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Structure of Stagnated Plasma in Aluminium Wire Array Z-pinches

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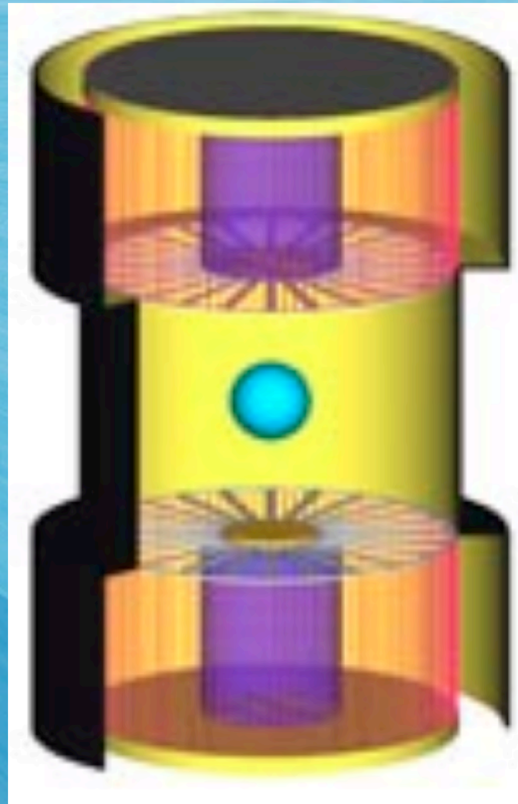
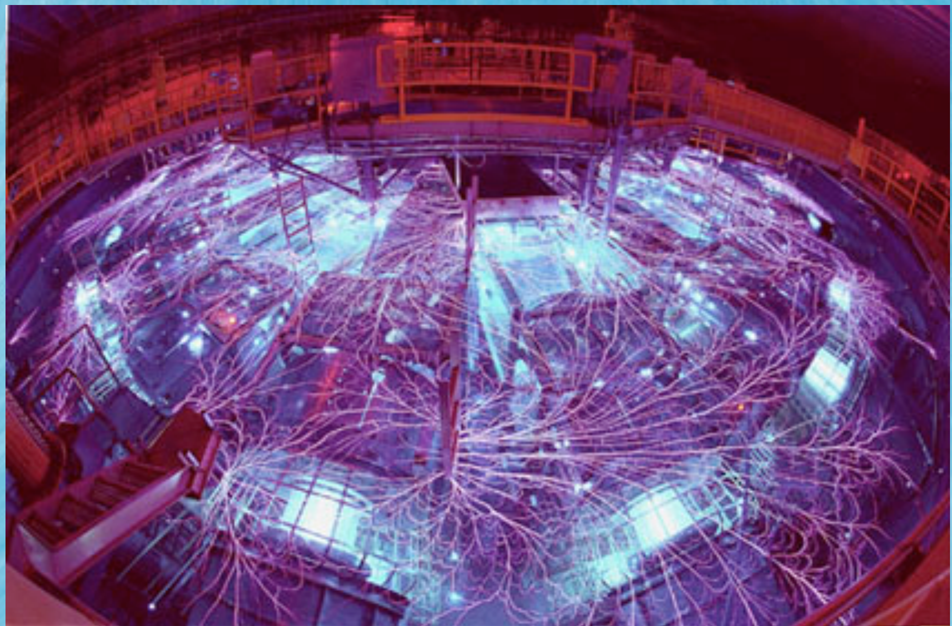
What is a Wire Array Z-pinch?

- Many fine wires (a few μm diameter) arranged in a cylinder.
- Large currents are passed through the wires, creating plasma and a global magnetic field.
- The Lorentz force results in an implosion onto the axis, producing a very powerful x-ray pulse.
- X-rays for heating fusion hohlraum?

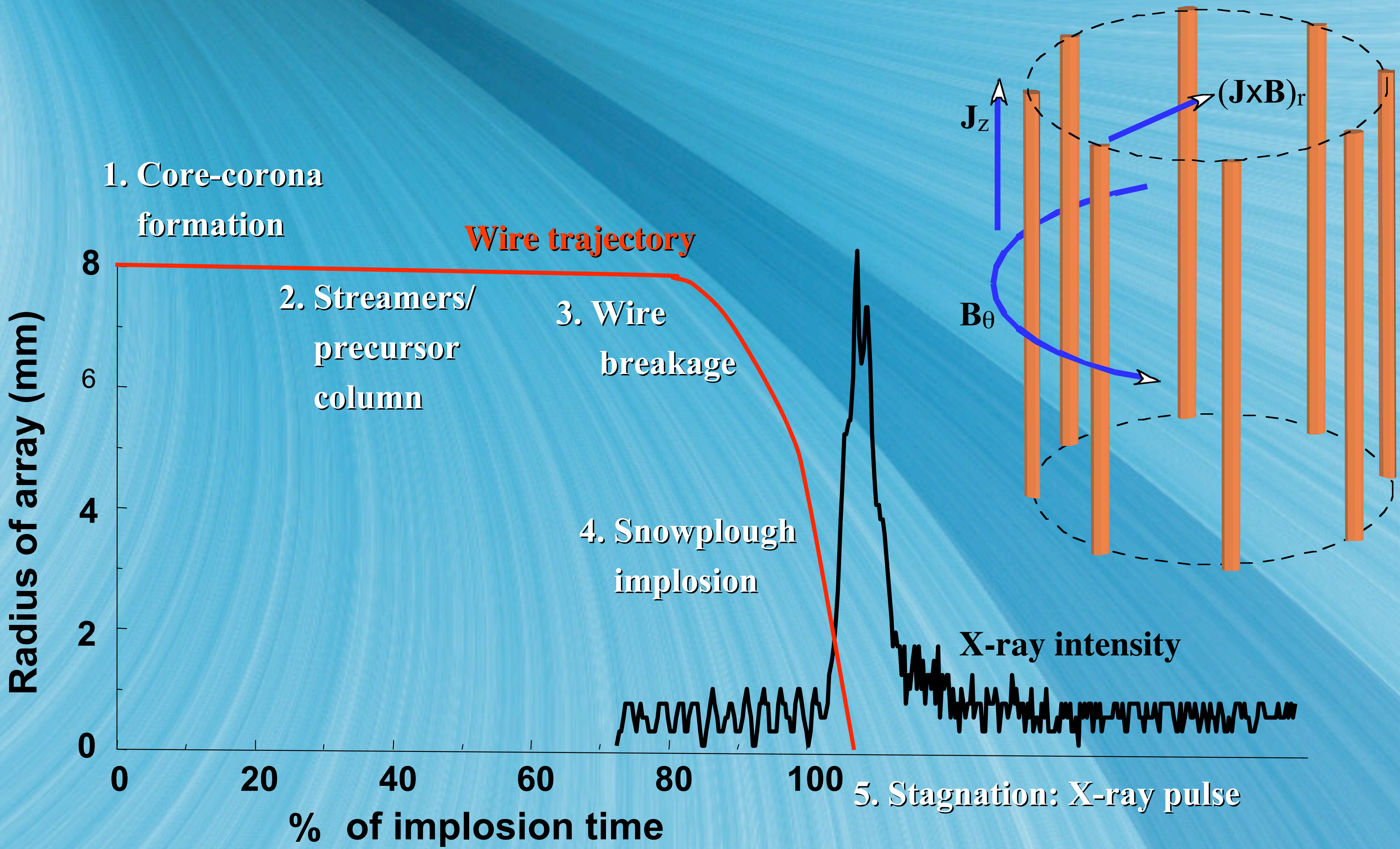


A wire array Z-pinch driven fusion hohlraum concept.



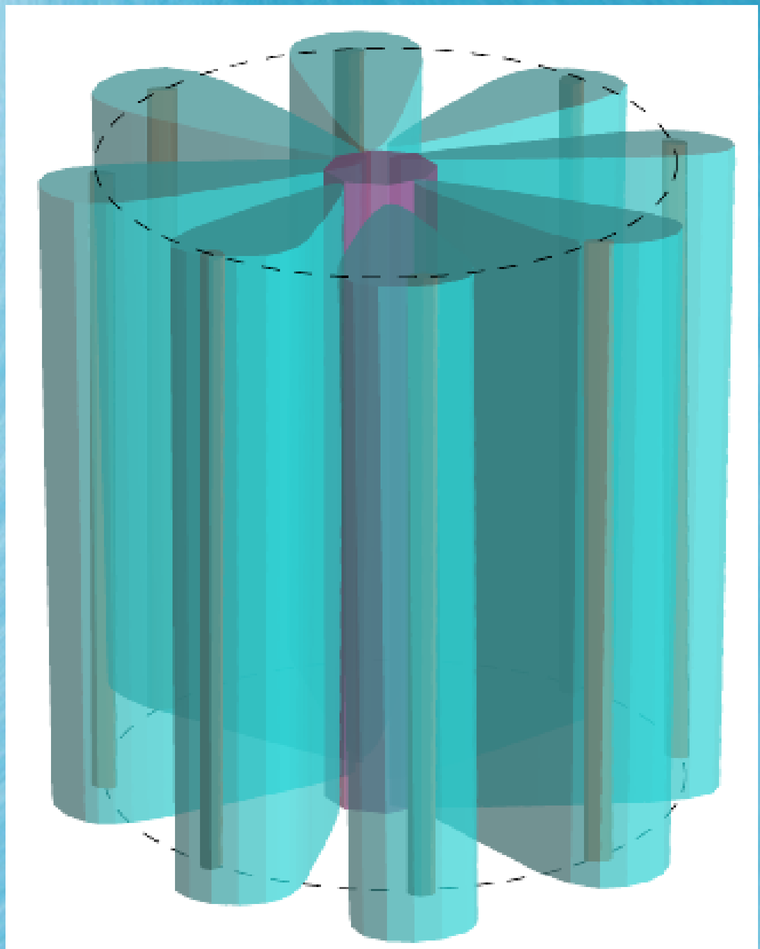
Z -generator at Sandia National Laboratories, 18MA, 100ns: **280TW of X-rays (1.8MJ in 4ns)**

Stages of a Wire Array Implosion



Streamers and Precursor Column

- Wires display core-corona structure: Cold, dense wire cores surrounded by corona of hot plasma. Coronal plasma streams towards the axis at constant velocity. Wire core ablation maintains the plasma in the corona.

