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Studies of precursor plasma conditions for stainless steel and copper wire arrays at the 1-MA Zebra facility

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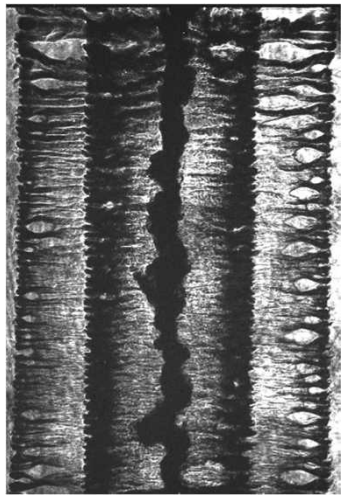
Background

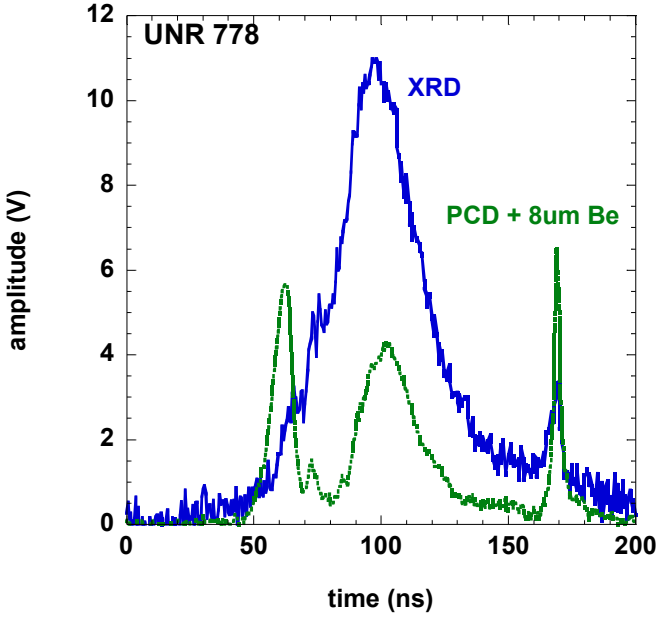
- Research at the 1 MA Zebra facility has encompassed a variety of loads and physics:
  - Wire arrays
  - X-pinches
  - Planar arrays
  - Conical arrays
  - Implosion dynamics

- Studies with cylindrical arrays have observed significant precursor radiation
  - Few wires allows good views of axis through imploding plasma, evaluation of precursor
  - Shadowgraphy used to study development of precursor
  - Radiation diagnostics show significant energy in precursor plasma
    - "soft" x rays
    - > 1 keV x rays
  - Multiple temperatures and densities to model measured spectra
  - Recent time-resolved spectra confirm precursors have T_e > 200 eV

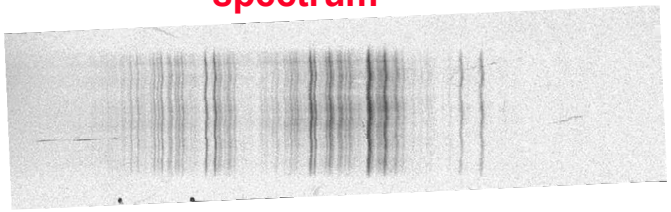
Diagnostics illustrate complex behavior in the z pinches



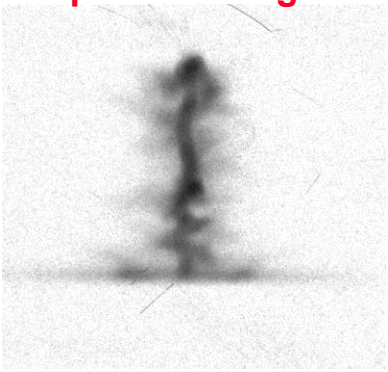
416, 12mm 6 wires
Shadowgraphy of ablation and precursor



775, 16mm 6 wires
Axially resolved, time-integrated L-shell spectrum



772, 12mm 6 wires
time-integrated pinhole image



Structure present on time-integrated images (spatially resolved spectra, pinhole images) mirrors that observed on precursor

- ***Suggests precursor plays significant role in final stagnation and radiation***

