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MAGPIE
Centre of Excellence in High Energy Plasma Physics

Origin of the interaction pulse in Nested Wire Array Z-pinches

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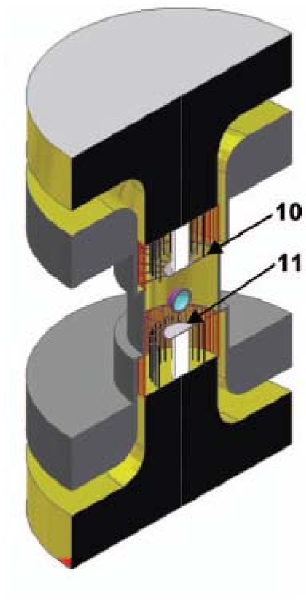
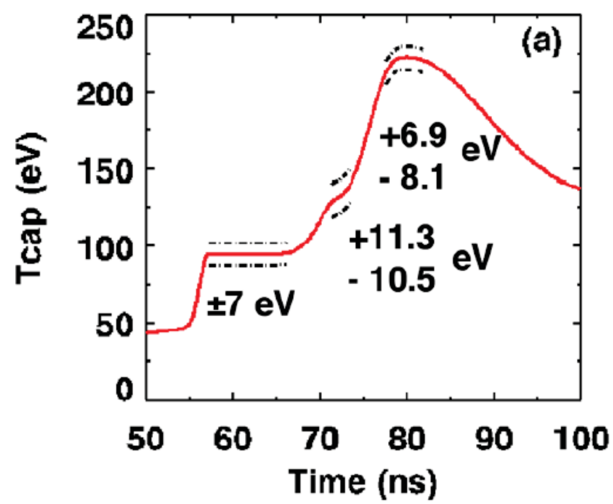
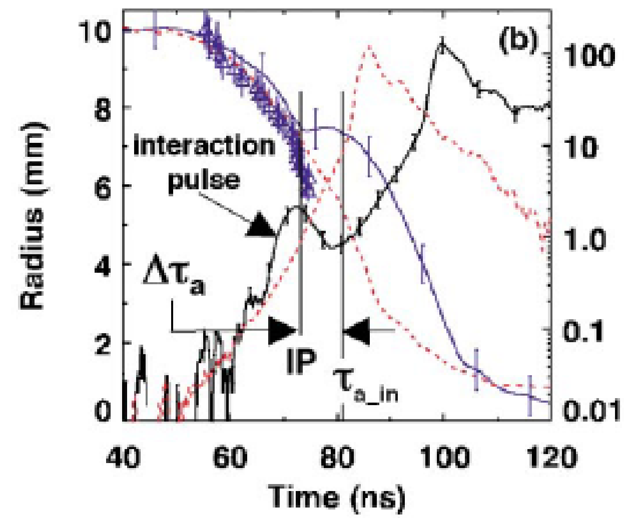
Pulse shaping is vital to z-pinch ICF concepts







- Three or more controlled x-ray pulses are required in order to heat a fusion capsule
- One suitable pre-pulse is observed as the imploding outer array of two nested arrays interacts with the inner array
- Detailed physical mechanism of the interaction pulse is not fully understood

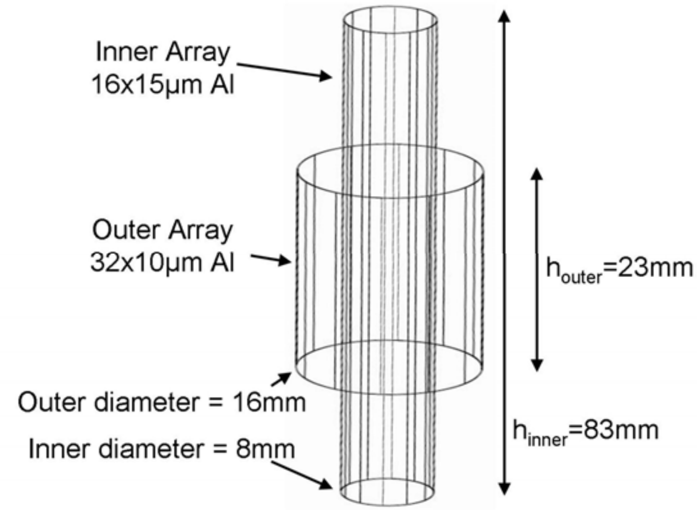
Images reproduced from
M.E. Cuneo et al. Phys Plas 13 056318, 2006

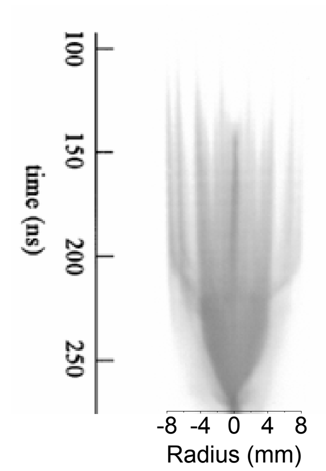
Nested wire arrays on MAGPIE use high inductance inner to suppress current through the inner array to be similar to Z

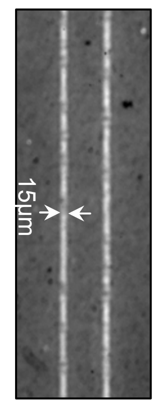
- High wire number in outer at 20MA leads to
  Inductive contrast: $L_{outer} \ll L_{inner}$

  e.g. Cuneo et al PRL 94, 225003 (2005)
- High wire number not possible at ~1MA
- Array design can give same inductive contrast
  (by lengthening inner)

  Lebedev et al. PRL 84, 1708 (2000)
- Negligible inner current confirmed by
  - Radial optical streak
  - X-pinch radiography
  - B-dot probes
- Present experiments use
  - Outer array 16-32 x 10μm Al 5056 at 16mm
  - Inner array 16 wire Al, W or CH at 8mm



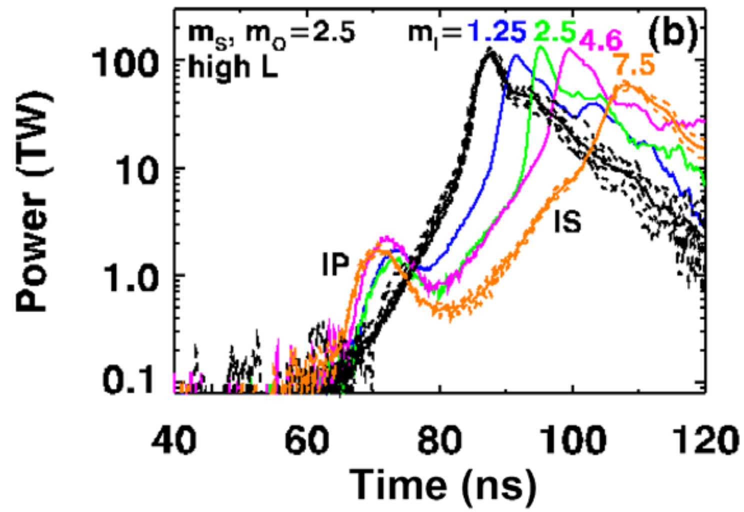




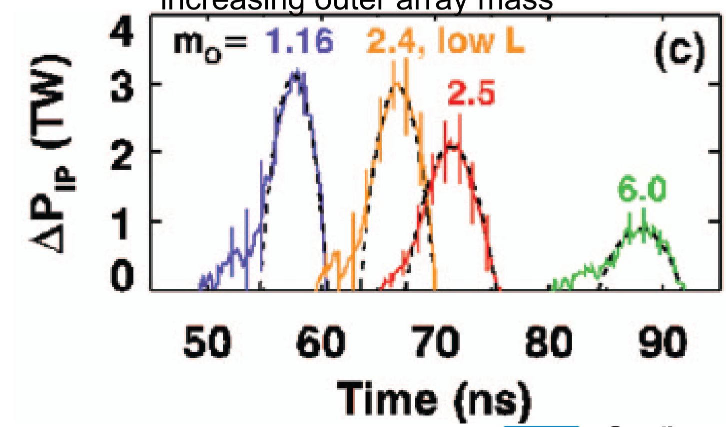
Interaction pulse on Z is critical for pulse shaping, but remains a puzzle

