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MAGPIE
Centre of Excellence in High Energy Plasma Physics

Pulse shaping techniques with nested wire arrays

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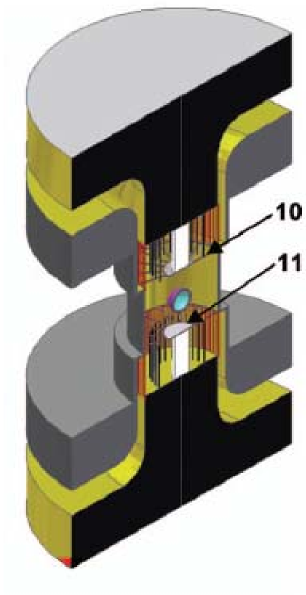
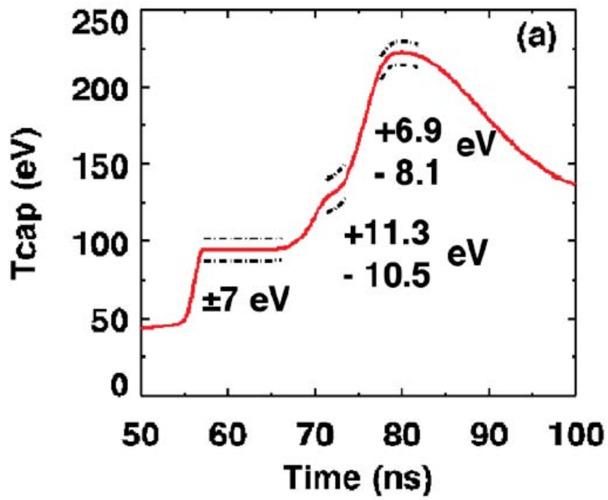
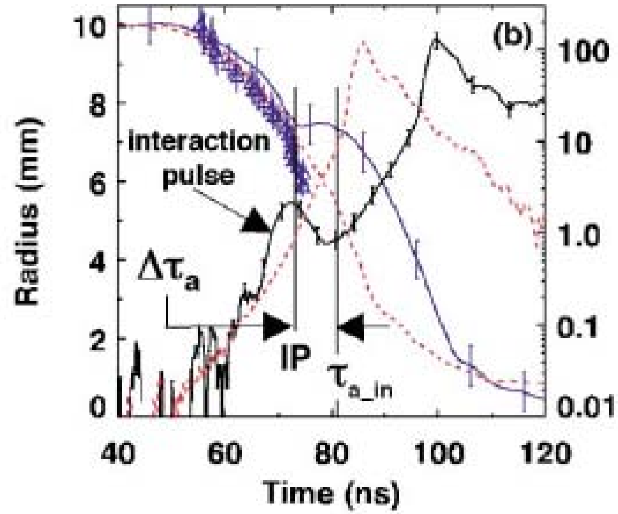
Pulse shaping is vital to z-pinch ICF concepts







- 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, however detailed physical mechanism of the interaction pulse is not fully understood
- Necessary to broaden main pulse (and interaction pulse)
  - nested arrays on Z are *too good* at temporal compression
- Gaining energy in the main pulse useful for both ICF and RES

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

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This talk will use MAGPIE data to help understand / interpret Z data

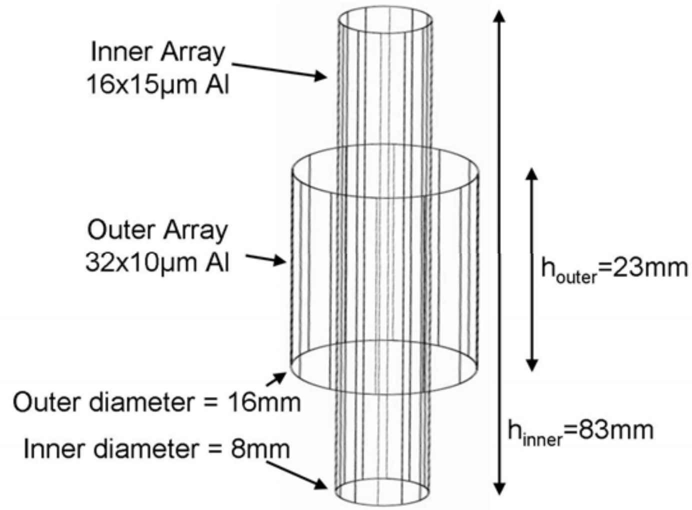
Aims:

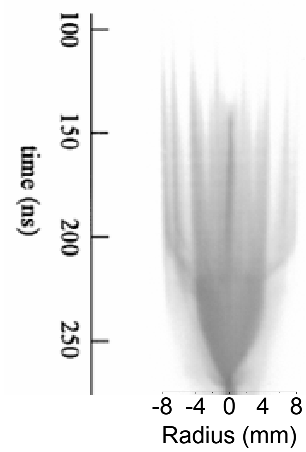
- Understand our present pulse shaping capability
  - New understanding of mechanism possibly responsible for interaction pulse
- New tools in the pulse-shaping toolbox
  - Look at what conical nested can bring to pulse shaping
- Measures that might increase efficiency of arrays
  - Discuss planned experiments to study elimination of cathode bubble
  - Possible applications to RES, Vacuum & Dynamic Hohlraum

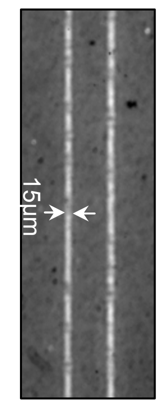
1MA experiments can be used to understand 20MA experiments if careful consideration given to getting appropriate setup and being aware of differences

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



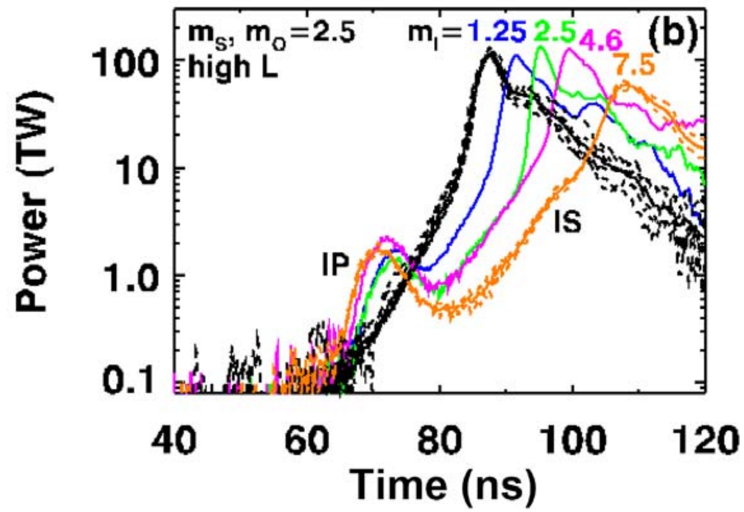




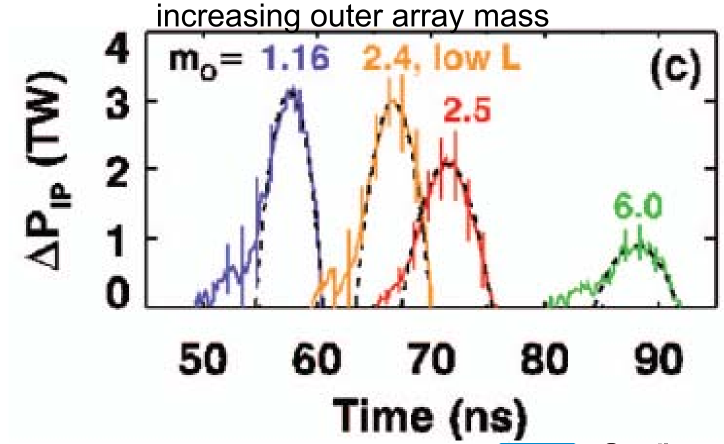
Interaction pulse on Z is critical for pulse shaping, but remains a puzzle

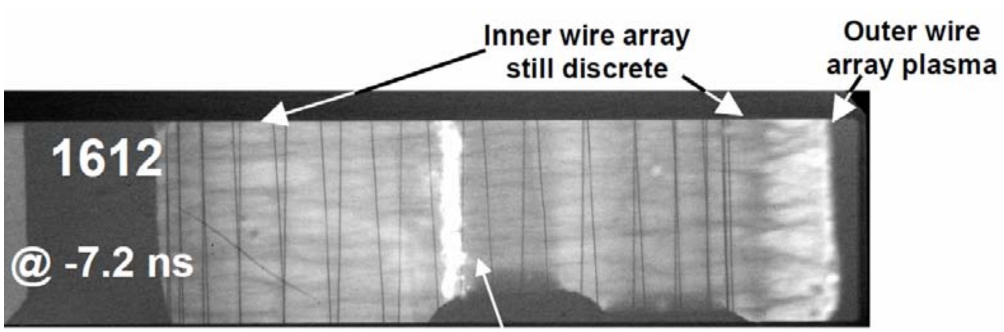
- Interaction energy measured is less than that predicted from hydrodynamic collision of outer and inner shells
- Nested arrays on Z now recognized to operate in a transparent mode
- Partial transparency cannot explain same power for different inner wire numbers
- Alternative models (e.g. ohmic heating, 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

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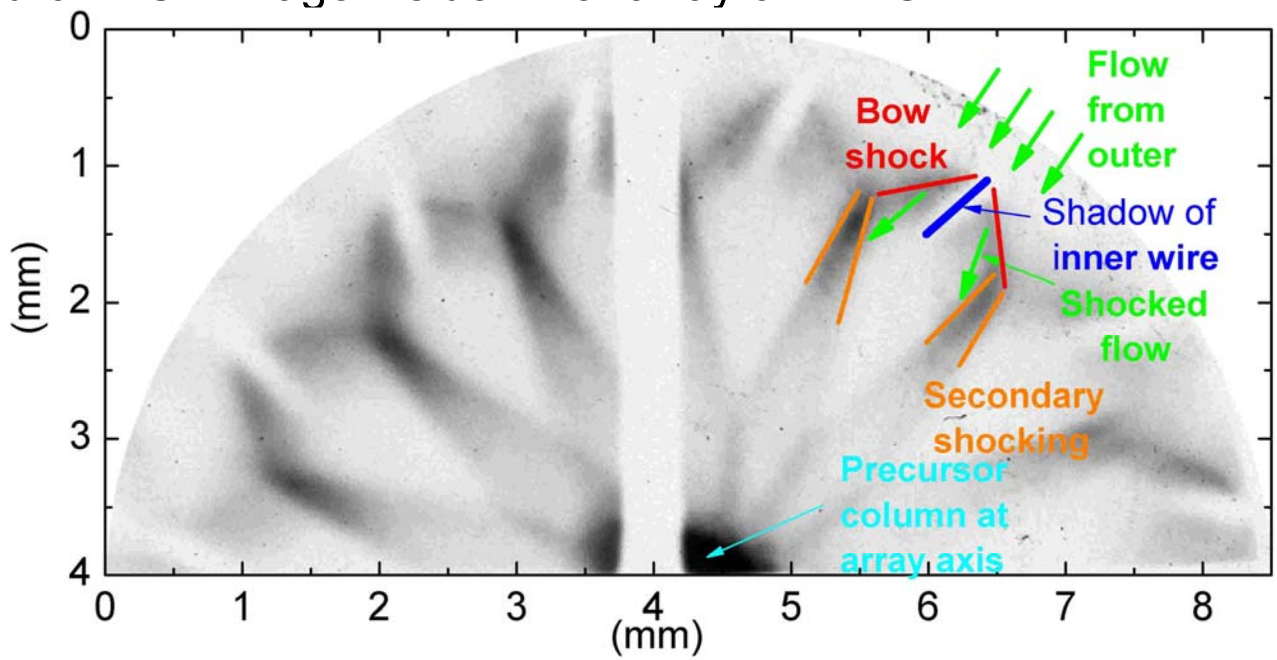
Ablation streams from outer array are supersonic and will shock on the inner array

- 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



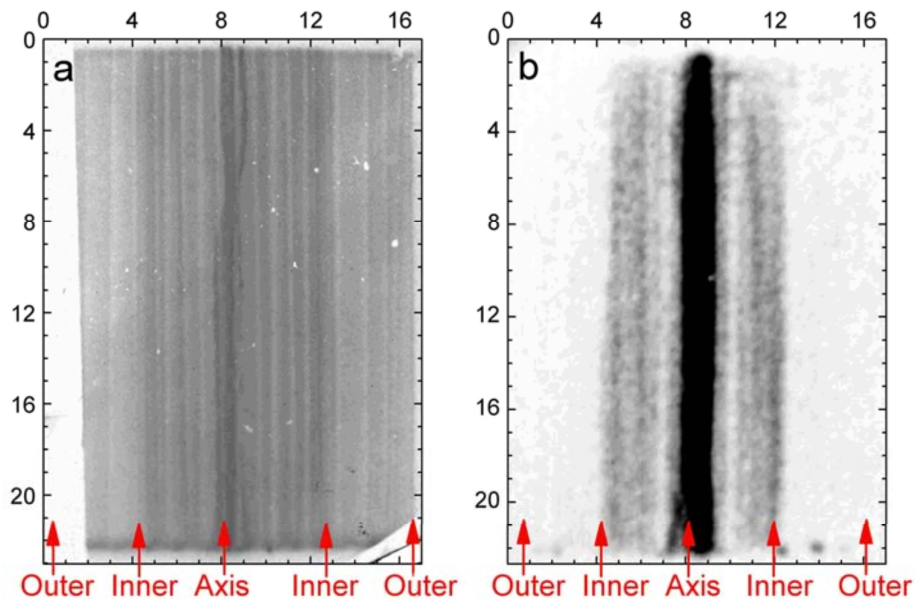
  - Define angle β as angle between initial precursor flow and shock

Shock will perturb plasma conditions in streams as they pass inner

- Perpendicular component of stream velocity will be reduced across shock

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

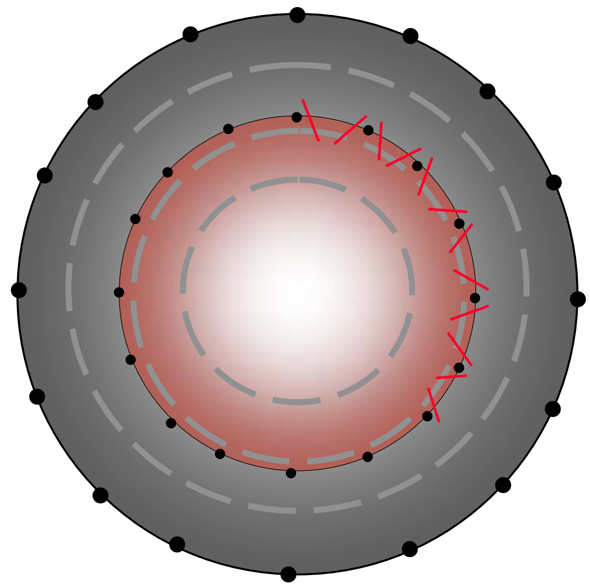
- Density will be increased by the compression ratio η
- Temperature of streams will also be increased
- Temperature and/or density jumps inferred from side-on emission imaging during ablation process
  - Definite change in plasma conditions near inner array, despite *'transparency'* :

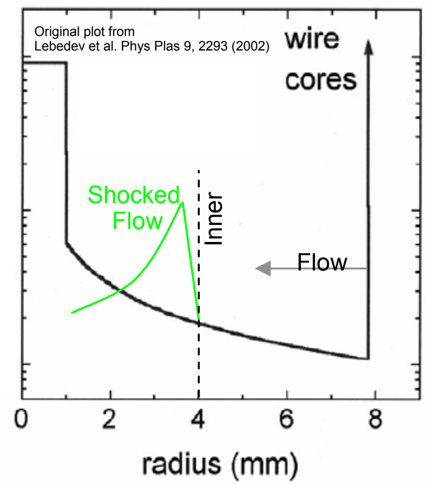


$h\nu > 30eV$ $\quad$ $h\nu > 220eV$

Perturbing the pre-fill will effect 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

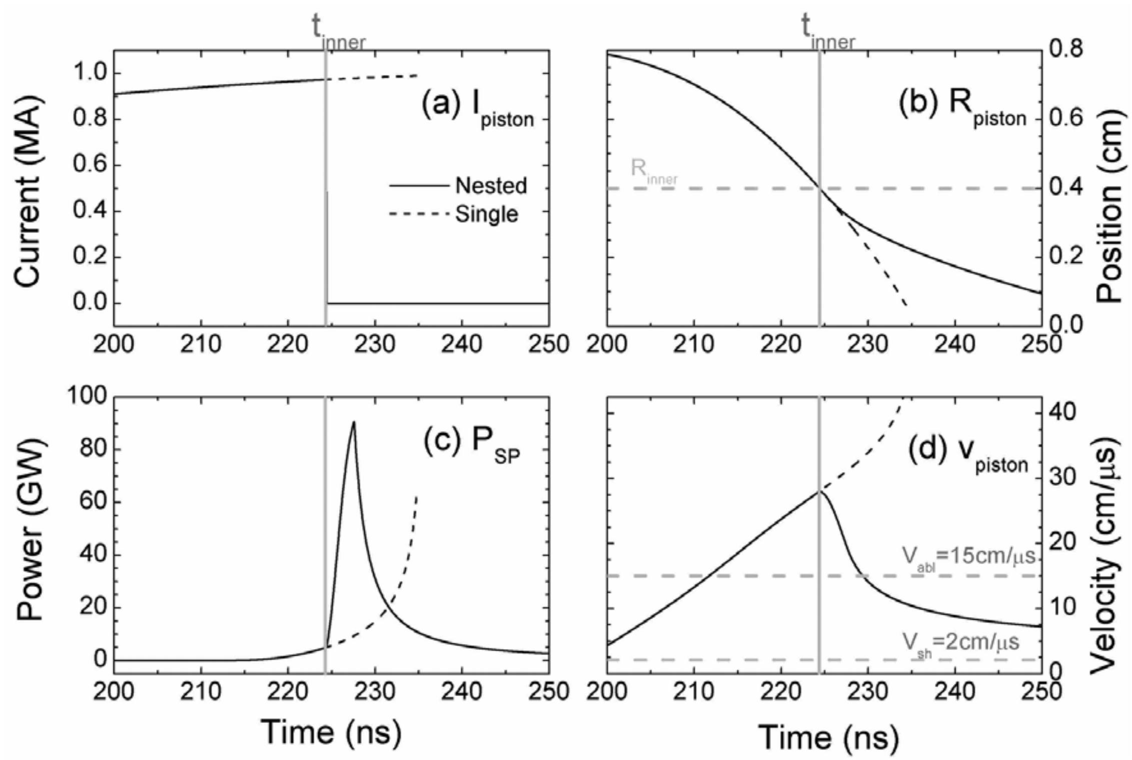




Snowplow model for perturbed system predicts enhanced emission above that of a single array