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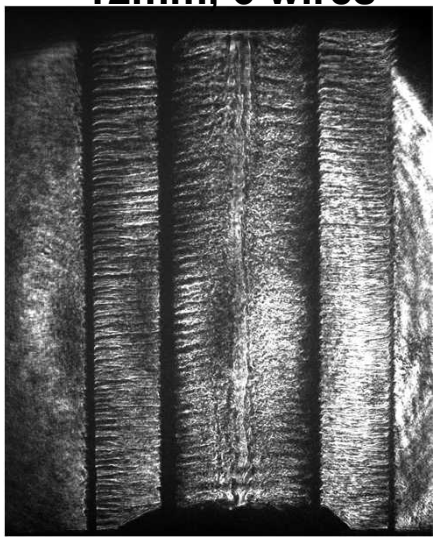
Shadowgraphy allows for detailed study of the imploding plasma

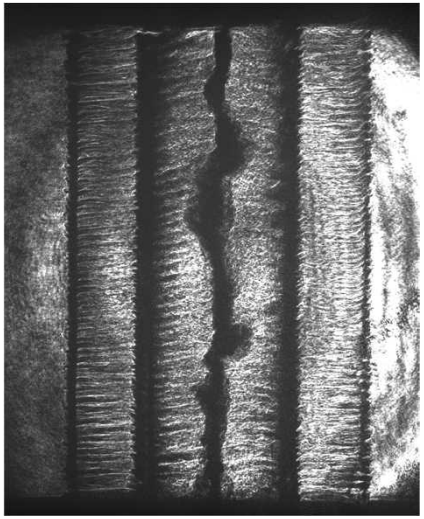
Copper wire arrays

UNR 772
12mm, 6 wires



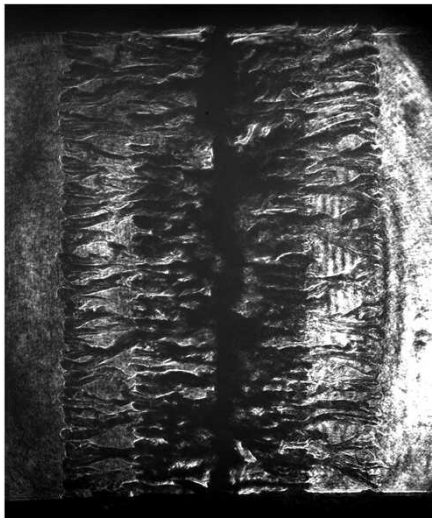
Before rising edge of precursor x-ray pulse

UNR 773
12mm, 6 wires



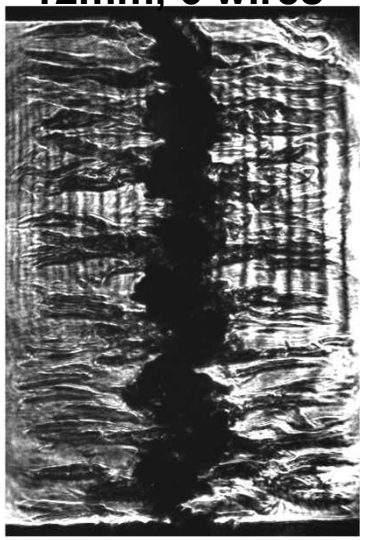
Falling edge of precursor x-ray pulse

UNR 781
12mm, 6 wires



Rising edge of main x-ray pulse

UNR 716
12mm, 6 wires



Peak of main x-ray pulse

Very nice precursor papers:
S.V. Lebedev et al., Laser Part. Beams 19, 355 (2001)
S. Bott et al., Phys. Rev. E 74, 046403 (2006)
S. Bott et al., IEEE Trans. Plasma Sci. 35, 165 (2007)