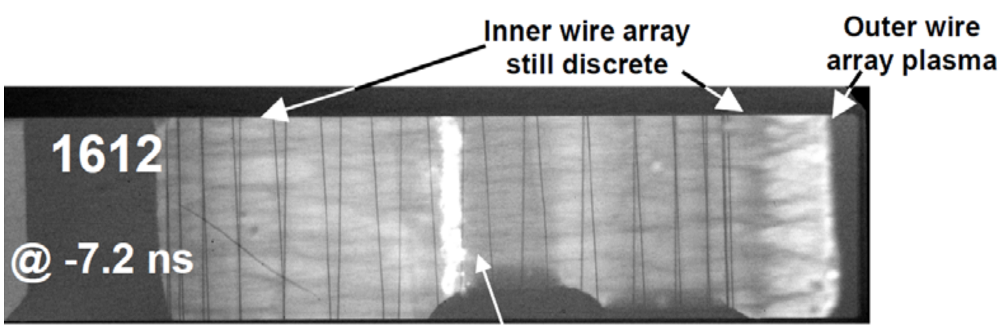
- Interaction energy measured is less than that predicted from hydrodynamic collision of outer and inner shells
- Nested arrays on Z now recognized to operate in a transparent mode
- Partial transparency cannot explain same power for different inner wire numbers
- Alternative models (e.g. ohmic heating, possibly by flux compression), do not recreate dependency on outer array mass, or explain small cores prior to interaction

Same IP. different inner wire numbers



IP power decreases with increasing outer array mass



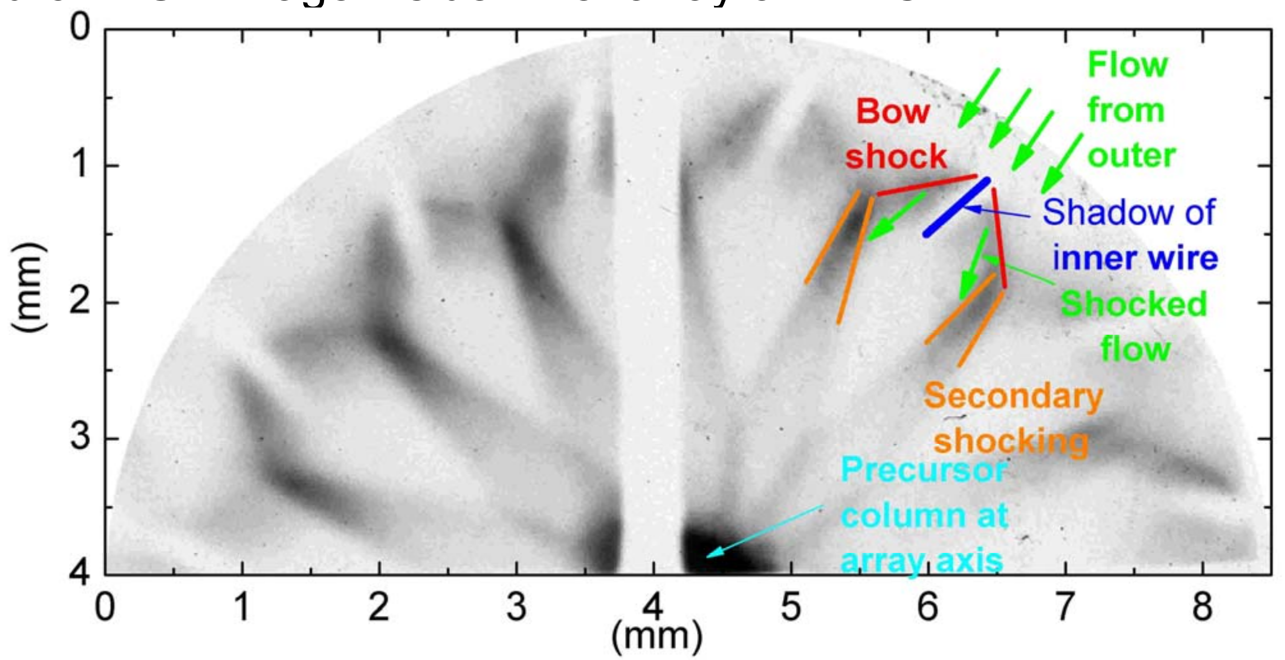


Plots reproduced from
M.E. Cuneo *et al.* Phys Plas **13**, 056318, 2006

Ablation streams from outer array are supersonic and will shock on the inner array

- Precursor plasma flows from outer are supersonic at position of inner:
  - MAGPIE (from spectra): T_e~40eV, Z~6 c_s~3cm/μs **M ~ 5**
  - Z (from MHD): T_e~25eV, Z~11 c_s~1.3cm/μs **M>11**

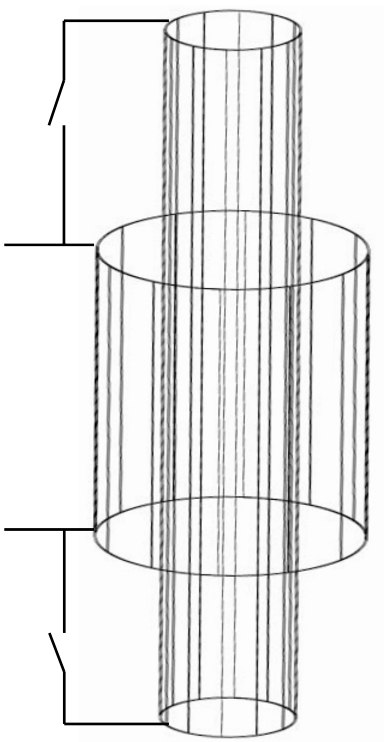
- At reaching the inner array the precursor flow will be shocked
  - end-on XUV image inside inner array on MAGPIE