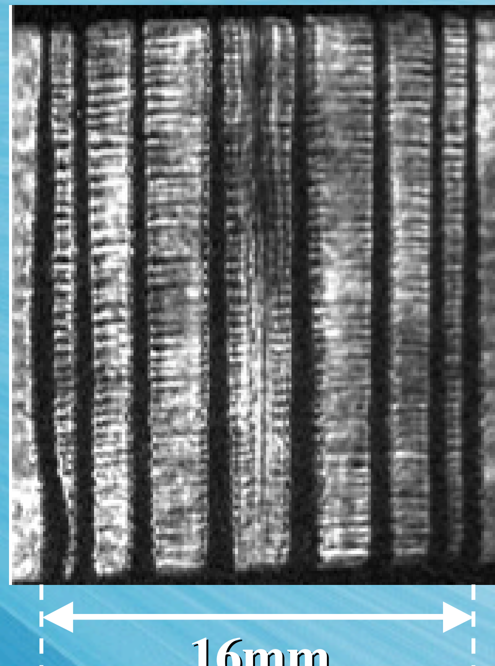


- Precursor column forms on axis. Wire cores remain at original wire positions.

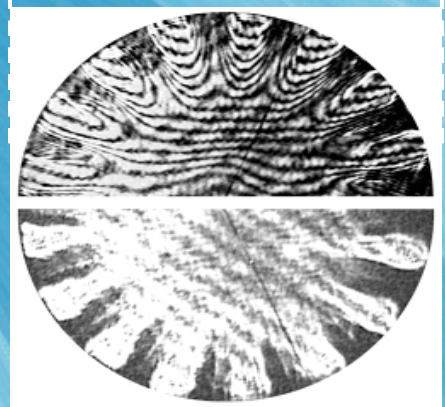
- Prior to wire breakage, current flows through a low inductance path at large array radius, close to the surface of the wire cores.

- Plasma streams show strong axial modulation:
  $\lambda_W \approx 0.25\text{mm}$
  $\lambda_{Al} \approx 0.5\text{mm}$

W, laser shadowgram, 124ns



Al, interferometry, 97ns



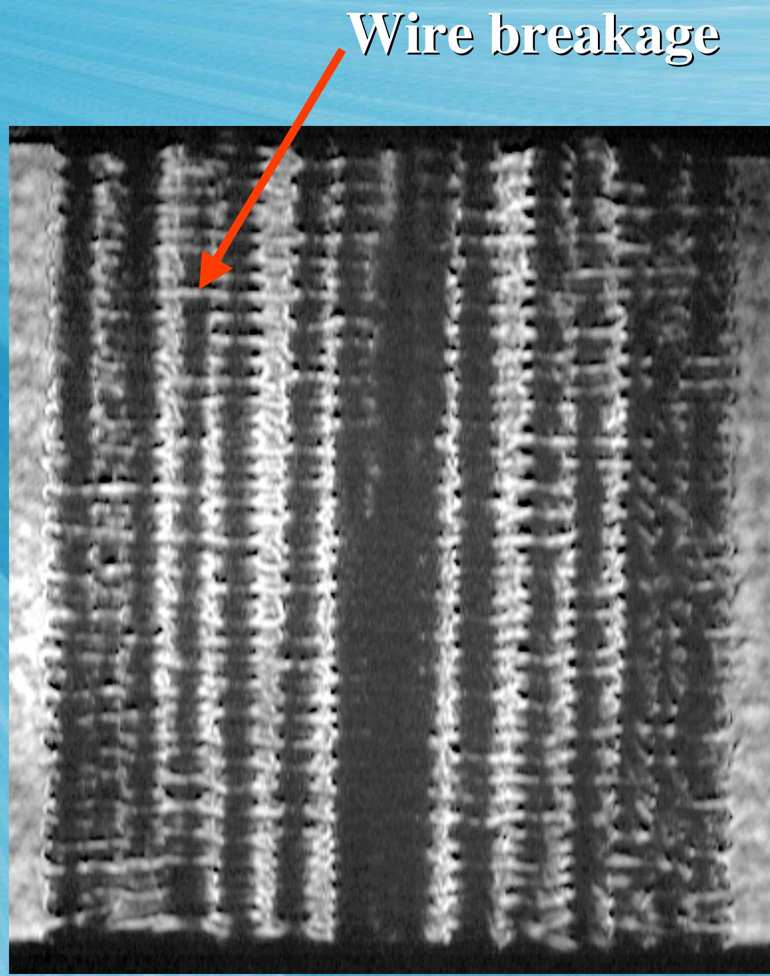
Al, laser shadowgram, 97ns (s0911)

Wire Breakage

- Wire cores remain in their original positions until ≈50% of the array mass has been ablated.

- Strong axial modulation of ablation is observed. This results in more mass removed/ablated at some points on the wires than at others. Wire breakage occurs when all mass is ablated from these points.

- After wire breakage, the lowest inductance path has moved. Now, the lowest inductance path is still axial, but at a smaller radius. This current carrying plasma is then swept inwards as the implosion begins.



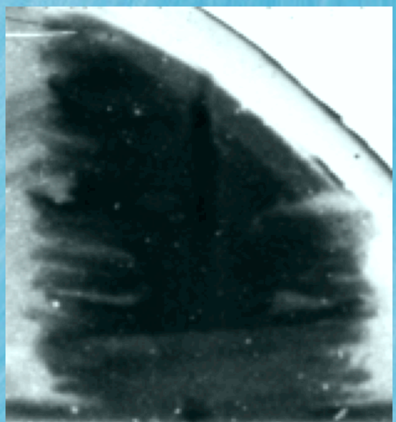
Al, laser shadowgram, 180ns (s0522)

