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# Pulse shaping techniques with nested wire arrays (and applications of novel wire arrays)


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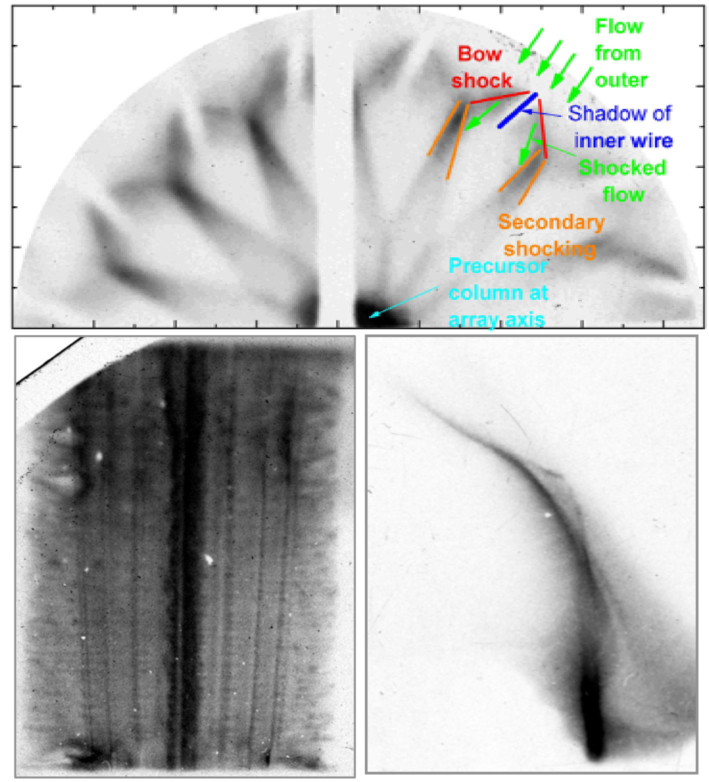



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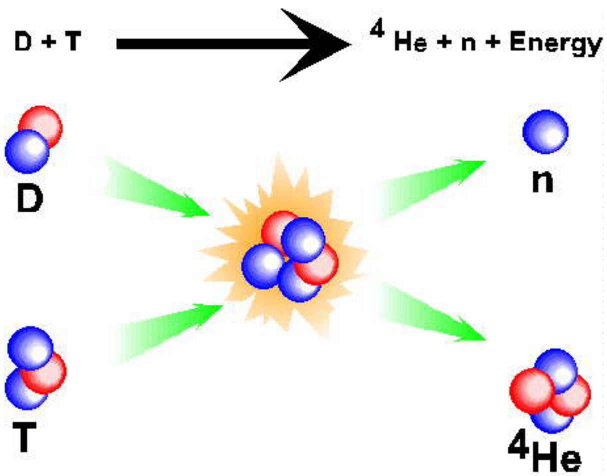
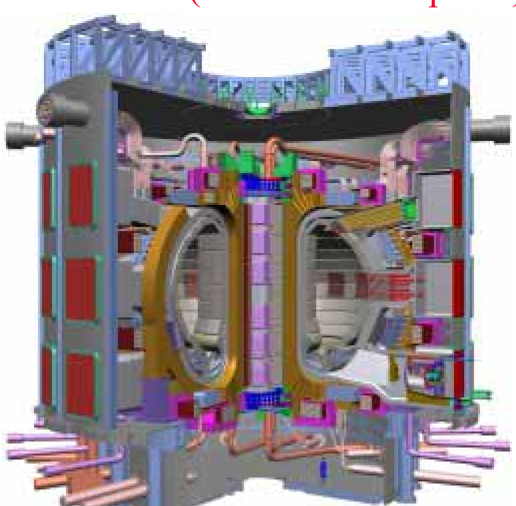
# Fusion needs a hot, confined plasma

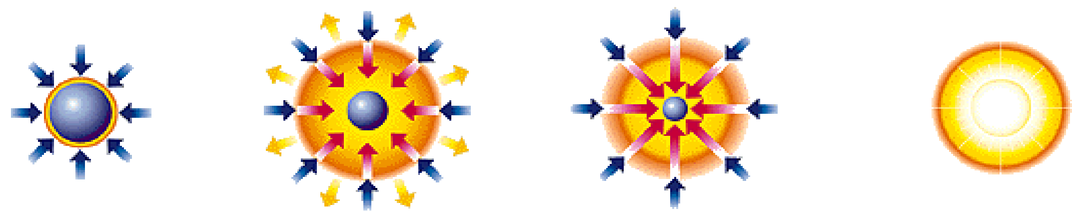



**Magnetic confinement:**
Tokomak (and classical z-pinch)



ITER

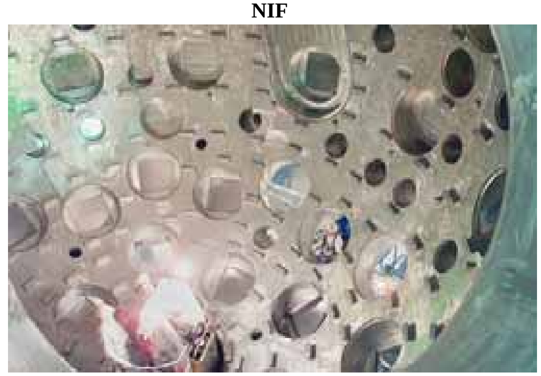
**Inertial confinement**



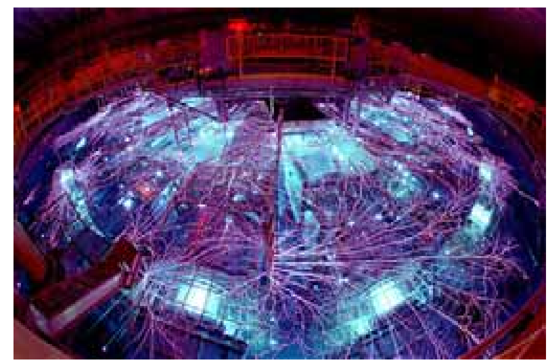
Atmosphere formation | Compression | Ignition | Burn

Laser (direct/x-ray)

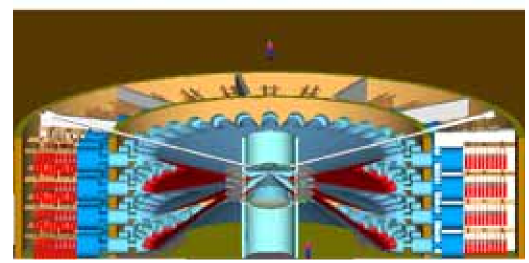
NIF



Wire array Z-pinch

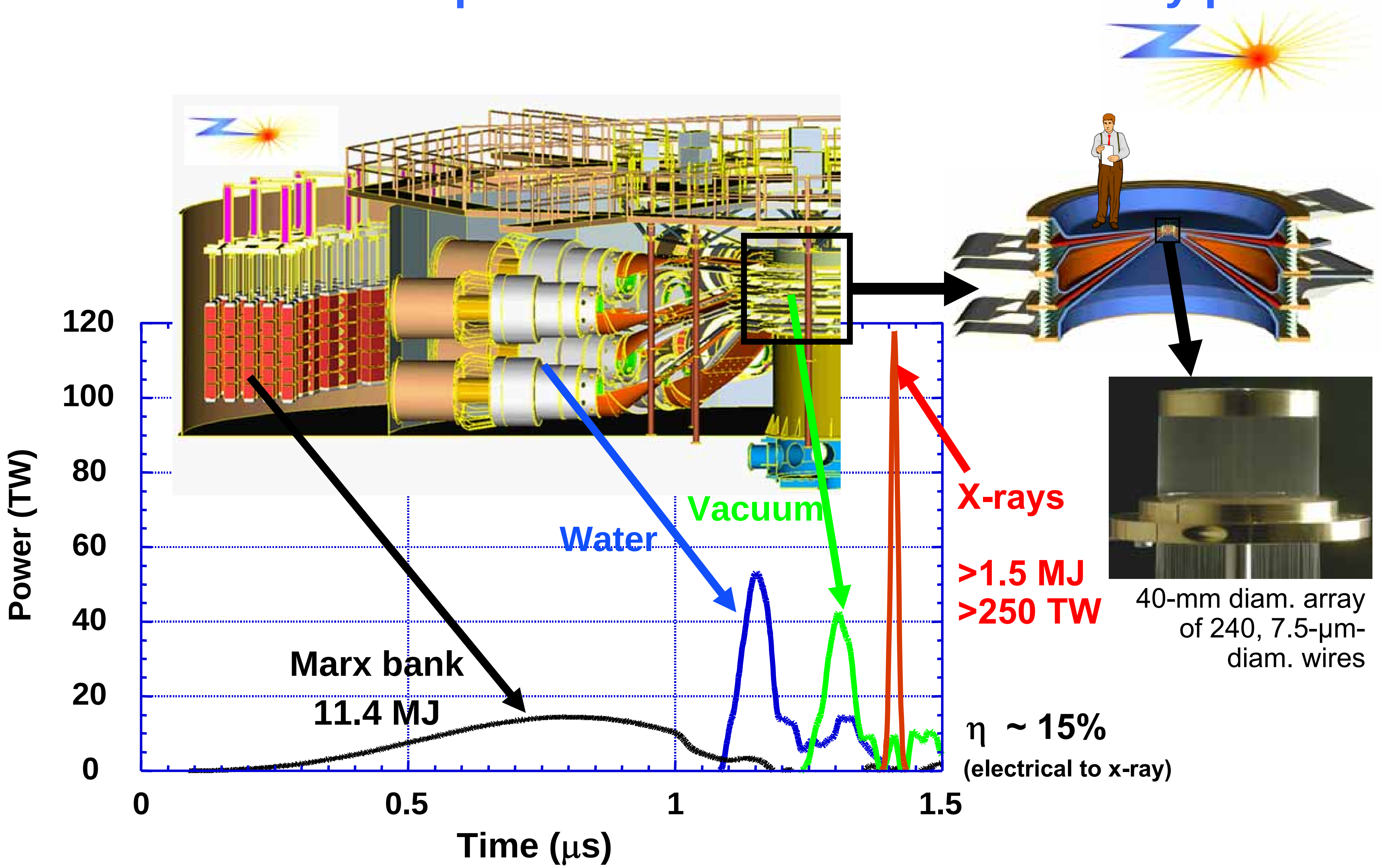


Z-machine



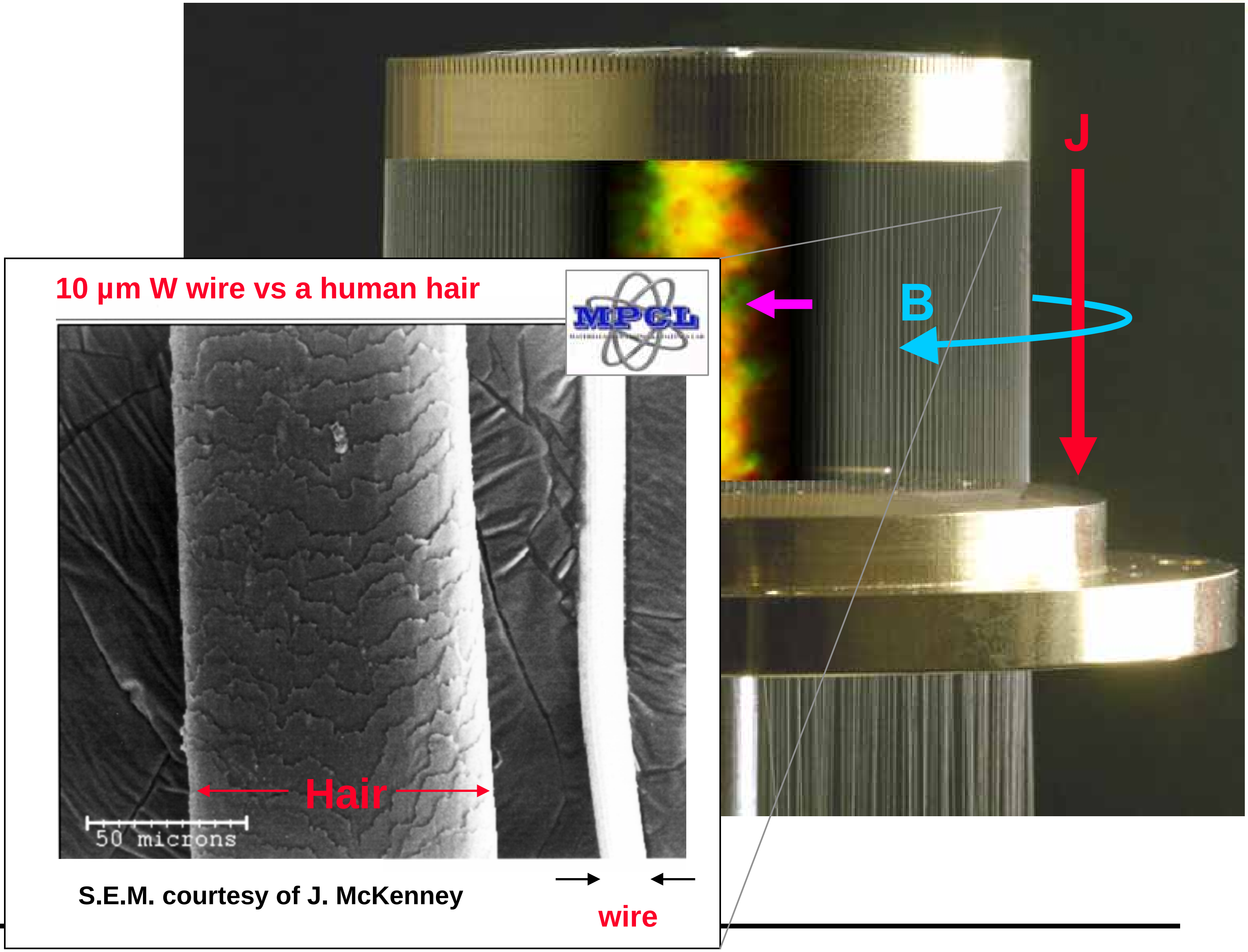
ZX concept

# Sandia's Z machine produces world-record soft x-ray powers

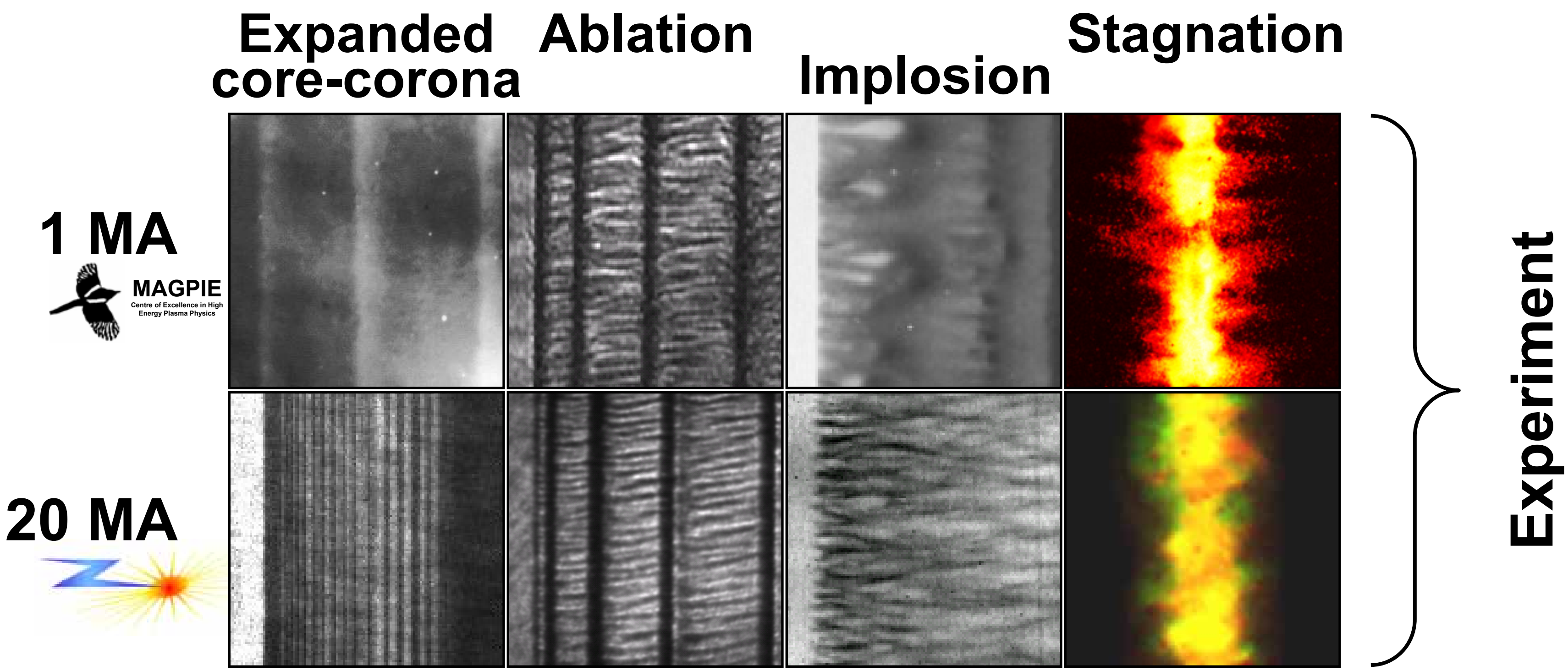



40-mm diam. array of 240, 7.5-µm-diam. wires

# J x B pinches wire array into a dense, radiating plasma



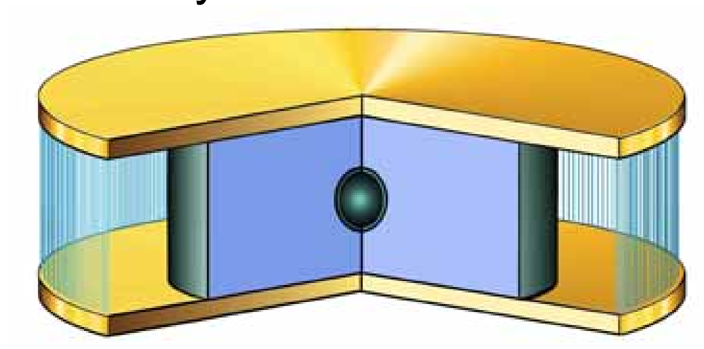
# Wire array dynamics are 3D

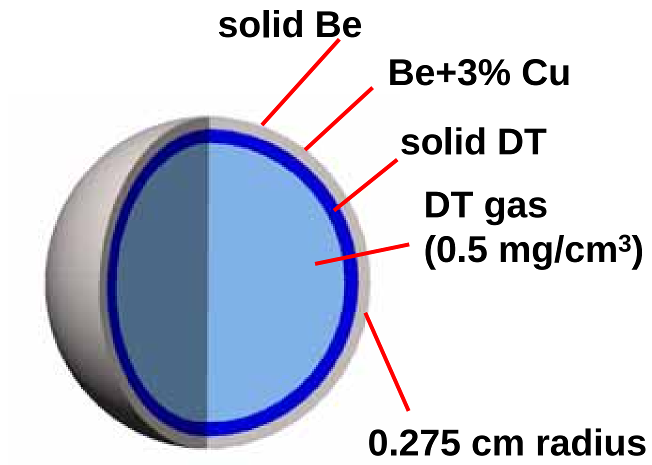


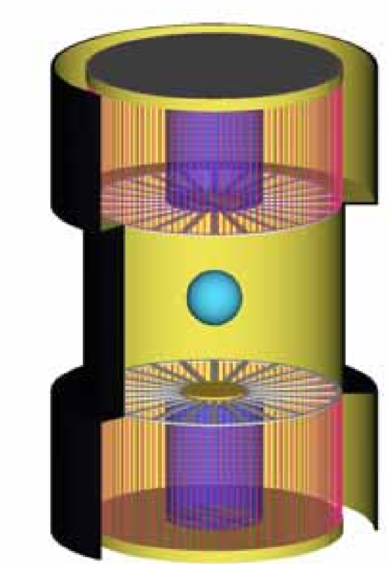

**Images courtesy of:** Brent Jones, Dan Sinars, Dave Bliss, Gennady Sarkisov, Christine Coverdale, Chris Garasi et al. (Sandia), Sergey Lebedev, Jerry Chittenden Malcolm Haines et al. (Imperial), Bob Clark, Jack Davis et al. (NRL), Darrell Peterson (LANL)