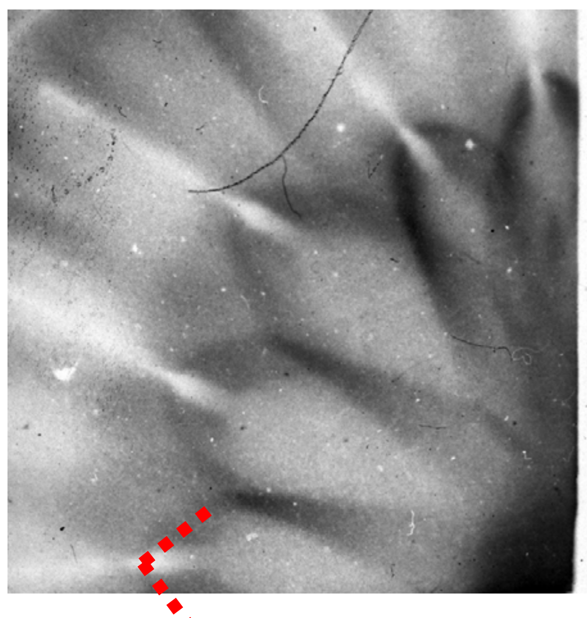
  - Define angle β as angle between initial precursor flow and shock

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

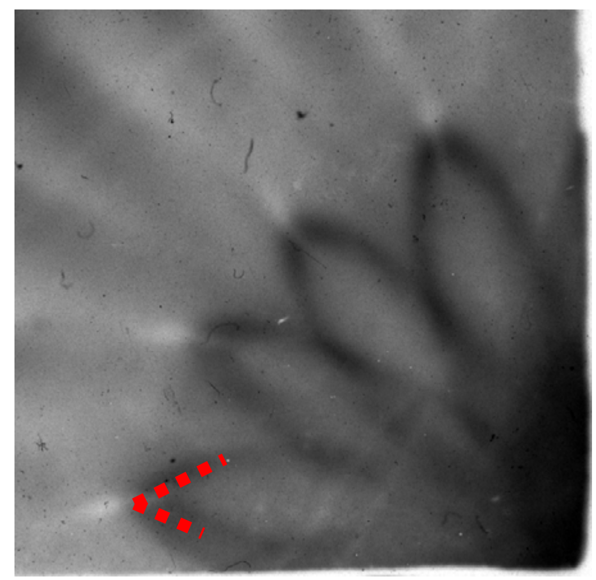
- By altering the current contact of the inner array, the weak magnetic field around each of the inner wires can be turned off
- Data shows that with this magnetic field present the opening angle of the shock is larger (~10degrees)



With field



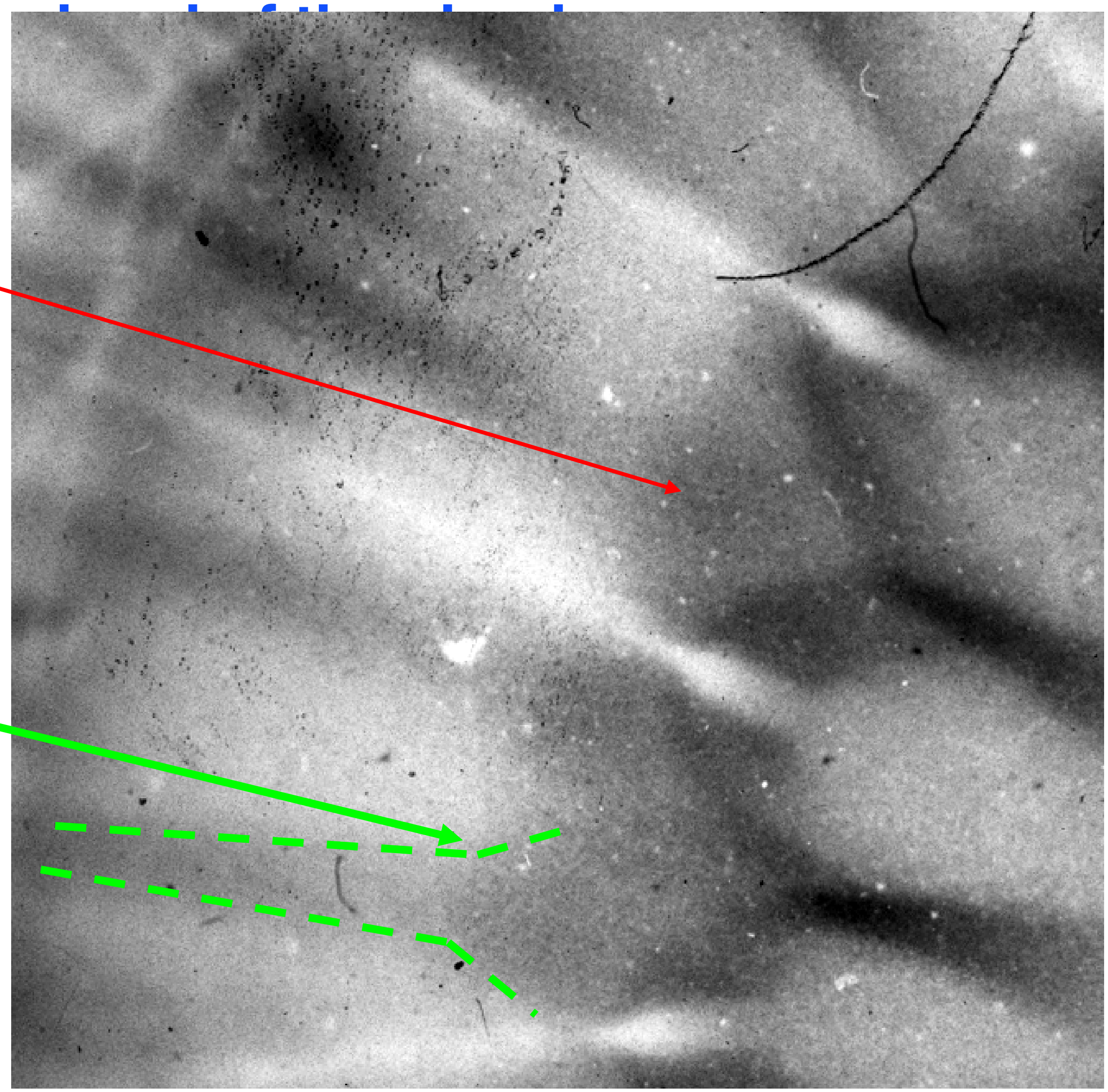
Without field



Setup with good diagnostic access demonstrates a possible radiative precursor

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

- Divergence of incoming stream consistent with preheat

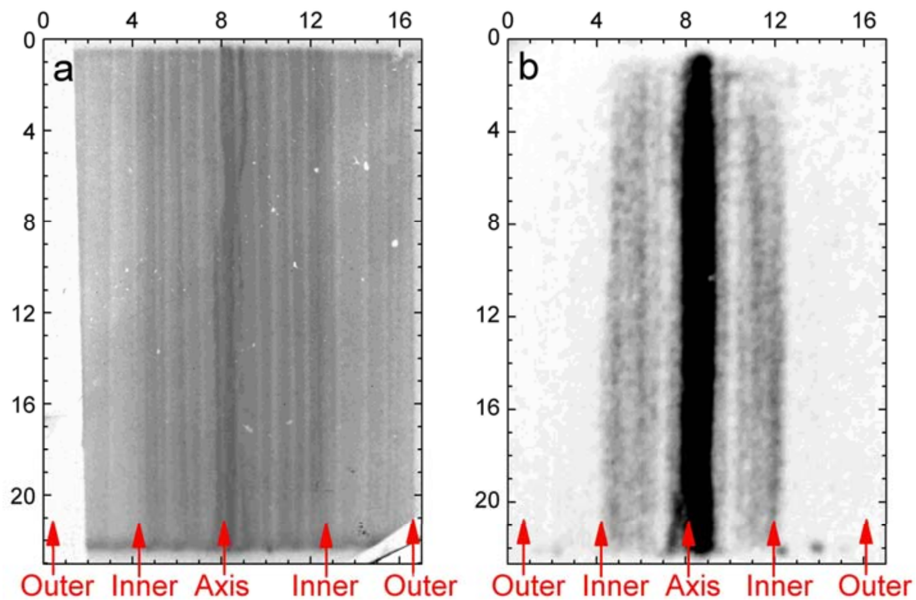


Shock will perturb plasma conditions in streams as they pass inner

- Perpendicular component of stream velocity will be reduced across shock

$$\frac{v_{\perp sh}}{v_{\perp abl}} = \frac{1}{\eta} = \frac{M_\perp^2(\gamma-1)+2}{M_\perp^2(\gamma+1)} \sim 0.14$$