Variable	MAGPIE	
$v_{\mathrm{abl}}(cm/\mu s)$ [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)
$\eta = \frac{v_{\mathrm{abl}}}{v_{\mathrm{sh}}}$	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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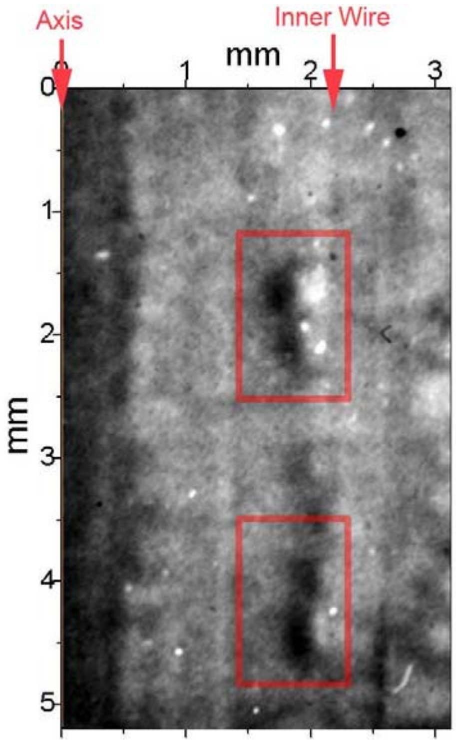

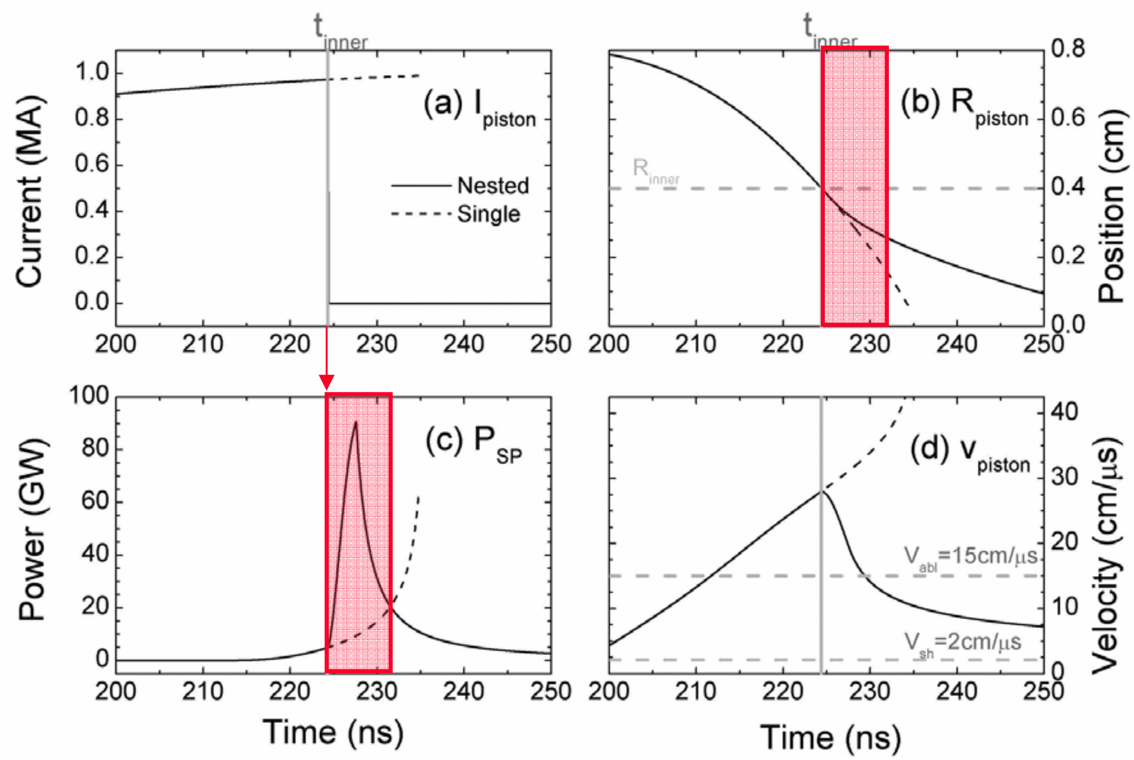

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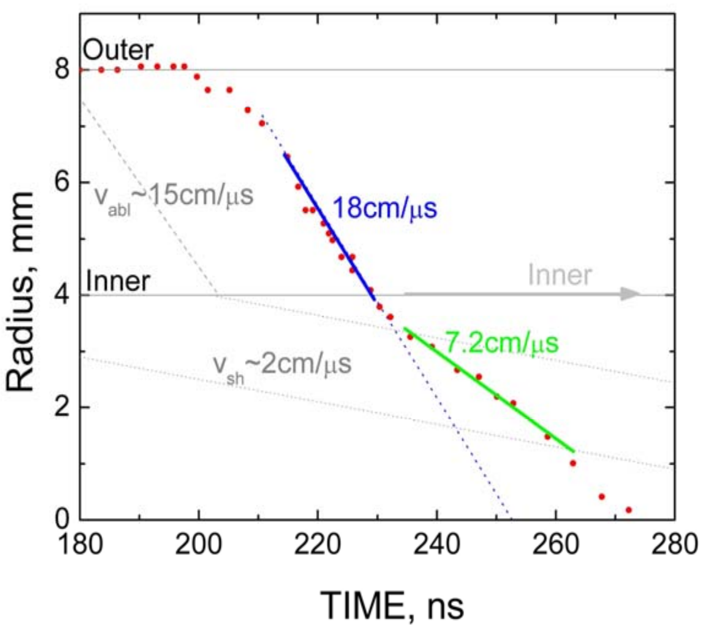

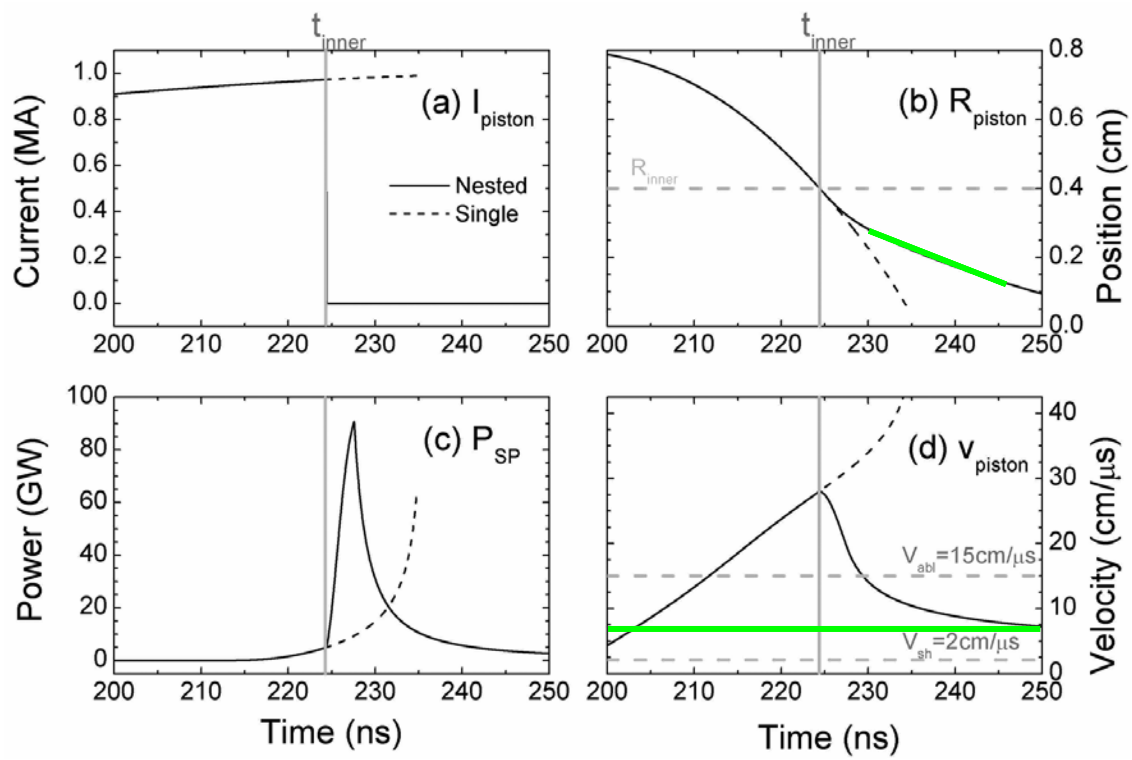

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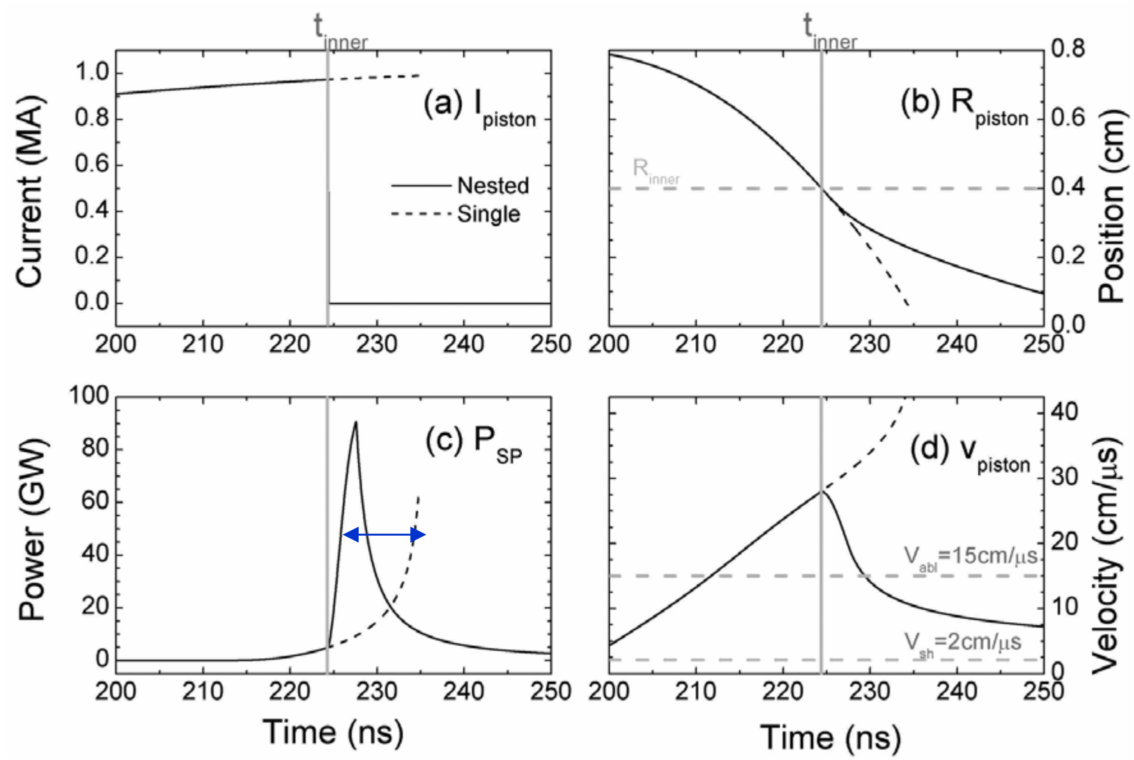

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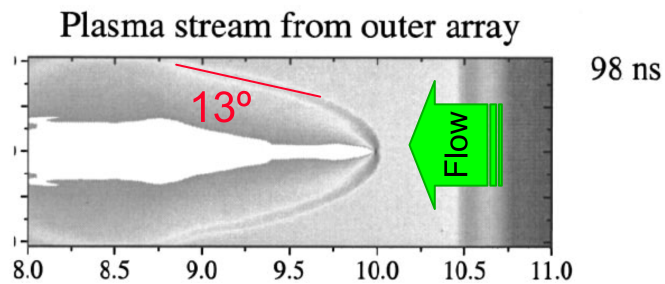
Applying similar model to a (more uniform) Z implosion allows a comparison of powers

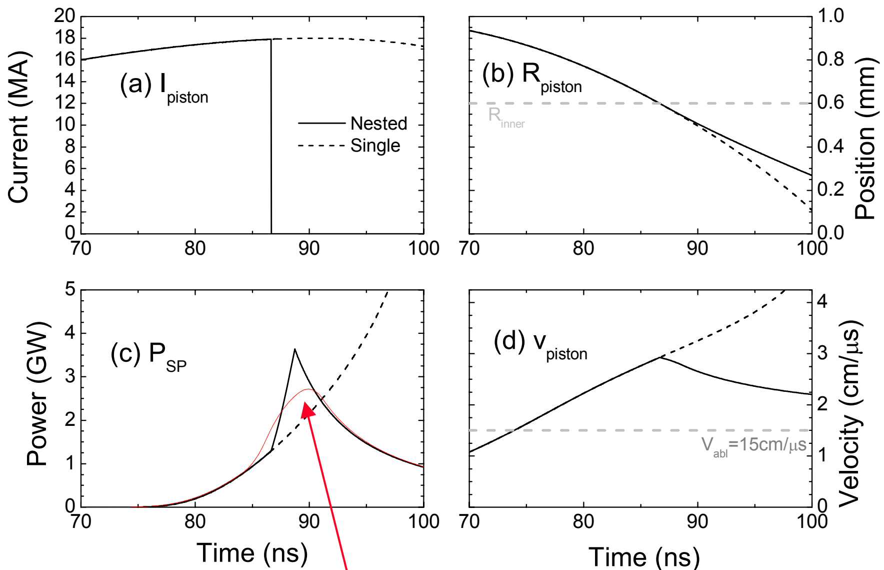
Variable	MAGPIE	Z-6mg
$v_{abl}(cm/\mu s)$ [1, 2]	15	15
$c_s(cm/\mu s)$ [2–4]	3	1.3
β (end-on image)	39° →	5°
γ [5]	1.1	1.1
$M_\perp = \frac{v_a sin(\beta)}{c_s}$	3.4	1.25
$\eta = \frac{v_{abl}}{v_{sh}}$	7.7	1.5

Shock angle smaller in sims of Z than measured on MAGPIE

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



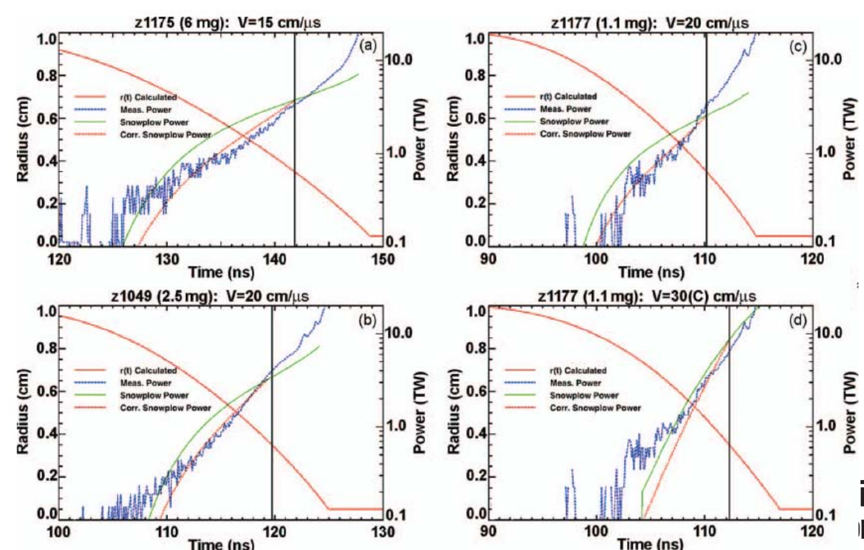
- Unclear whether MHD best tool for this problem
- Further simulations planned by Ciardi & Sherlock using hybrid code



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)



Snowplow model recreates interaction pulse for Z outer array mass scan

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

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

?