# High yield fusion is one of the major motivators for the z-pinch research at Sandia

Dynamic Hohlraum





Z-pinch Driven Hohlraum

**Important considerations:**

- Intensity of radiation incident
- Radiation symmetry
- Radiation pulse shape
- Mechanics of power station

| | |
|---|---|
| Peak drive temperature | 350 eV |
| In-flight aspect ratio | 48 |
| Implosion velocity | $3.3 \times 10^7$ cm/s |
| Convergence ratio | 27 |
| DT KE @ ignition | 50% |
| Peak density | 444 g/cm$^3$ |
| Total $\rho r$ | 2.14 g/cm$^2$ |
| Driver energy | 12 MJ |
| Absorbed energy | 2.3 MJ |
| Yield | 527 MJ |
| Burnup fraction | 34% |

Estimates predict 2 drivers, each 60MA required for ignition

Controlled radiation pulse-shape vital!

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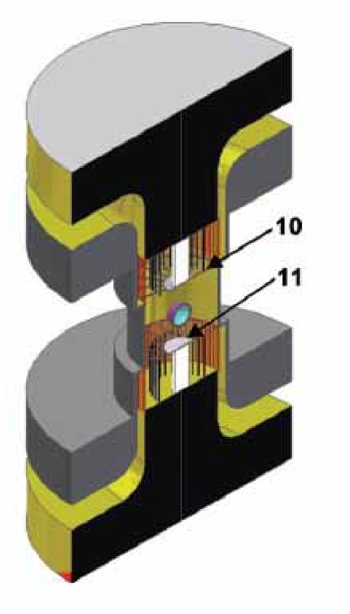
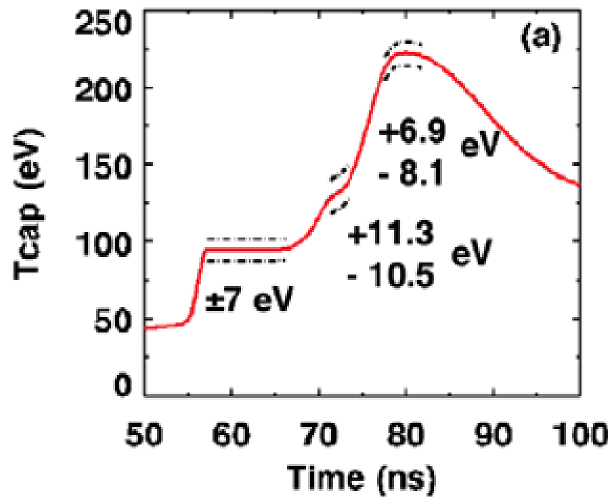
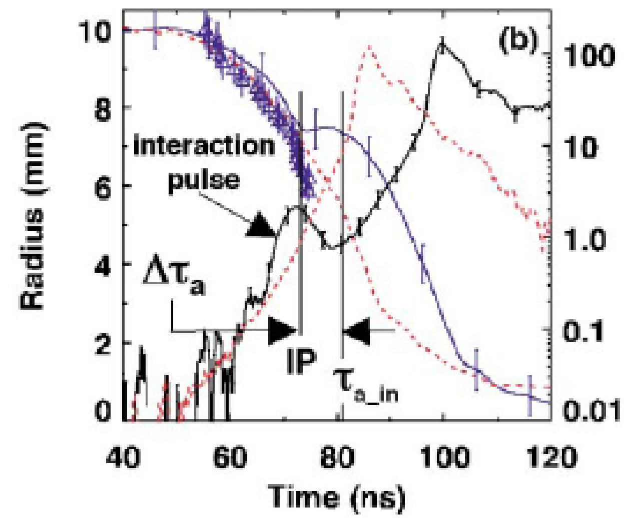
# Pulse shaping is vital to z-pinch ICF concepts




- 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
- Increasing energy density in the main pulse useful for ICF

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 / predicting Z data

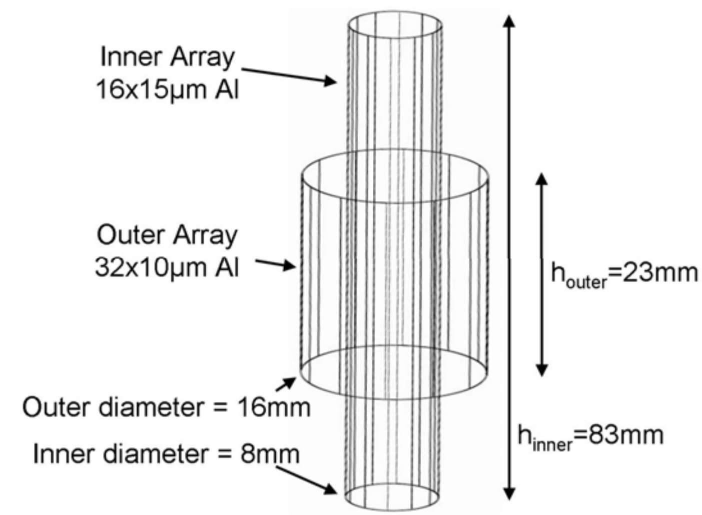
Aims:

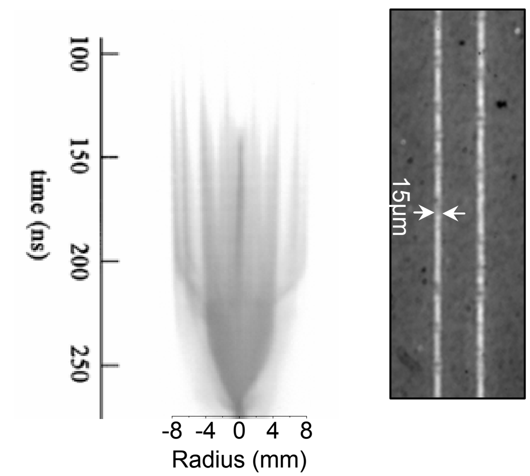
- Understand our present pulse shaping capability
  - New understanding of mechanism possibly responsible for interaction pulse
- New tools in the pulse-shaping toolbox
  - Look at what conical nested can bring to pulse shaping
- Novel arrays
  - Discuss experiments performed on Saturn to study elimination of cathode effects
  - Radial arrays will be discussed both for ICF and lab-astrophysics
  - Conical wire arrays will be discussed with regard to lab-astrophysics

**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

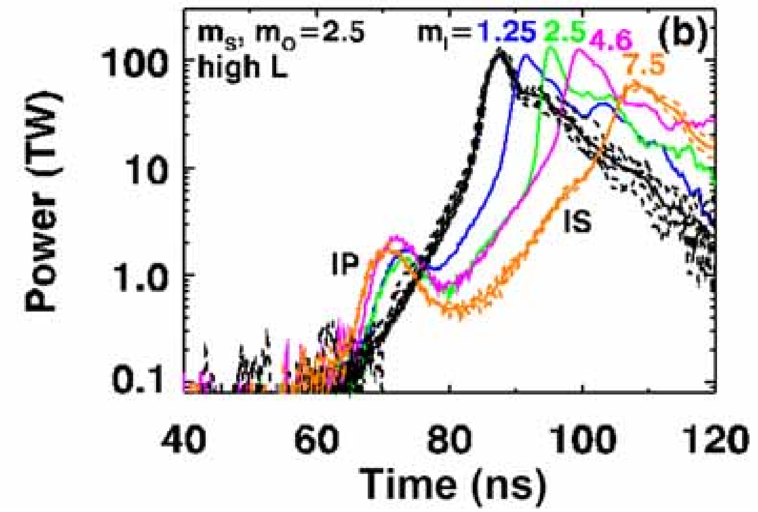


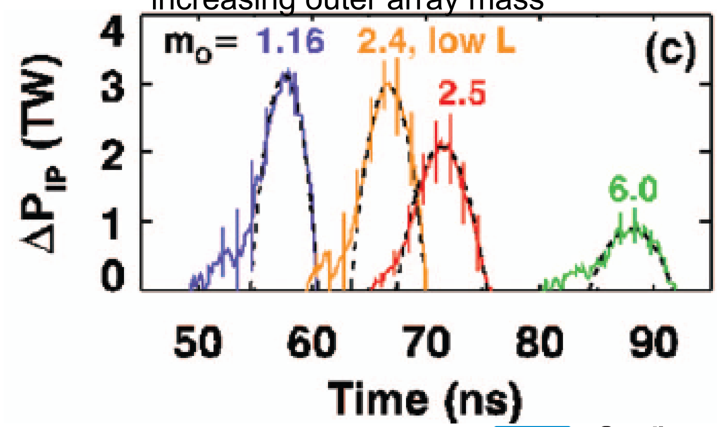
# Interaction pulse on Z is critical for pulse shaping, but remains a puzzle

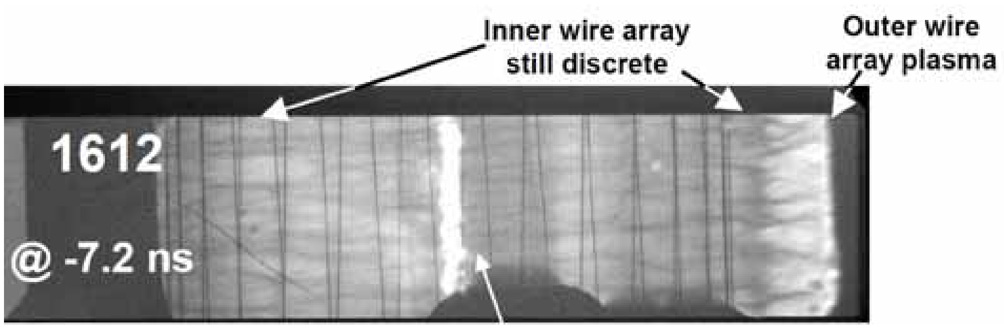
- Interaction energy measured is less than that predicted from hydrodynamic collision of outer and inner shells
- Nested arrays on Z now recognized to operate in a transparent mode
- Partial transparency cannot explain same power for different inner wire numbers
- Alternative models (e.g. ohmic heating,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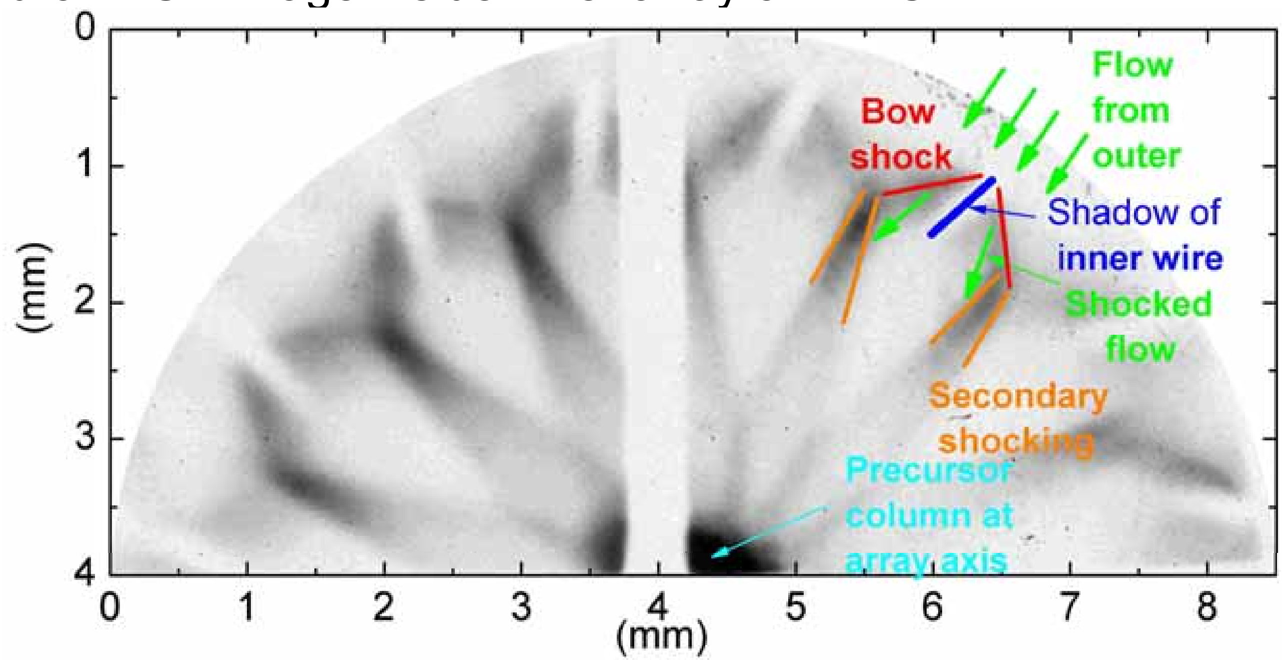
# Ablation streams from outer array are supersonic and will shock on the inner array

- 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

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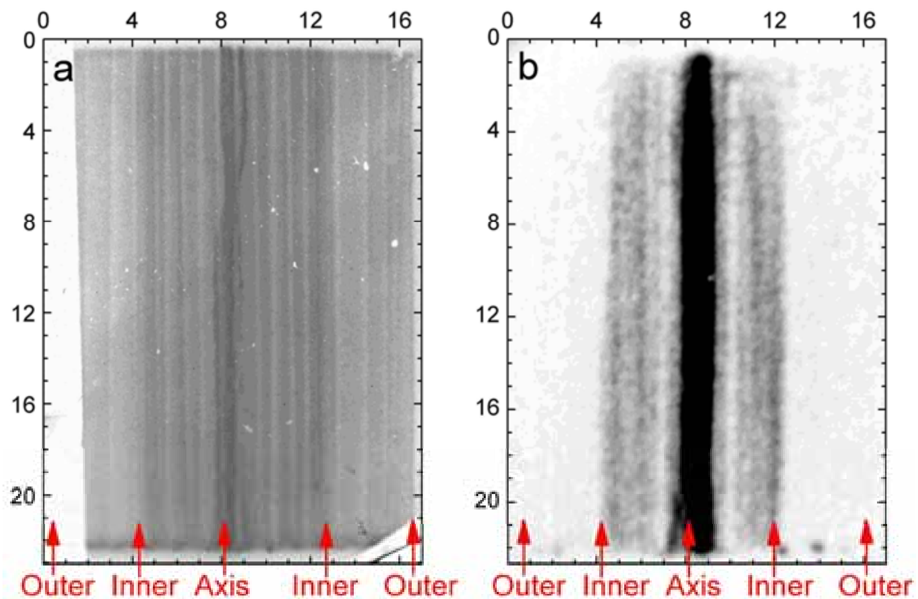
# Shock will perturb plasma conditions in streams as they pass inner

- Perpendicular component of stream velocity will be reduced across shock

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

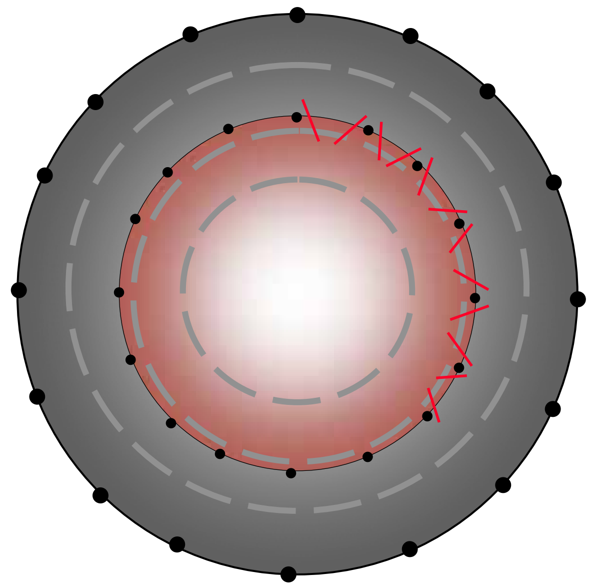
- Density will be increased by the compression ratio $\eta$
- Temperature of streams will also be increased
- Temperature and/or density jumps inferred from side-on emission imaging during ablation process
  - Definite change in plasma conditions near inner array, despite *'transparency'* :