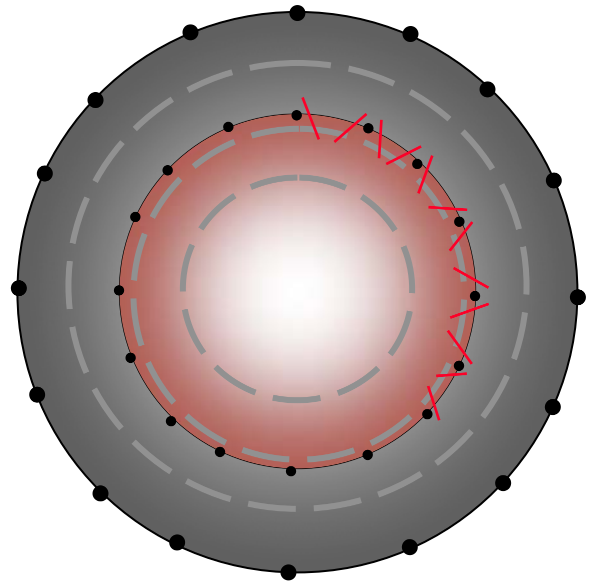
- Density will be increased by the compression ratio η
- Temperature of streams will also be increased
- Temperature and/or density jumps inferred from side-on emission imaging during ablation process
  - Definite change in plasma conditions near inner array, despite *'transparency'* :

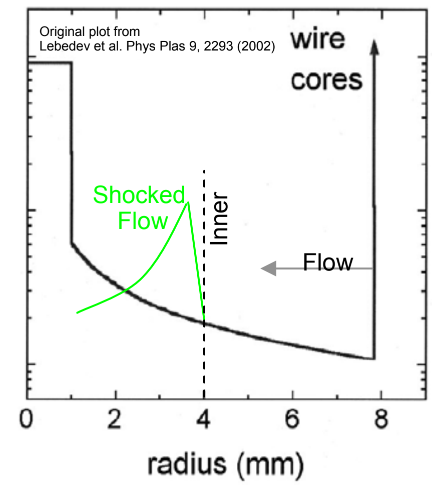


$h\nu > 30eV$ $h\nu > 220eV$

Perturbing the pre-fill will affect the snowplow

- For single array snowplow of pre-fill by implosion results in emission
- Power radiated by snowplow emission is
  - $P_{SP} \propto \rho(r,t)\,(v_{piston} - v_{prefill})^3$
- Comparing nested with single, ρ and $v_{prefill}$ both altered by jump conditions
- Modifications act to enhance snowplow emission.
- Can adapt a snowplow model to incorporate these jumps





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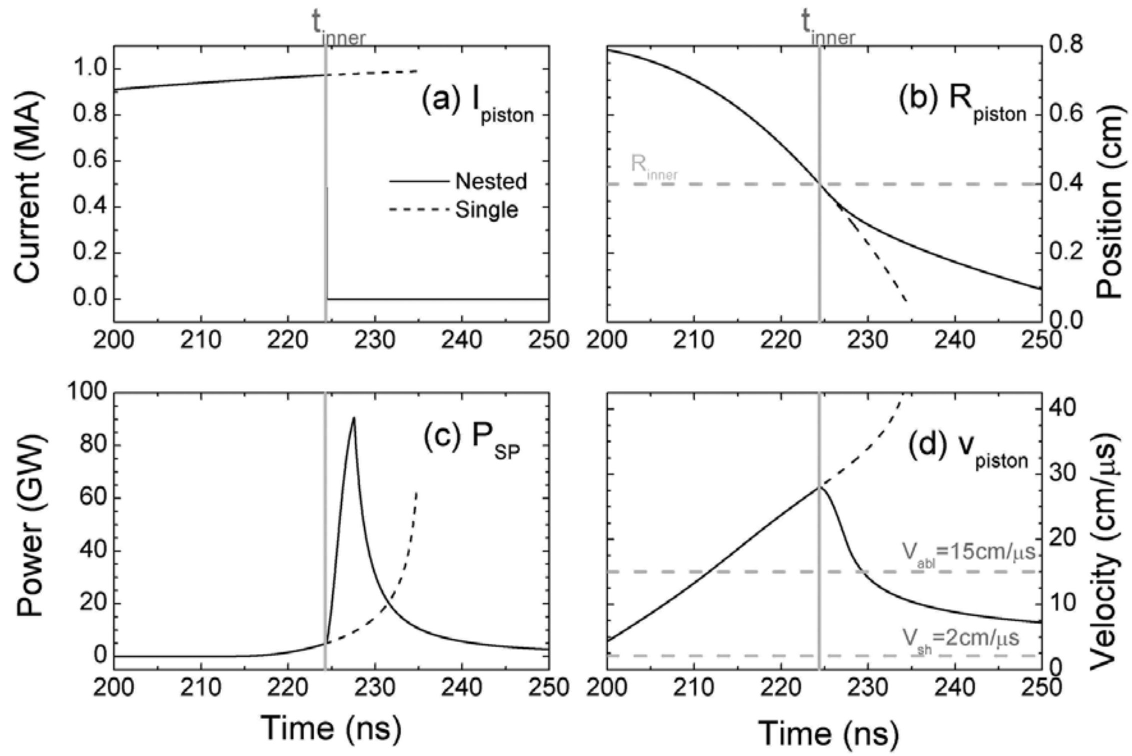
Snowplow model for perturbed system predicts enhanced emission above that of a single array

Variable	MAGPIE	
$v_{\rm abl}(cm/\mu s)$ [1, 2]	15	(Ablation velocity)
$c_s(cm/\mu s)$ [2–4]	3	(Sound speed)
β (end-on image)	39°	(Shock angle)
γ [5]	1.1	(Adiabatic index)
$M_\perp = \frac{v_a sin(\beta)}{c_s}$	3.4	(Mach numb perp)
$\eta = \frac{v_{\rm abl}}{v_{\rm sh}}$	7.7	(Compression)

[1] S. V. Lebedev et al., Plas. Phys. Contr. Fus. 47, A91 (2005).
[3] S. V. Lebedev et al., Laser Particle Beams 19, 355 (2001).
[4] J. P. Chittenden et al., Phys. Plasmas 8, 675 (2001).
[5] R. P. Drake, High Energy Density Physics (Springer, 2006).