16mm

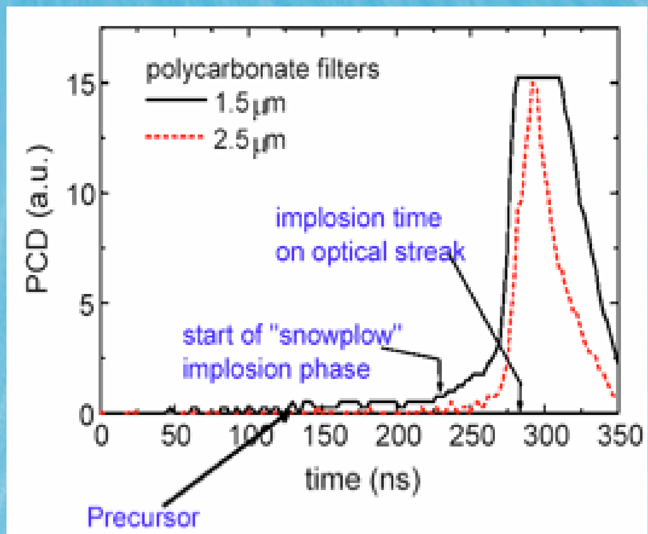
Snowplough Implosion

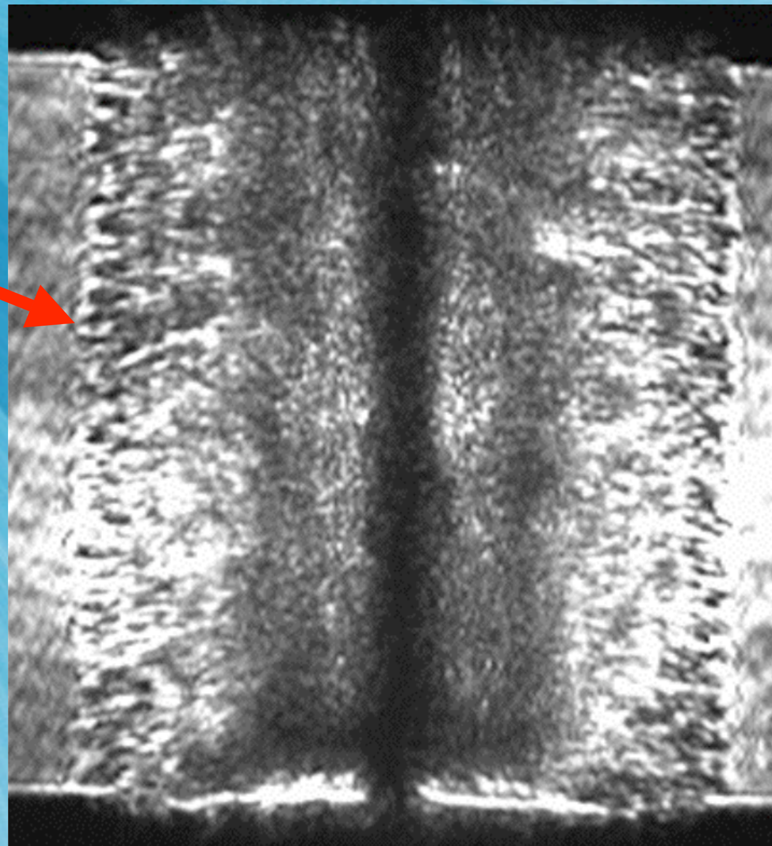
- At the time of wire breakage, a sheath of plasma begins an implosion towards the axis. The inbound plasma/current sheath "snowploughs" the plasma inside the array (i.e. the sheath gathers up the plasma with it as it travels).
- Implosion trajectory suggests ≈10% of array mass in snowplough implosion. Large amount of mass (≈40%) remains in **debris field**
- At the time when the sheath impacts on the precursor column, main x-ray pulse begins.

XUV camera



Start of x-ray pulse

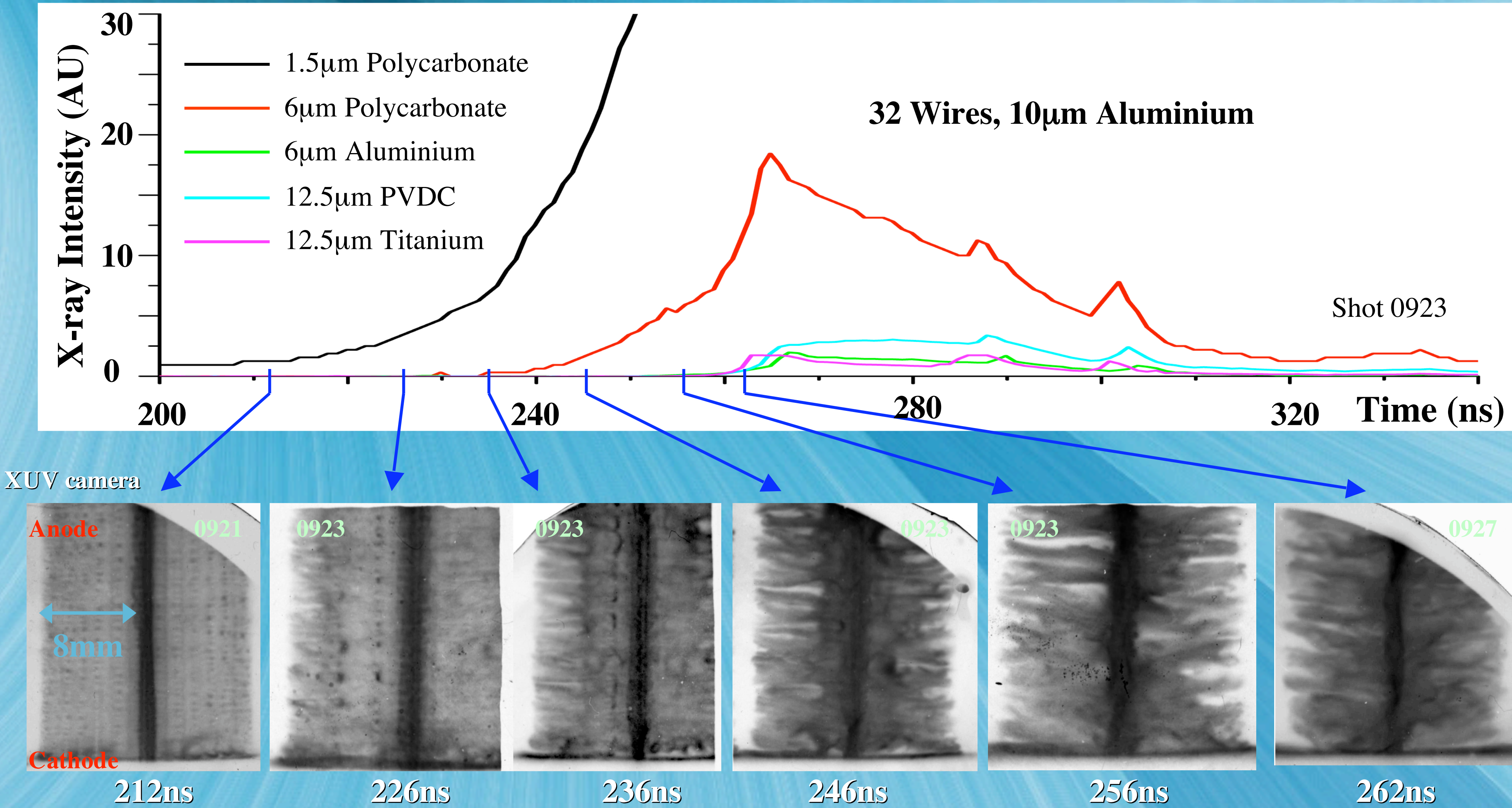




W, laser shadowgram, 224ns (s0122)

16mm

Stagnation: Before X-ray Peak

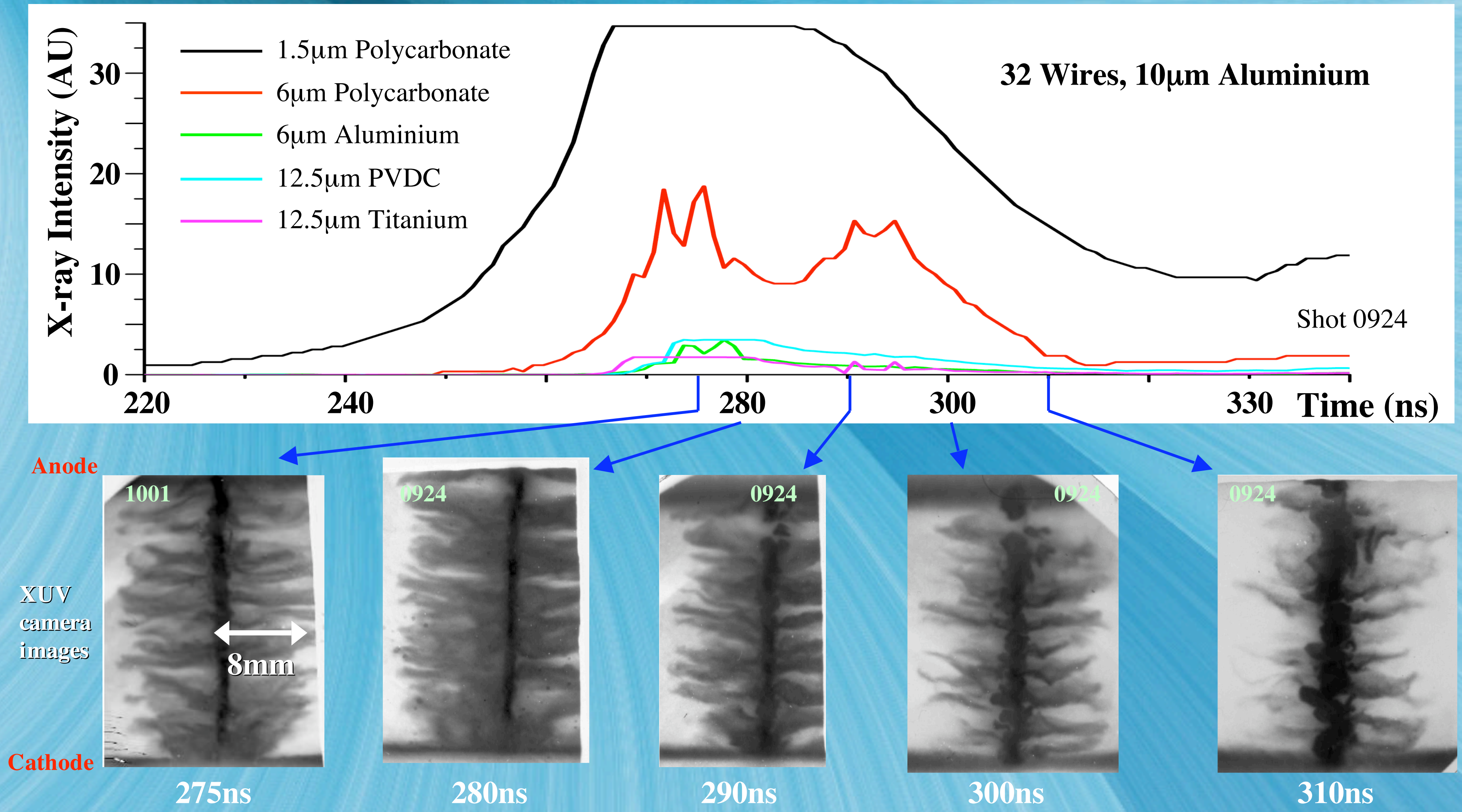


Breaks appear in wires

Snowplough implosion: plasma sheath travels towards axis, gathering mass as it proceeds. X-ray intensity increases as piston accelerates and heats more plasma.