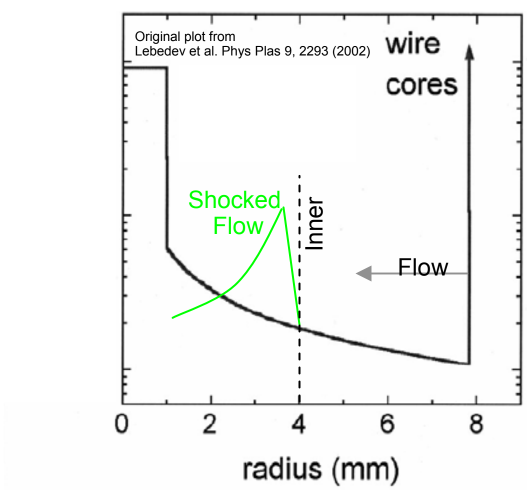



$h\nu > 30eV$ $h\nu > 220eV$

# 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, $\rho$ 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

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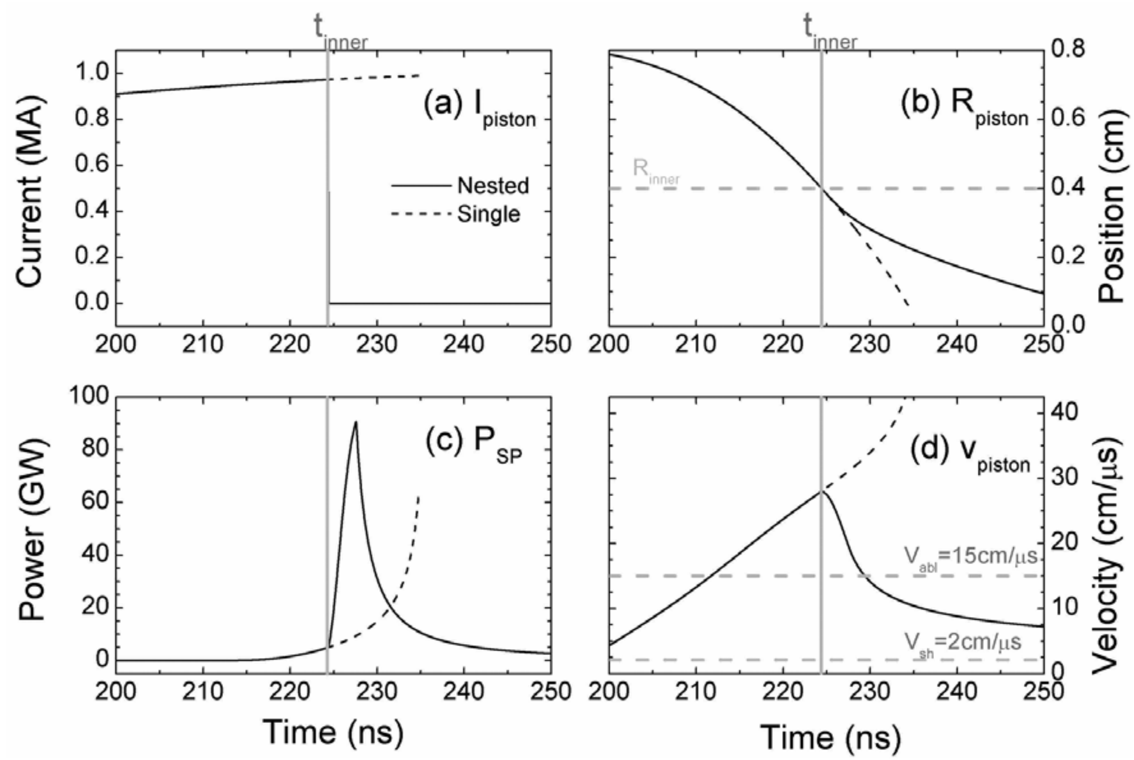
| Variable | MAGPIE | |
|---|---|---|
| $v_{abl}(cm/\mu s)$ [1, 2] | 15 | (Ablation velocity) |
| $c_s(cm/\mu s)$ [2–4] | 3 | (Sound speed) |
| $\beta$ (end-on image) | 39° | (Shock angle) |
| $\gamma$ [5] | 1.1 | (Adiabatic index) |
| $M_\perp = \frac{v_a sin(\beta)}{c_s}$ | 3.4 | (Mach numb perp) |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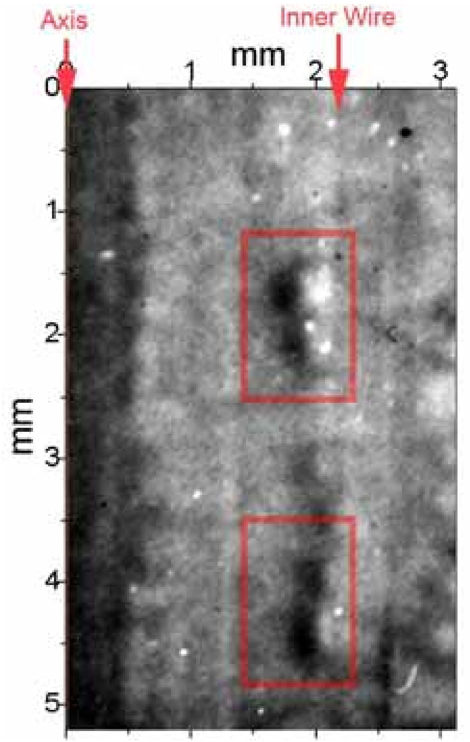


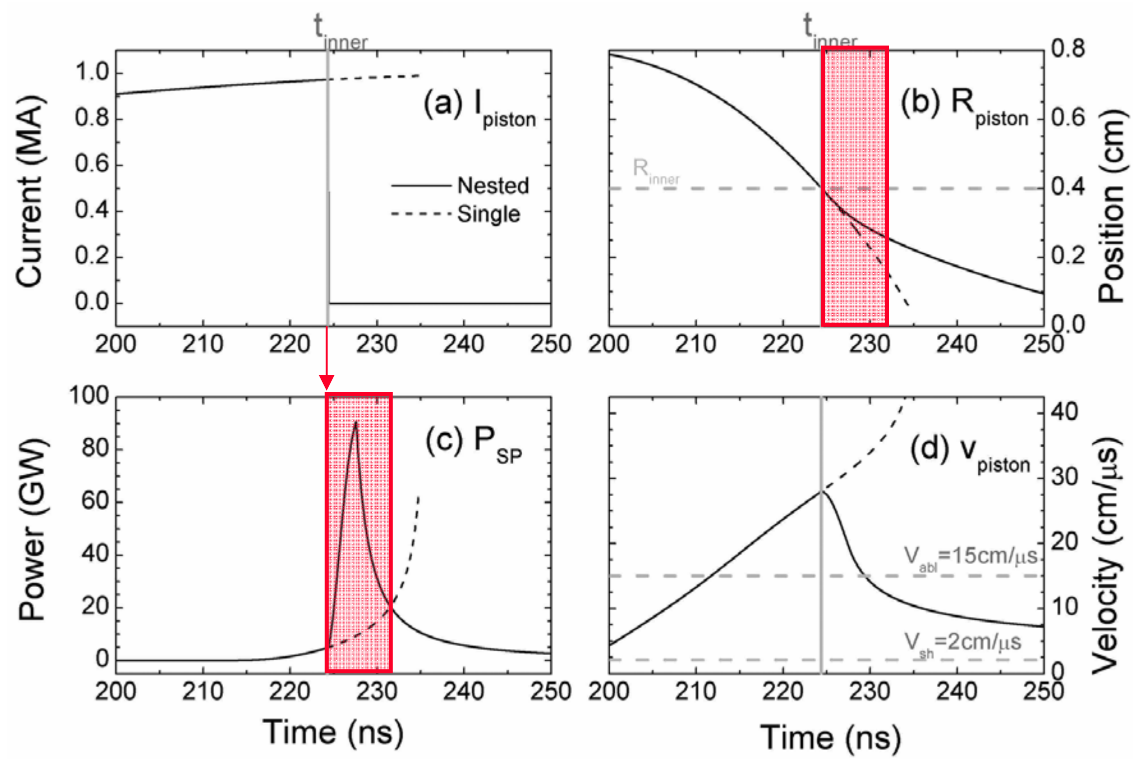


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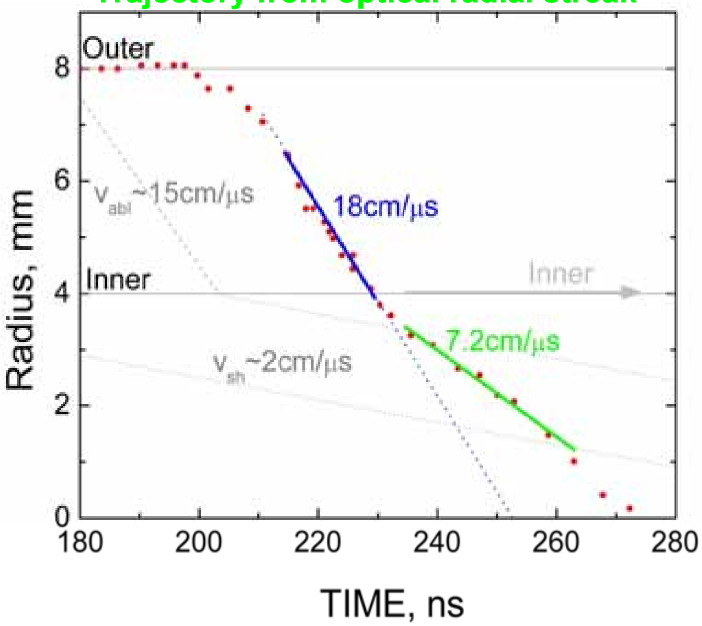
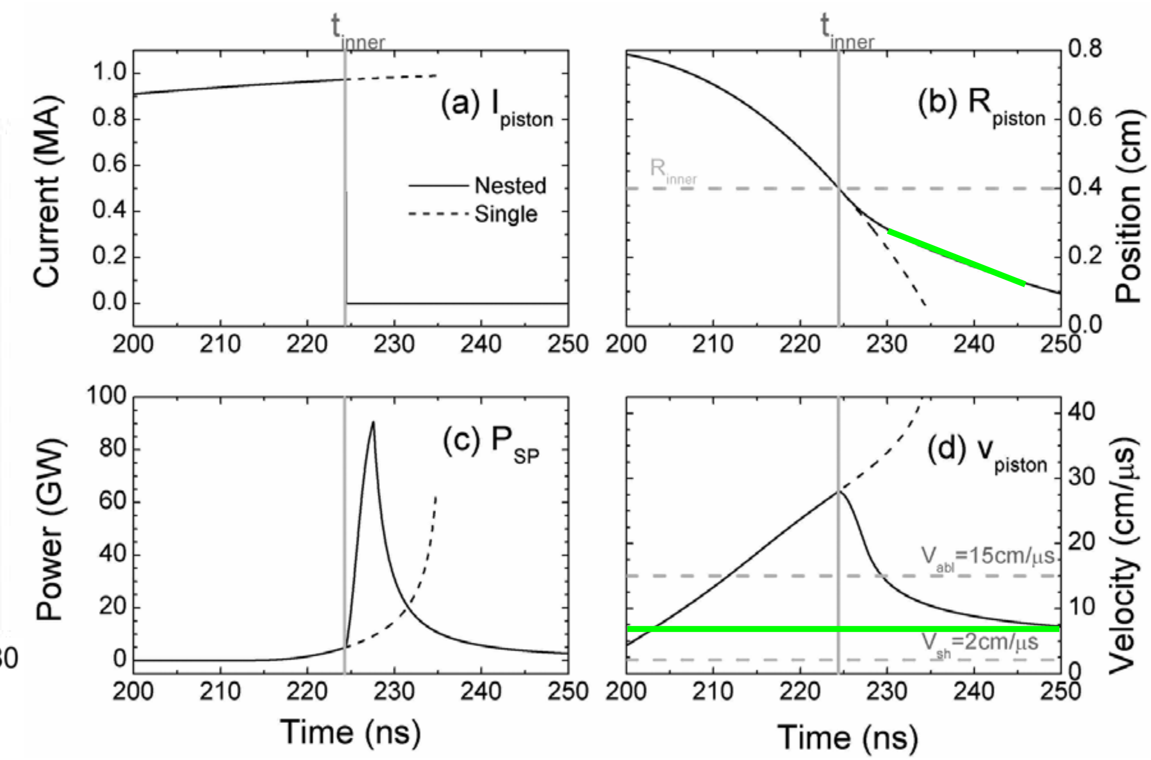
Trajectory from optical radial streak

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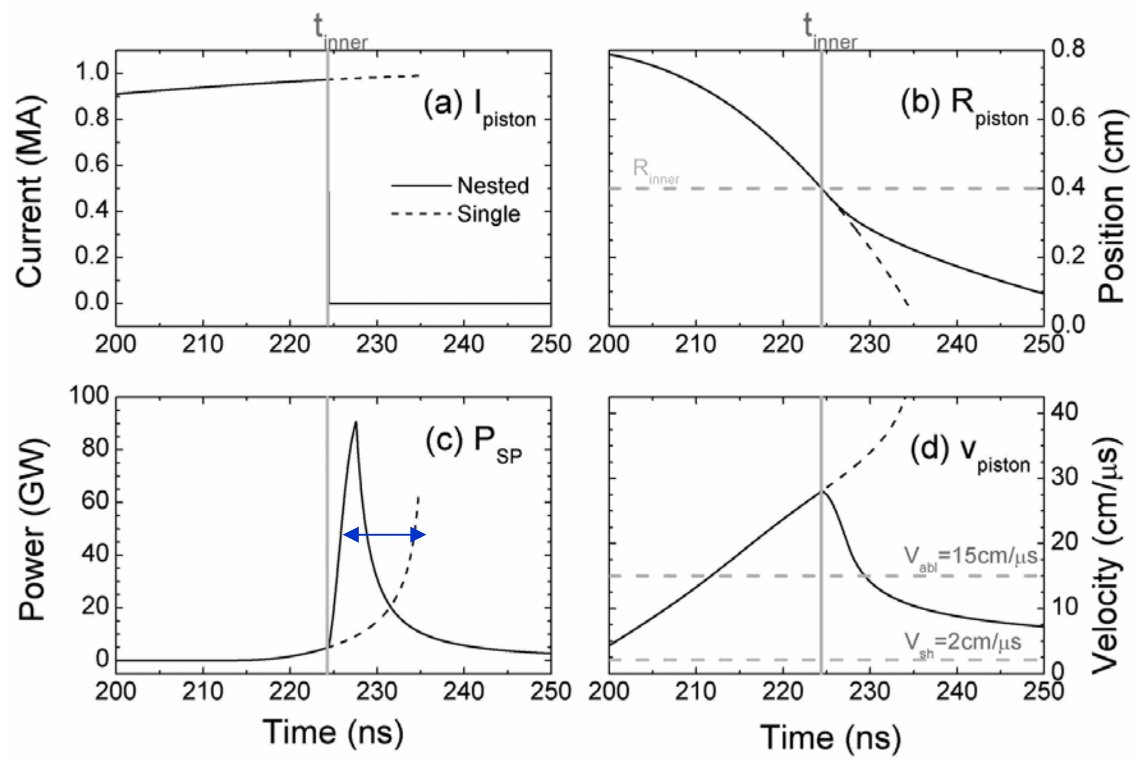
| $\beta$ (end-on image) | 39° |
| $\gamma$ [5] | 1.1 |
| $M_\perp = \frac{v_a \sin(\beta)}{c_s}$ | 3.4 |
| $\eta = \frac{v_{abl}}{v_{sh}}$ | 7.7 |

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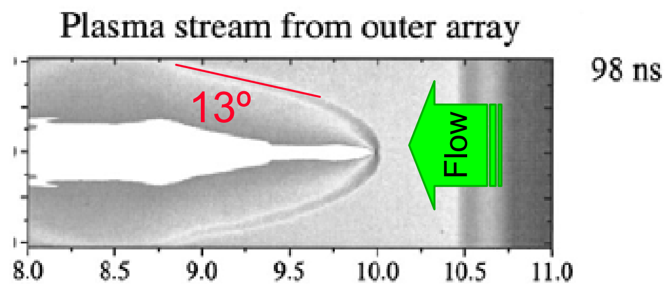
# Applying similar model to a (more uniform) Z implosion allows a comparison of powers

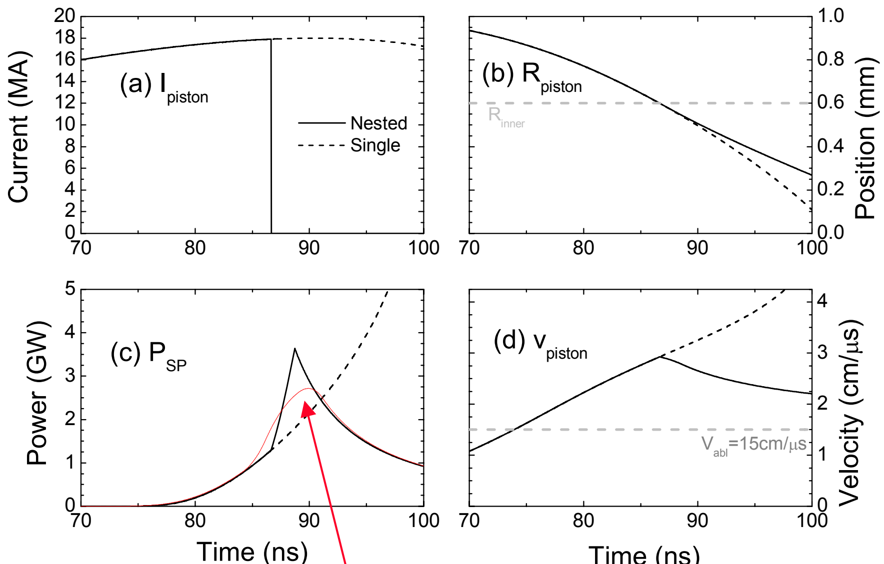
| Variable | MAGPIE | Z-6mg |
|---|---|---|
| $v_{abl}(cm/\mu s)$ [1, 2] | 15 | 15 |
| $c_s(cm/\mu s)$ [2–4] | 3 | 1.3 |
| $\beta$ (end-on image) | 39° → | 5° |
| $\gamma$ [5] | 1.1 | 1.1 |
| $M_\perp = \frac{v_a sin(\beta)}{c_s}$ | 3.4 | 1.25 |
| $\eta = \frac{v_{abl}}{v_{sh}}$ | 7.7 | 1.5 |