[1] S. V. Lebedev et al., Plas. Phys. Contr. Fus. 47, A91 (2005).
[2] D. B. Sinars et al., Phys. Plasmas 13, 042704 (2006).
[3] S. V. Lebedev et al., Laser Particle Beams 19, 355 (2001).
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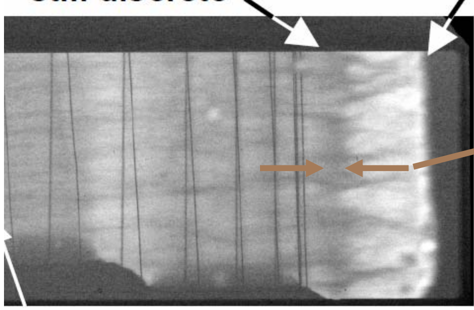
[5] R. P. Drake, High Energy Density Physics (Springer, 2006).
[6] M. E. Cuneo et al., Phys. Plasmas 13, 056318 (2006).

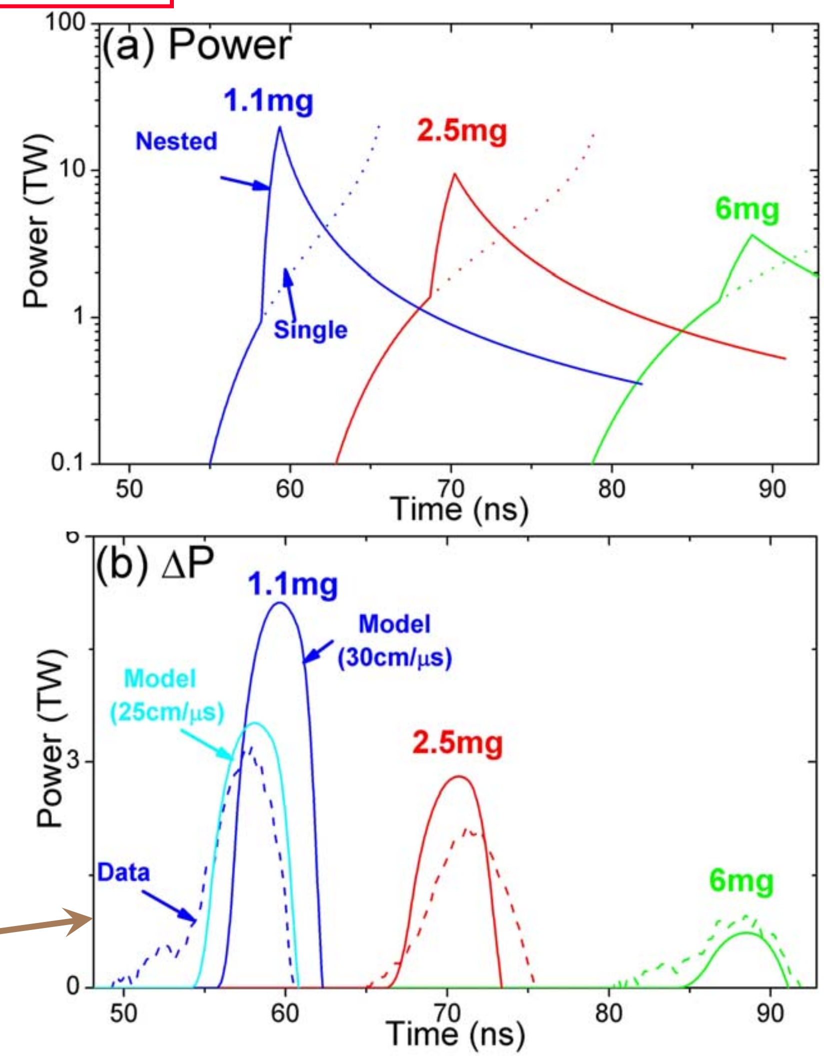
Inner wire array still discrete

Outer wire array plasma



Experimental images indicate finite thickness to piston

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



Using an angle β more like MAGPIE or MHD would increase powers predicted, but reduce mass dependence

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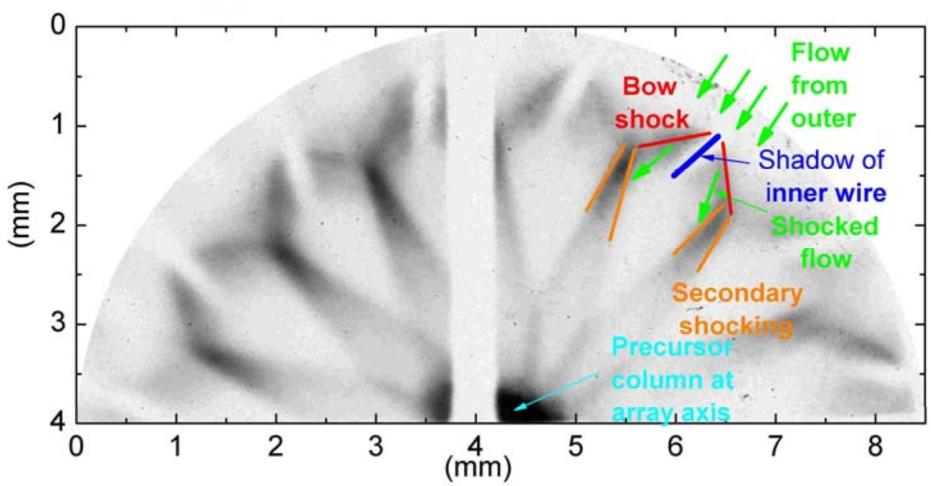
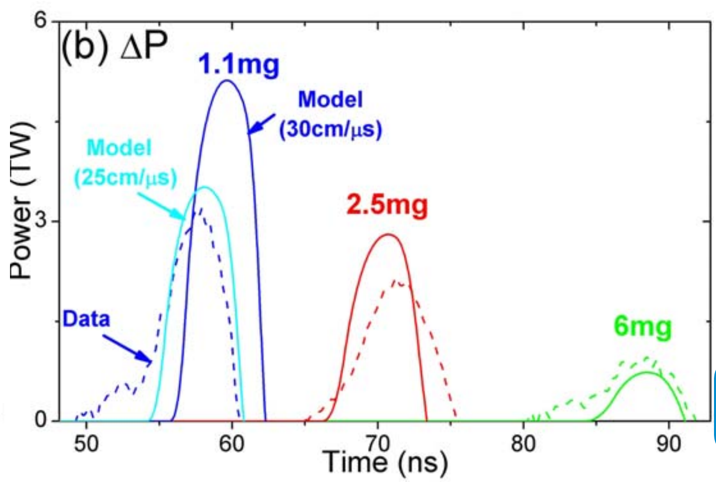
Part 1 Summary : Perturbed snowplow can lead to observed Interaction Pulse

- 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

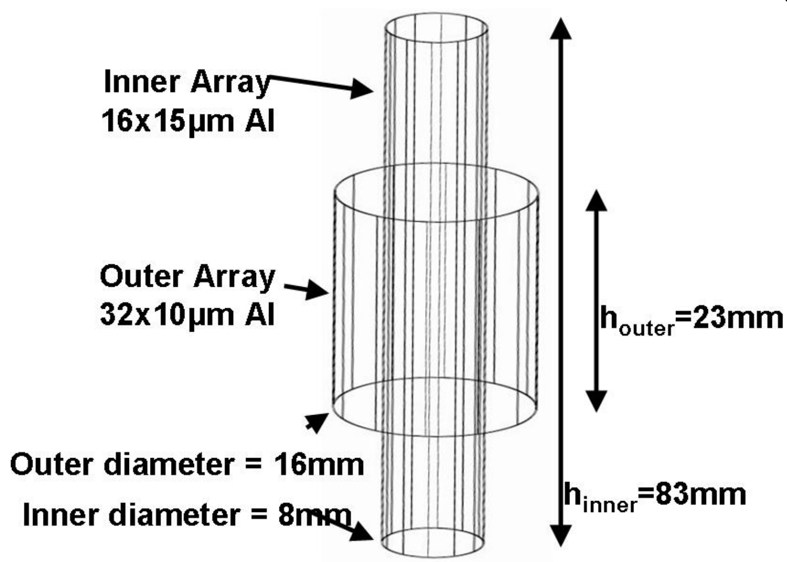


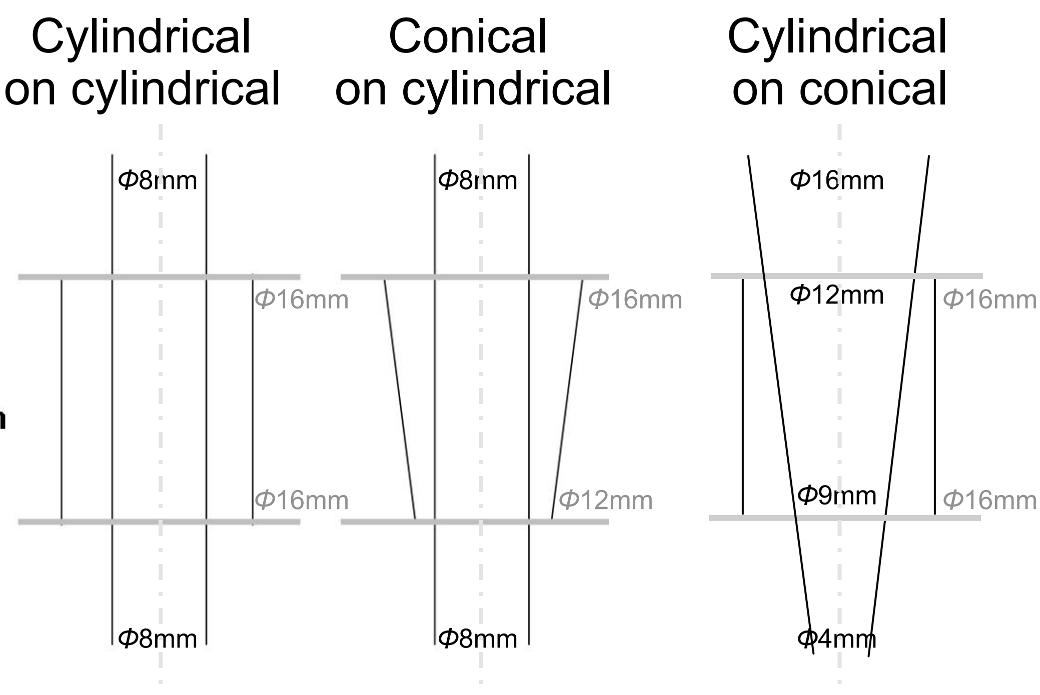


Part 2: Conical nested

- One suggested technique to lengthen the main pulse from nested arrays is to seed a zipper using conical arrays
  c.f. zipper observed in gas puff experiments

- Two modified setups tested on both MAGPIE and Z





Use of a conical outer array will alter mass ablation rate

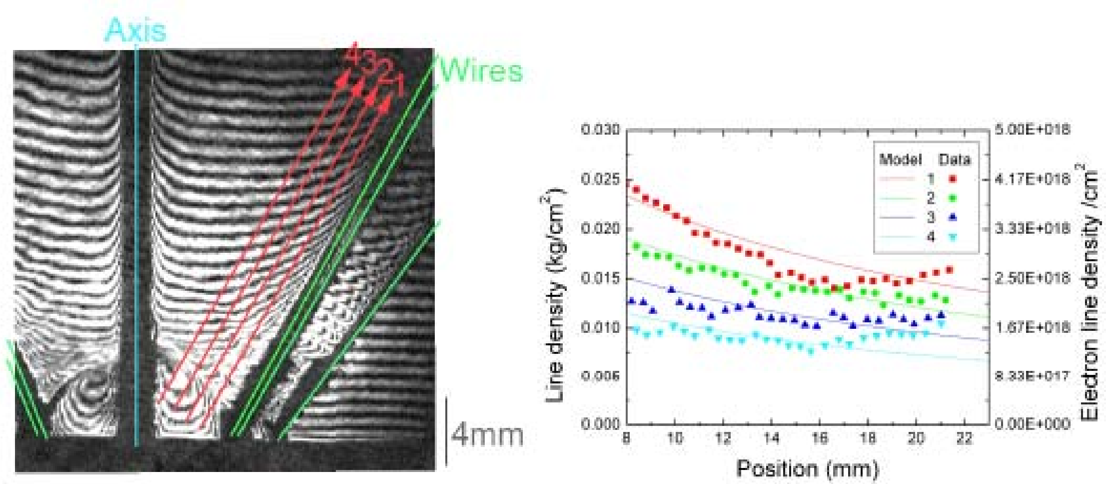
- With conical outer array the global field strength is varied along the length of the wire

$$B(z,t) = \frac{\mu_0 I(t)}{2\pi R(z)} = \frac{\mu_0 I(t)}{2\pi(R_0 + z\tan(\alpha))}$$

- Variation in global field alters mass ablation (due to fixed v_{abl})

$$\dot{m} = \frac{\mu_0 I(t)}{2\pi V_{abl}(R_0 + z tan(\alpha))}$$

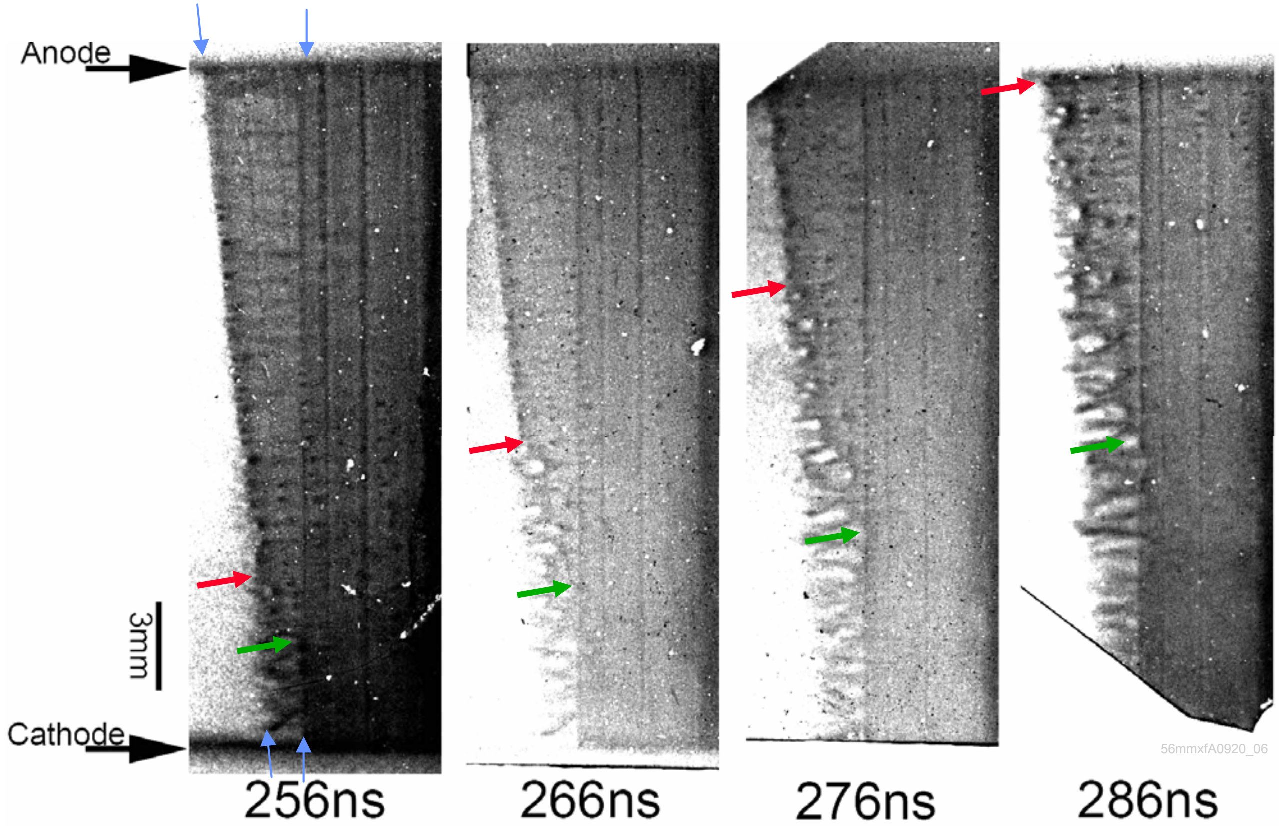
  - Mass density profiles in single conical arrays are consistent (v_{abl}~15cm/μs)



- Time of mass depletion (for single or nested) is expected to be a function of axial position

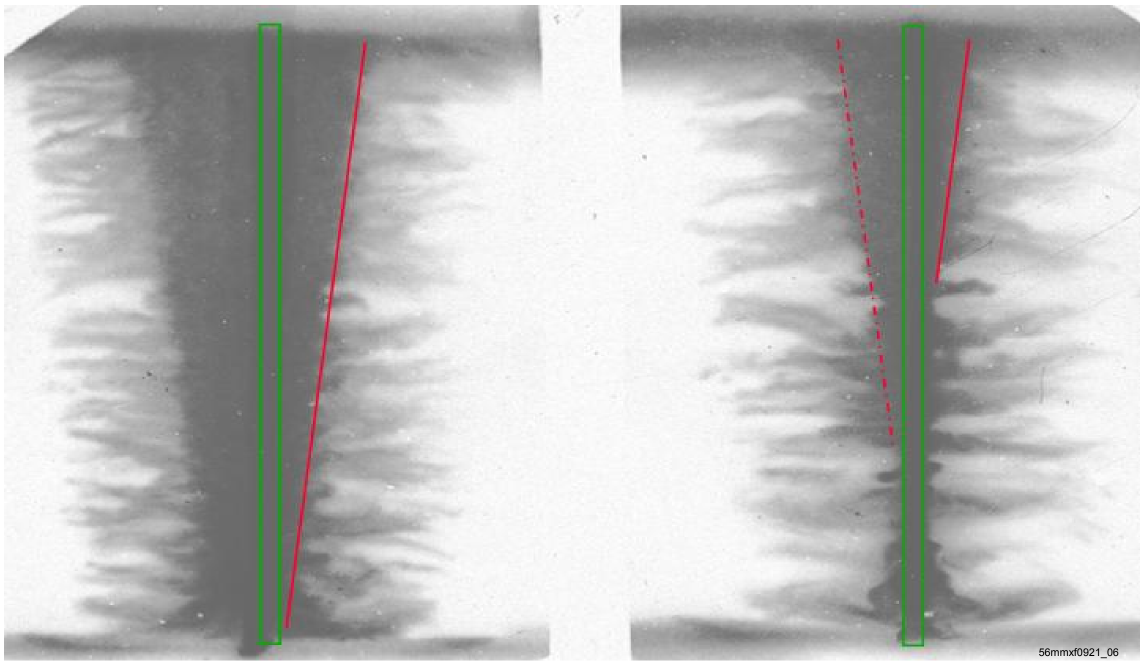
A conical outer array can be used to seed an axial zipper