Model setup
- Ablation model for fill
- Jump conditions at inner
- Snowplow model for implosion trajectory



Results of model
- Snowplow model shows excess emission despite current being switched out of piston prior to experiencing perturbed density
- Excess emission is AFTER piston passes inner wires (in shocked region)
- Experiments show that piston slows below ablation velocity, despite 100% transparency
- Averaging emission over total MAGPIE array smoothes out interaction pulse due to azimuthal and axial non-uniformities

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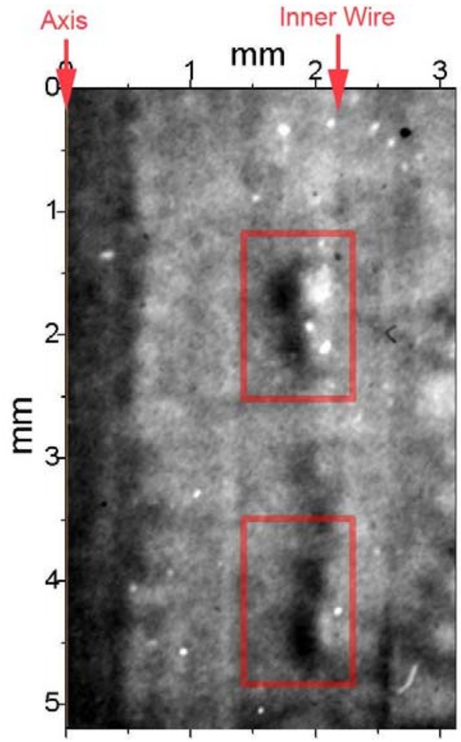

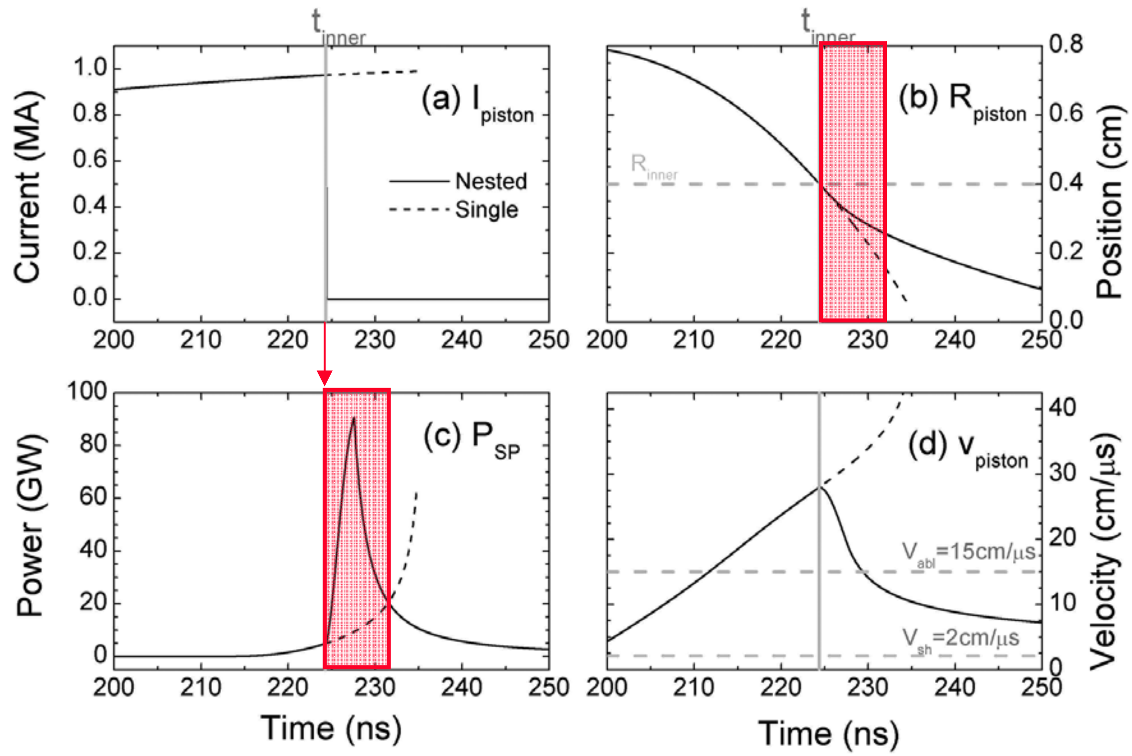

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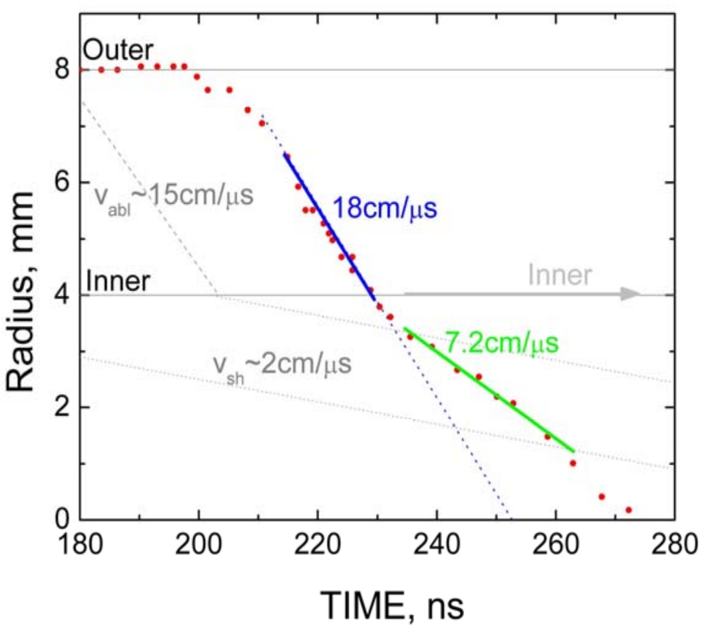