## Shock angle smaller in sims of Z than measured on MAGPIE

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



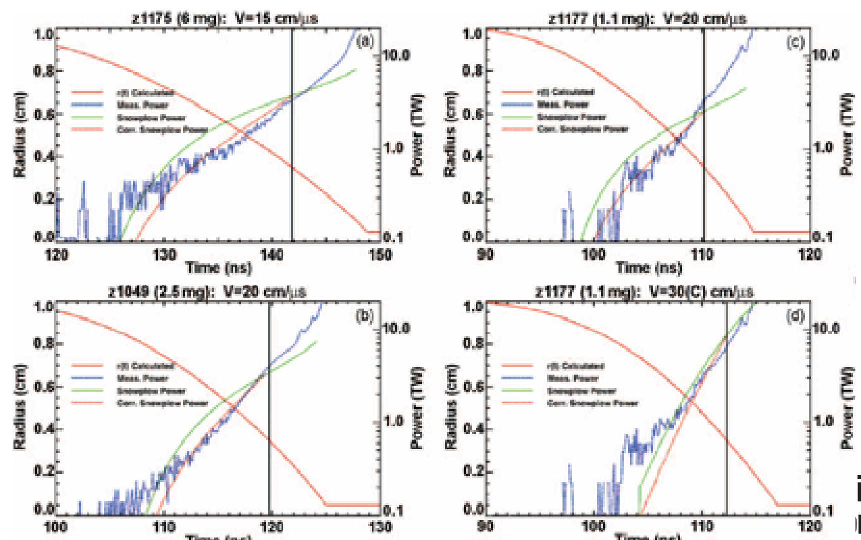

- Unclear whether MHD best tool for this problem
- Further simulations planned by Ciardi & Sherlock using hybrid code




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 |
|---|---|---|---|---|---|
| $v_{abl}(cm/\mu s)$ [1, 2] | 15 | 15 | 20 | 30 | 25 |
| $c_s(cm/\mu s)$ [2–4] | 3 | 1.3 | 1.3 | 1.3 | 1.3 |
| $\beta$ (end-on image) | 39° | 5° | 5° | 5° | 5° |
| $\gamma$ [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 |
| $\eta = \frac{v_{abl}}{v_{sh}}$ | 7.7 | 1.5 | 2.5 | 5.0 | 3.7 |
| $E_{Sp}(kJ)$ | - | 3.0 | 12.4 | 22.5 | 15.3 |
| $E_{Exp}(kJ)$ [6] | - | 5.2 | 12.1 | 15.0 | 15.0 |
| $P_{Sp}(TW)$ | - | 0.7 | 2.8 | 5.1 | 3.5 |
| $P_{Exp}(TW)$ [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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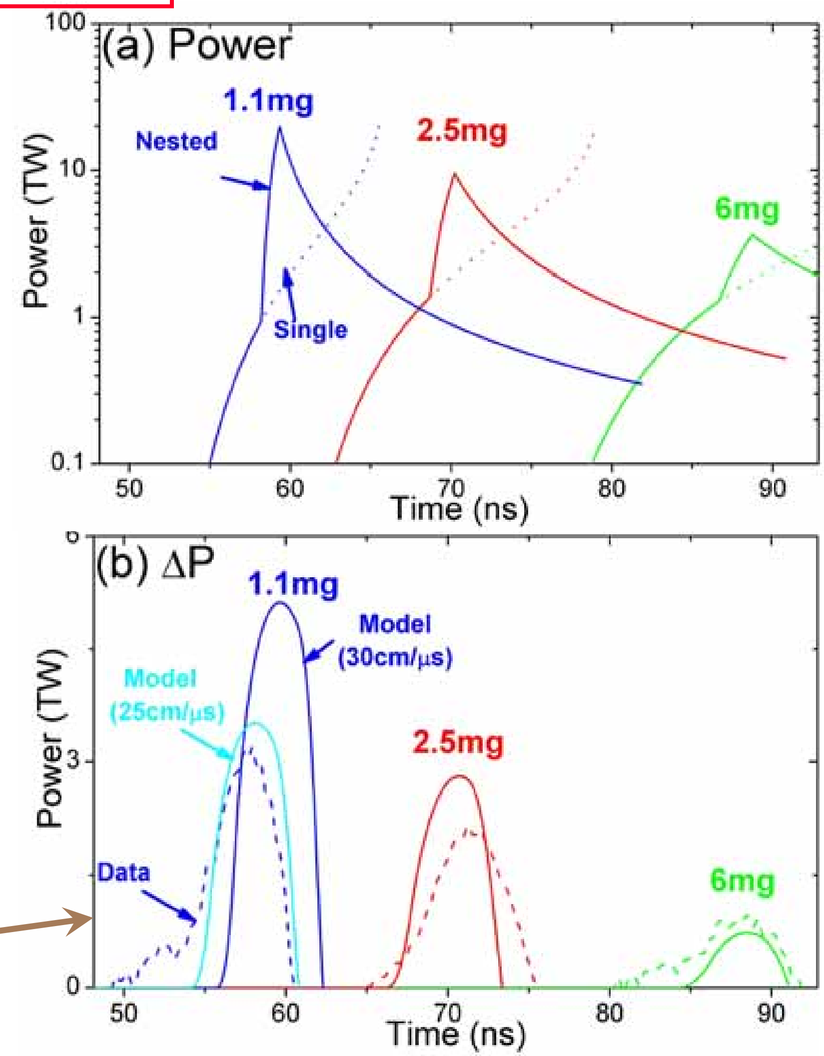
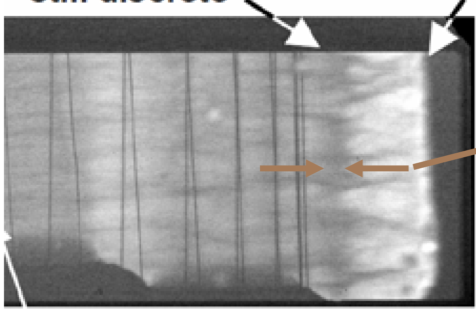



Inner wire array still discrete

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**

# Upcoming experiments will aim to better diagnose shocks on MAGPIE, for both W & Al

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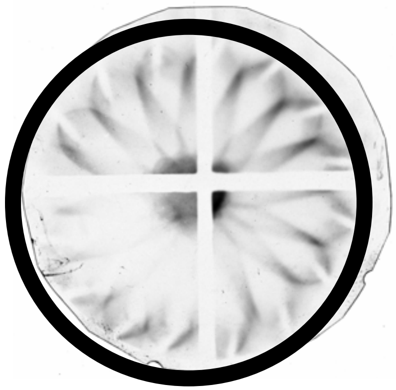
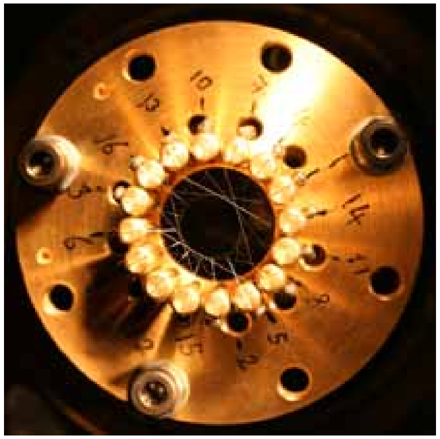
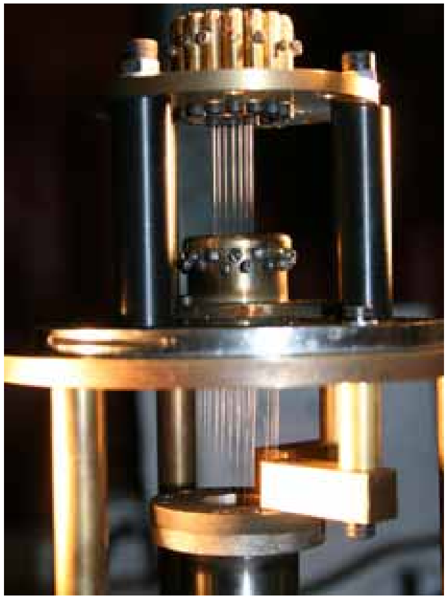
- Normal nested array hardware prevents the end-on viewing of the streams prior to meeting the inner array
- We do not need to see the full evolution of the nested wire array to image shock structures and diagnose jump conditions
- New array configuration aims to allow imaging of streams before and after passing the inner array
- Potentially evaluate shock jump conditions using end-on diagnostics, and investigate differences between W & Al







Hardware design (*Spider Array*) and photos courtesy of Dr G.N. Hall (Imperial)

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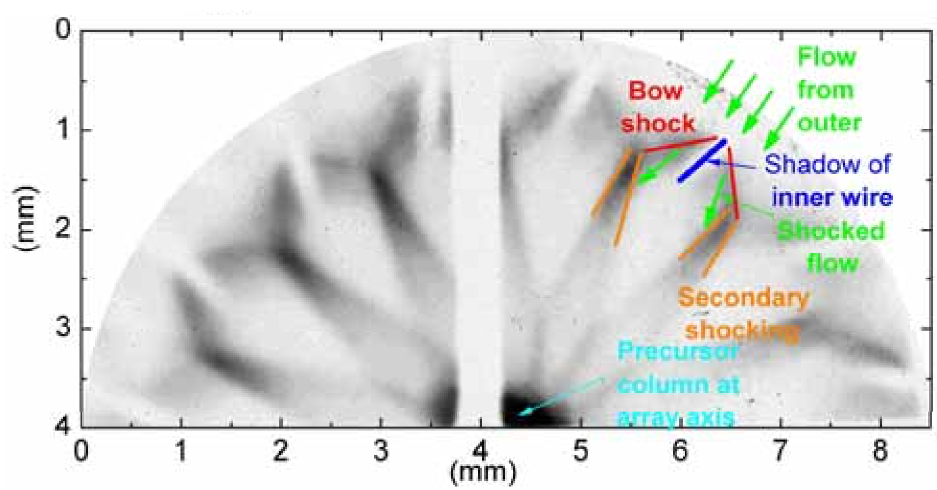
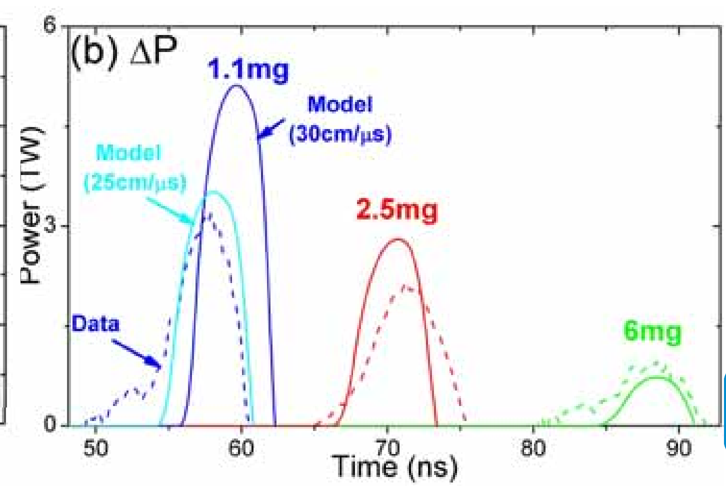
# Part 1 Summary : Perturbed snowplow can lead to observed Interaction Pulse

- 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



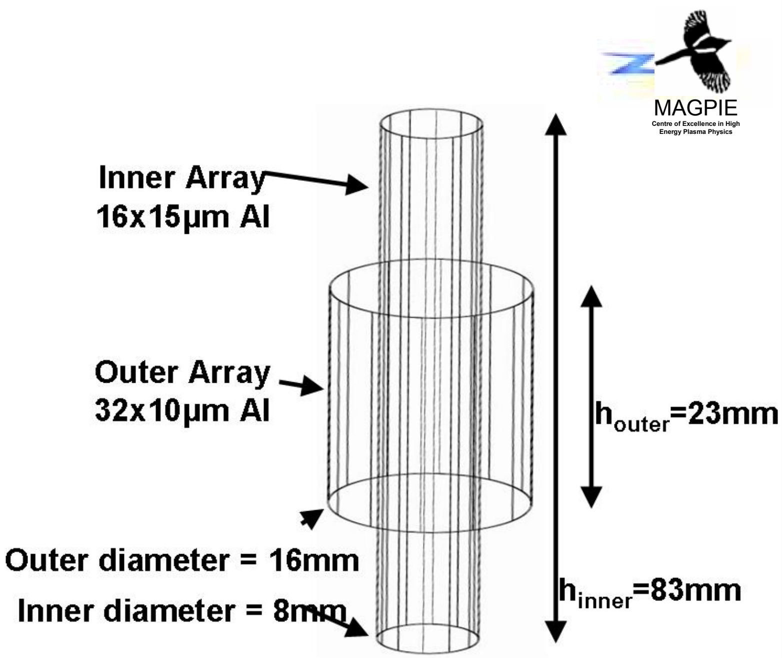



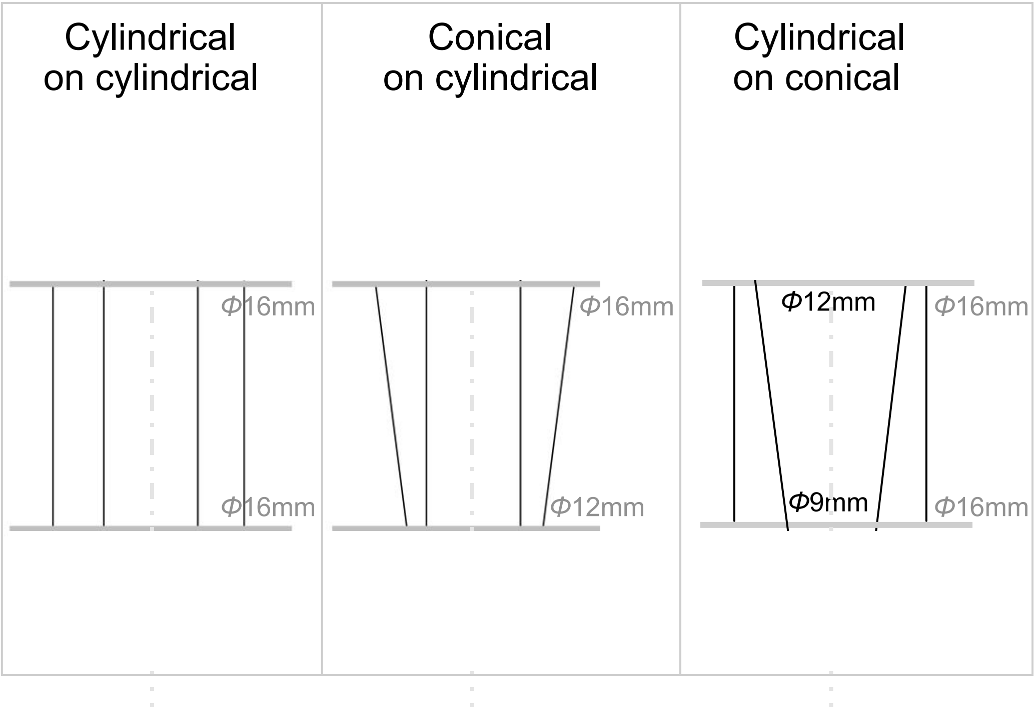
# Part 2: Conical nested arrays may be able to enhance control of x-ray pulse

- 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

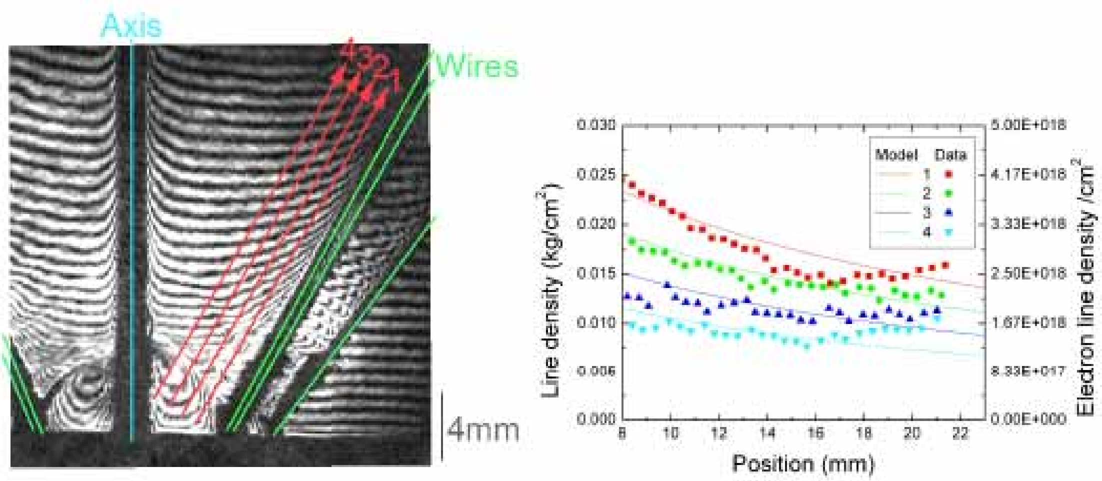
- With conical outer array the global field strength is varied along the length of the wire

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

- 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

D.J. Ampleford, PhD Thesis, Imperial College London, 2005
D.J. Ampleford et al., to be submitted