- Nested conical data agrees with predicted delay in time of wire breakage



- Also see that zipper of implosion gives an axial dependence time of interaction with the inner array

Axial zipper survives through the interaction, leading to a zippered implosion of inner



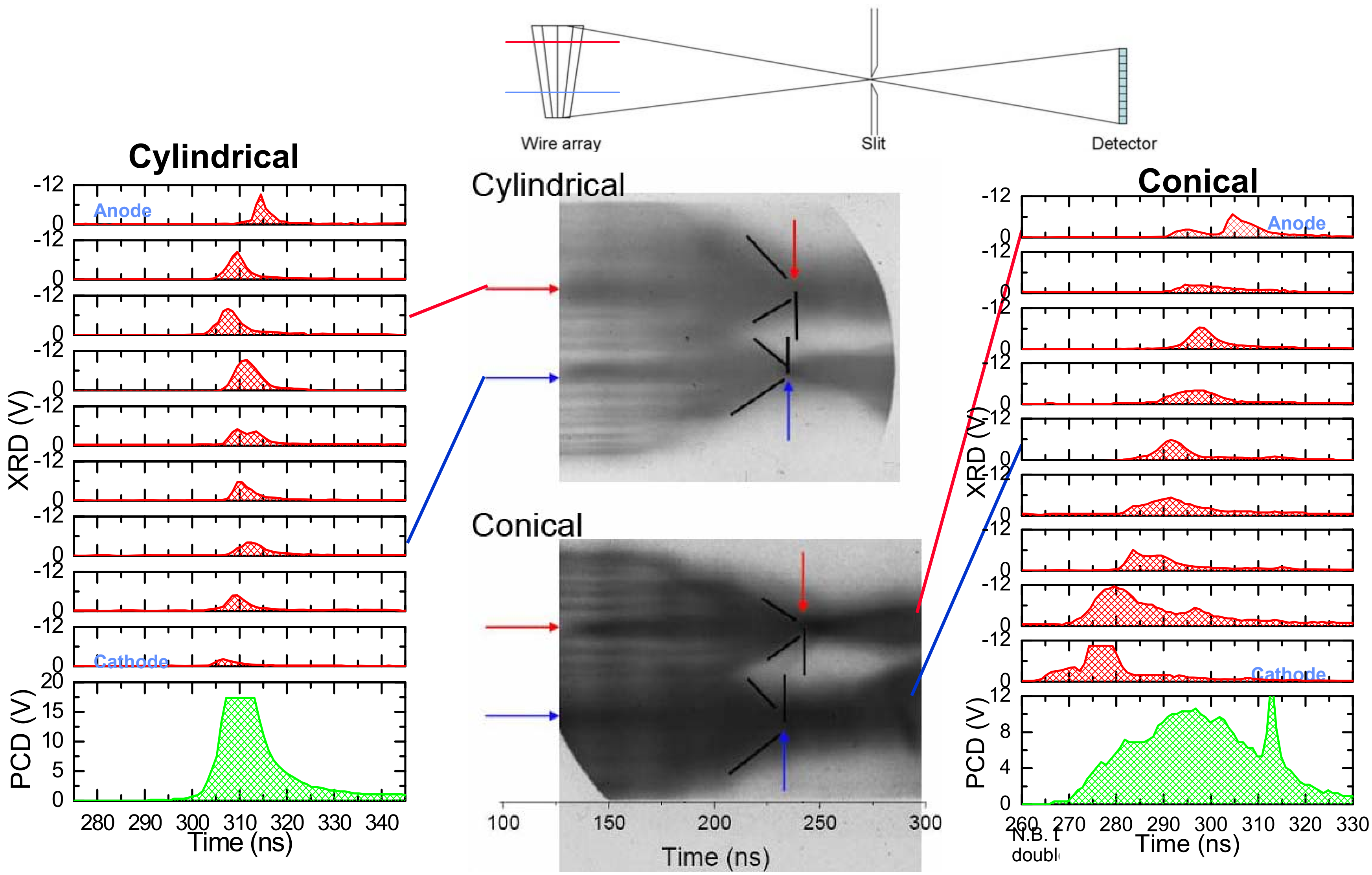
Time: 291ns 301ns

- Data indicates zipper velocity ~139cm/μs
- Estimated zipper over this time frame indicates zipper along full axis Δt_{zip}~16.5ns
- On MAGPIE, left-right asymmetry also present due to concentricity issue,

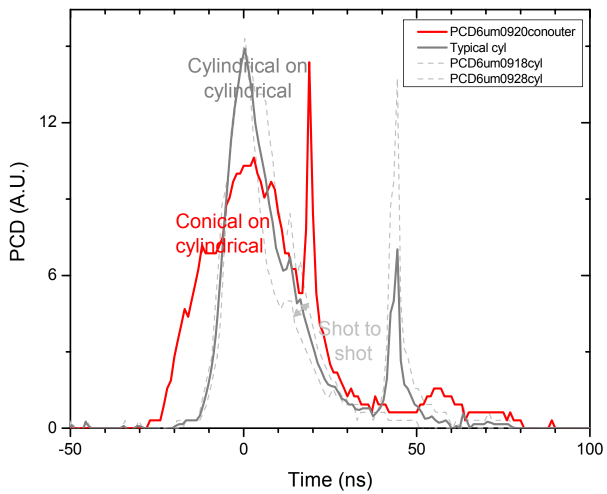
  - will effect pulse, but temporal effect is less ($\Delta t_{L\text{-}R}$~7ns)

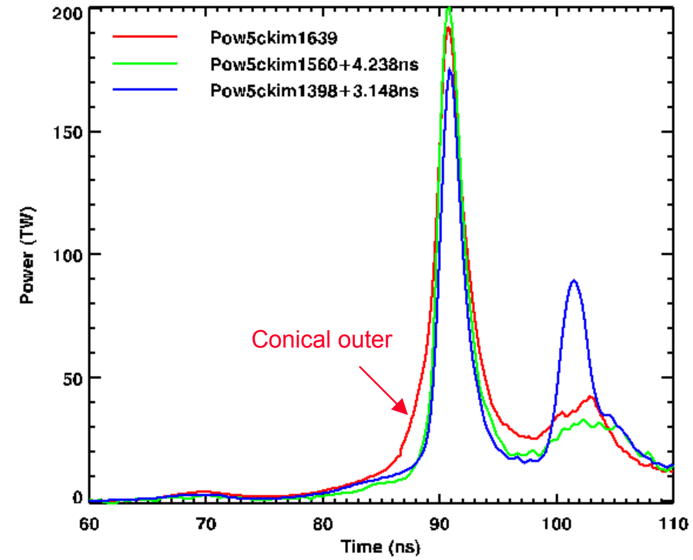
Seeded zipper translates into a zippered stagnation, and elongated x-ray pulse

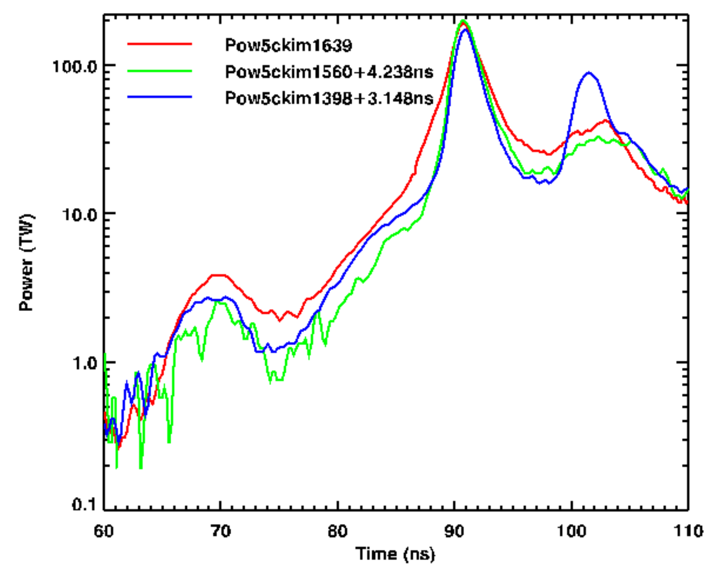
- Twin radial optical steak and zipper array each indicate conical outer zippers stagnation
- Axial dependence of stagnation time leads to pulse lengthening



Comparison of conical and cylindrical outers indicates success at widening main pulse







For conical outer on MAGPIE:

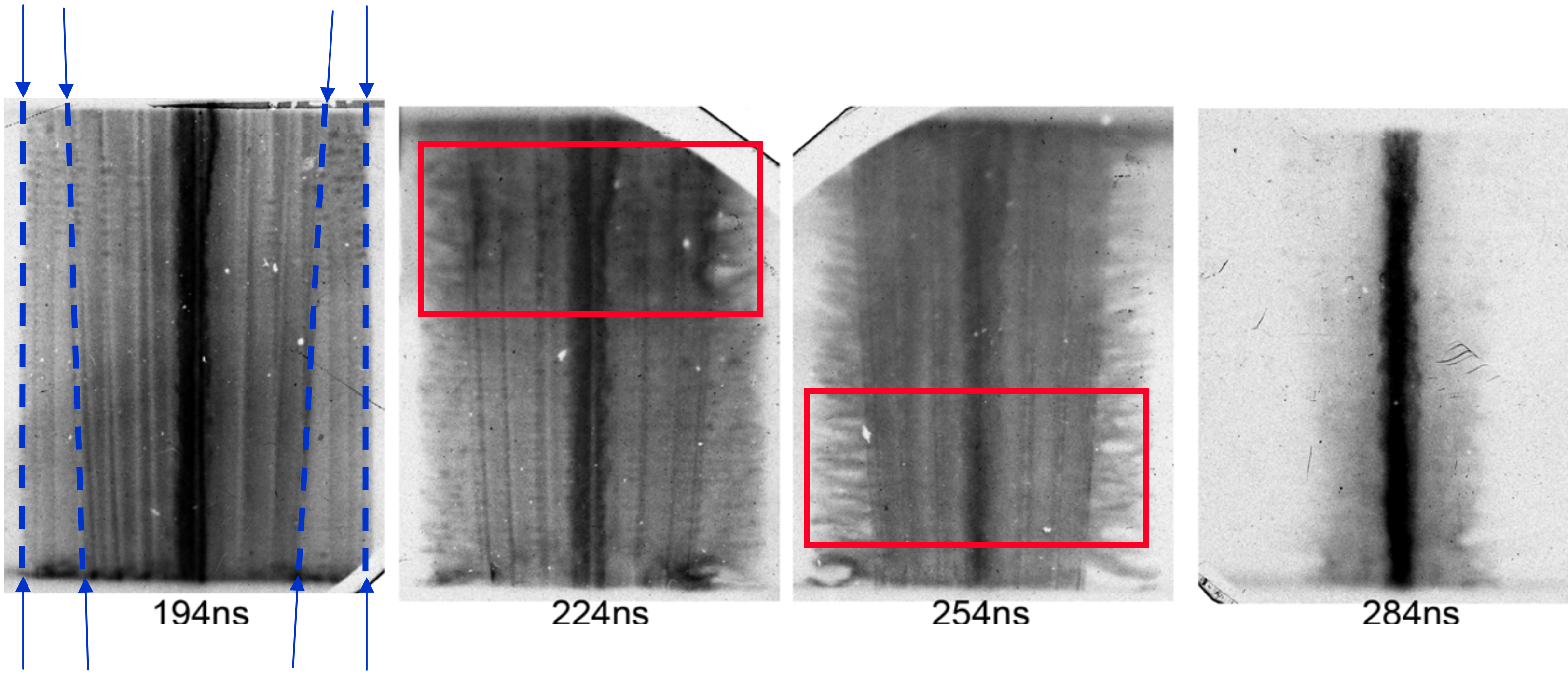
- See a longer rise in x-ray pulse
- Peak power down, but total energy similar
  - (possibly 25% higher for conical outer)

For conical outer on Z:

(Z1639, Cuneo et al., 22mm Cathode, 20m anode, 12mm inner)

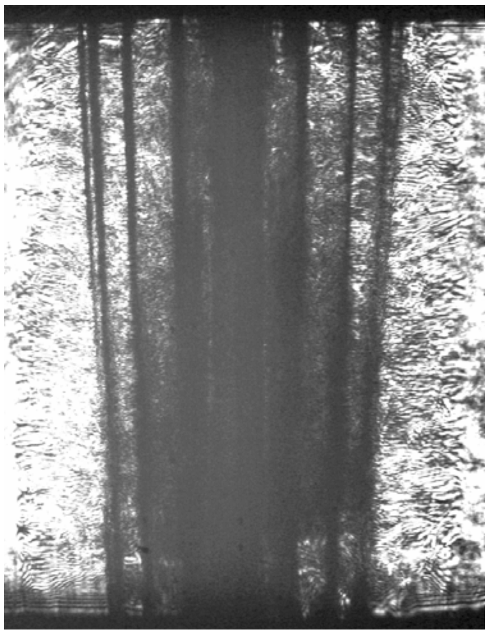
- Increased foot pulse power by 45% because of increase in outer velocity
- Increase first step by zippering implosion onto foam
  - power by a factor of ~4.6
  - energy by ~4.2
- Increase energy in the first step from 25 kJ to 104 kJ
- Energy radiated after the first step is unchanged
- Conical outer increases energy radiated in the main peak 22%

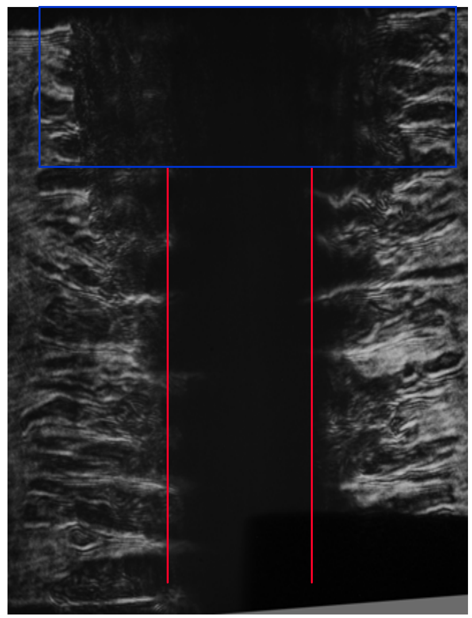
Inclining inner leads to change of time of flight of outer to inner, and alters timing of Interaction

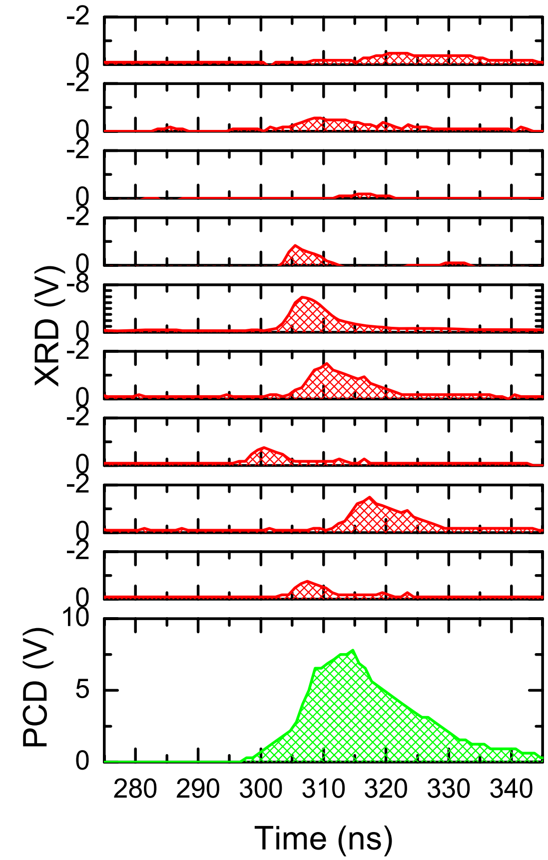


- Cylindrical wire arrays show variation in time of inner collision with inner array diameter
- Conical inner shows that time of interaction varies with z
- Power pulse will be lengthened
- Zipper less significant after inner ablation

Nested array with conical inner does not globally zipper stagnation on MAGPIE, but would alter Interaction Pulse