X-ray intensity increases very rapidly as piston arrives at precursor. Kinetic energy is thermalised into x-rays.

Stagnation: During / After X-ray Peak



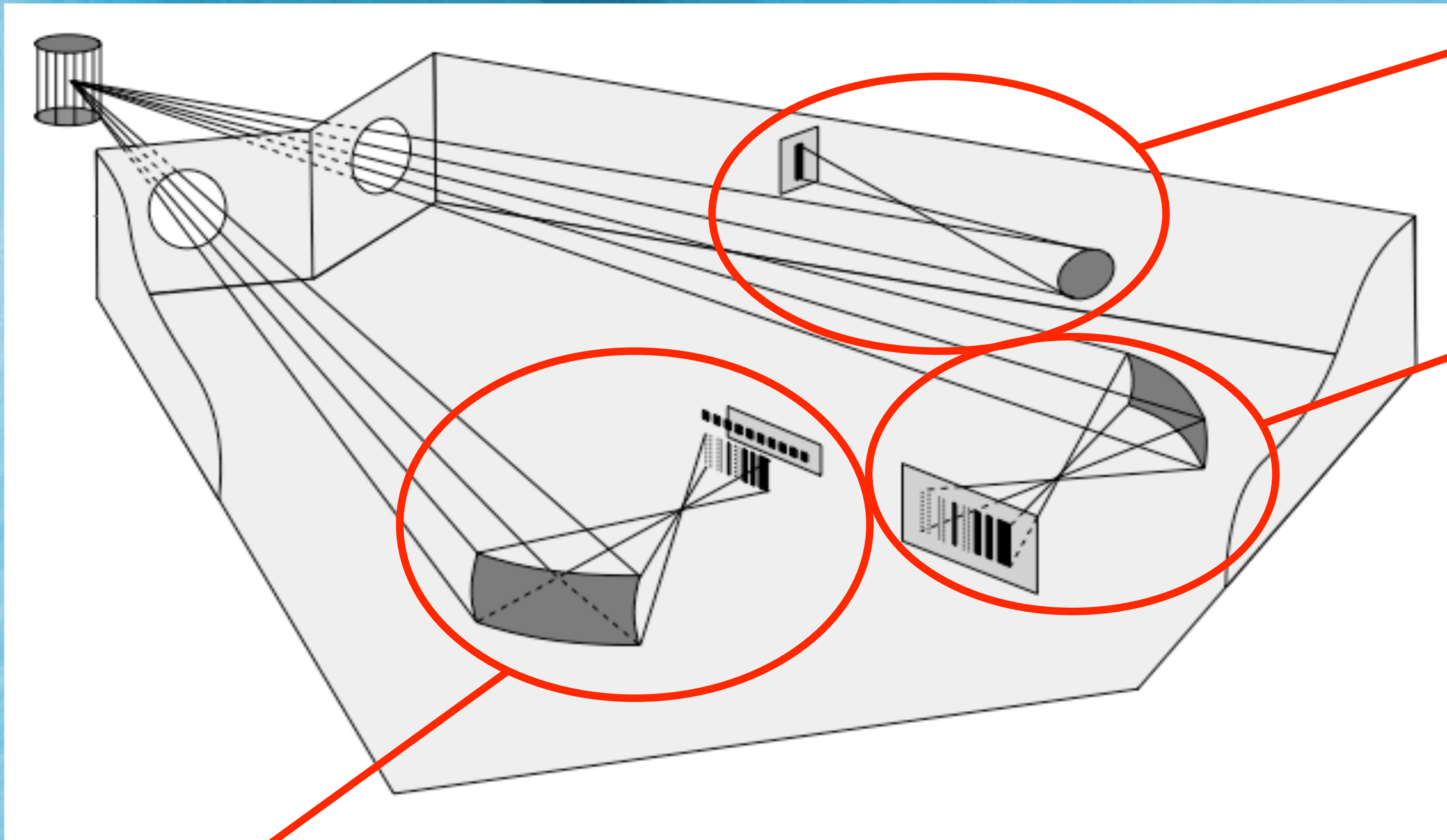
Stagnating column is compressed to its minimum diameter. X-ray intensity reaches peak.

Column becomes unstable and begins to expand. Onset of m=1 instability shortly after peak?

Large-scale instabilities. Incoming trailing mass.

A New Diagnostic For MAGPIE

Spherically-Bent Crystal Spectrometer

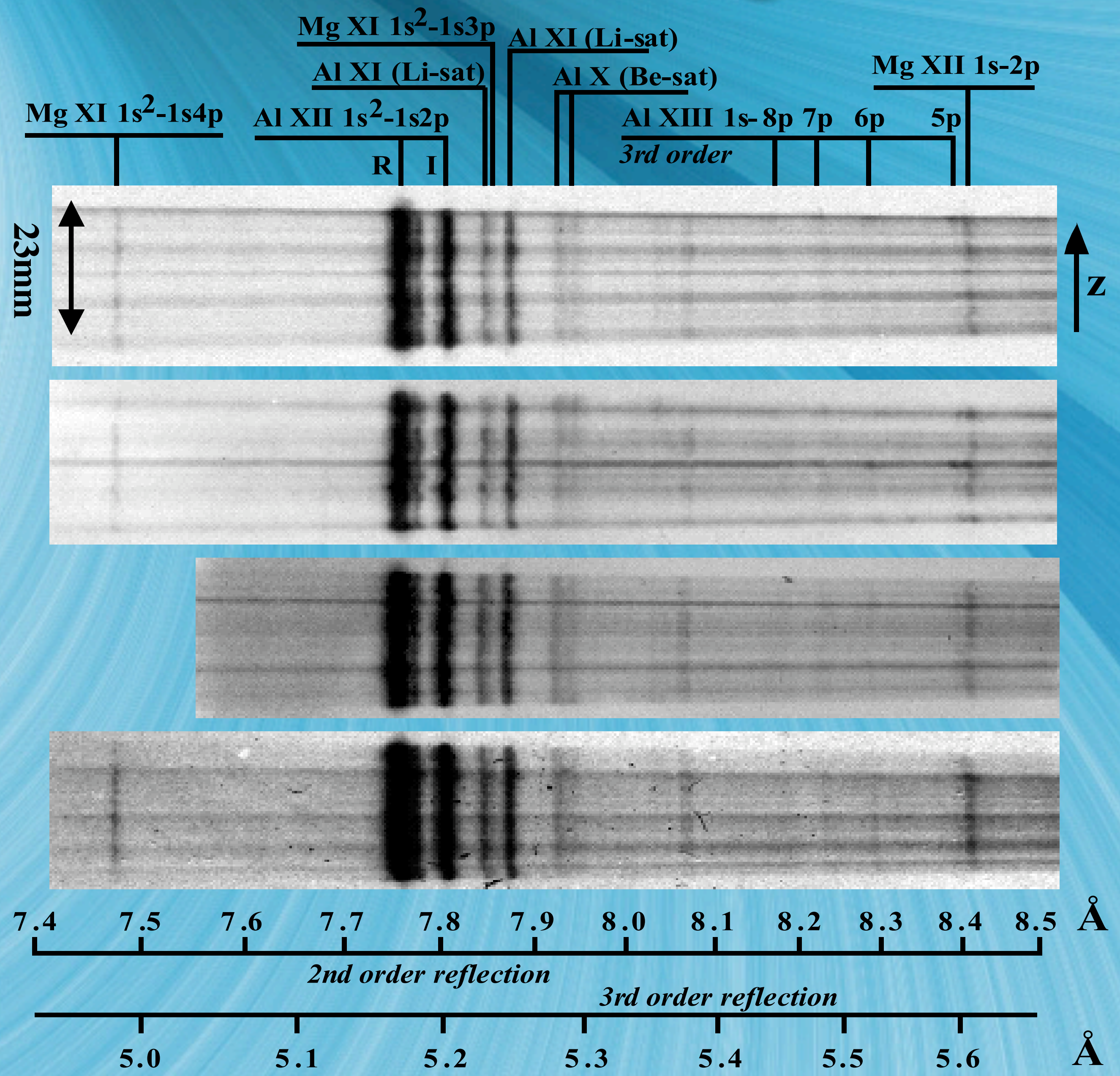


Quartz crystal
R=250mm
$\theta \approx 88^0$, $\lambda \approx 6.65Å$
DEF film pack

Mica crystal
R=186mm
$\theta \approx 53^0$, $\lambda_0 \approx 7.9Å$
(2^{nd} order)
DEF film pack