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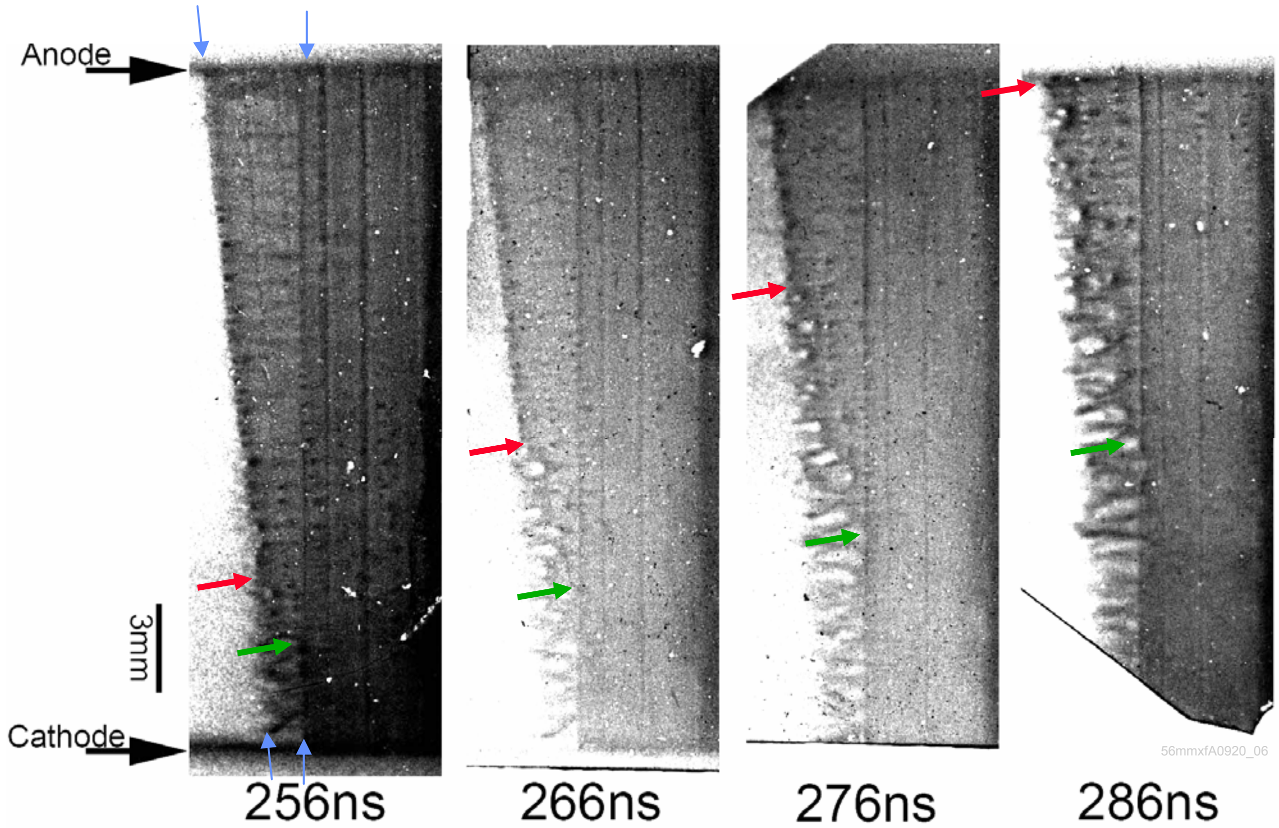
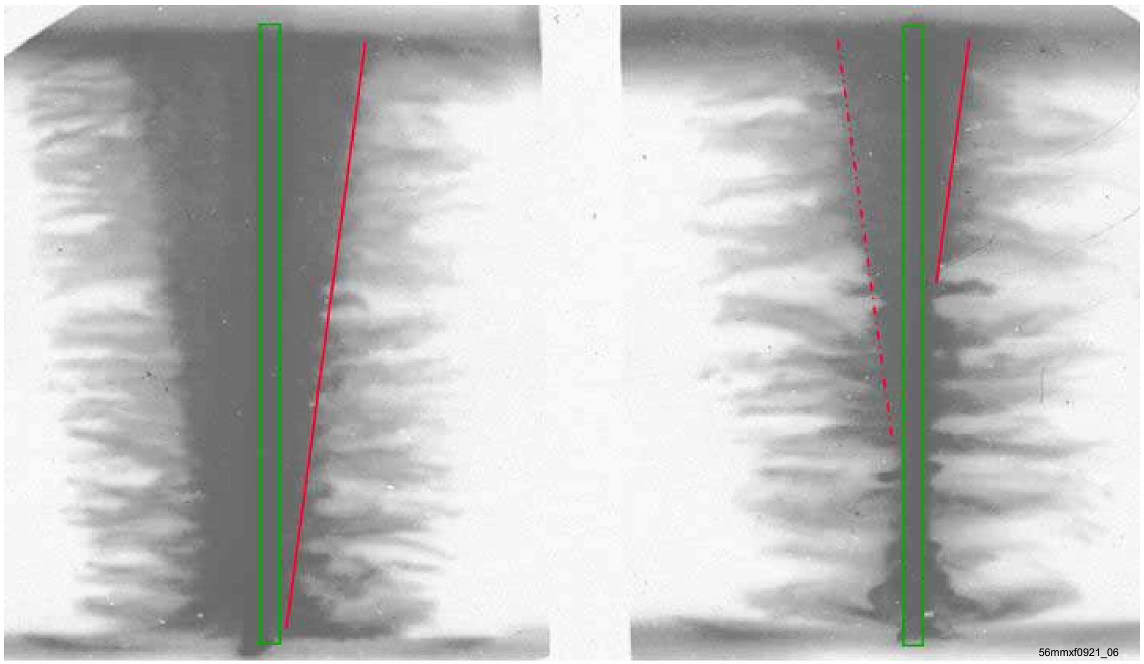
# A conical outer array can be used to seed an axial zipper

- 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 change in implosion position 13.9mm in 10ns
- Implies zipper velocity ~139cm/μs
- Zipper can be extrapolated to estimate zipper along full axis $\Delta t_{zip}$~16.5ns
- On MAGPIE, left-right asymmetry also present due to concentricity issue,
  - will effect pulse, but temporal effect is less ($\Delta t_{L-R}$~7ns)

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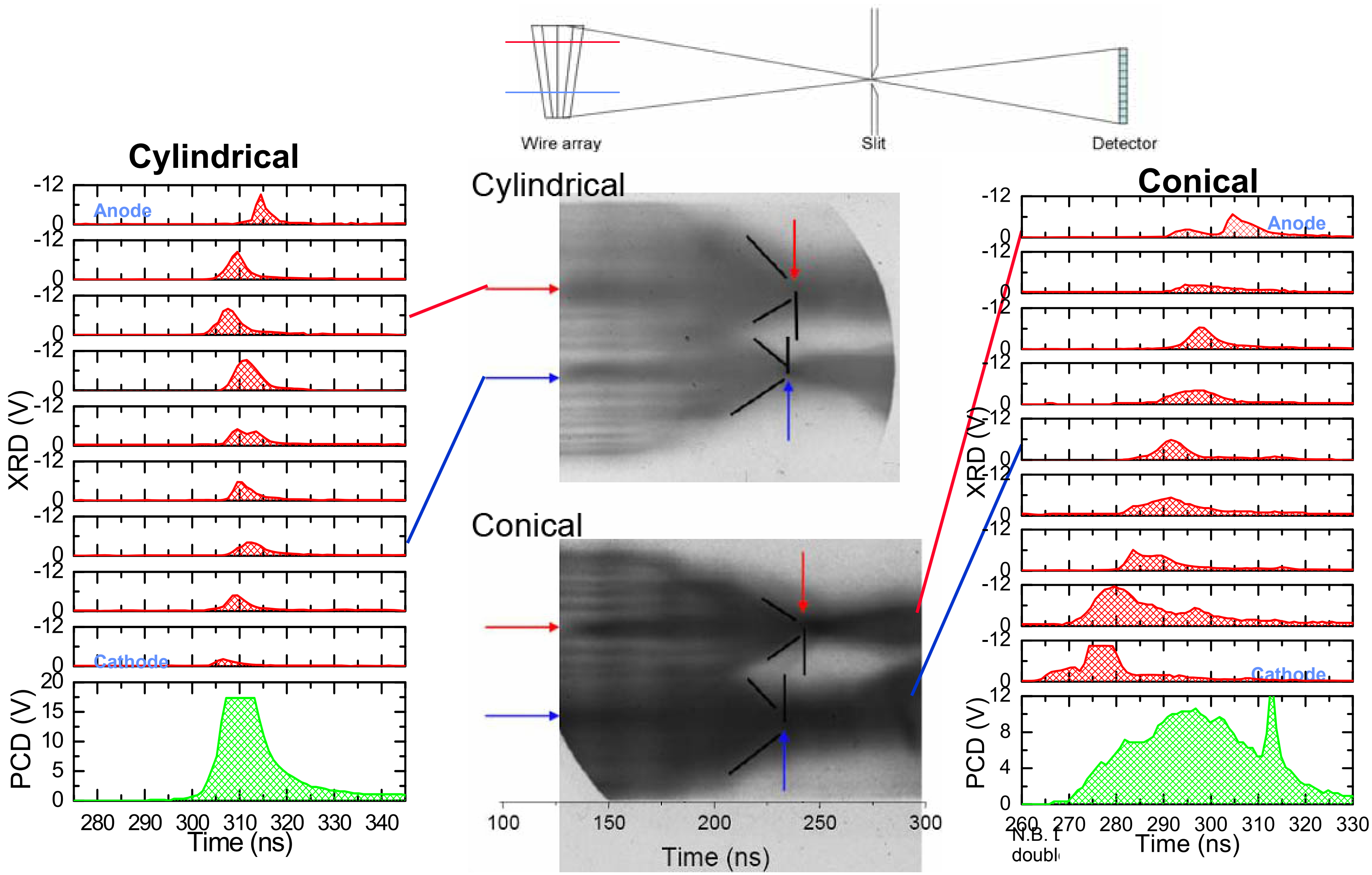
# Seeded zipper translates into a zippered stagnation, and elongated x-ray pulse

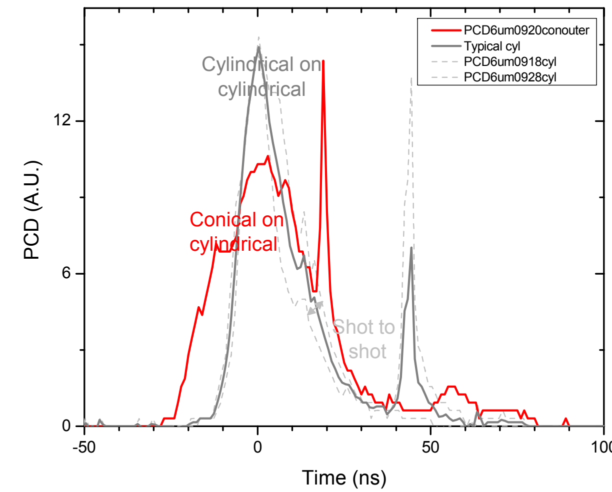
- Twin radial optical steak and zipper array each indicate conical outer zippers stagnation
- Axial dependence of stagnation time leads to pulse lengthening



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

**For conical outer on MAGPIE:**

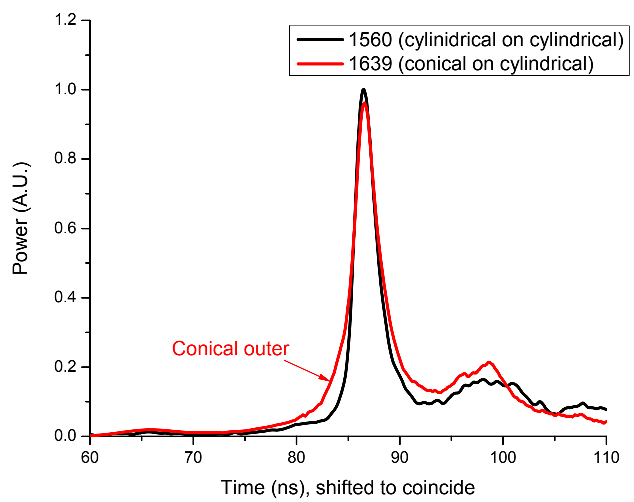
- See a longer rise in x-ray pulse with outer array
- Peak power down,
- Total energy similar (possibly 25% higher for conical outer)

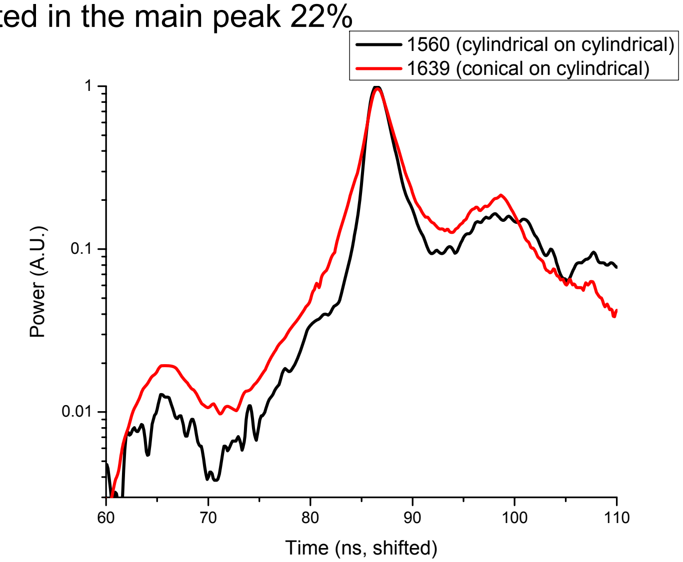



**For conical outer on Z:**

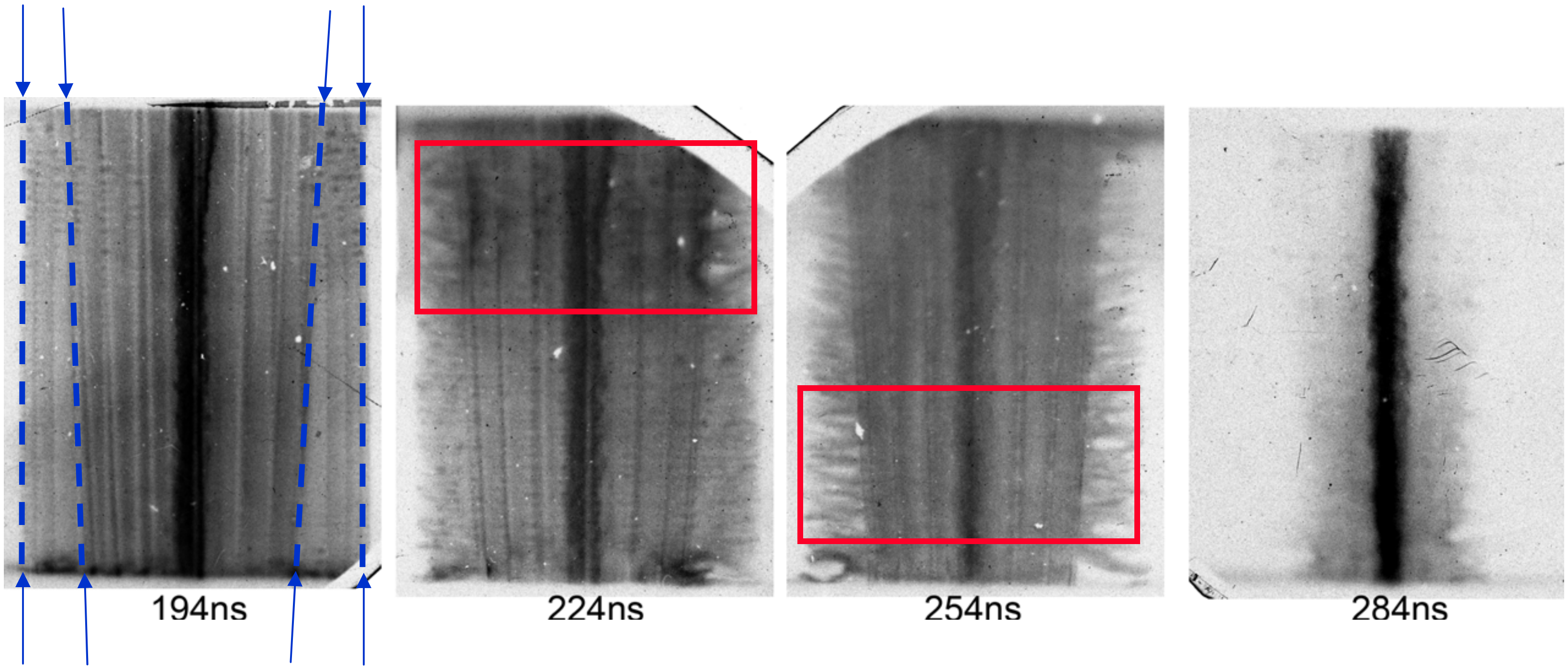
(Z1639, Cuneo et al., 22mm Cathode, 20m anode, 12mm inner)

- 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

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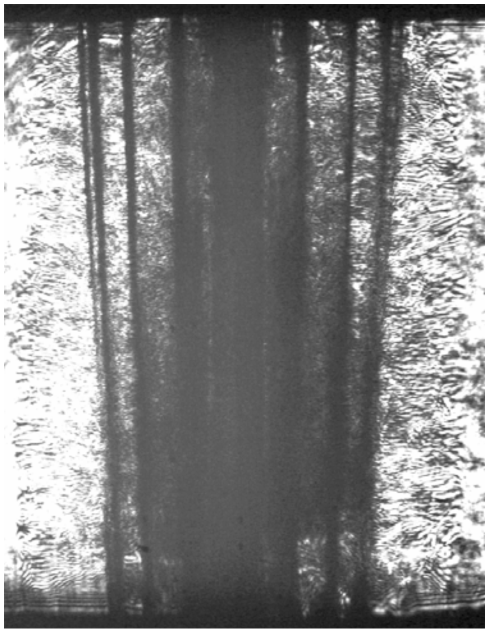
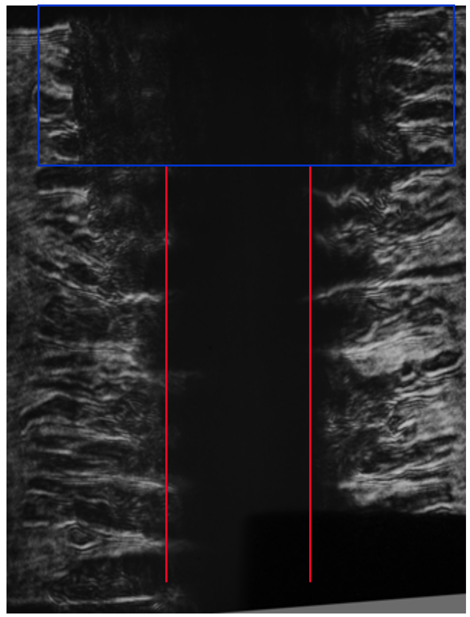
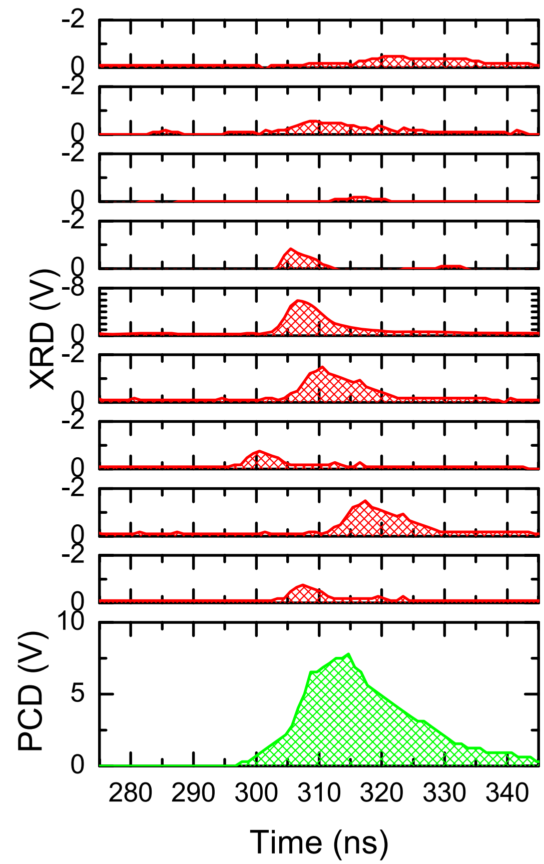
# Nested array with conical inner does not globally zipper stagnation on MAGPIE, but would alter Interaction Pulse