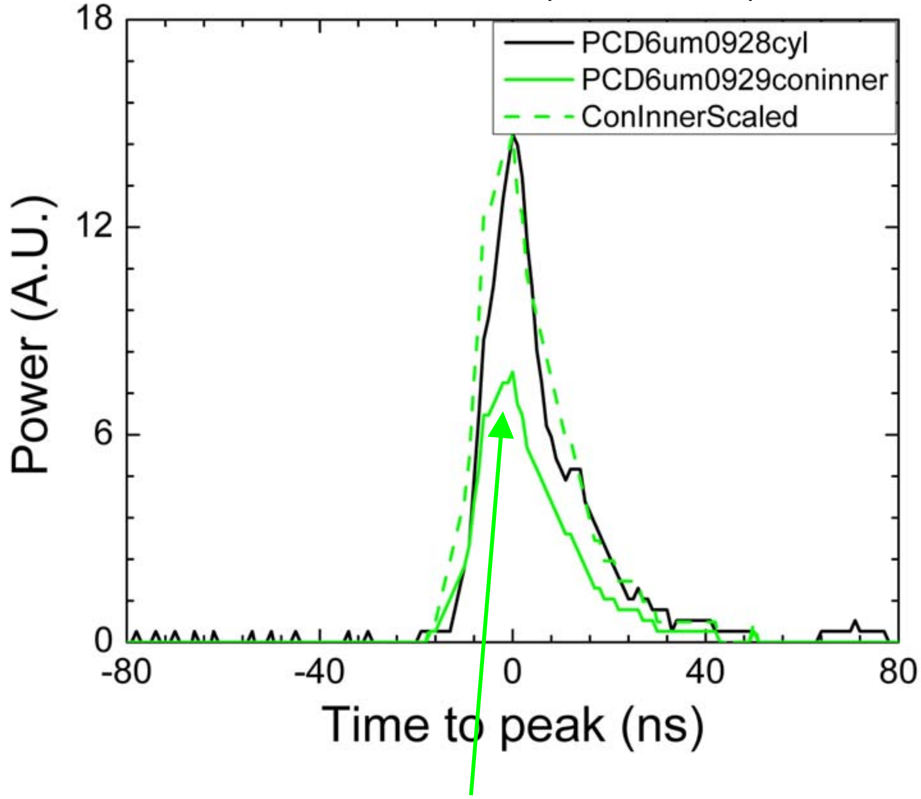




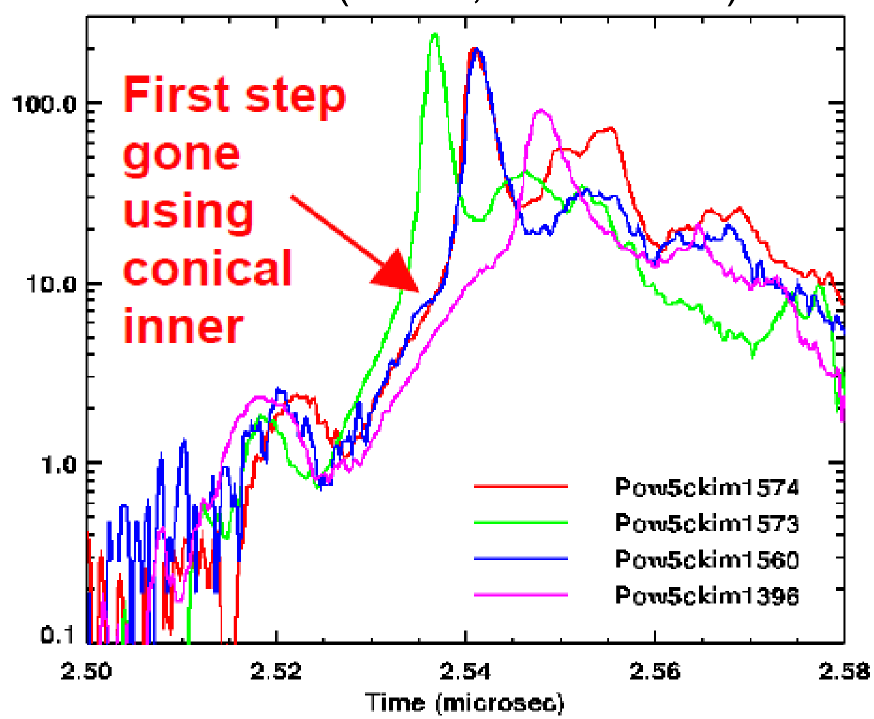
- Laser imaging after interaction indicates no substantial zipper
- Zipper array confirms no zipper in stagnation
- Laser imaging does show top section does not participate in implosion

Conical inner has some effects, but does not alter width of main pulse on MAGPIE or Z

MAGPIE: PCD (hv>200eV)



Z: XRD (Z1574, Cuneo et al.)



MAGPIE power lower than cylindrical
due to part of array not participating in implosion

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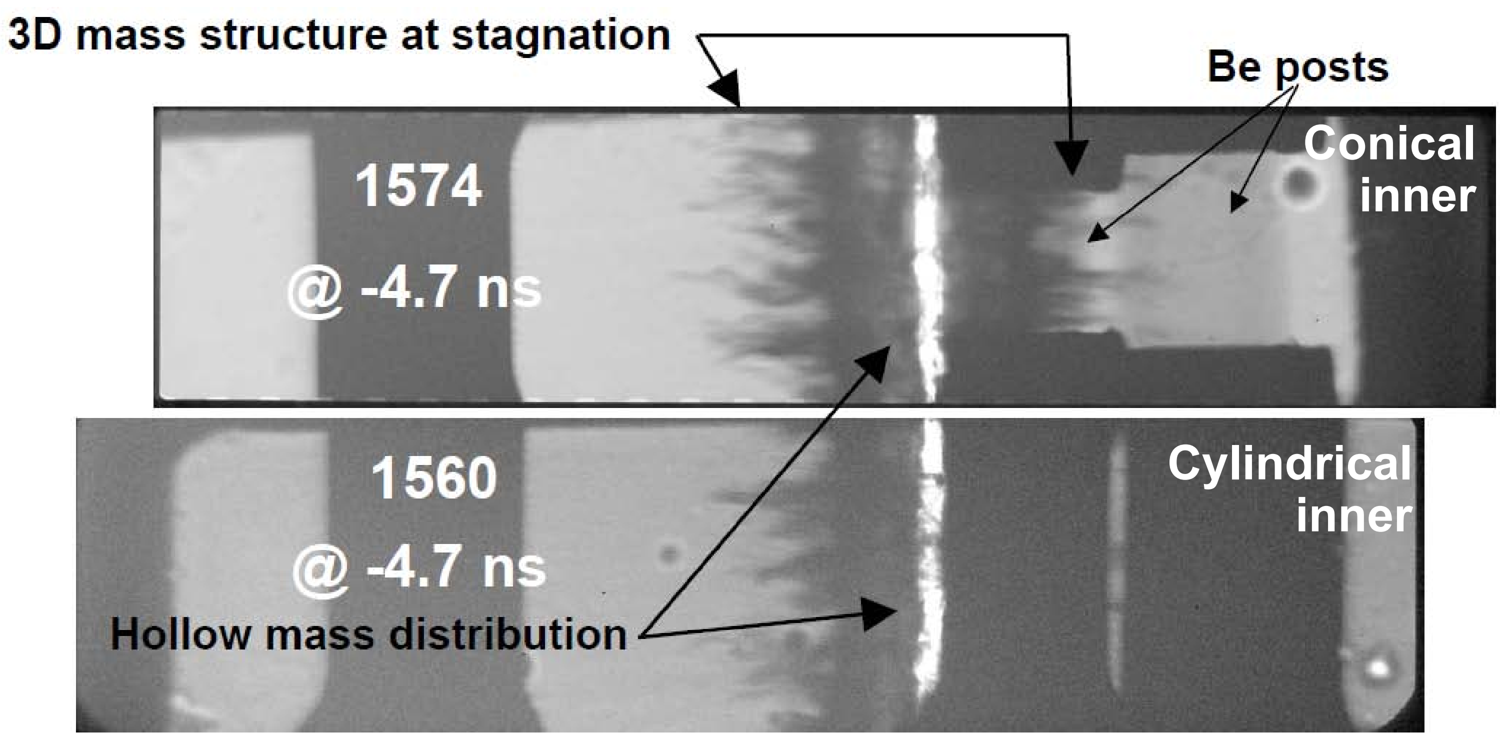
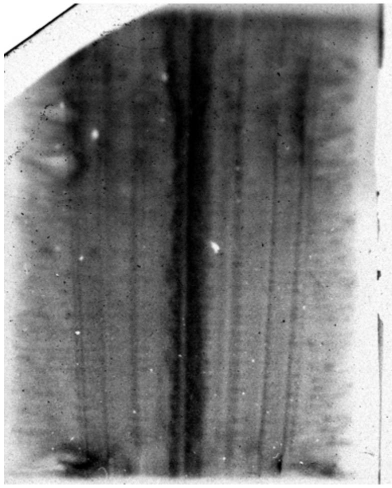
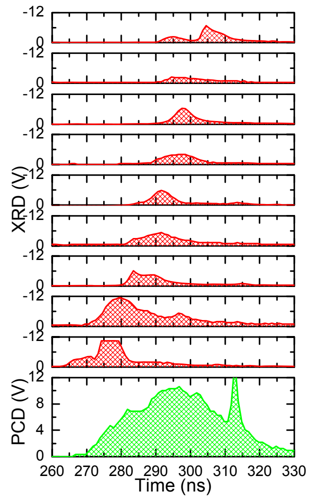
Radiography on Z indicates no zipper present after interaction



- For Z see no evidence of change to the mass distribution post-interaction

Part 2 Summary: What can we now control

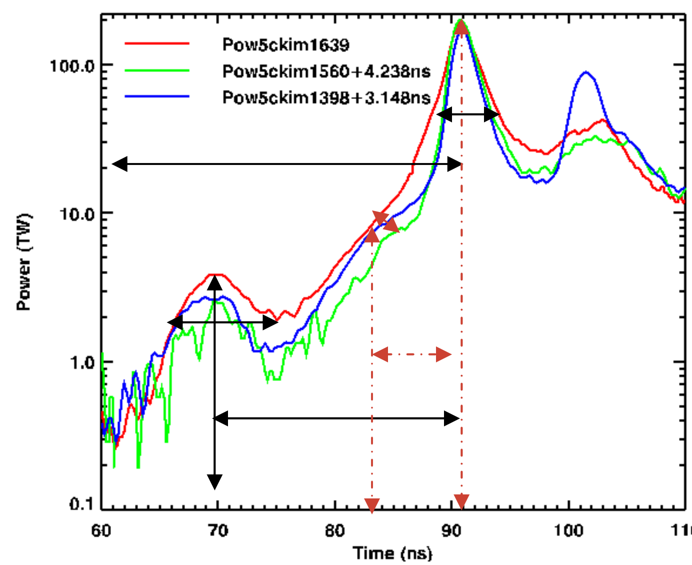




- Conical inner can control
  - Time scale of interaction
- Conical outer can control
  - Time scale of interaction (MAGPIE)
  - Time scale of main stagnation
- Need a more quantitative comparison

Combine with previous data (Cuneo et al.), now have control of:

- Time of peak (Outer mass, inner mass, outer diameter)
- Interaction to peak (inner diameter and mass)
- Pulse length of stagnation (outer angle)
- Pulse length of interaction (relative angle between outer and inner – needs verification)
- Understanding of interaction may lead to control of amplitude and length (need more experiments)



End effects impact arrays at all current levels

XUV and soft x-ray imaging on MAGPIE

S.N. Bland et al. Rev Sci Inst 75, 3941 (2004)

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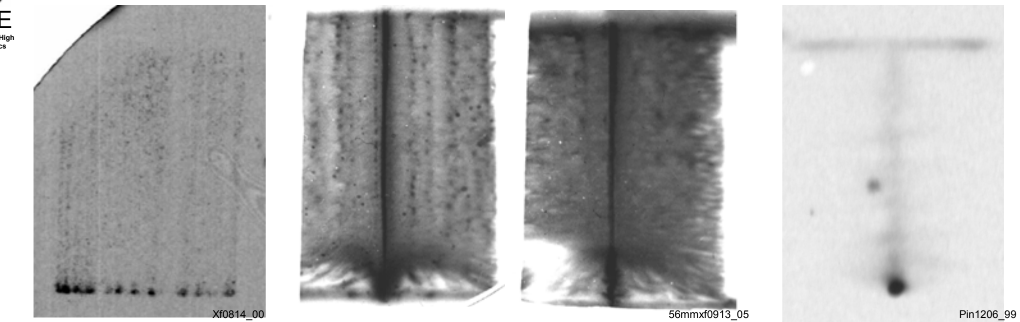
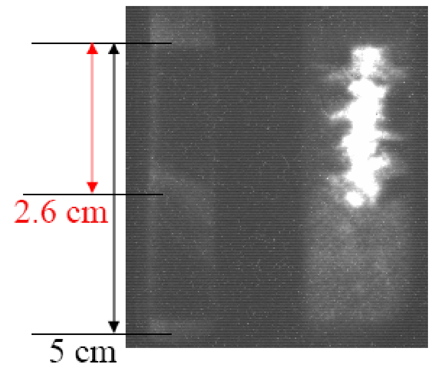


MAGPIE: 92ns | 239ns | 249ns | Time integrated

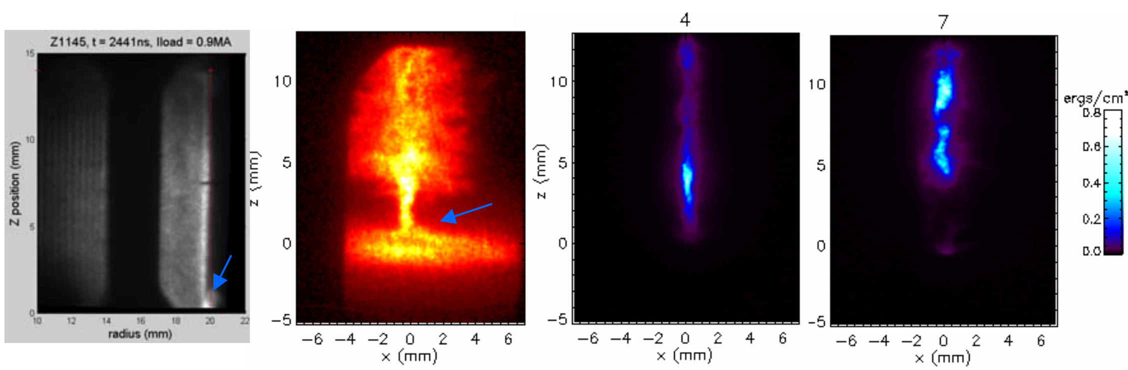
Optical self emission on Sphinx at Gramat

Calamy et al, IEEE-TPS 34, 2279 (2006)



Laser, Multilayer-mirror (MLM) monochromatic and pinhole imaging on Z

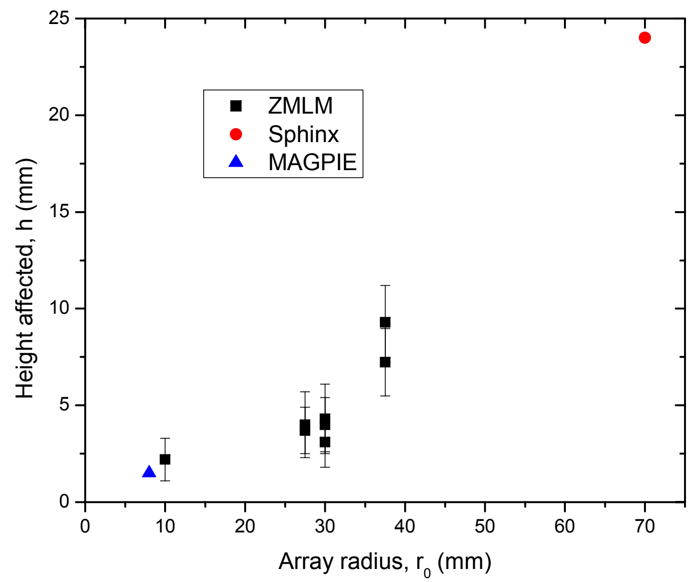
B. Jones et al. Rev Sci Inst 75, 4029 (2004)



Z1145, Optical emission
Bliss, Sanford et al. WAW04

Z1617, 277eV
sub-K-shell emission

Z1616, Cu K-shell emission:
Cu nest, 20 mm tall, 60 on 30 mm array dia., 80 on 40 wires, 0.598 on 0.299 mg/cm