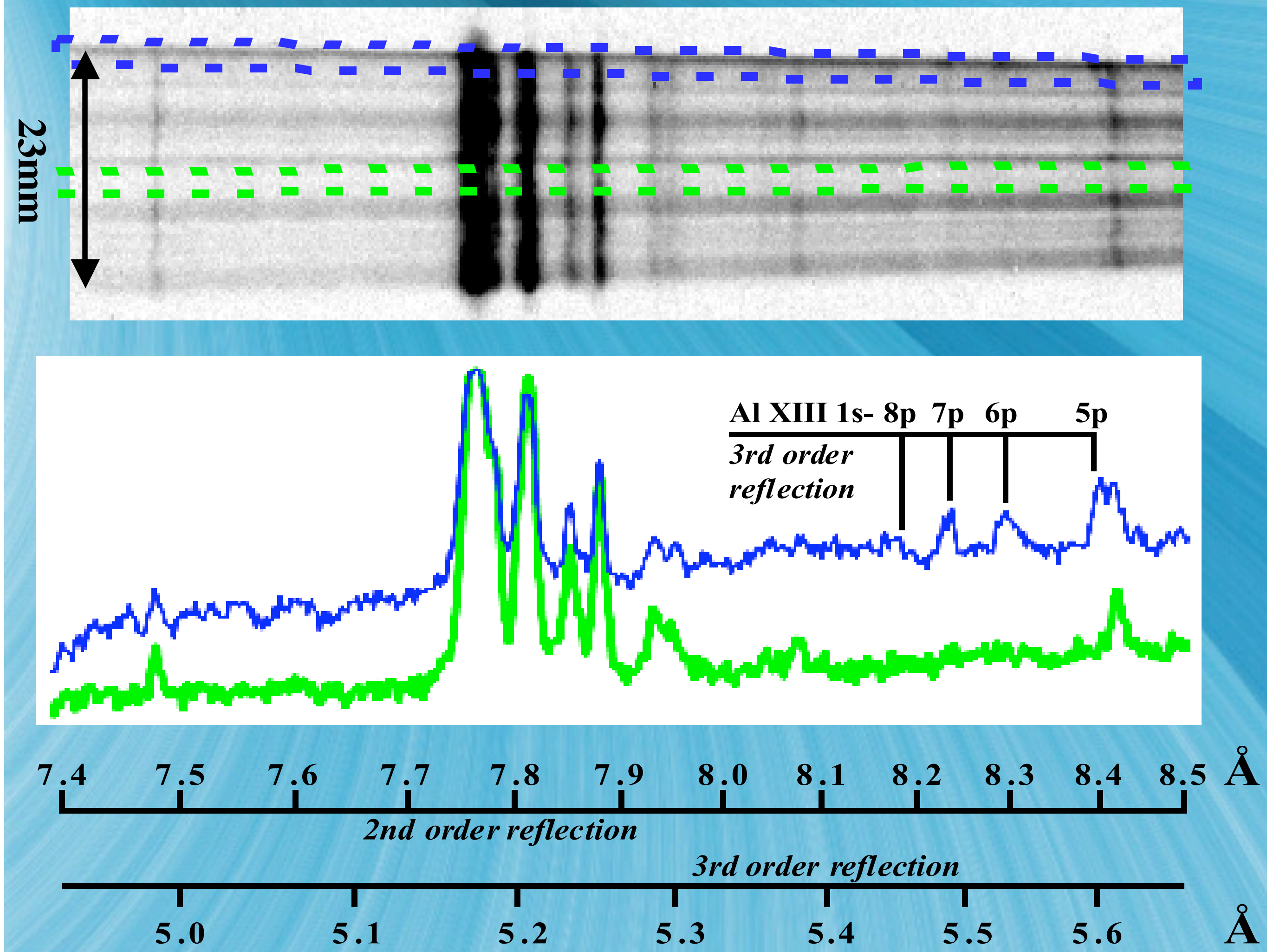
Mica crystal R=100mm, *$\theta \approx 53^0$, $\lambda_0 \approx 7.9Å$ (2^{nd} order)*
10-element silicon diode array (time resolved, 1ns)
DEF film pack (for spectral positioning)

Time Integrated Spectra



- Continuum radiation is seen from narrow sections randomly distributed along the pinch.
- Typically 3-5 intense continuum regions per shot with Δz ranging from 0.4mm to 1.6mm.
- The wider, less intense continuum zones are actually groups of faint, narrow regions.
- Line radiation is more intense at axial positions where continuum is also present.

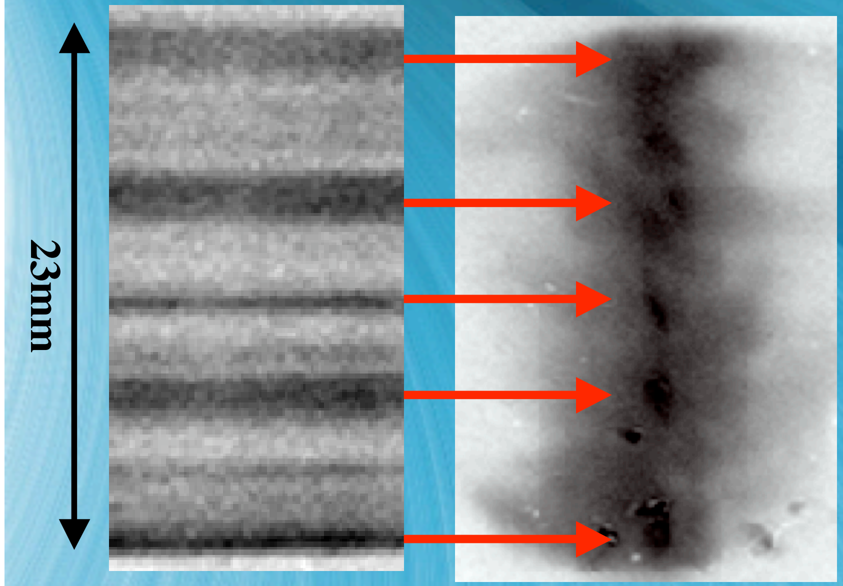
Continuum-Line Comparison



- Lines from hydrogen-like aluminium are only present where there is intense continuum radiation.
- All other lines, from less ionised species, are present along entire axis.
- This means that the continuum regions are probably hotter than non-continuum regions. They are intensely emitting “bright spots”.

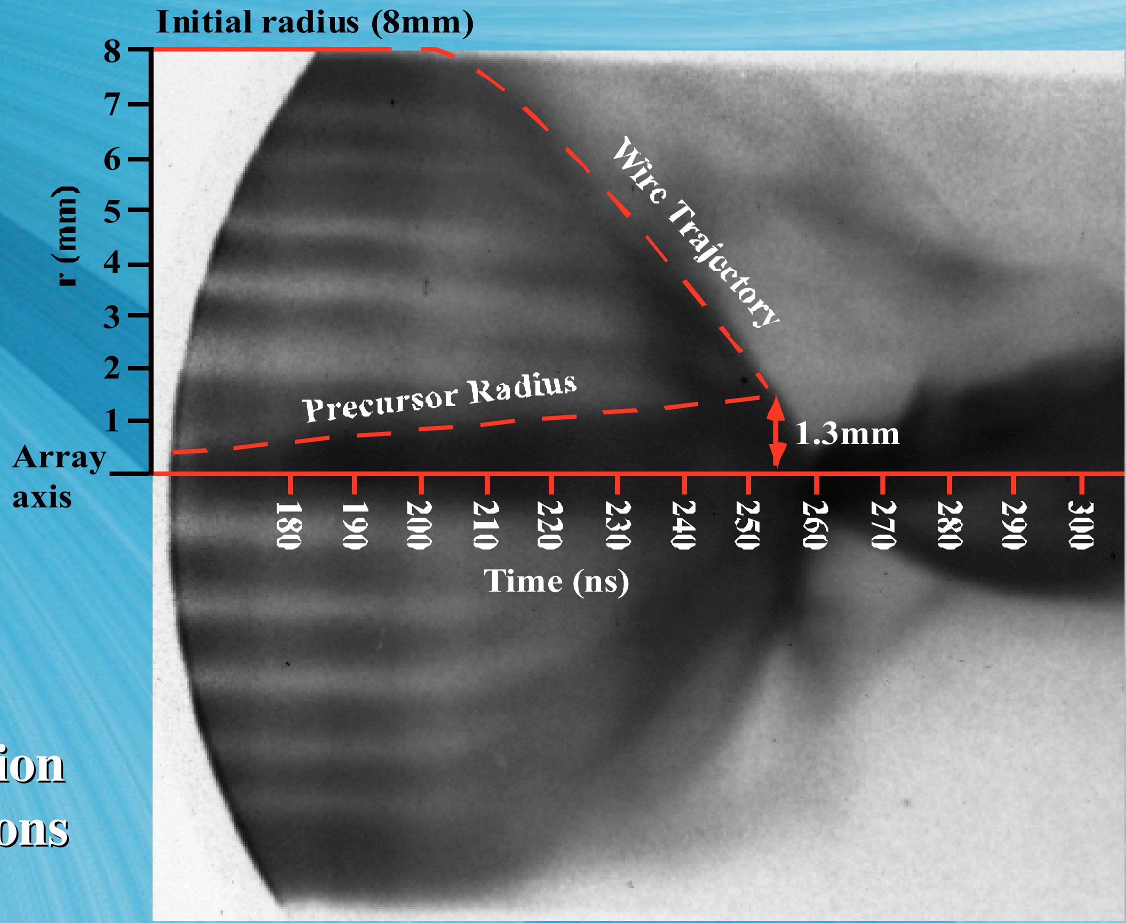
- What combination of electron temperature and ion density is needed to produce He-like Aluminium ions, but not H-like ions? The continuum regions may be hotter and denser, whilst the non-continuum regions may be cooler and less dense.