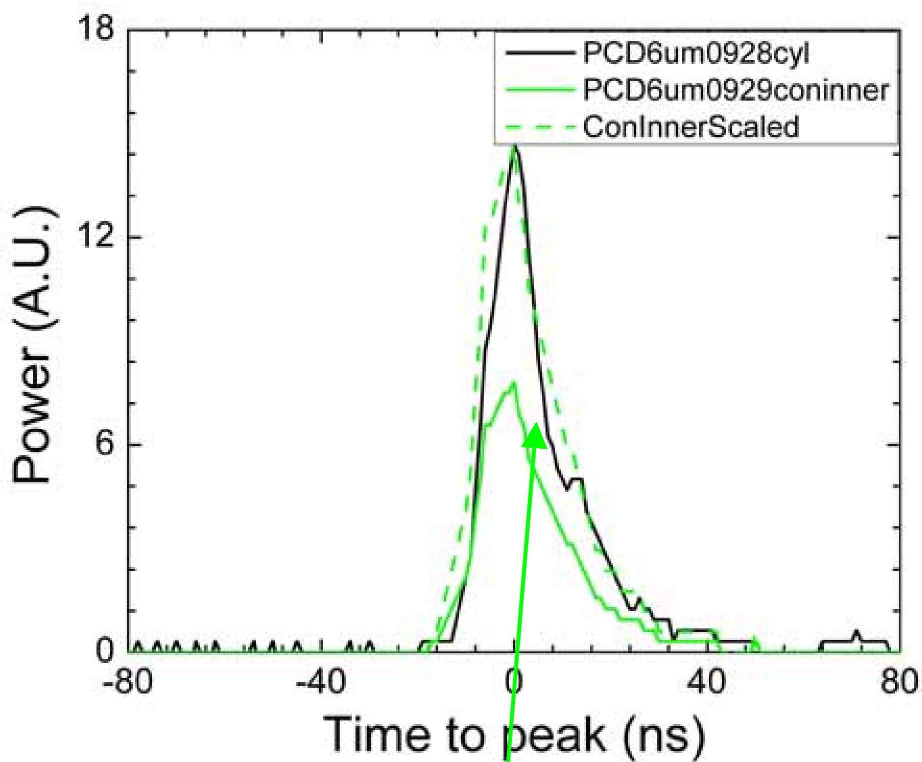




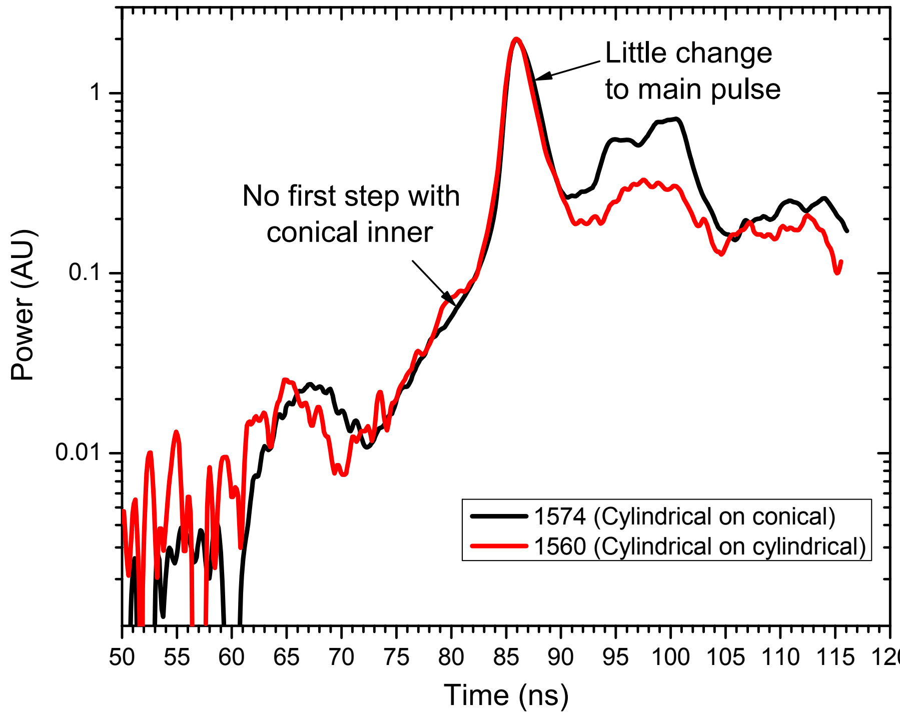

- Laser imaging after interaction indicates no substantial zipper
- Zipper array confirms no zipper in stagnation
- Laser imaging does show top section does not participate in implosion

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

**MAGPIE:** PCD (hv>200eV)

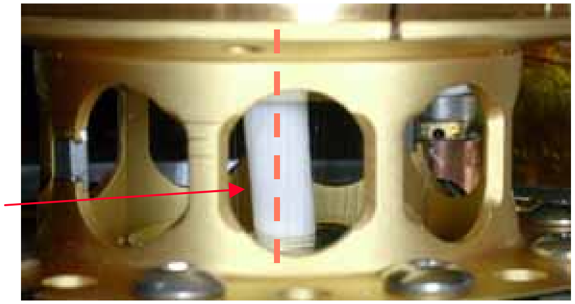



**Z:** XRD (Z1574, Cuneo et al.)

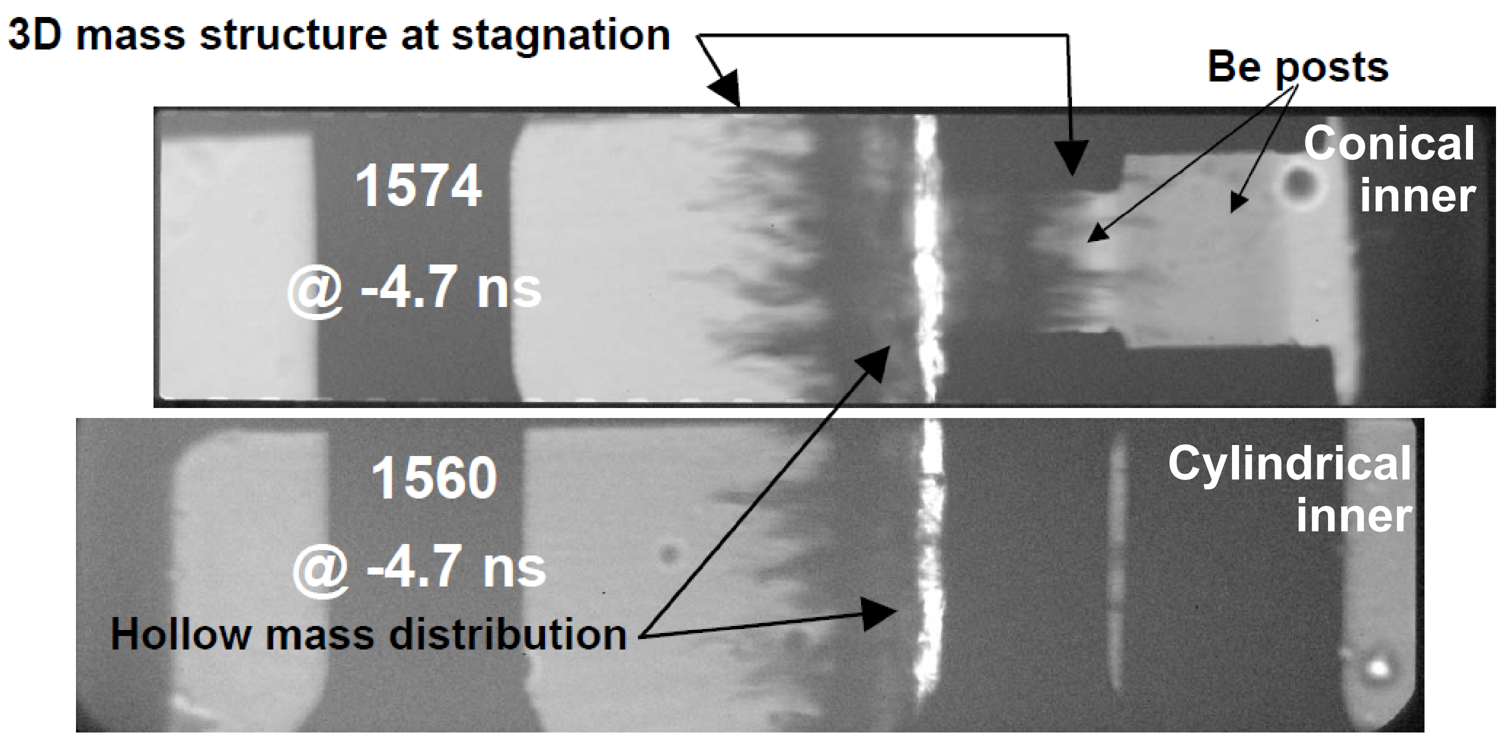



MAGPIE power lower than cylindrical
due to part of array not participating in implosion

Lack of first step on Z may be related to foam position

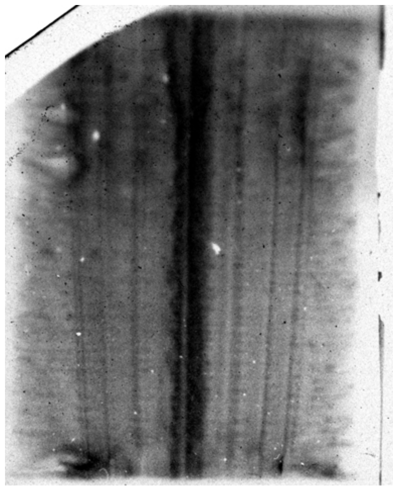


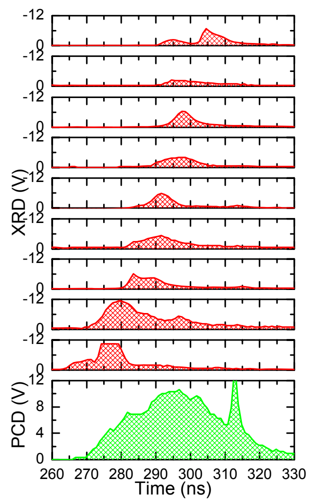
# Radiography on Z indicates no zipper present after interaction




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

# Part 2 Summary: What can we now control

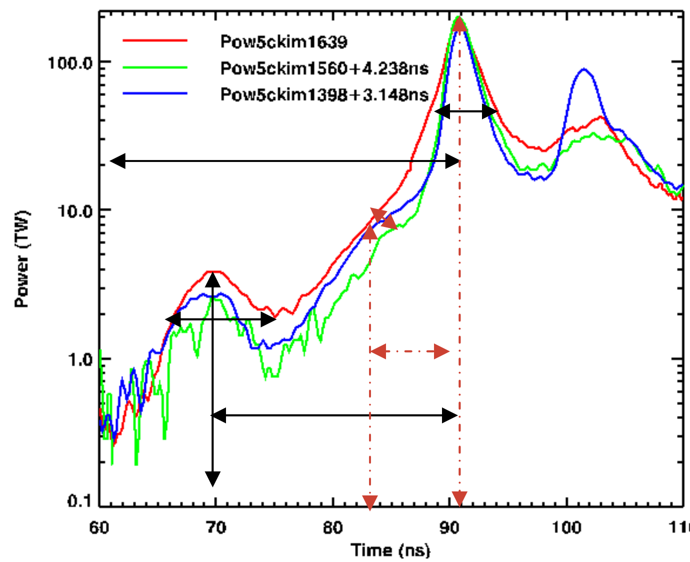





- Conical inner can control
  - Time scale of interaction
- Conical outer can control
  - Time scale of interaction (MAGPIE)
  - Time scale of main stagnation
- Need a more quantitative comparison

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

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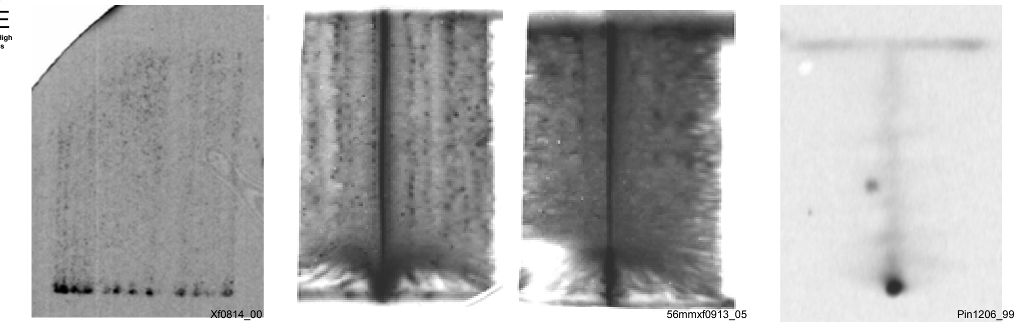
## XUV and soft x-ray imaging on MAGPIE

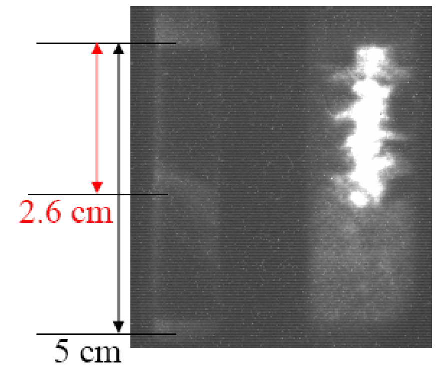
S.N. Bland et al. Rev Sci Inst 75, 3941 (2004)




MAGPIE: 92ns 239ns 249ns Time integrated

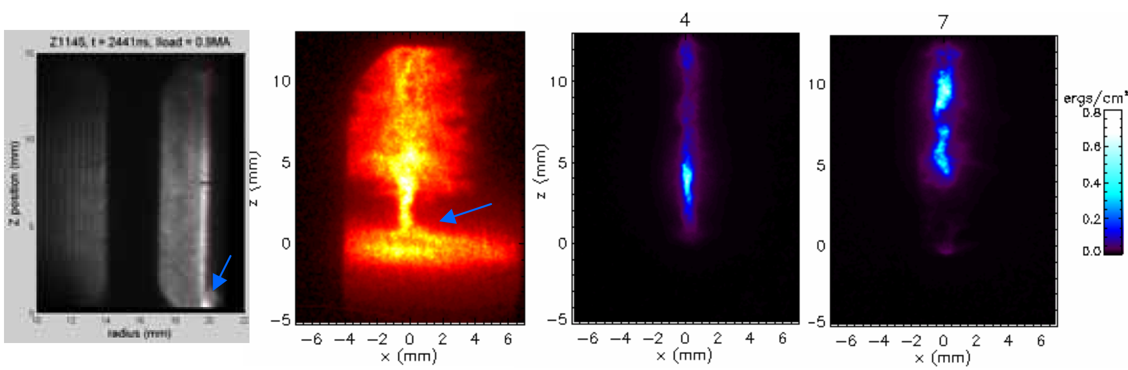
## Optical self emission on Sphinx at Gramat

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




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

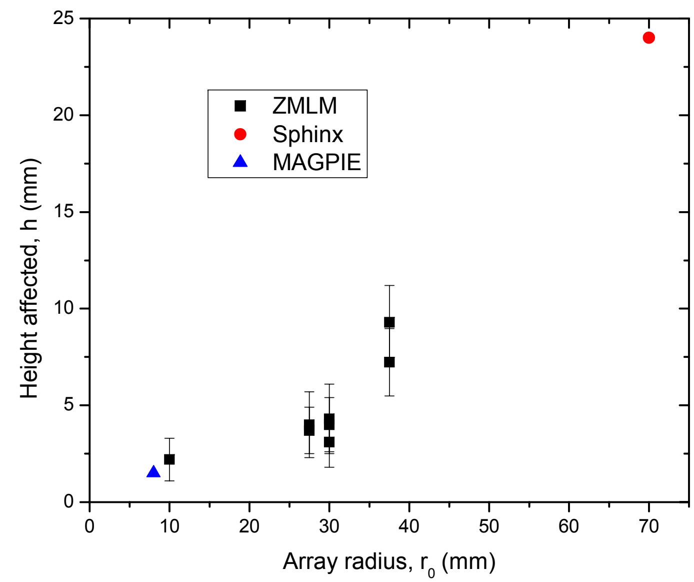
B. Jones et al. Rev Sci Inst 75, 4029 (2004)




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




Data and diagnostics from:

*B. Jones, C.A. Coverdale, D. Bliss, T.W.A. Sanford et al. (SNL),*
*H. Calamy (CEA), S.N. Bland, S.V. Lebedev & J.P. Chittenden (IC)*