Previous WAW talks by Sanford, Calamy, Jones & Chittenden

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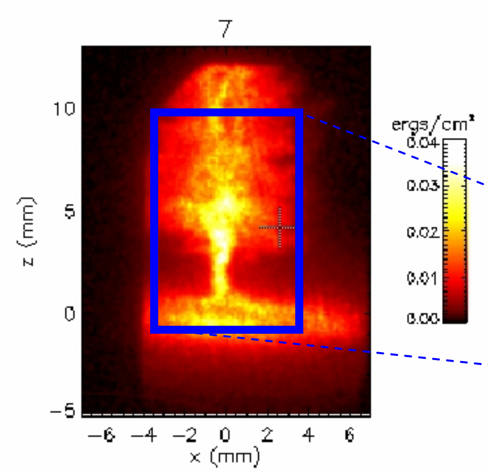
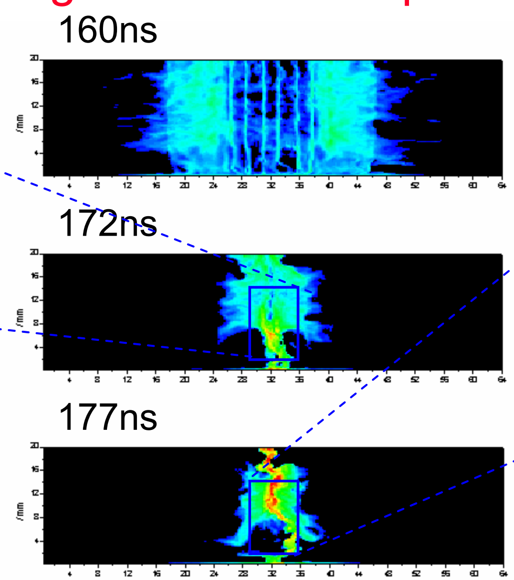
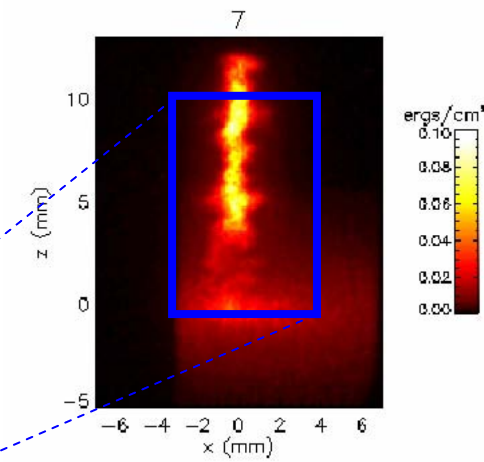
Simulations can reproduce effect and show possible mitigation with step

Integrated emission profiles





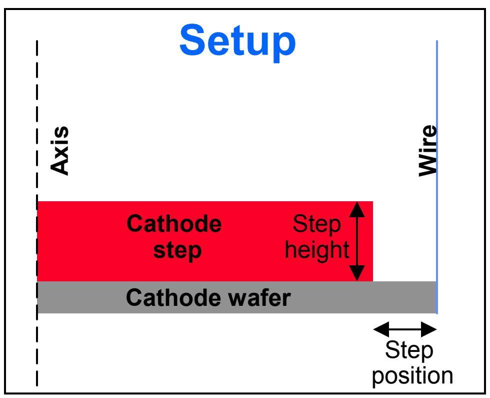


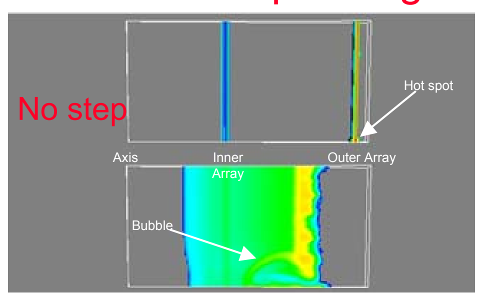
Bubble initiated with 0.5eV hotspot at the base of each wire

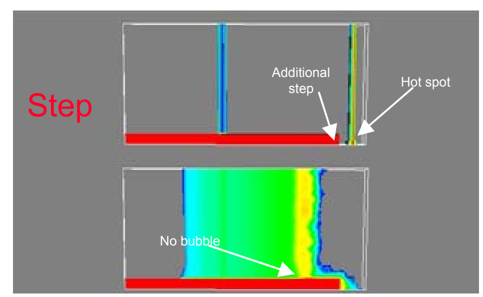
Simulation of Z Shot 1617

- 60mm on 30mm array diameters
- 80 on 40 copper wires

Presence of step on cathode step changes dynamics







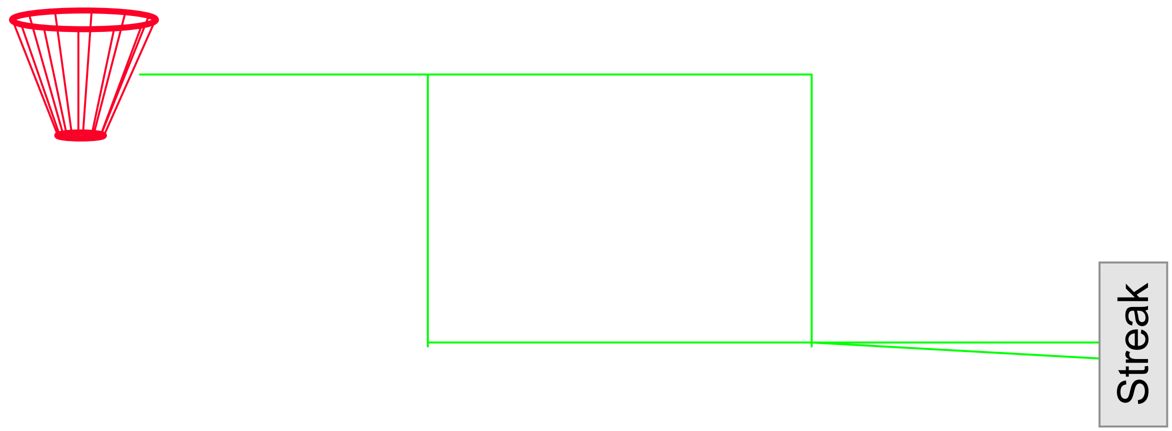
Simulations by C. Jennings using Gorgon 3D resistive MHD code

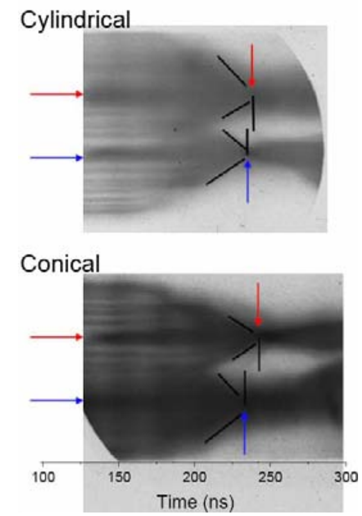
J.P. Chittenden et al. PPCF 46, B457 2004

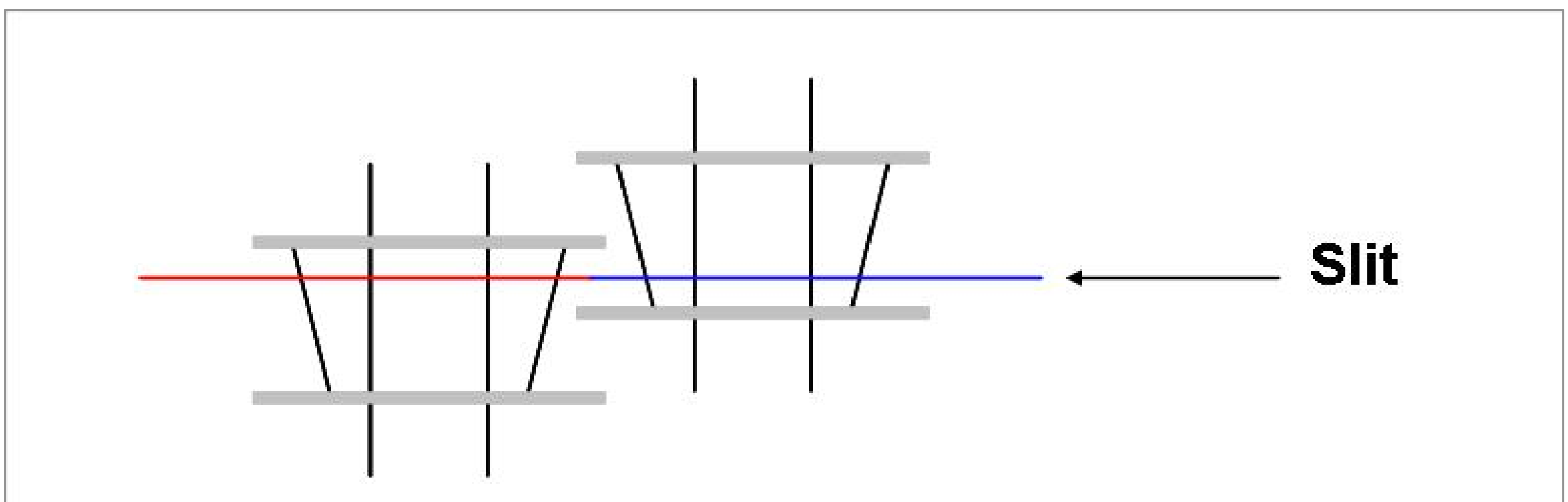
Experiments to test idea planned for Saturn in May-June

Backup

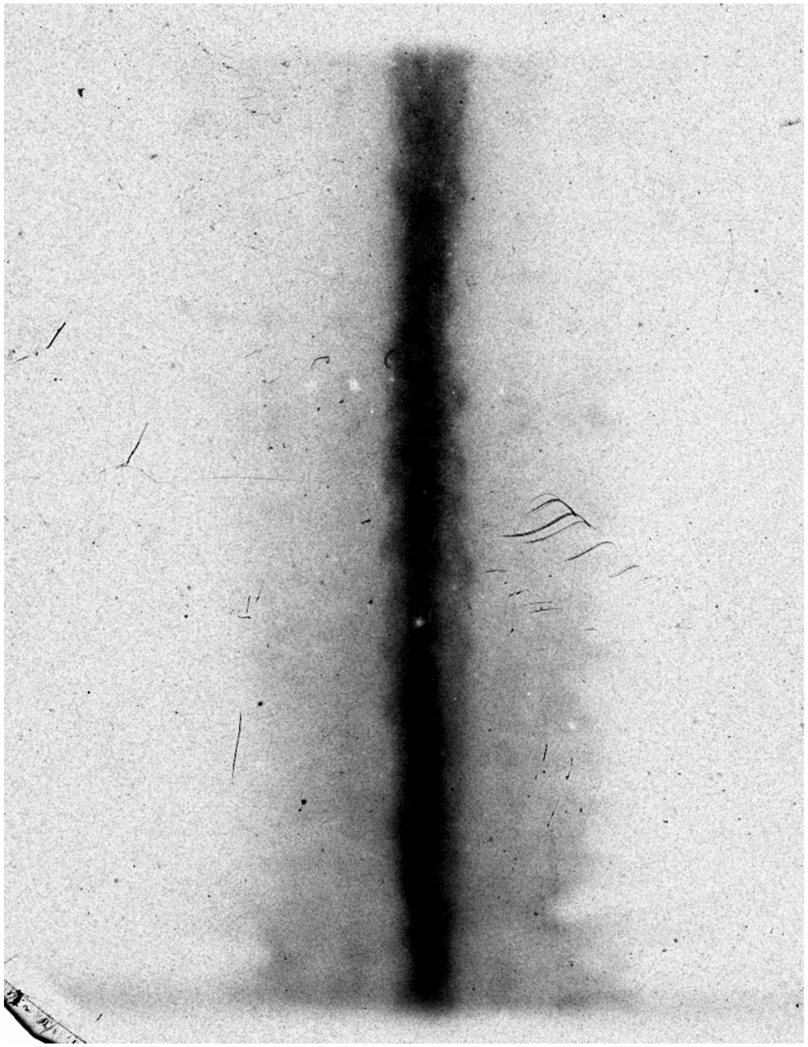
Streak setup for dual image



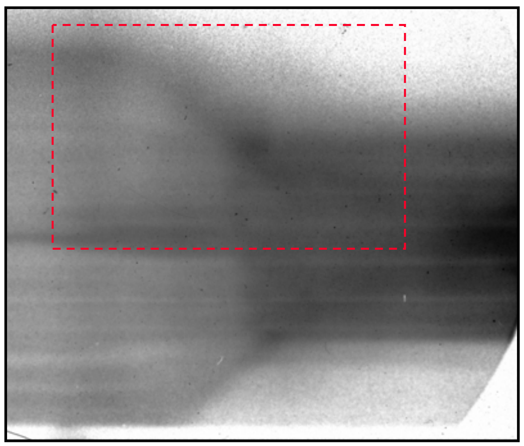


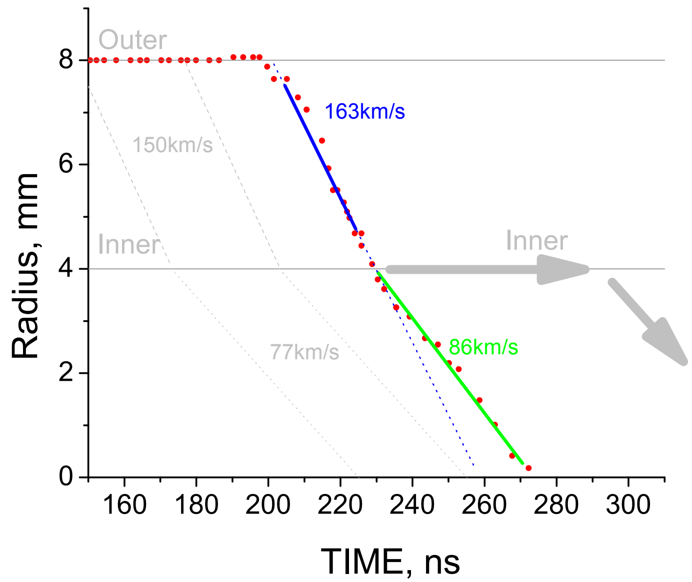


XUV images can be overlaid to show evolution

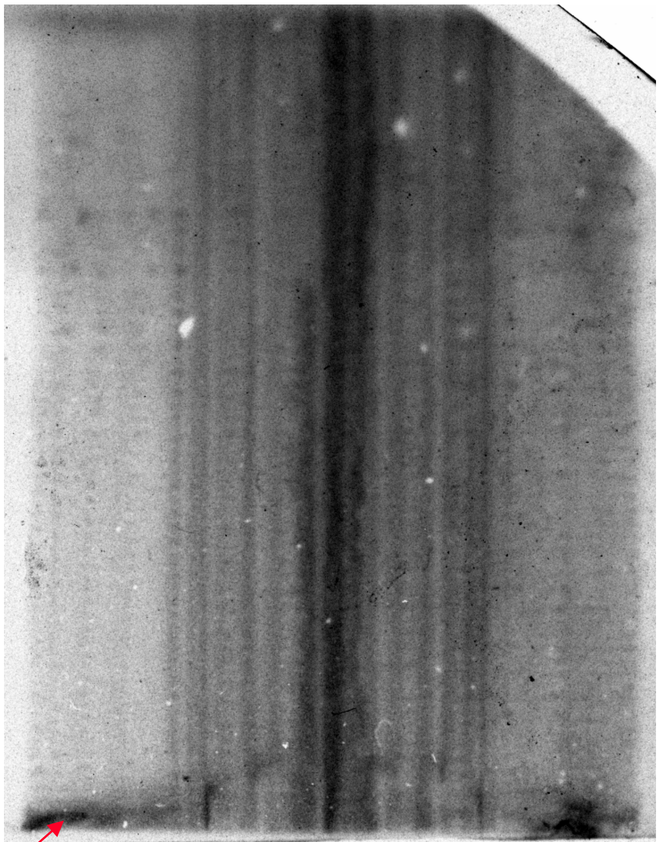


Streak shows evolution after interaction





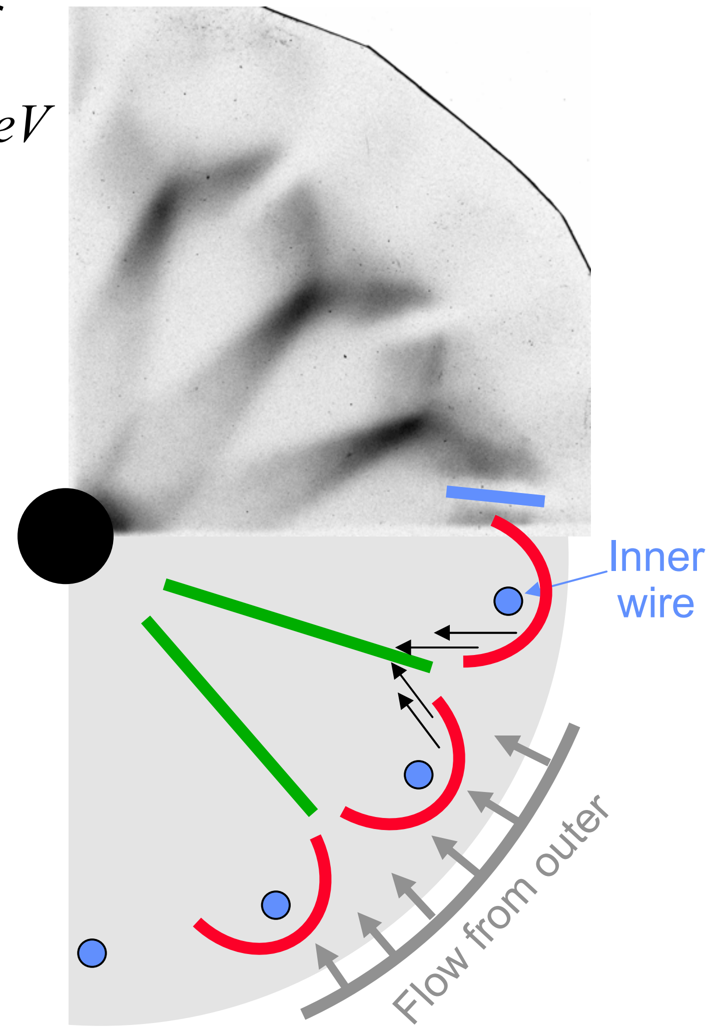
Precursor plasma streams are shocked as they pass the inner array