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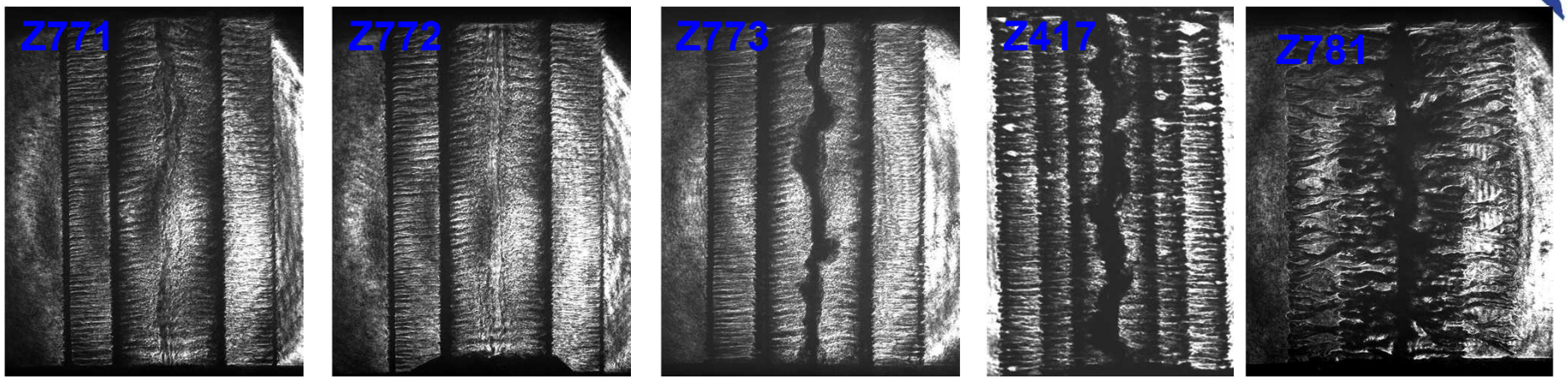
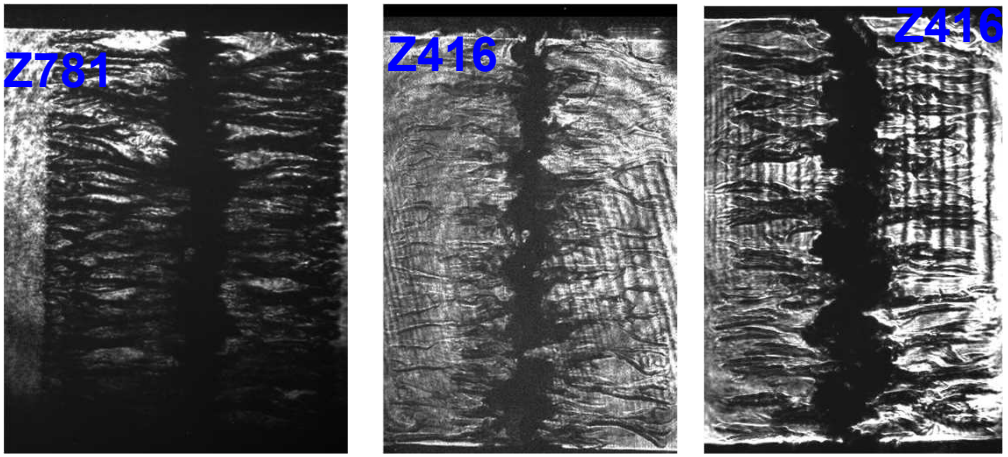
12mm dia., 6 wire Copper array (optimal for radiated output)



time →



Basic evolution similar for other Cu arrays fielded

Structure of precursor forms very early; implosion of remaining mass smooths some of those features but is dominated by instability growth. Trailing mass is clearly evident

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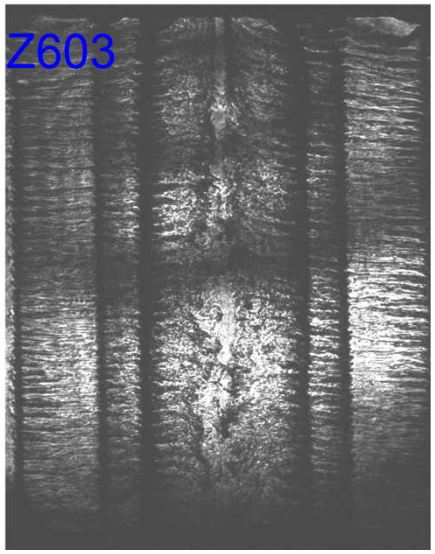
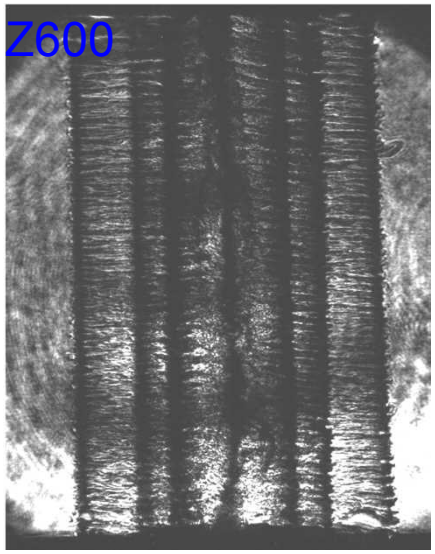
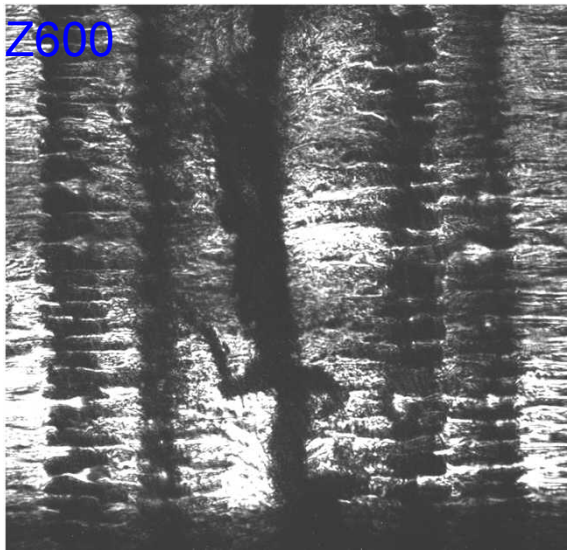
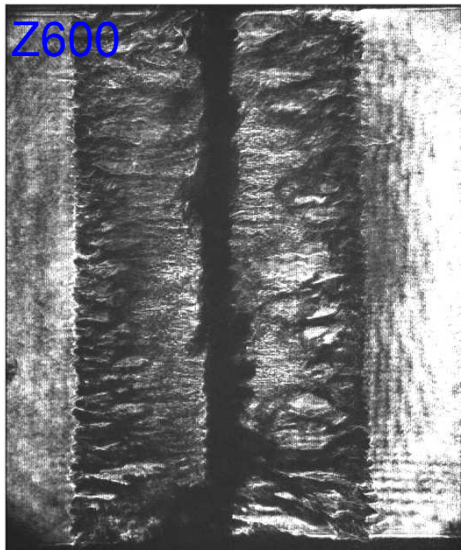
Similar behavior is observed for stainless steel wire arrays