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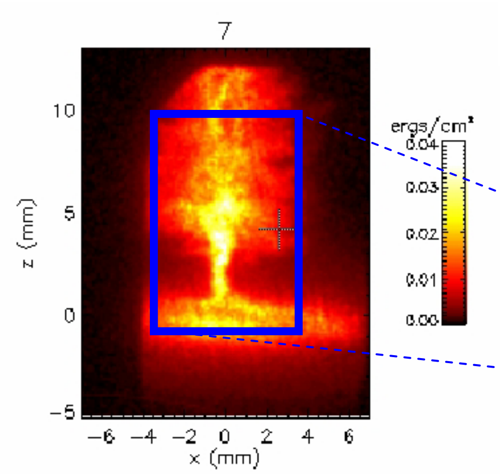
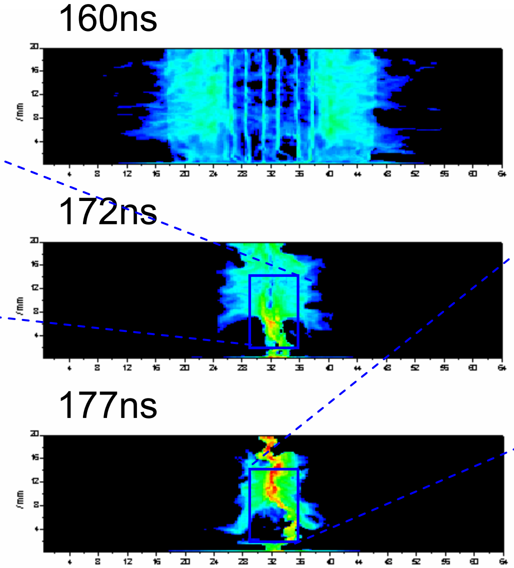
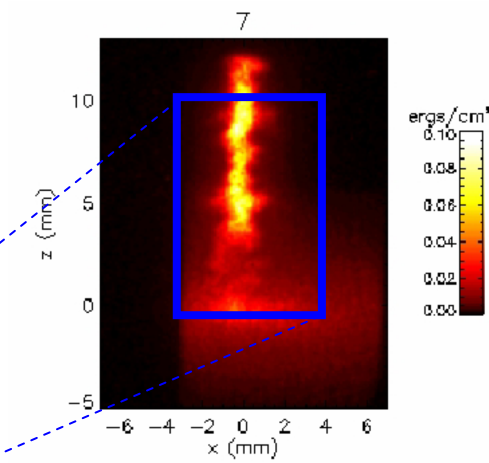
# Simulations can reproduce effect and show possible mitigation with step

Integrated emission profiles



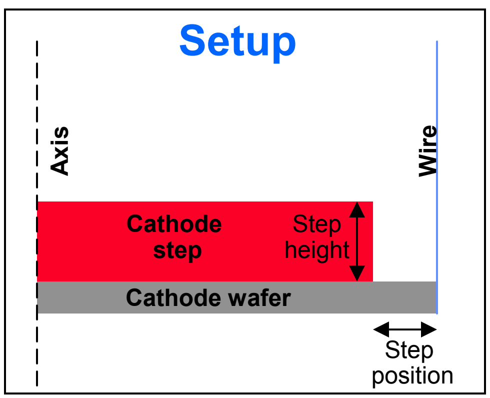



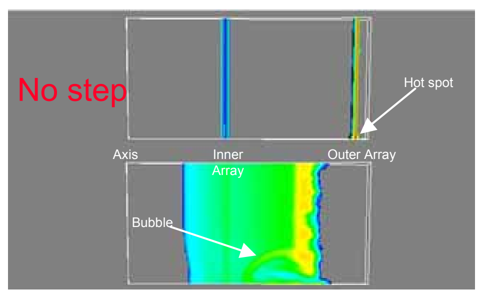

Bubble initiated with 0.5eV hotspot at the base of each wire

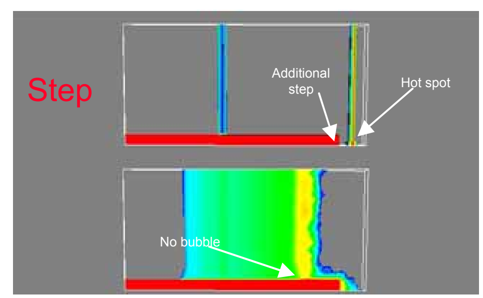
Simulation of Z Shot 1617

- 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

Data and diagnostics from B. Jones, C.A. Coverdale (SNL)
Simulations by C.A. Jennings (SNL)

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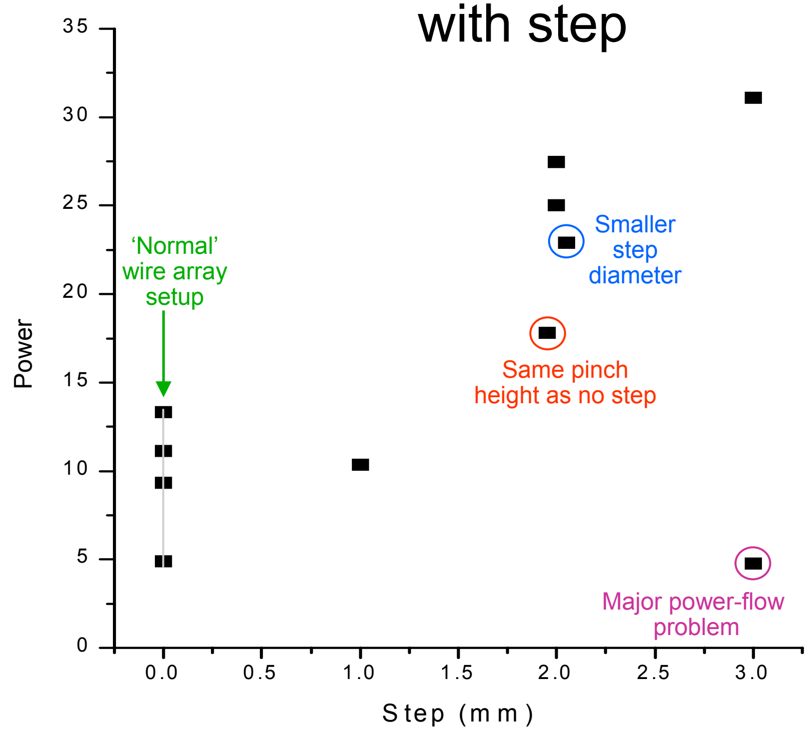
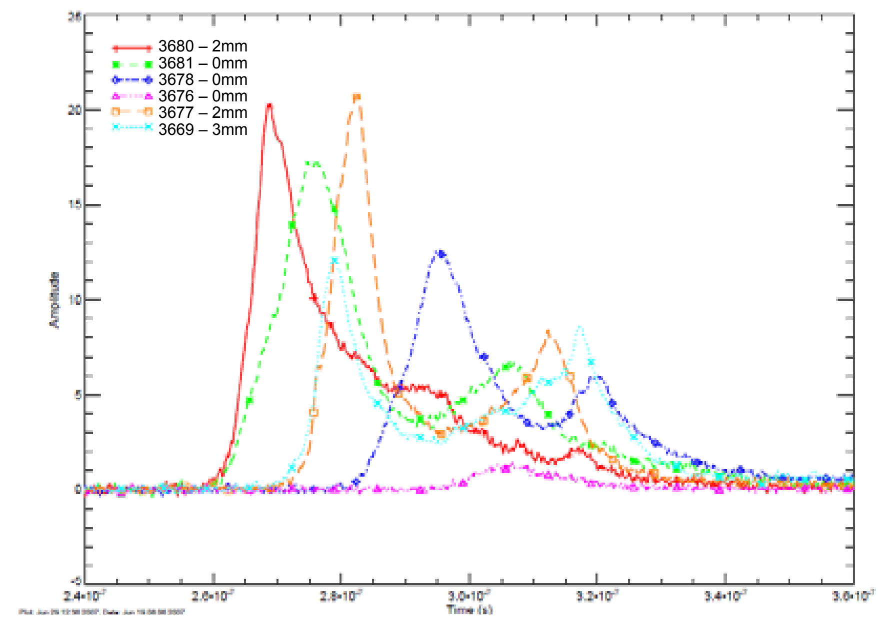
# Initial analysis of data from recent Saturn shots indicates zippering is eliminated

## Peak total power increased with step




## K-shell rise time shortened




- Data indicates higher powers with the step present
- K-shell diagnostics demonstrate a much faster rise with the step, however not higher K-shell yield
- Analysis still in progress!!

# Bubble formation not necessarily a bad thing!
# Radial wire arrays have applications as an ICF driver

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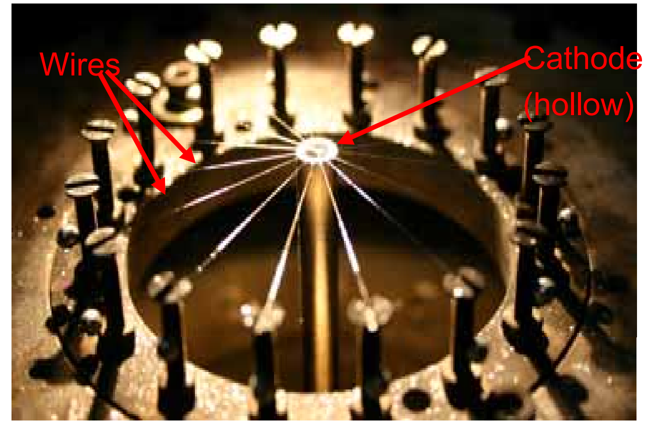
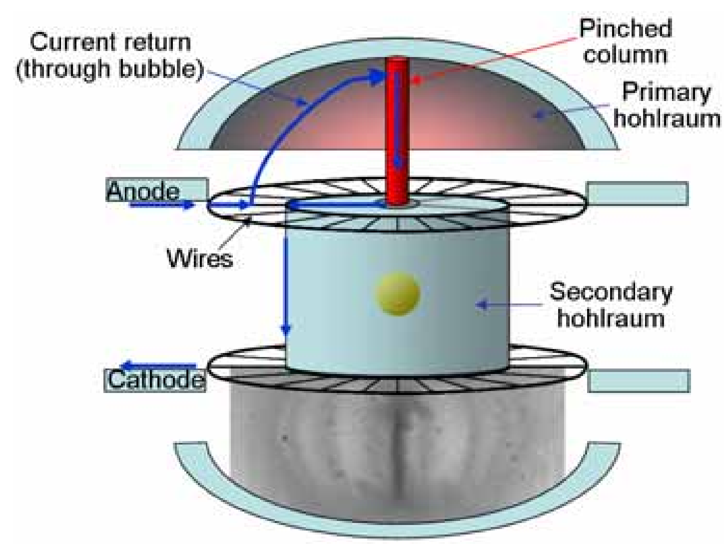
SATURN

- New idea for a compact x-ray source to drive ICF hohlraums
- MAGPIE data indicates significantly higher power densities than cylindrical arrays
- Experiments planned for Saturn to investigate scaling to higher current drives
- Potentially could get >4x higher power densities

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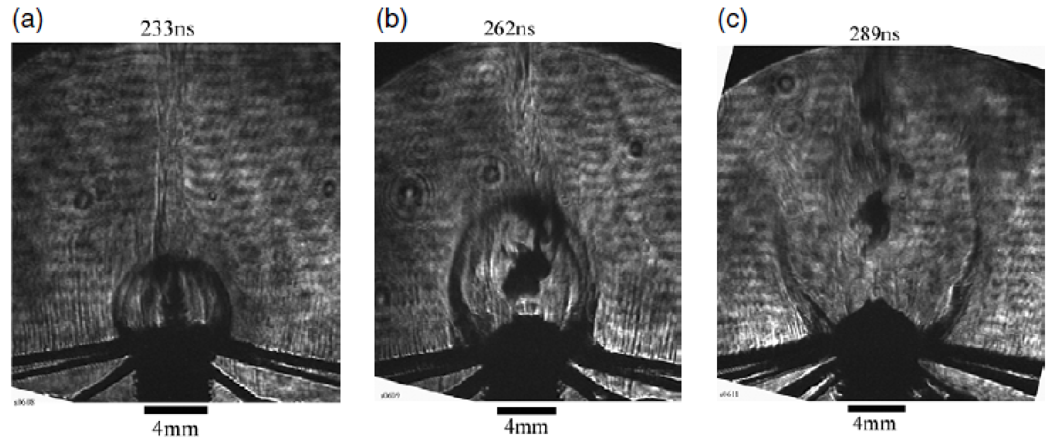
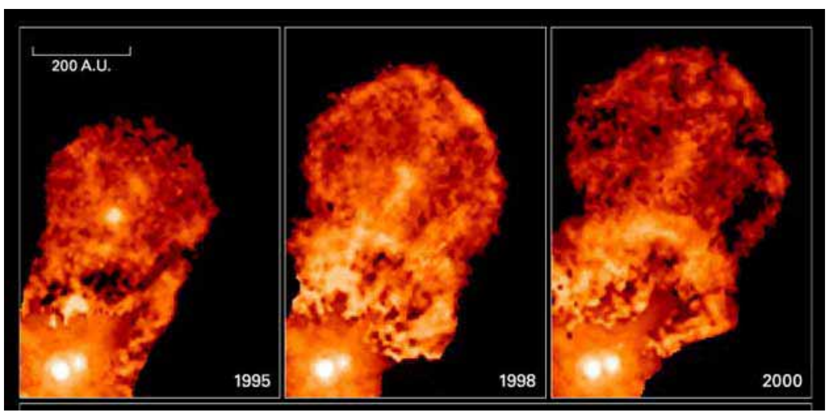
# And also to astrophysics

- The evolution of a radial wire array includes the formation of a magnetically driven jet
- For some configurations multiple jets can be formed
- Magnetic cavities are thought to be most likely formation mechanism for protostellar jets
- Simulations recreate features of lab-jet

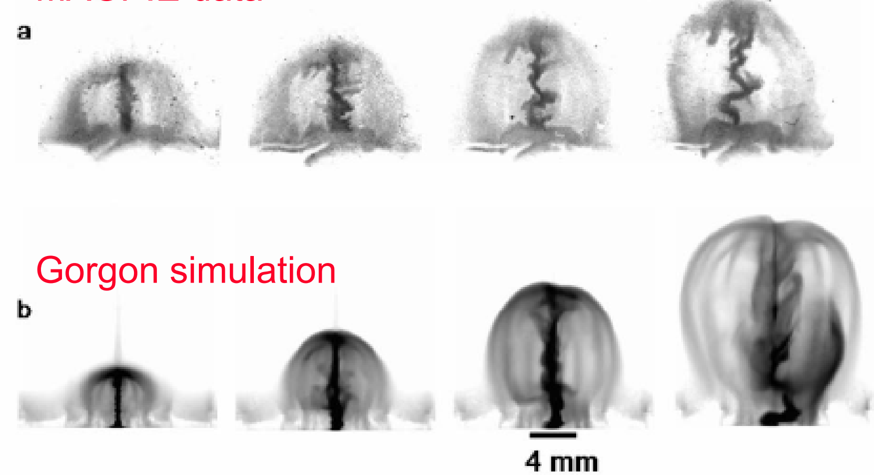



Astrophysical jet




XZ TAU. Credits: John Krist (STScI) et.al. WPFC2, HST, NASA

MAGPIE data




- High Energy Density Laboratory Astrophysics is an emerging area of research, which provides understanding and benchmarking to the astrophysical community
- Need to carefully consider appropriate scaling requirements to compare systems/codes

S.V. Lebedev et al., Mon Not Royal Ast. Soc 361, 97 (2005).
A. Ciardi et al., Phys Plasmas 14, 056501 (2007)

# Jets produced by conical wire array z-pinches can be used to model protostellar jets far from source

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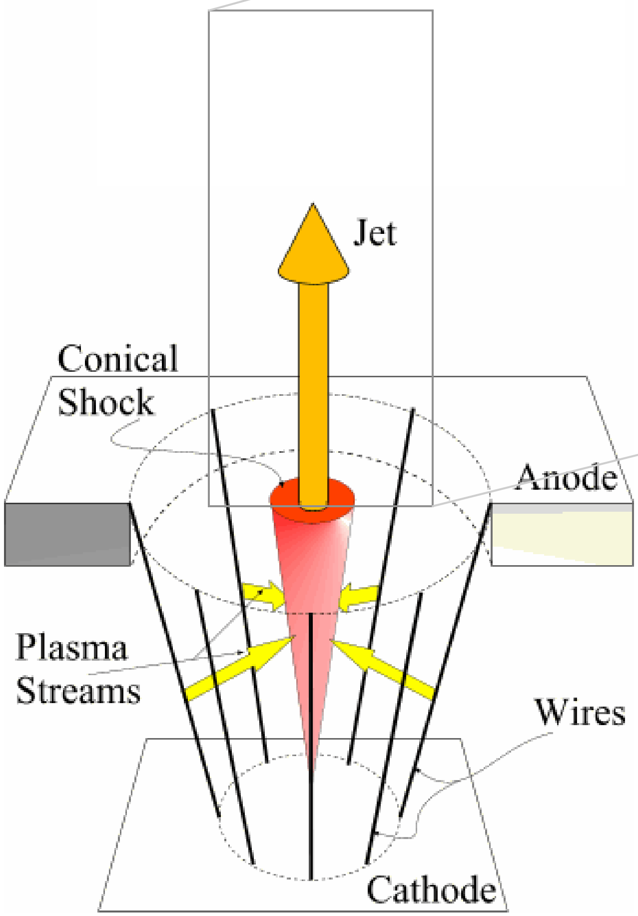