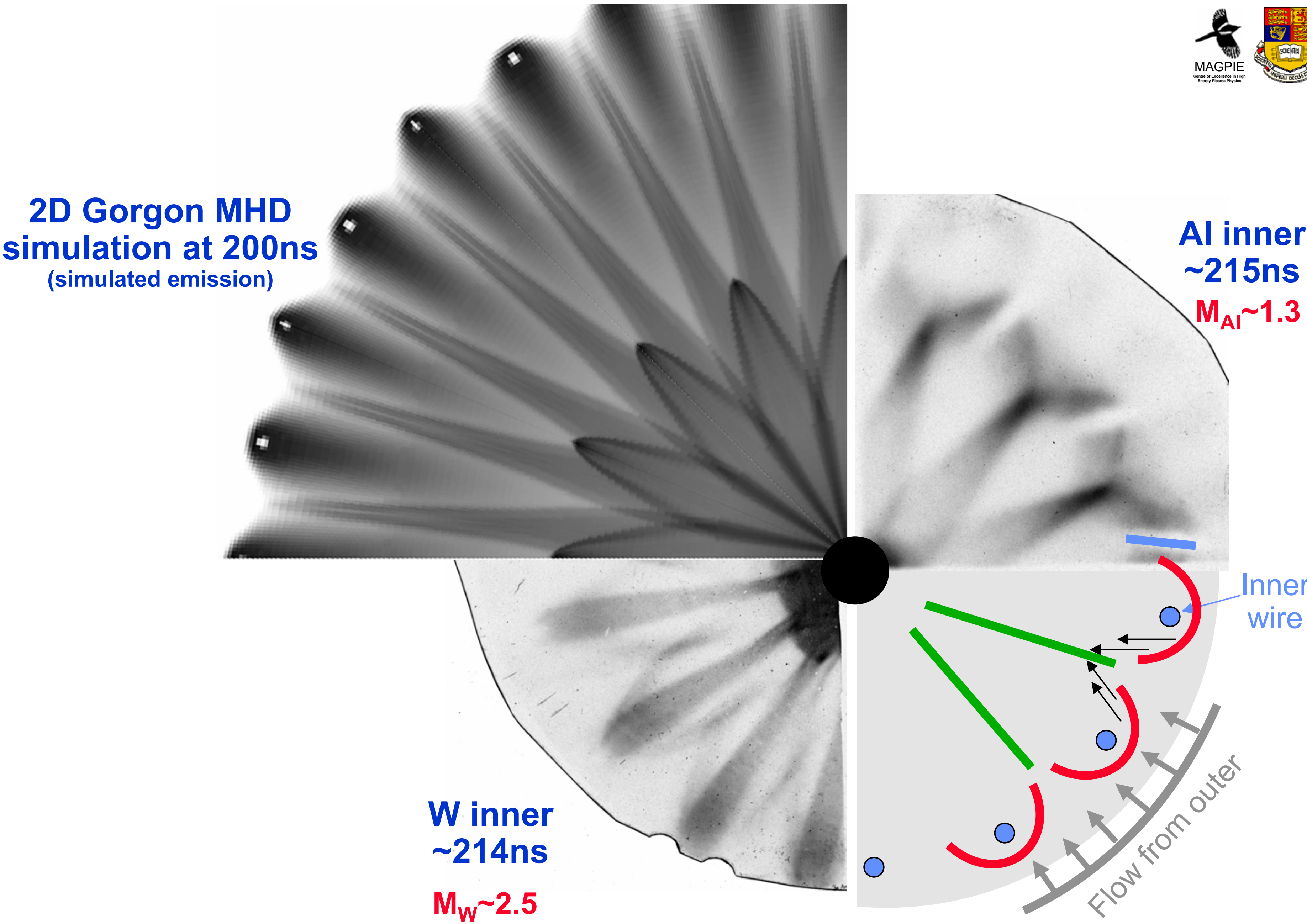
Saturn experiments being planned to investigate mitigation of cathode effects

Inner array

Al inner
~215ns
$h\nu > 30eV$



- Ablated streams perturbed by presence of inner forming bow shocks
- Shock leads to increased emission at position of inner (shock heating and change in density distribution)



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Shock jump in precursor streams

- For MAGPIE conditions estimate M~1.3, γ~1.3
- Estimate jump conditions:

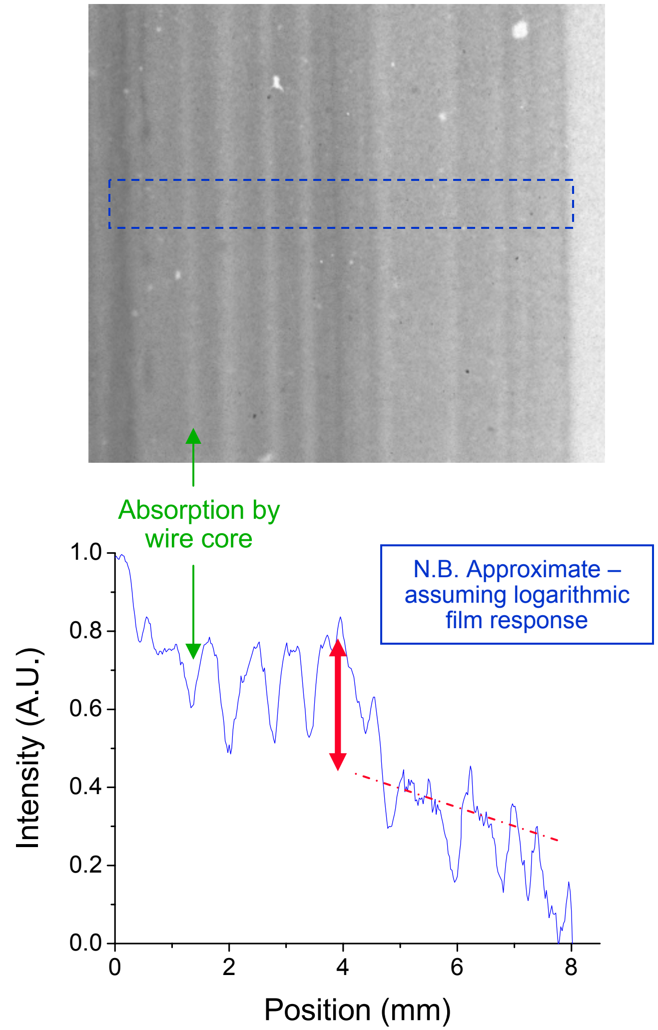
$$\frac{T_1}{T_0} = 1 + \frac{2(\gamma - 1)}{(\gamma + 1)^2} \frac{M_{\perp 0}^2 - 1}{M_{\perp 0}^2} \left[\gamma . M_{\perp 0}^2 + 1\right] \sim 1.1$$

$$\frac{\rho_1}{\rho_0} = \frac{(\gamma + 1) M_{\perp 0}^2}{(\gamma - 1) M_{\perp 0}^2 + 2} \sim 1.5$$

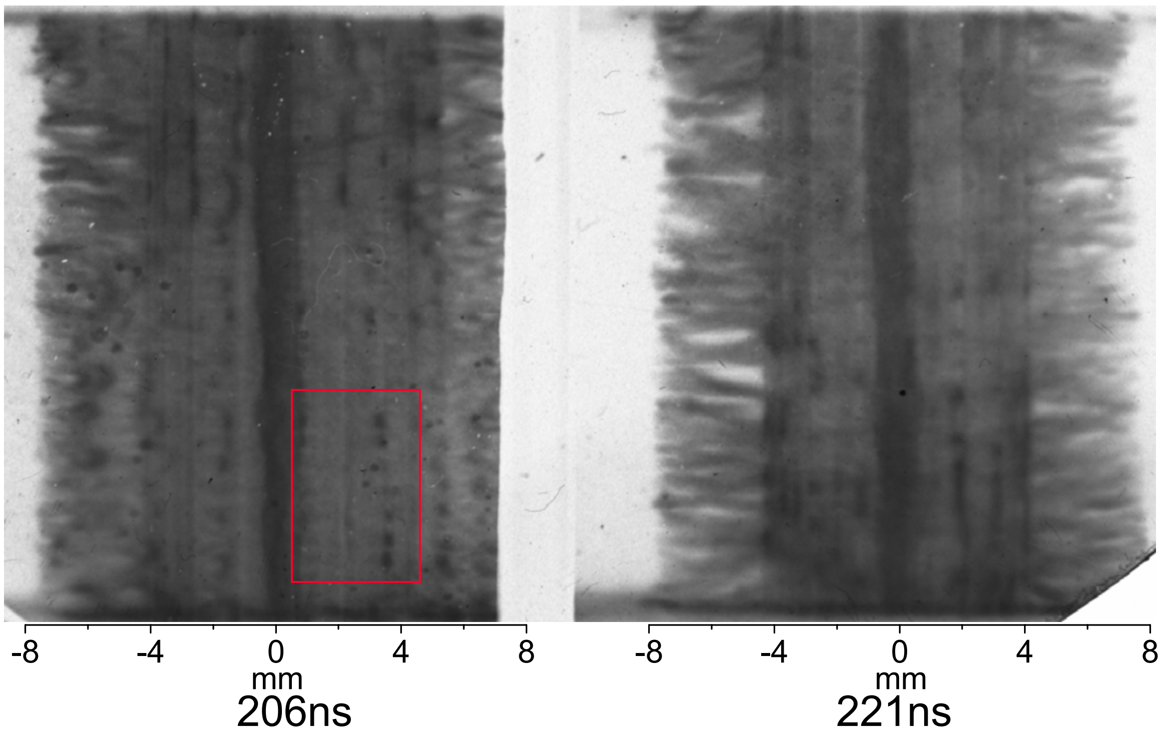
- From these, can estimate change in emission from incoming flows, e.g. assuming recombination emission:

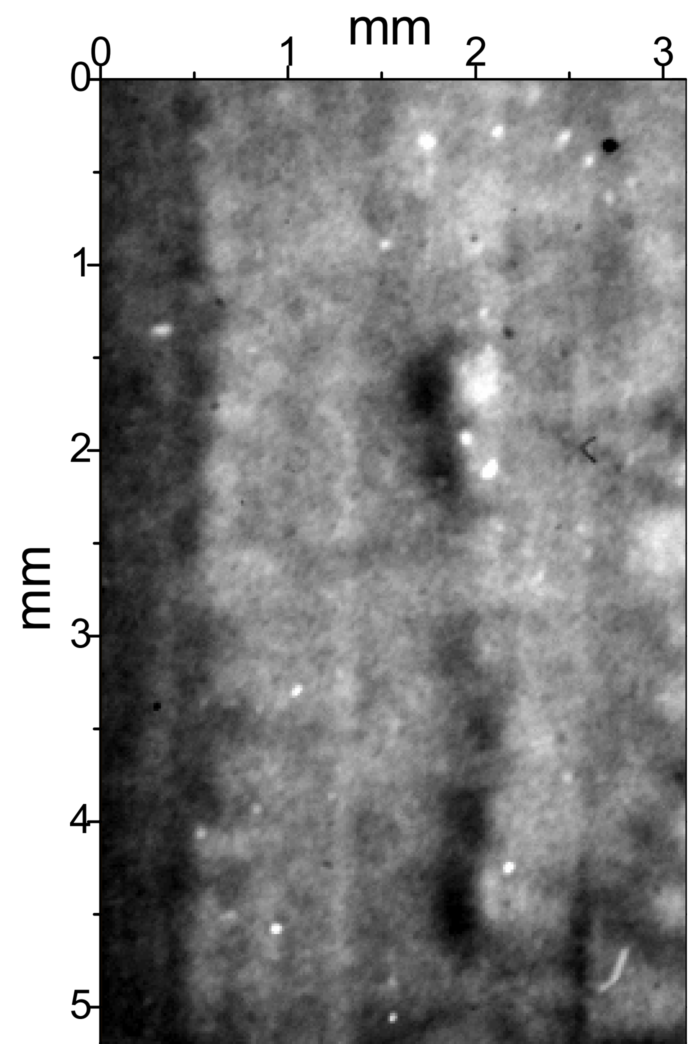
$$\frac{P_1}{P_0} = \frac{\rho_1^{\,2} / \sqrt{T_1}}{\rho_0^{\,2} / \sqrt{T_0}} \sim 2.2$$

- Lineout of image is consistent (no Abel inversion…)
- Shock setup should be steady state before imploding outer reaches it



Interaction: Bubbles emit as they pass inner



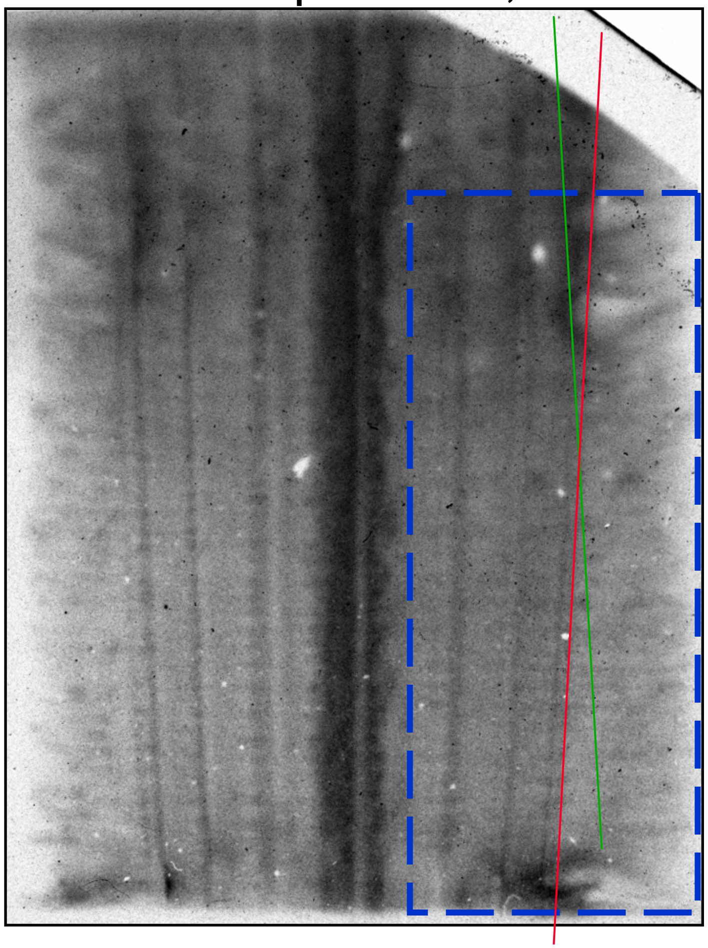


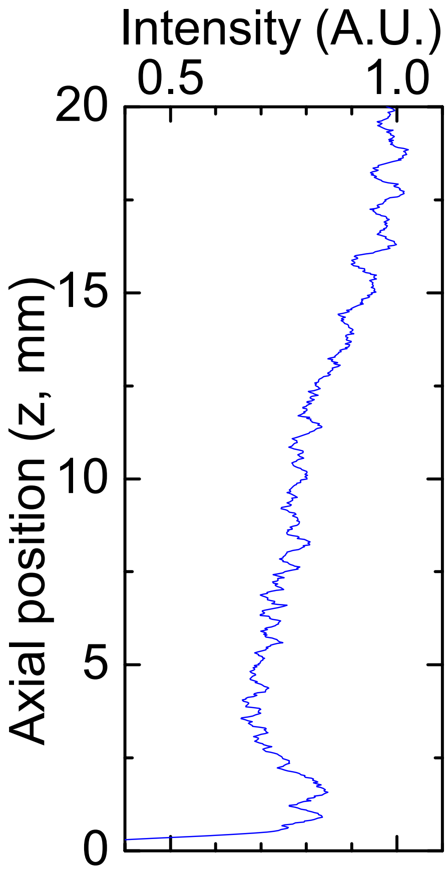
On MAGPIE see enhanced emission from imploding bubbles as they reach the inner array

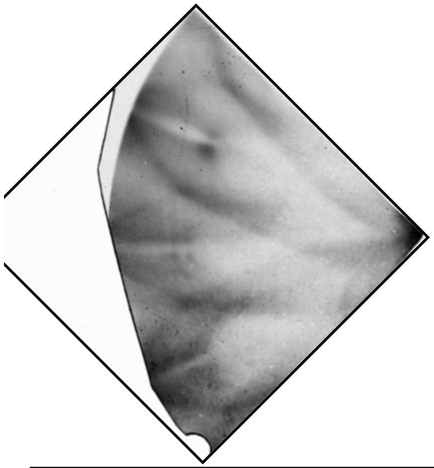
Detailed image demonstrates this emission increases inside the inner wires

Conical inner isolates snowplow from interaction

- Setup designed such that snowplow is constant along axis, however interaction time changes
- See emission from bubbles interacting with inner near for larger inner radius positions, but not at smaller inner radius