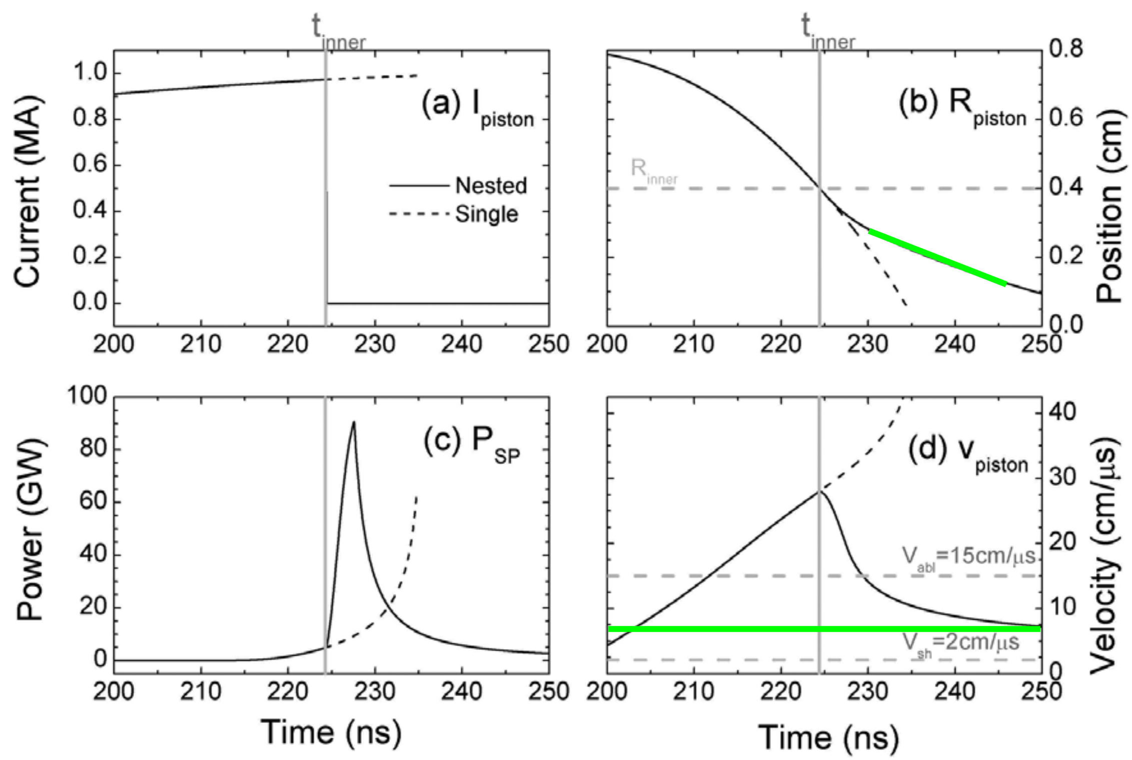

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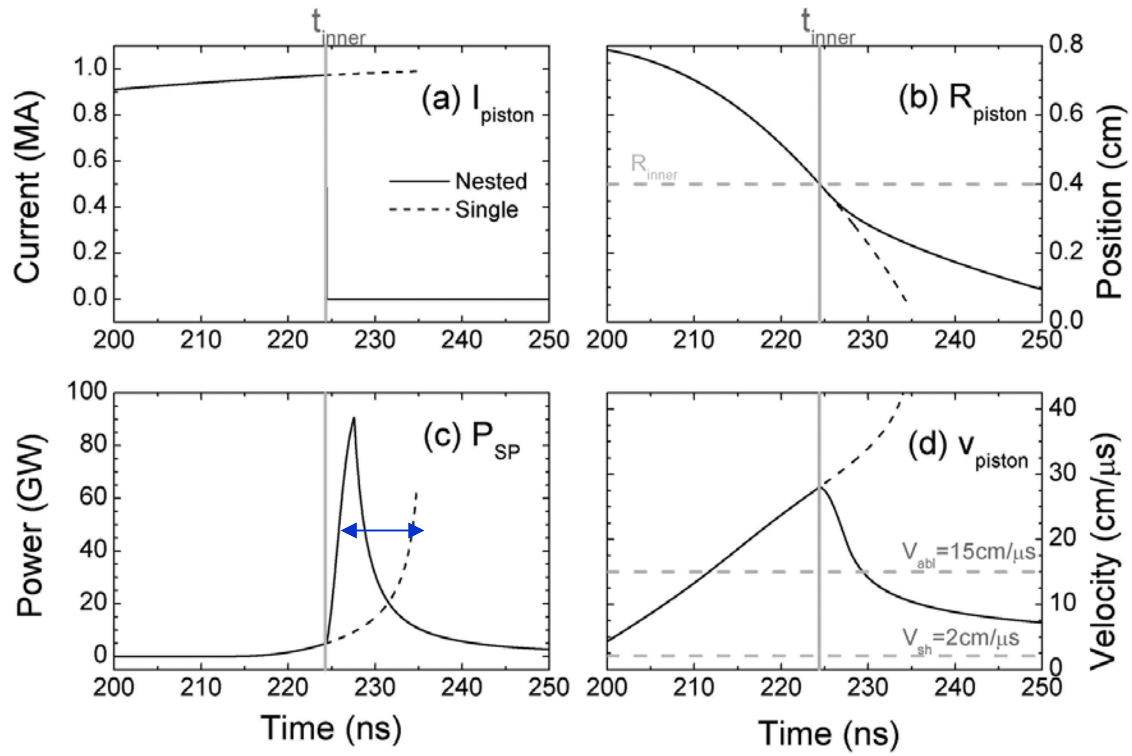

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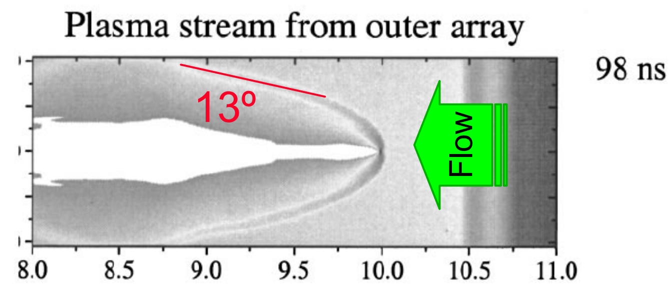
Applying similar model to a (more uniform) Z implosion allows a comparison of powers

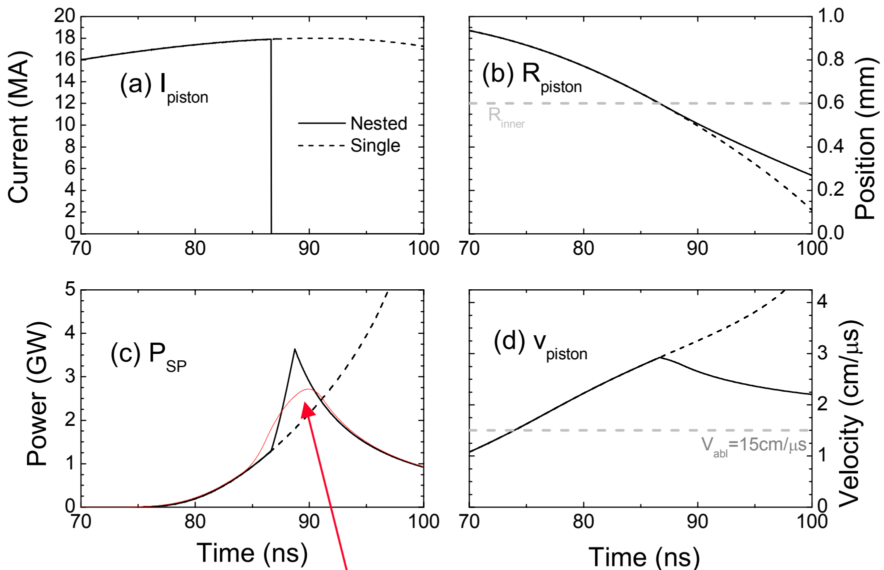
Variable	MAGPIE	Z-6mg
$v_{\rm abl}(cm/\mu s)$ [1, 2]	15	15
$c_s(cm/\mu s)$ [2–4]	3	1.3
β (end-on image)	39° →	5°
γ [5]	1.1	1.1
$M_\perp = \frac{v_a sin(\beta)}{c_s}$	3.4	1.25
$\eta = \frac{v_{\rm abl}}{v_{\rm sh}}$	7.7	1.5

Shock angle smaller in sims of Z than measured on MAGPIE

Chittenden *et al.* Phys Plas **8**, 675 (2001)