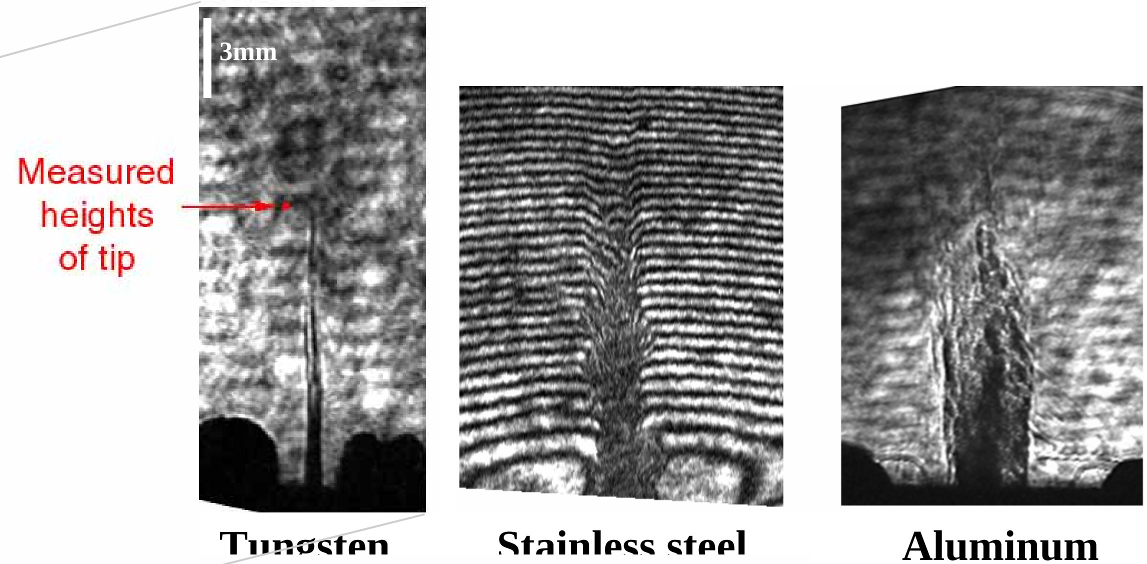


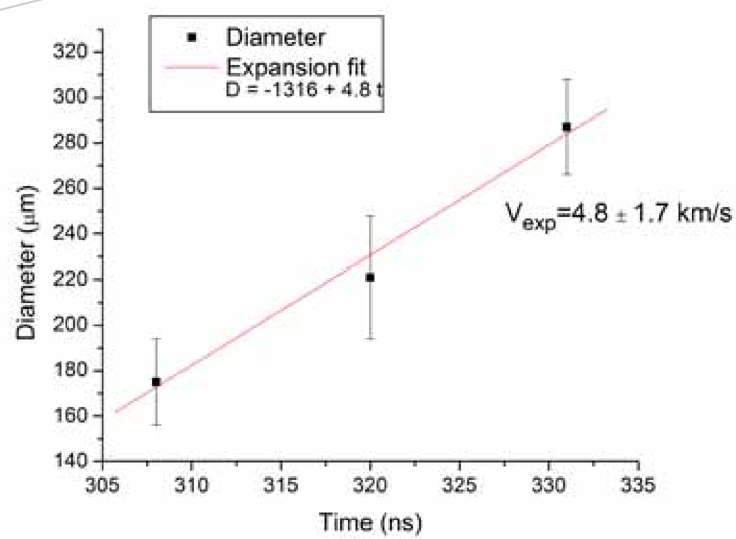


## Parameters

- $v_{tip}$ ~270 km/s
- $n_e$ ~ $10^{19}$ $cm^{-3}$
- $T_e$~10eV
- Mach 20-60


S.V. Lebedev et al., Astrophysical Journal, 564:113, 2002.
D.J. Ampleford, PhD Thesis, Imperial College London, 2005


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# Conical wire arrays can be used to model protostellar jets further from the source object.

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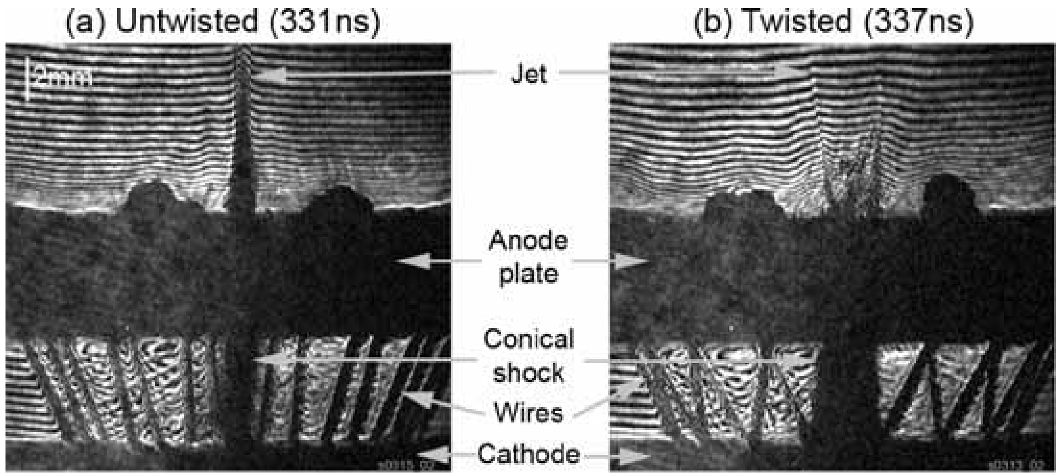
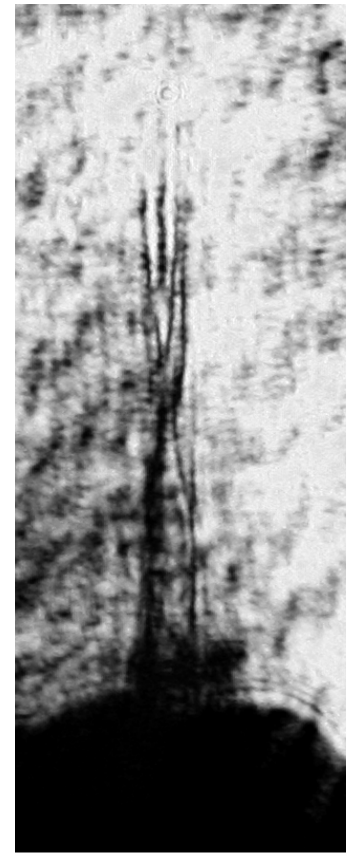
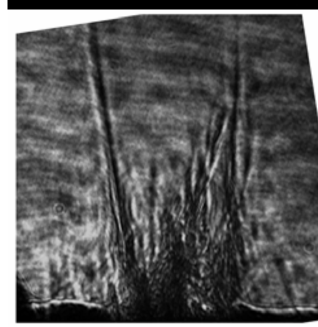
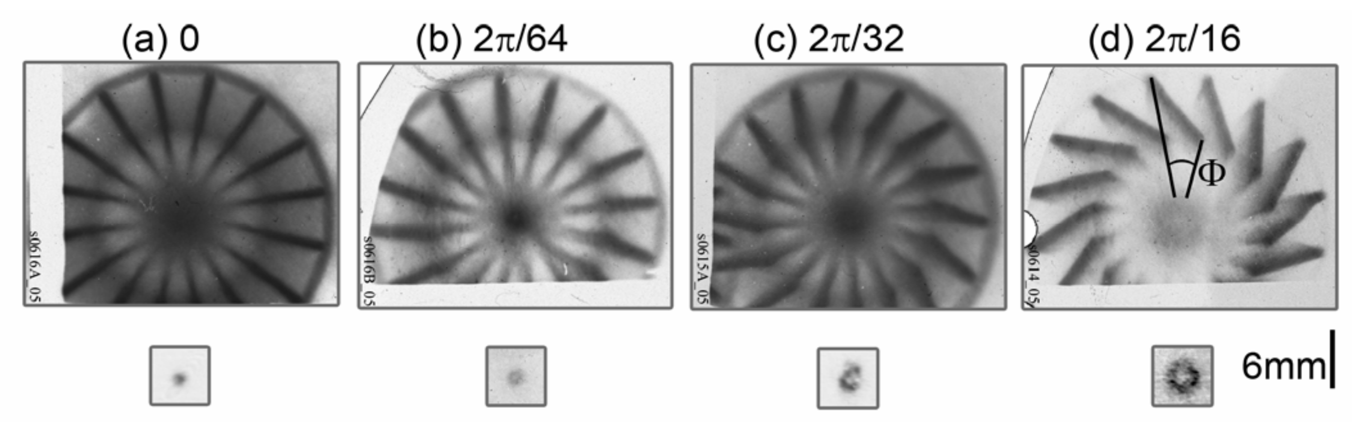


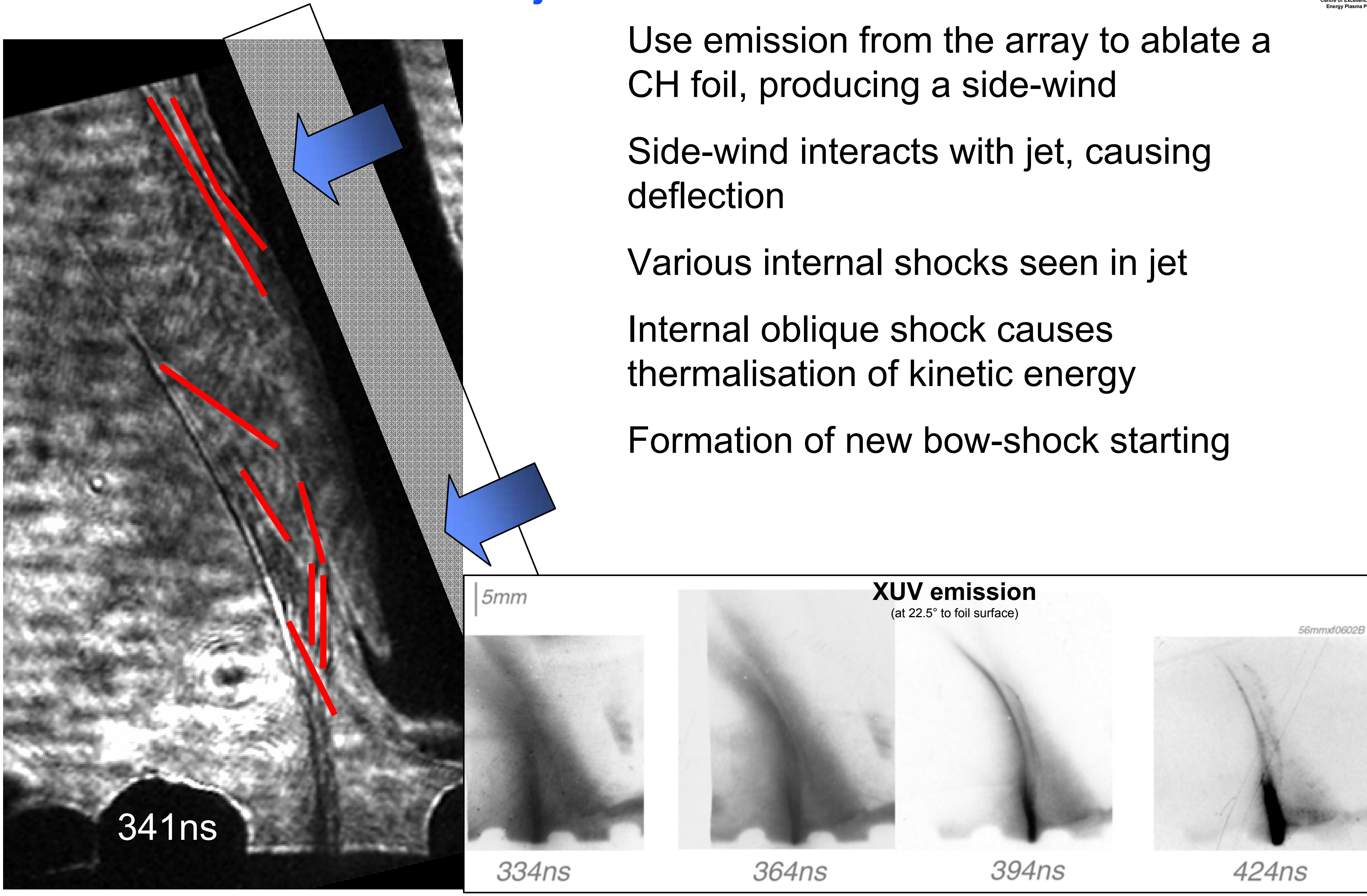


- By twisting array, generate $B_z$, hence introducing $J_r x B_z$ component to Lorentz force
- Rotation leads to hollow shock on axis
- Jet produced maintains angular momentum, and becomes divergent for larger rotation rates.




D.J. Ampleford et al., Astrophys Space Sci 307, 51 (2007)
D.J. Ampleford et al. *submitted* (2007)

# Conical wire arrays can also be used to understand interaction of jets with ambient medium




Use emission from the array to ablate a CH foil, producing a side-wind

Side-wind interacts with jet, causing deflection

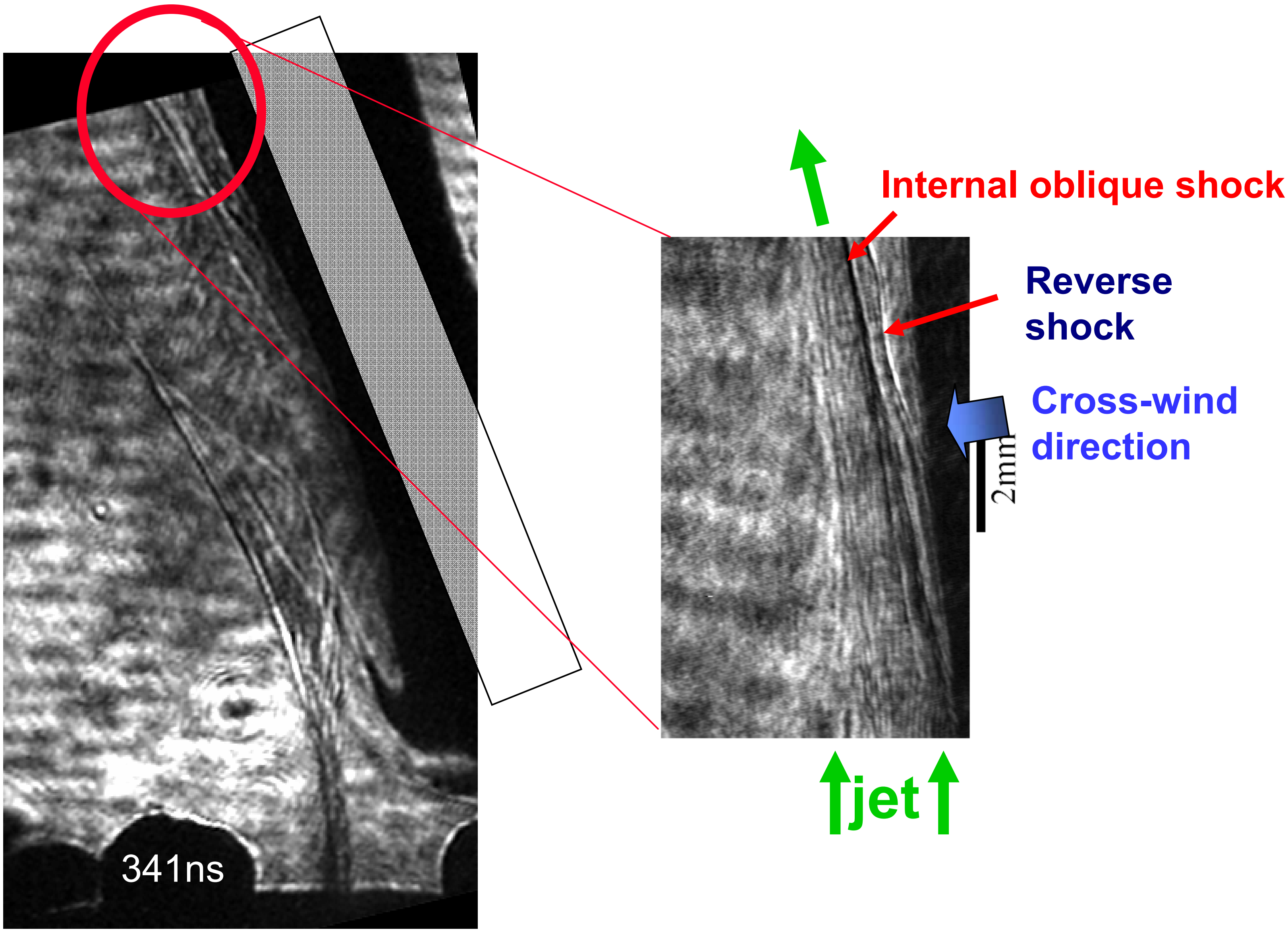
Various internal shocks seen in jet

Internal oblique shock causes thermalisation of kinetic energy

Formation of new bow-shock starting

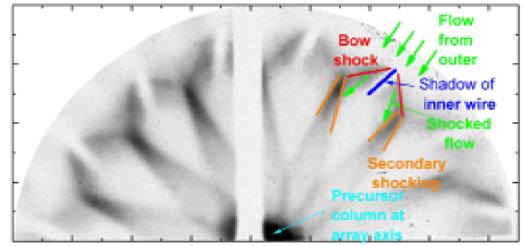
S.V. Lebedev et al., Astrophysical Journal, 616, 988 (2004).
D.J. Ampleford et al., Astrophys Space Sci 307, 29 (2007)

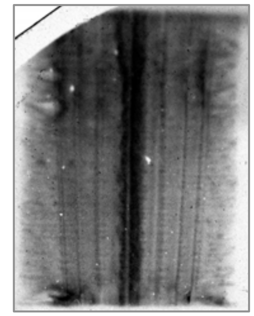
# Low density tip interaction

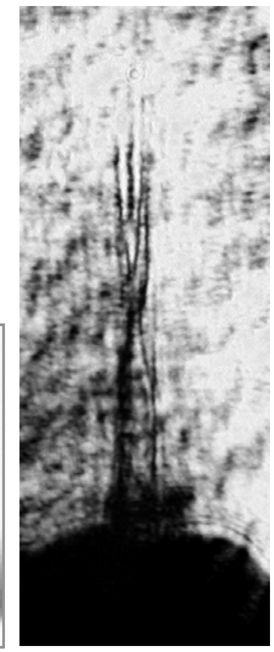



D.J. Ampleford, PhD Thesis, Imperial College London, 2005
D.J. Ampleford et al., Astrophys Space Sci 307, 29 (2007)

# Summary





- Wire array Z-pinches have many applications, especially when tailored to meet the needs
- For ICF, nested arrays can provide a tailored pulse shape
  - Interaction of implosion with a prefill that has been perturbed by the presence of the inner array leads to an interaction pulse
  - Altering array configuration (e.g. conical nested) can lead to additional pulse shaping controls
- Novel array configurations can be used for
  - Improving the performance of cylindrical arrays
  - As a source for compact ICF hohlraums
  - To understand phsyics of astrophysical jets
    - In MHD mode (formation and near the source)
    - In hydrodynamic mode (far from the source, including interaction with ambient medium)