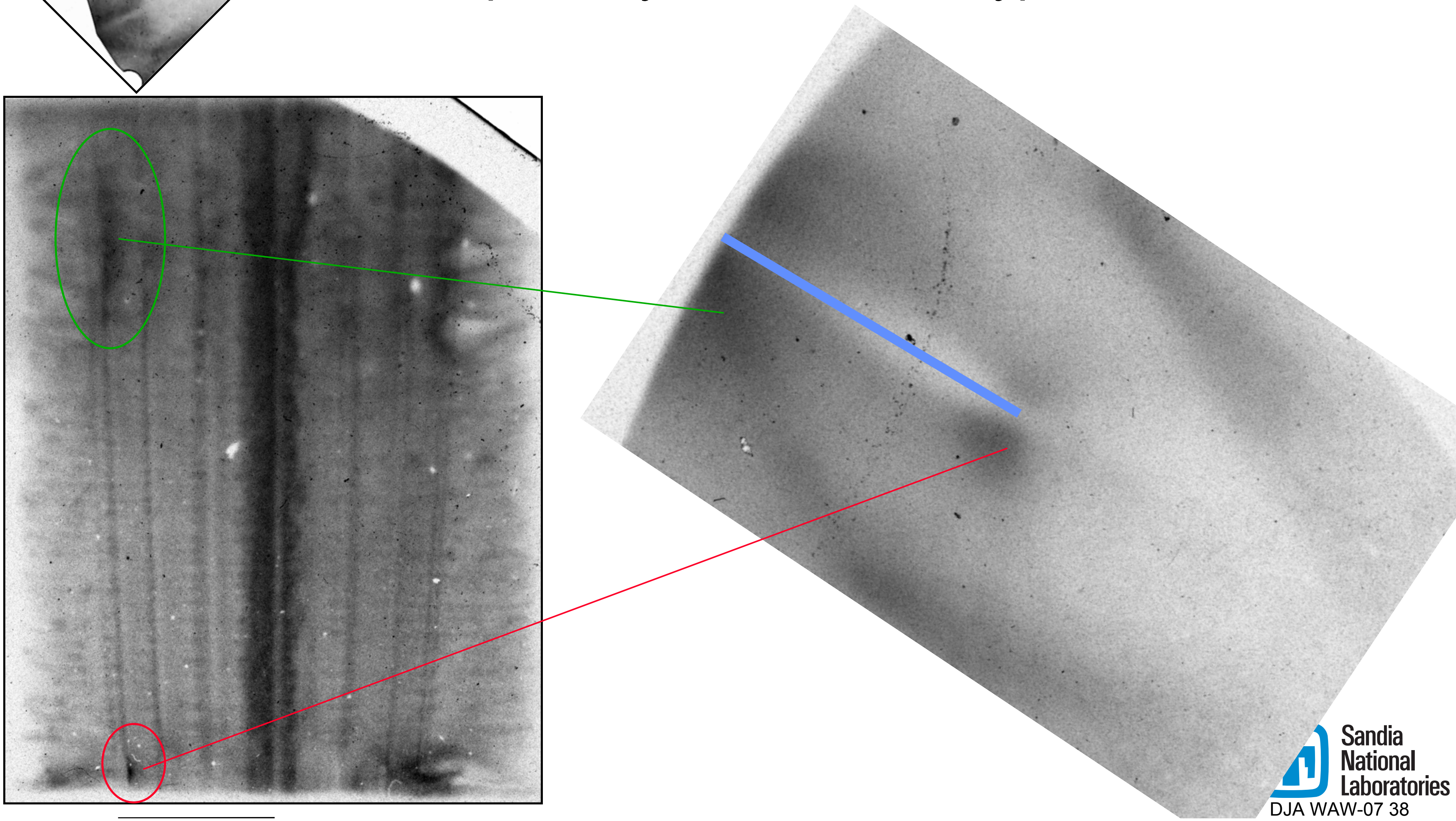




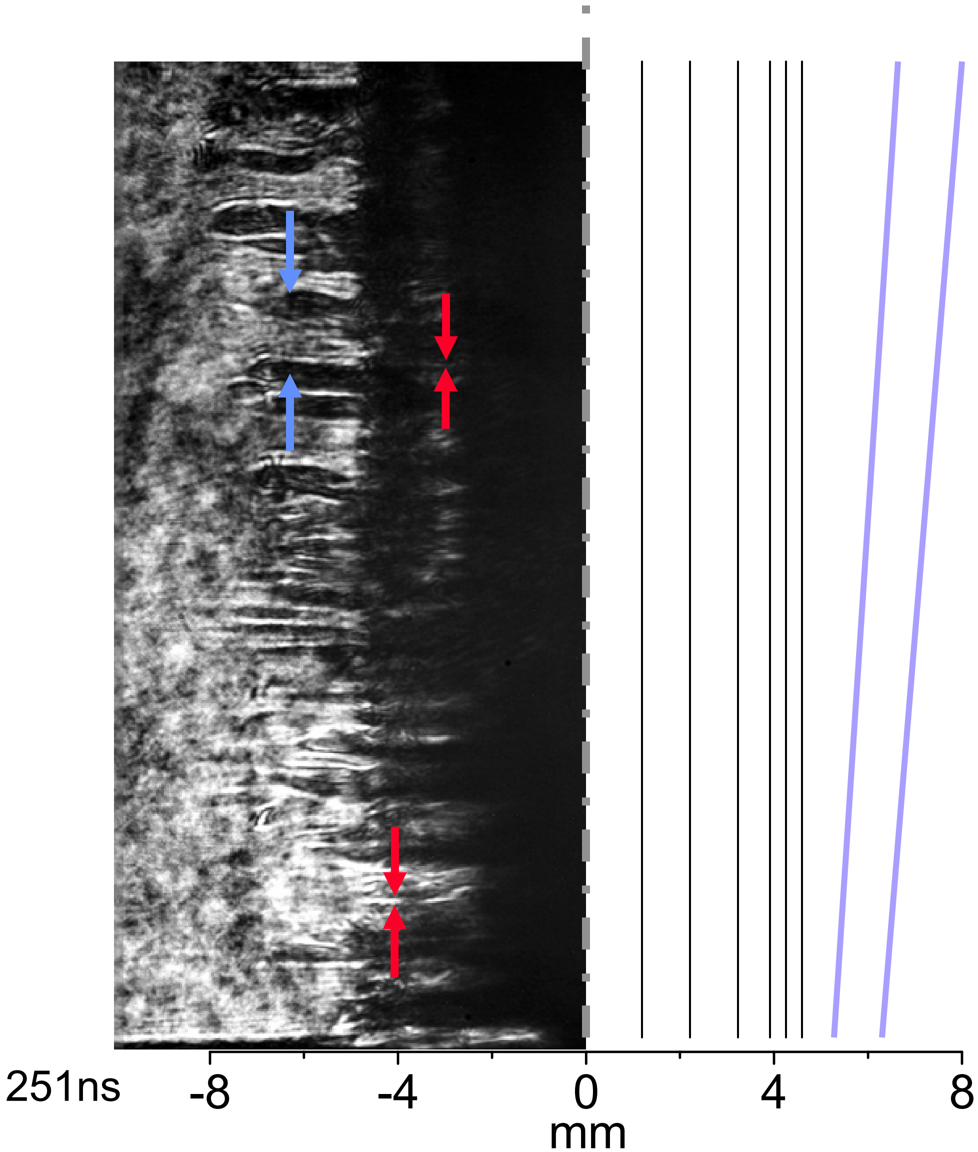


End-on probing shows interaction

- See interaction emission surrounds wire, possibly in bow-shock type structure

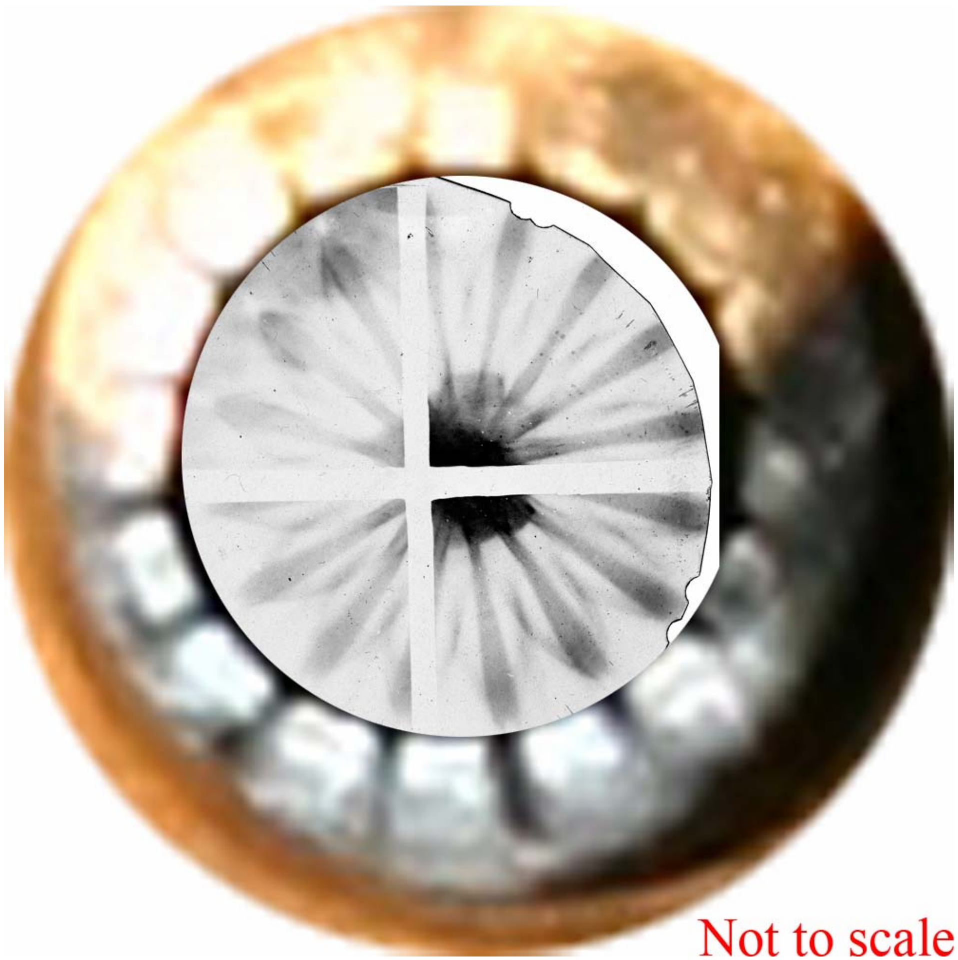


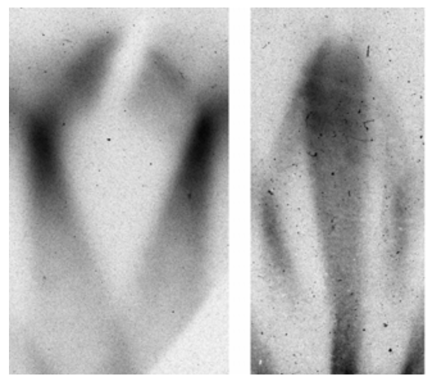
Interaction with inner resets implosion wavelength



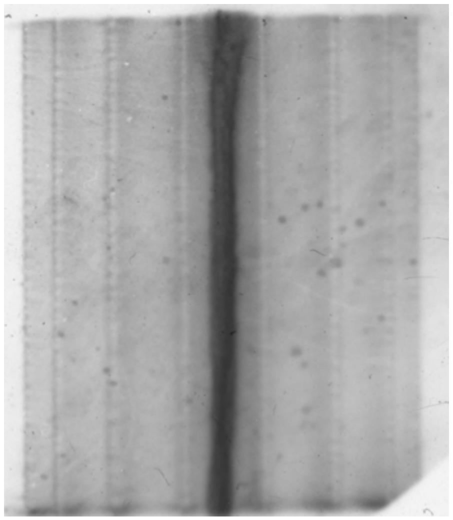
- Conical outer onto cylindrical inner shows change in wavelength is different before and after interaction with inner
- Interaction resets wavelength to sub-mm natural mode

End-on orientation

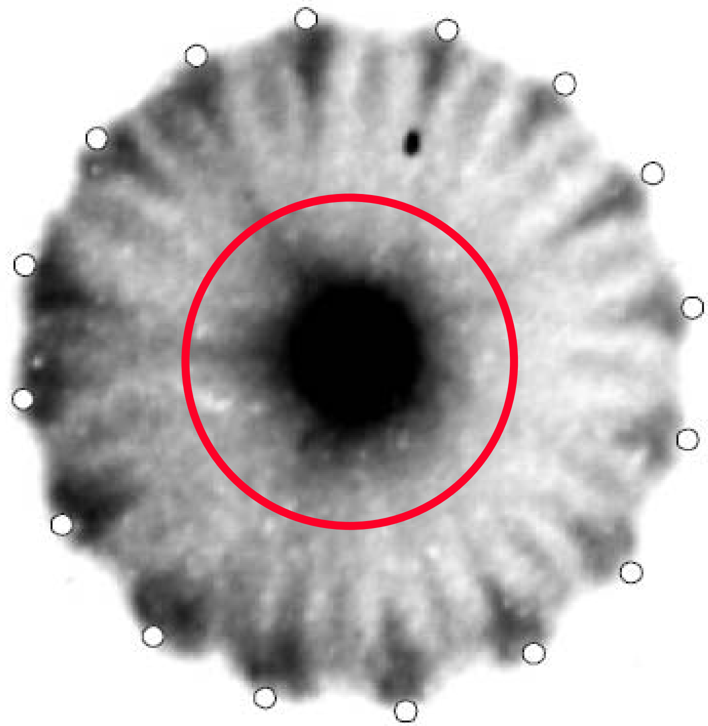


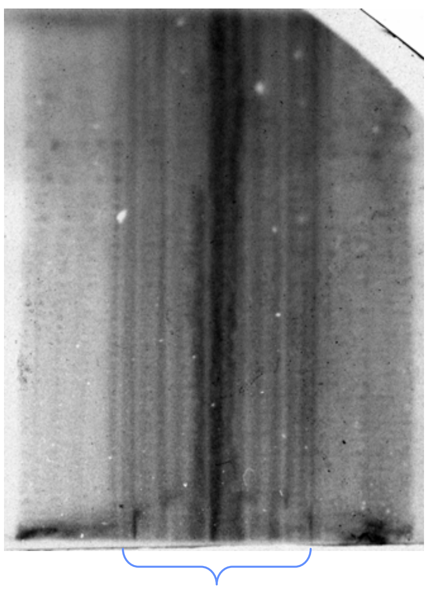


Single/nested side-on and end-on

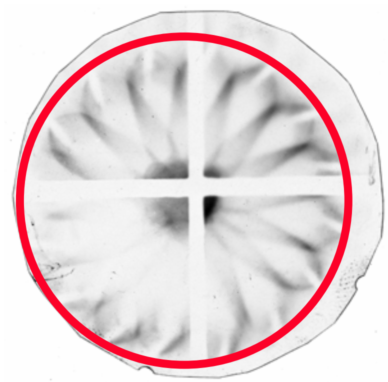


Single array
(16 Al wires)





Nested array
(32 Al onto 16 Al)



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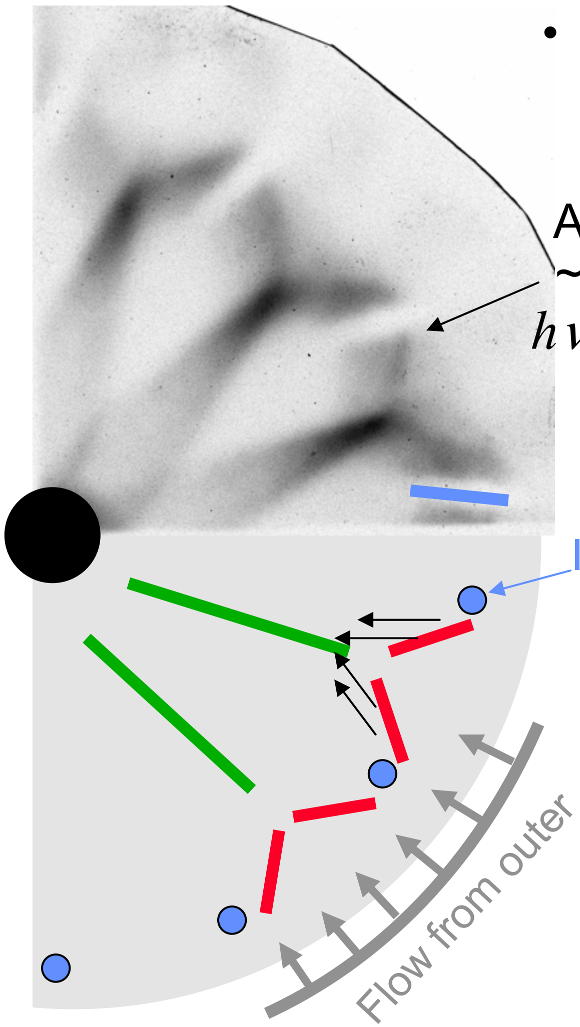
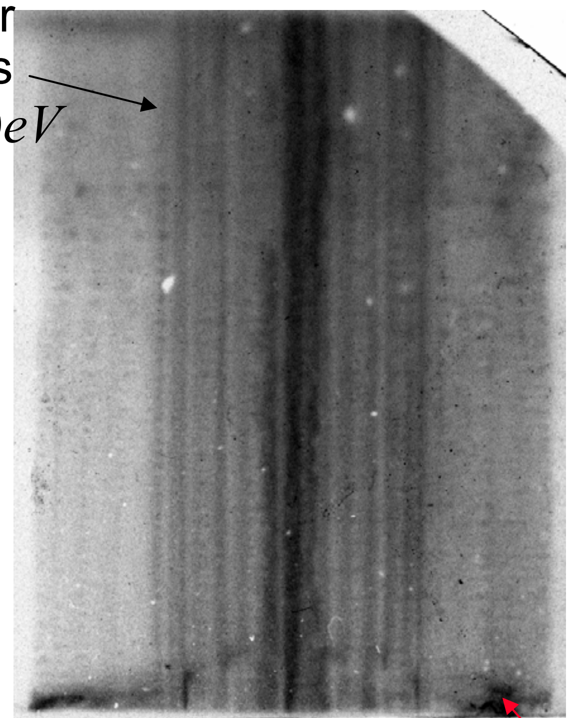
Al inner
~215ns
$h\nu > 30eV$





See APS poster GP1.00097
by C.A. Jennings et al.

W inner, at 214ns

MHD
simulation