Localisation of Hot Spots



Mica-crystal Spectrum (continuum section)

Quartz-crystal Monochromatic image

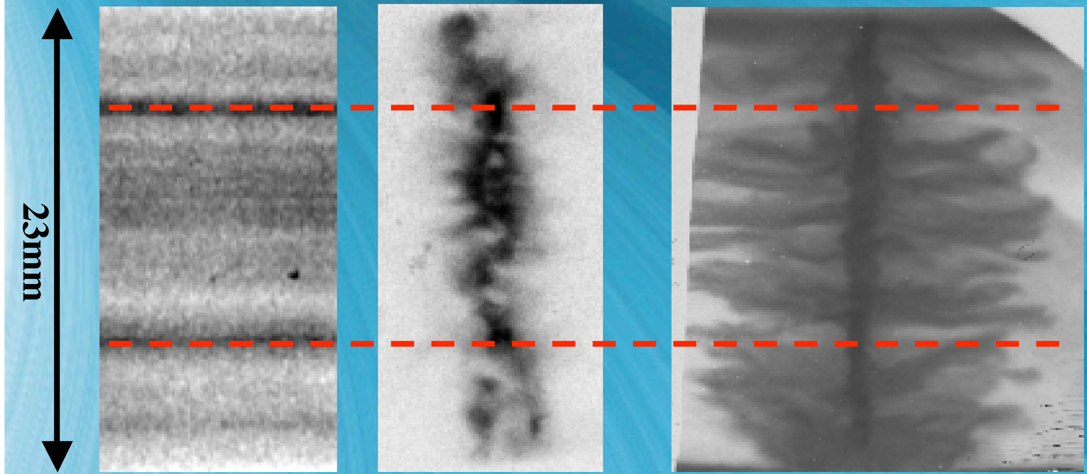


- The axial location of continuum radiation corresponds closely to bright spot regions near the axis.

- The adial extent of the bright spot regions is very similar to the radius at which the imploding sheath impacts upon the precursor.

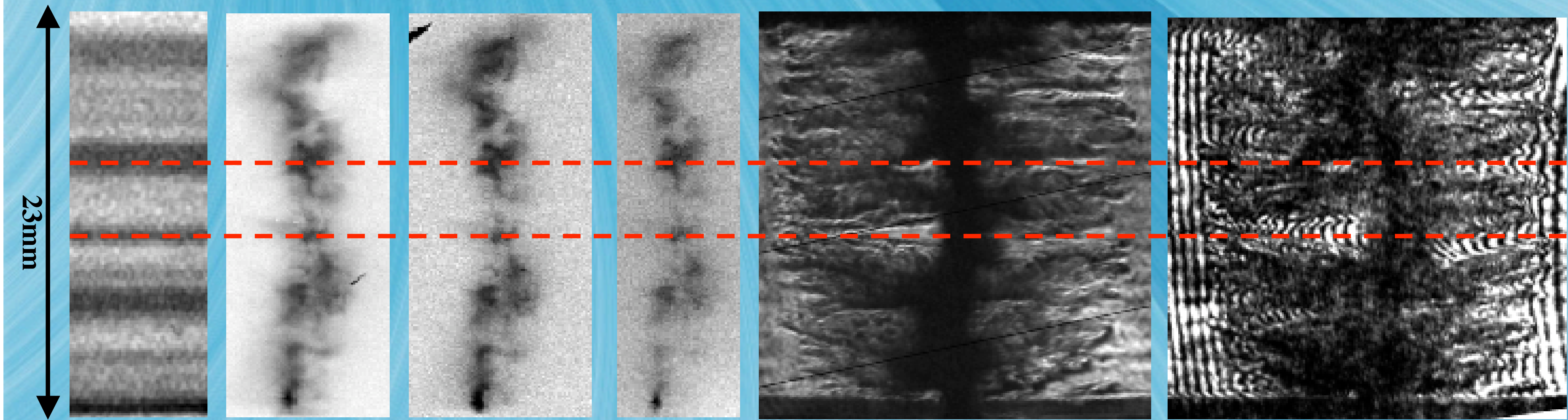
- Are these bright spots a direct consequence of impact upon the precursor?

Hot Spot Position and Global Structure



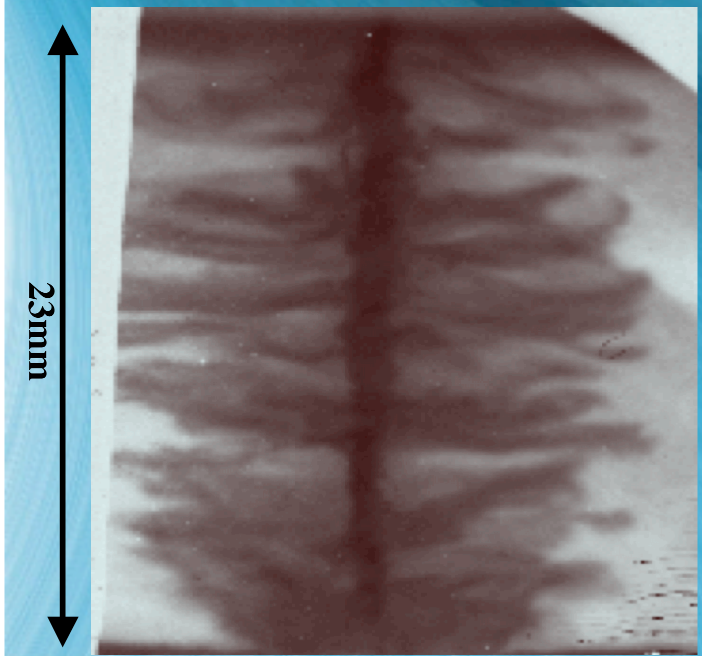
Mica-crystal Spectrum | Quartz-crystal Monochromatic | XUV Framing Camera 14ns prior to X-ray peak

- The leading edge of the imploding sheath is modulated: At times close to x-ray peak the majority of wire material has arrived on axis at some positions ("swept out" regions). At other positions a lot of mass has yet to arrive.
- Intense continuum and bright spot positions correlate to these "swept out" regions.



Mica Spectrum | 20μm Be 12.5μm PVDC/Al 15μm Si Time Integrated Pinhole Imaging | Schlieren Laser Probing 3ns prior to X-ray peak | Interferometric Laser Probing 3ns prior to X-ray peak

Summary of Time Integrated Spectra



XUV Framing Camera

Observation of narrow regions of continuum radiation

H-like lines are only present in these regions, therefore regions may be hotter and denser

Bright spots formed in similar sized region to the precursor at the time when the imploding sheath impacts upon it

Axial positions at which most mass has been swept onto the stagnating column correspond to bright spot positions

?

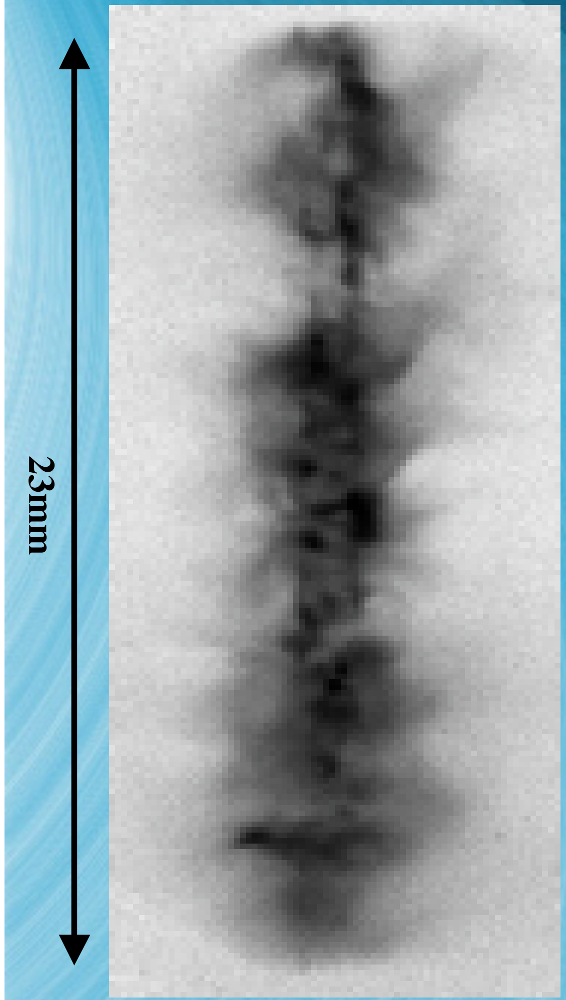
Are bright spots created through the delivery of a pulse of kinetic energy onto the outside of the precursor column at the swept out regions?