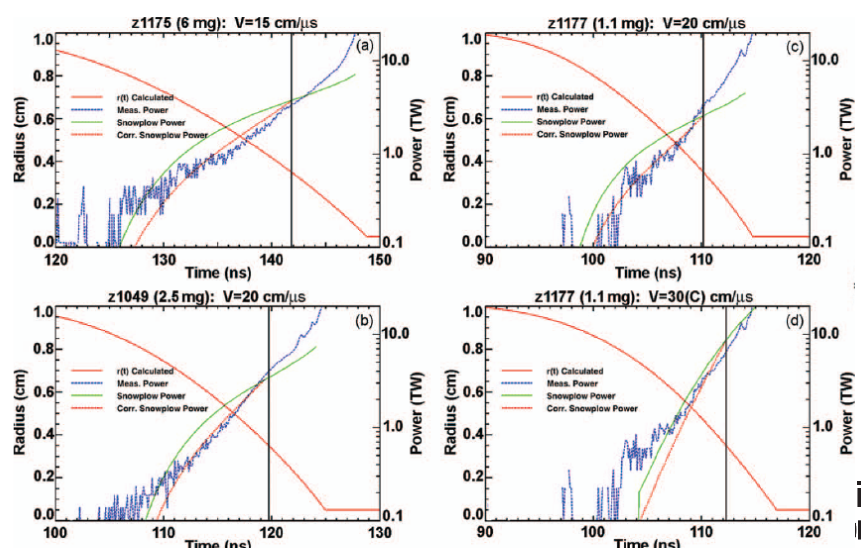
- Unclear whether MHD best tool for this problem
- Further simulations planned by Ciardi & Sherlock using hybrid code



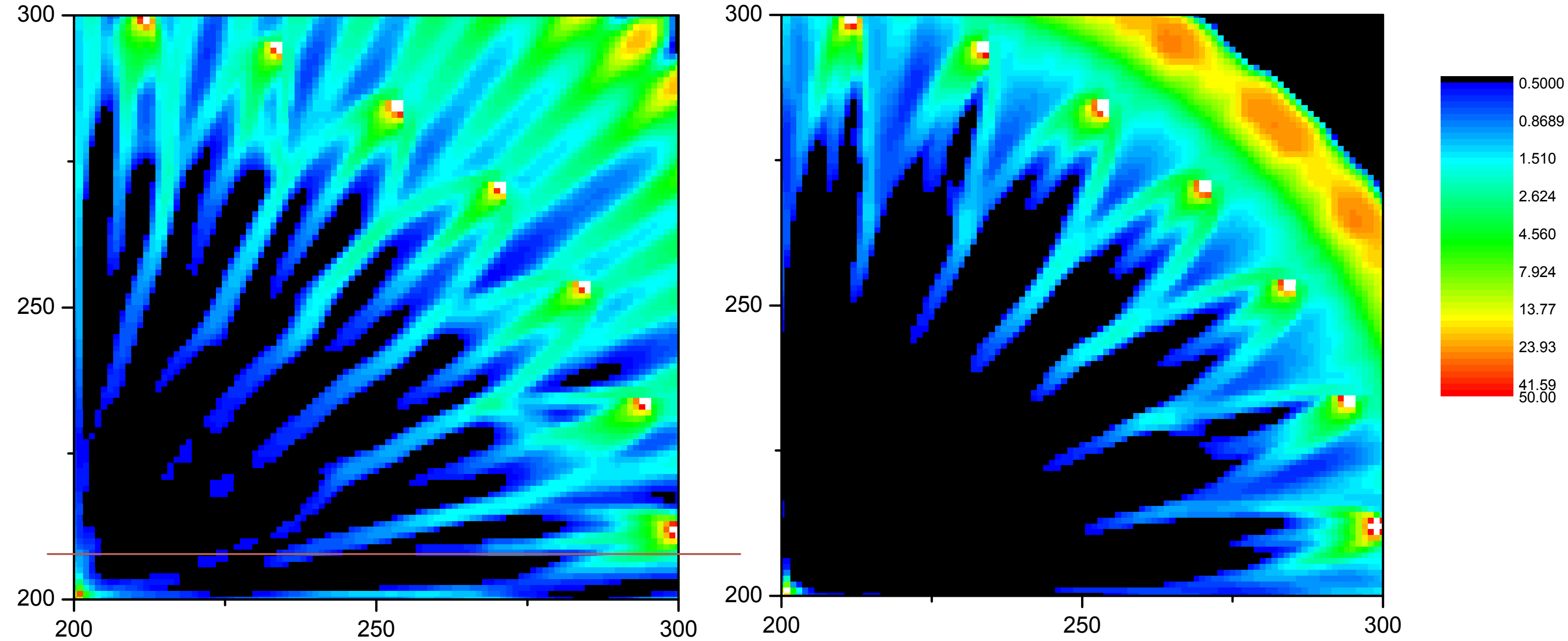
Temporally spread to account for experimentally measured width of piston

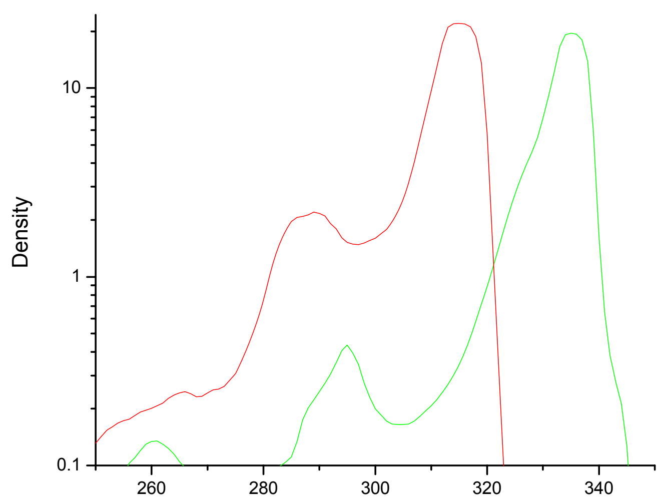
Snowplow for 6mg outer on Z gives good fit for v_{abl}

Sinars *et al.* Phys Plas **13**, 042704 (2006)



MHD simulations show formation of shocks for Z compact arrays, with correct jumps





