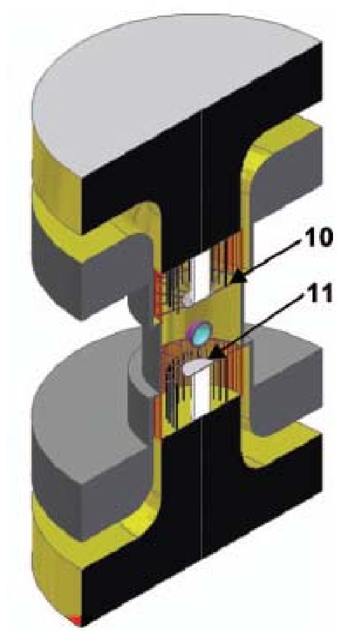
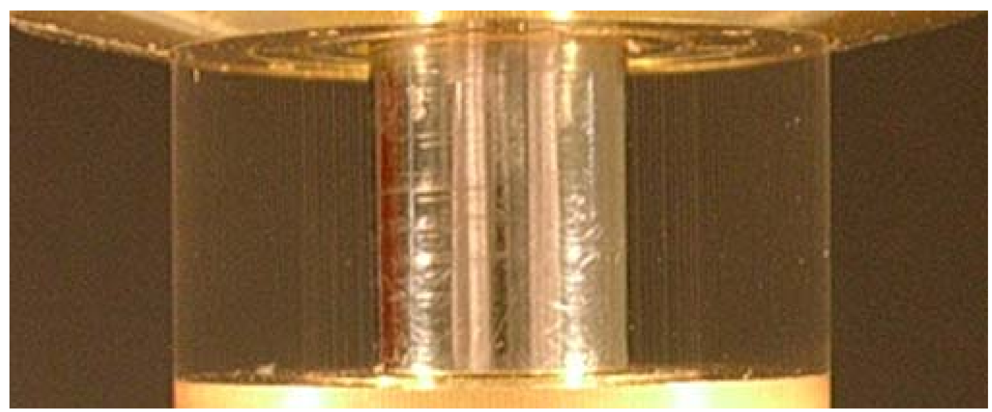
Experiments on Z would widen parameter space

- Z-machine at Sandia has significantly larger peak current (20MA), so density of streams is much higher
- Higher rate of radiative energy dissipation from the shock
- Higher rate or energy absorption upstream of shock
- Data indicates that some control of flow velocity by varying wire size (or wire number)





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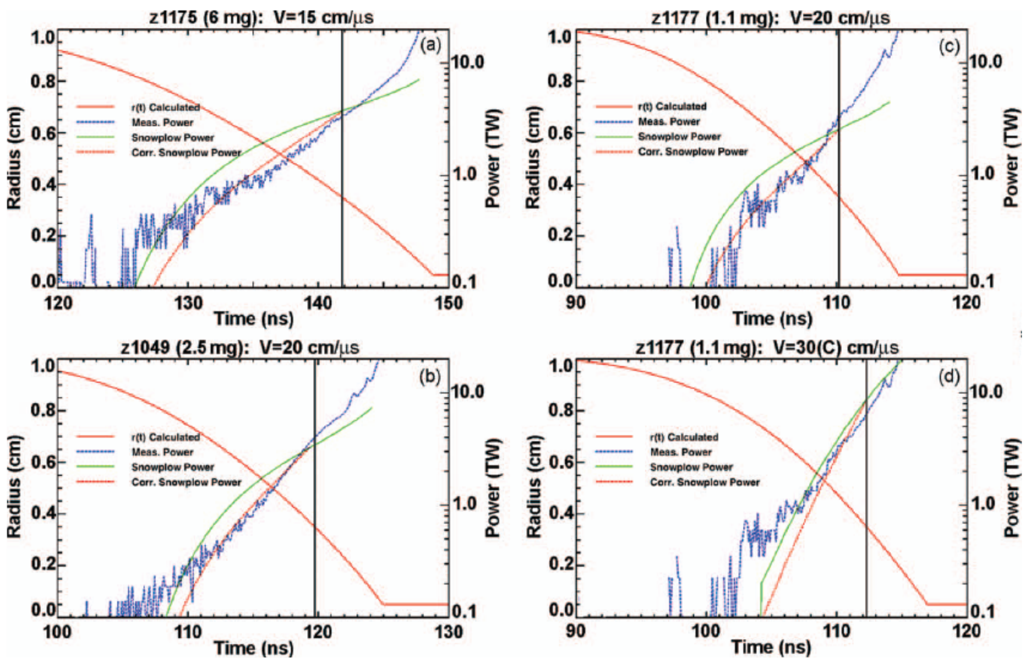
Aside: Density and velocity jumps at the shock can lead to the interaction pulse in nested wire arrays

- Presence of shocks perturb the density distribution within the array
- In a single array early time emission can be explained by the imploding piston snowplowing material and thermalizing kinetic
- Substituting jump conditions into the expected pre-fill density and velocity profiles can explain the observed *interaction pulse*

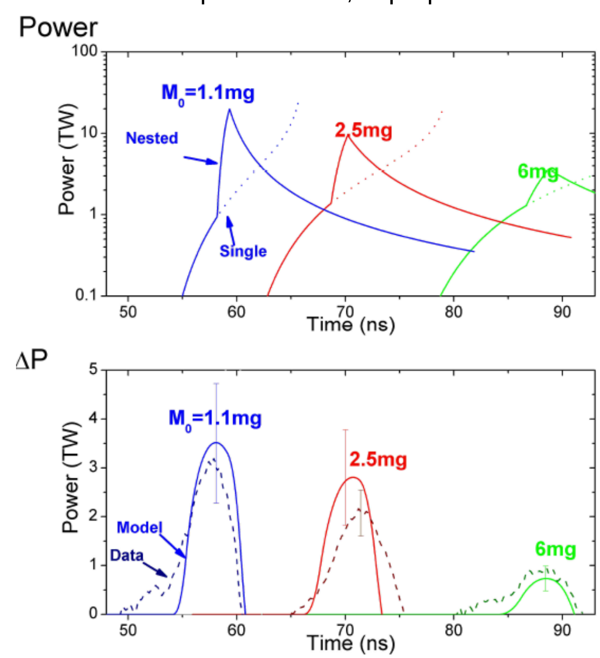
Single array snowplow fits to power

Sinars et al., Phys Plasmas 13, 042704 (2006)



Snowplow model for nested array

Ampleford et al., in preparation



Z data courtesy of D.B. Sinars & M.E. Cuneo

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Summary: Steady state radiatively cooled bow shocks can be created and controlled in the laboratory

- In nested wire arrays, bow shocks are formed as ablated material passes static inner wires
- Experiments on MAGPIE have demonstrated control of the shock angle with
  - Magnetic field pressure associated with inner array (current contact)
  - Rate of radiative cooling (material)
- There is some evidence for a radiative precursor upstream of the shock
  - More analysis and modeling required
- End-on XUV radiography system is being developed which would allow more quantitative diagnosis of the shocks
- MHD simulations of this nested system reproduce shock structures, and more quantitative experimental data would allow more thorough benchmarking of simulations
- More work needs to be performed on the similarity of these flows and shocks astrophysical systems