Are bright spots a result of current being concentrated near the axis, driving MHD instabilities (sausage, kink, etc.) and/or Ohmic heating?

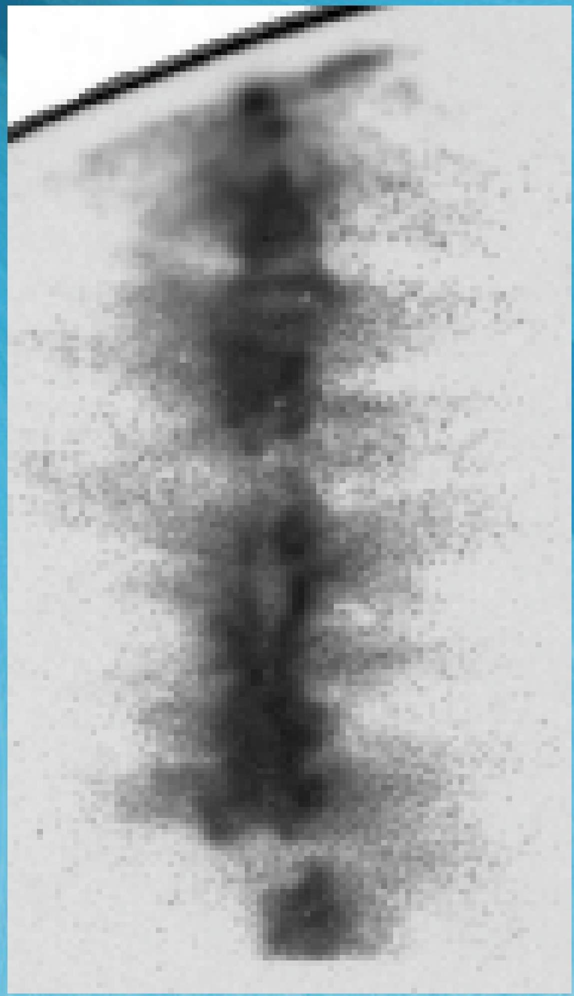
?

Could electron beams be heating the bright spots?

Radial Structure From 2-D Imagingz



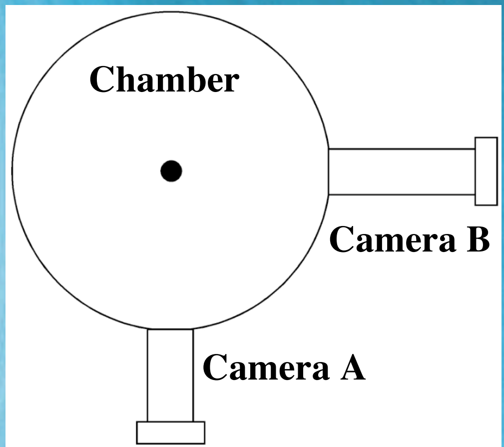
Time-integrated pinhole camera, 6μm Al filter



Time-resolved pinhole camera, 2ns prior to X-ray peak, 7μm Be filter

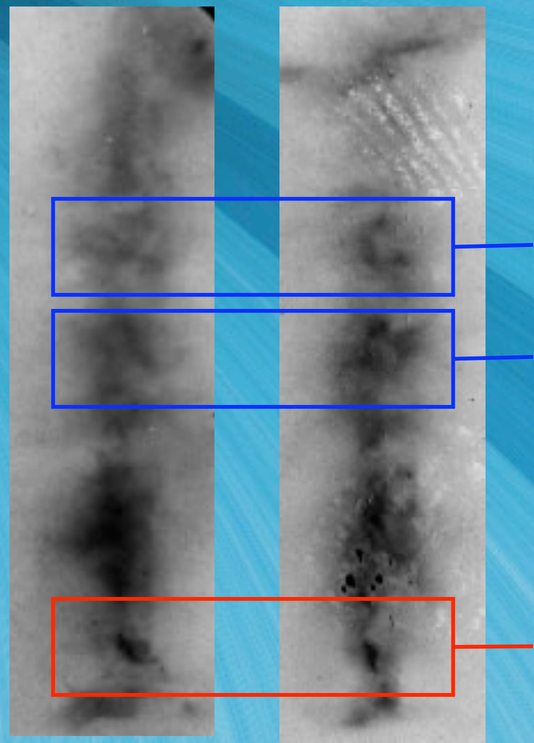
- Monochromatic imaging shows that the maximum distance away from the axis that bright spots are formed ranges from 1.4mm to 1.9mm.
- The radius at which the imploding sheath impacts upon the precursor ranges from ≈ 1.25mm to 1.5mm, so bright spots can be formed outside of this impact zone.
- Both time integrated and time resolved pinhole imaging suggest a “hollow” radiation structure to the stagnating column: what appears to be bright spots distributed around the outside of a cold, precursor-sized object.

Radial Structure from 2-Angle Imaging



Two time integrated pinhole cameras, A and B, are separated azimuthally by 90°.

Shot 1013: 16 Wires, 10µm Al



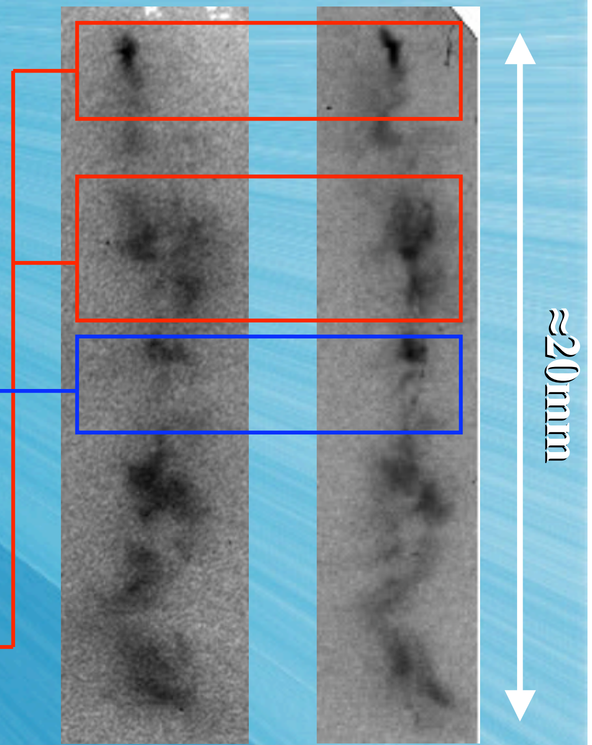
Camera A
20µm pinhole, 15µm silicon filter

Camera B
50µm pinhole, 15µm silicon filter

Some features are present on one image, but not the other.

Some features are present in both images, but appear shifted due to rotation of perspective.

Shot 1015: 32 Wires, 10µm Al

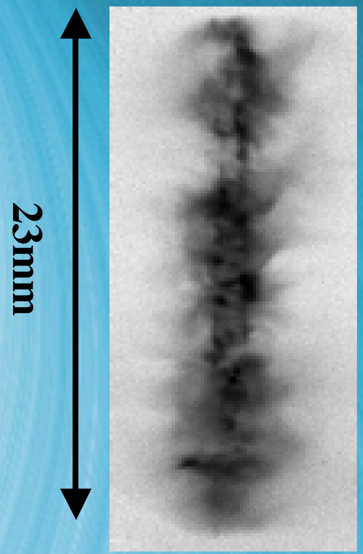


Camera A
20µm pinhole, 15µm silicon filter

Camera B
50µm pinhole, 15µm silicon filter

- Some features are present on one image but not the other, whilst other features are present on both images but appear to shift horizontally or change shape.
- This indicates that some hot spots are located away from the axis. Also, it suggests that the plasma on axis is opaque to some bright spot radiation.