Simulations show static shocks near inner wires

Jump in density profile of ~x2

Snowplow will see this jump during implosion

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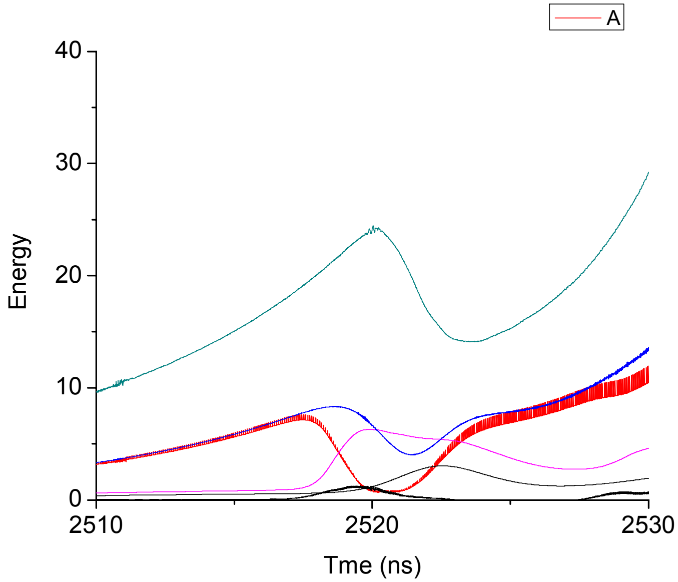
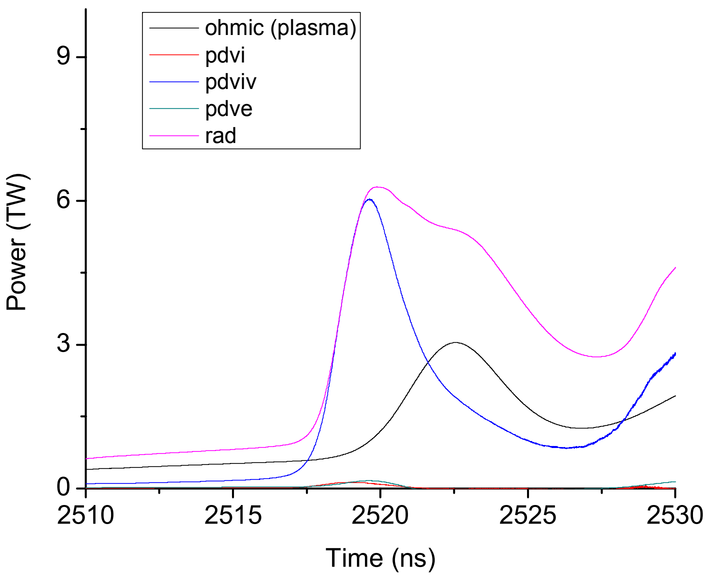
Energy balance indicates viscous work from snowplow of shocked inner is responsible for most of interaction pulse





Simulations track different contributions to emitted power

Results indicate that viscous emission from outer array snowplowing shocked outer array material is responsible for most of the interaction pulse

Snowplow model recreates interaction pulse for Z outer array mass scan

Variable	MAGPIE	Z-6mg	Z-2.5mg	Z-1.1mg	Z-1.1mg
$v_{\rm abl}(cm/\mu s)$ [1, 2]	15	15	20	30	25
$c_s(cm/\mu s)$ [2–4]	3	1.3	1.3	1.3	1.3
β (end-on image)	39°	5°	5°	5°	5°
γ [5]	1.1	1.1	1.1	1.1	1.1
$M_\perp = \frac{v_a sin(\beta)}{c_s}$	3.4	1.25	1.66	2.5	2.0
$\eta = \frac{v_{\rm abl}}{v_{\rm sh}}$	7.7	1.5	2.5	5.0	3.7
$E_{\rm Sp}(kJ)$	-	3.0	12.4	22.5	15.3
$E_{\rm Exp}(kJ)$ [6]	-	5.2	12.1	15.0	15.0
$P_{\rm Sp}(TW)$	-	0.7	2.8	5.1	3.5
$P_{\rm Exp}(TW)$ [6]	-	1.2	2.2	3.2	3.2

Variable ablation velocity
Sinars *et al.* Phys Plas **13**, 042704 (2006)

[1] S. V. Lebedev et al., Plas. Phys. Contr. Fus. 47, A91 (2005).
[2] D. B. Sinars et al., Phys. Plasmas 13, 042704 (2006).
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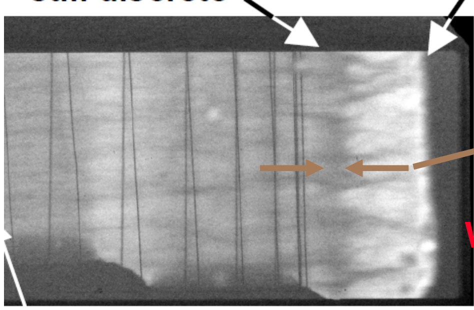
[6] M. E. Cuneo et al., Phys. Plasmas 13, 056318 (2006).

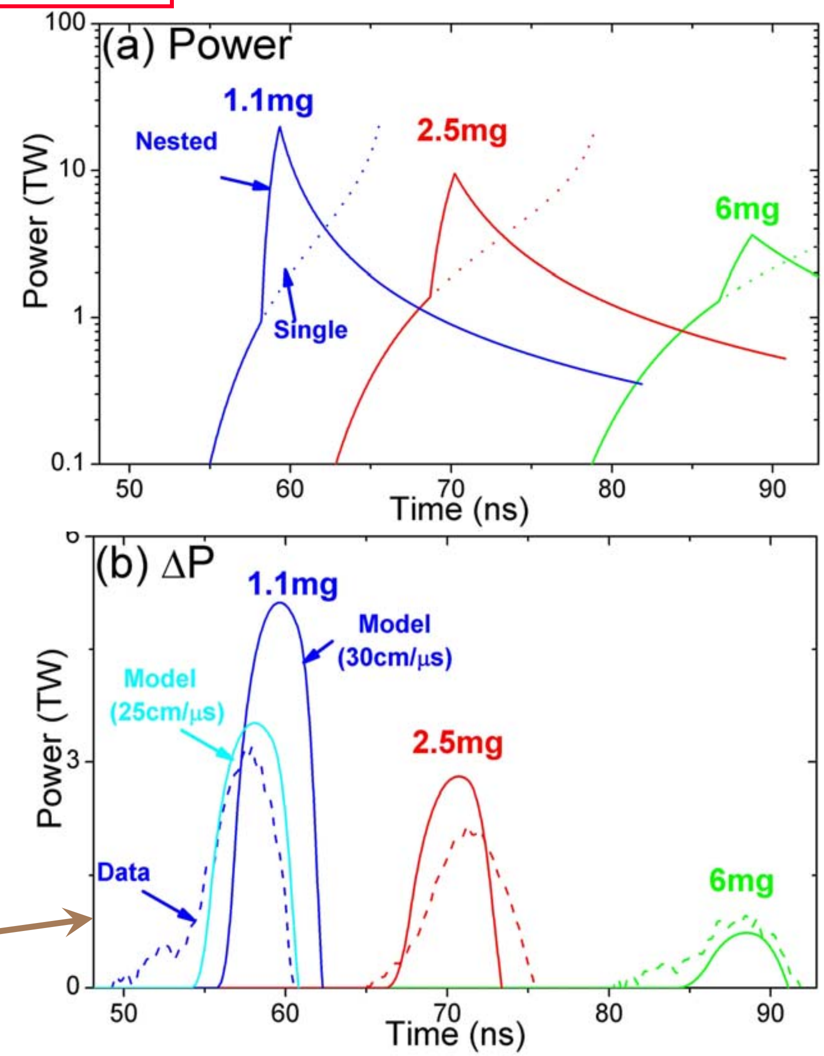
Inner wire array still discrete

Outer wire array plasma



Experimental images indicate finite thickness to piston

$\Delta P = \{P_{nest} - P_{single}\}_{smoothed}$



Within available parameters can get correct interaction pulses
More work needed to constrain things

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Summary : Perturbed snowplow can lead to observed Interaction Pulse

- Inner array shocks precursor plasma streams on MAGPIE
- Shock will alter *ρ, T, v* of the streams
- This jump is likely to alter the snowplow emission as the outer array implodes
- For Z conditions this change in snowplow radiation can be comparable to the observed interaction pulse
- Able to recreate correct outer mass dependency
- Future plans include analytics, simulations and experiments to better determine correct angle β for W arrays on Z
- To increase interaction pulse would need to increase implosion velocity or minimize field within the array