Summary of Radial Structure Imaging



"Hollow" radiation structure observed at stagnation

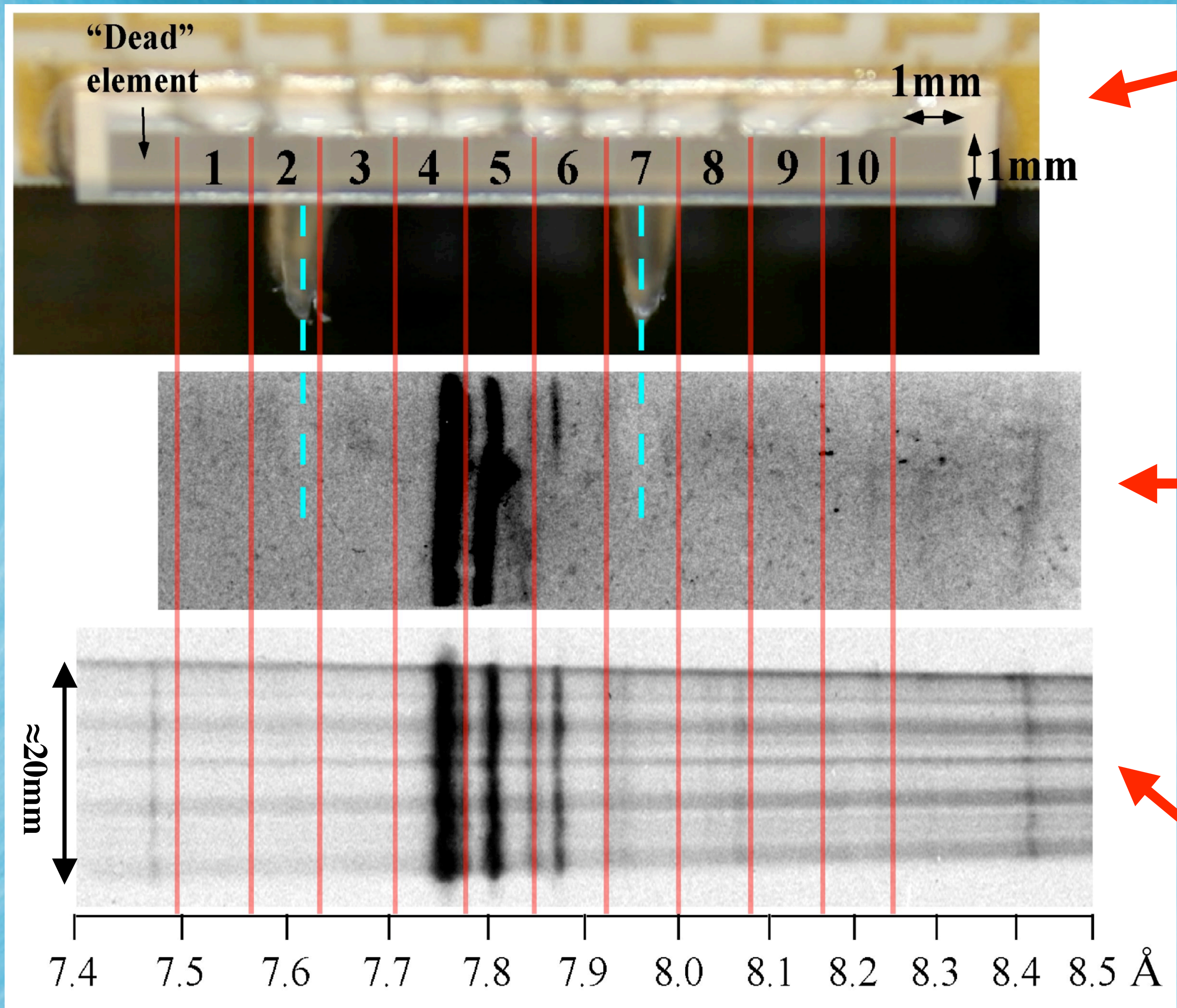
Observation of bright spots further from the axis than the sheath-precursor impact zone

Multiple-angle cameras show bright spots are indeed located away from the axis and can be obscured by cold on-axis plasma

- If current concentration is responsible for producing the bright spots, then current does not flow directly on axis, nor in an azimuthally symmetric manner? Might there be some kind of current striation?
- If current concentration is producing m=0 instabilites then this is NOT the classic azimuthally-symmetric on-axis m=0 instability responsible for bright spots in single-wire z-pinches and x-pinches.
- It would appear that it is possible to have more than one bright spot at one axial position - are they separated azimuthally or temporally?

Time-Resolved Spectra: X-ray Detector Array

Shot 1015: 32 Wires, 10μm Aluminium

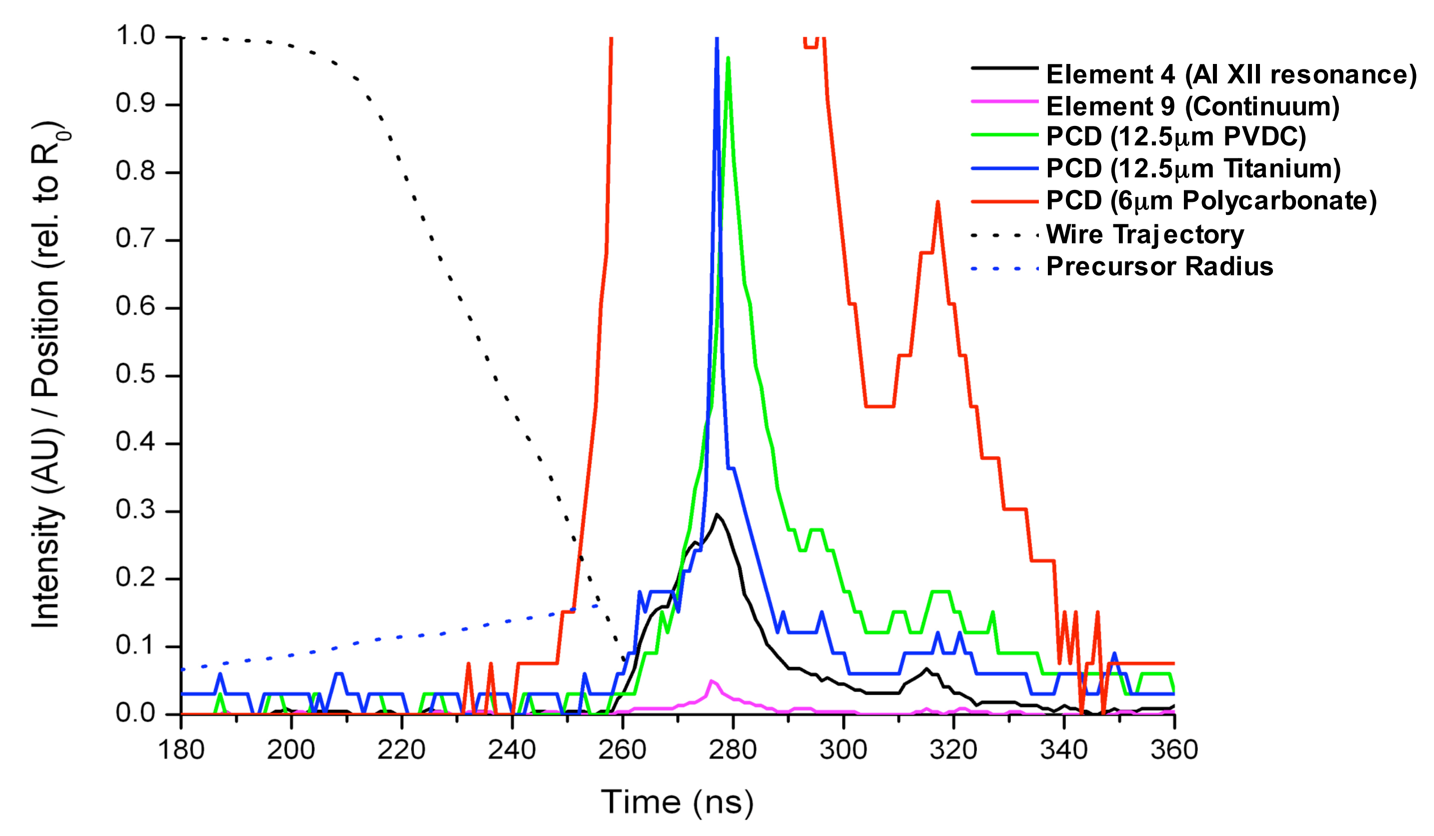


The upper section of an FSSR 1-D spectrum is imaged onto the array elements by the 100mm mica crystal. Two markers are fixed to the underside of the array.

The lower section of the spectrum is imaged, slightly defocused, onto a film pack immediately behind the array. The markers, visible as unexposed sections of the film, are used to determine the position of the spectrum relative to the array elements.

Comparison of the 100mm defocused spectrum with the 186mm focused spectrum reveals which spectral features were detected by each array element.

Time Resolved Spectra



- Within experimental errors, all five signals were seen to peak at the same time.
- The line radiation and continuum radiation are not produced during the snowplough phase of the implosion.
- The FWHM of the continuum radiation is 3-4 times shorter than the line radiation.

The mechanism responsible for producing the continuum radiation is active for a shorter time (or active *efficiently*) than the mechanism responsible for heating the bulk plasma

Does the 20ns gap between the impact of the imploding sheath onto the precursor and the sharp rise of the continuum radiation suggest anything about the mechanism for bright spot production?

Conclusions

- A new diagnostic using spherically-bent crystals has been used to diagnose aluminium wire arrays.

- Continuum radiation is seen from narrow sections of the pinch. The presence of H-like aluminium shows them to be bright spots, possibly hot and dense.

- Comparison of crystal, pinhole and laser imaging shows a correlation between bright spot positions and where little trailing mass remains.

- Pinhole imaging suggests a hollow radiation structure. Multiple-angle imaging shows off-axis bright spots and opaque plasma on axis.

- Time-resolved measurement of line and continuum radiation intensity shows simultaneous peak, but shorter FWHM of continuum radiation.

Future Work

- Time resolved spherically-bent crystal imaging.
- Role of precursor size: different wire materials and wire diameters.
- Spherical wire arrays: comparison of a different implosion geometry.

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