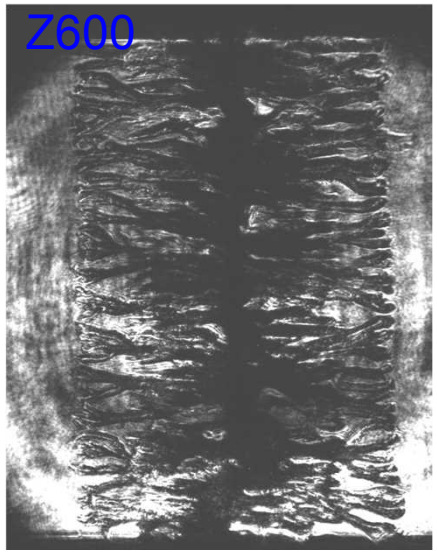






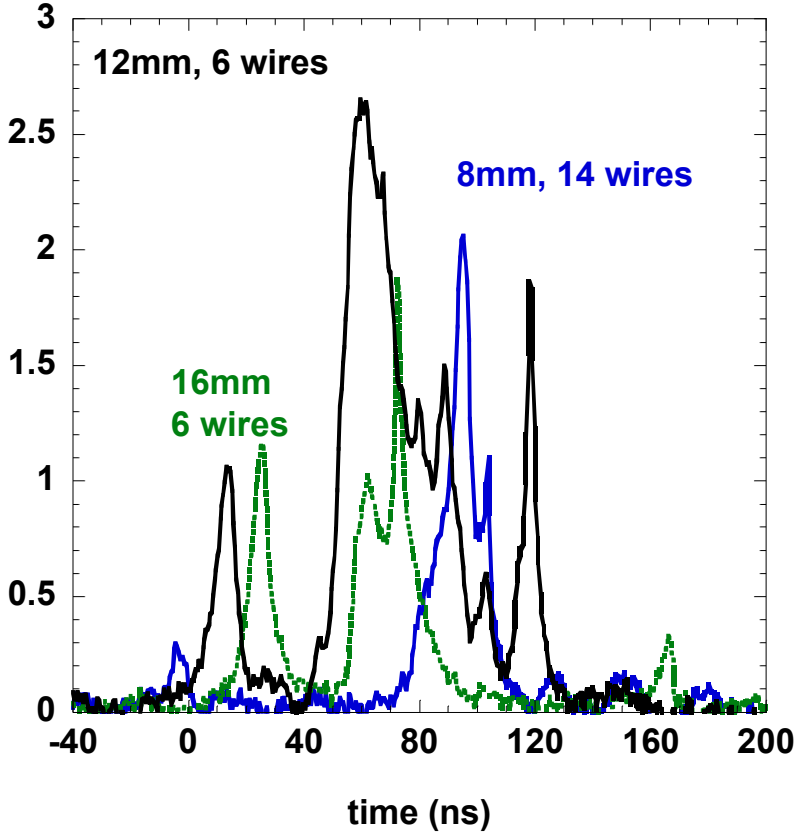
time



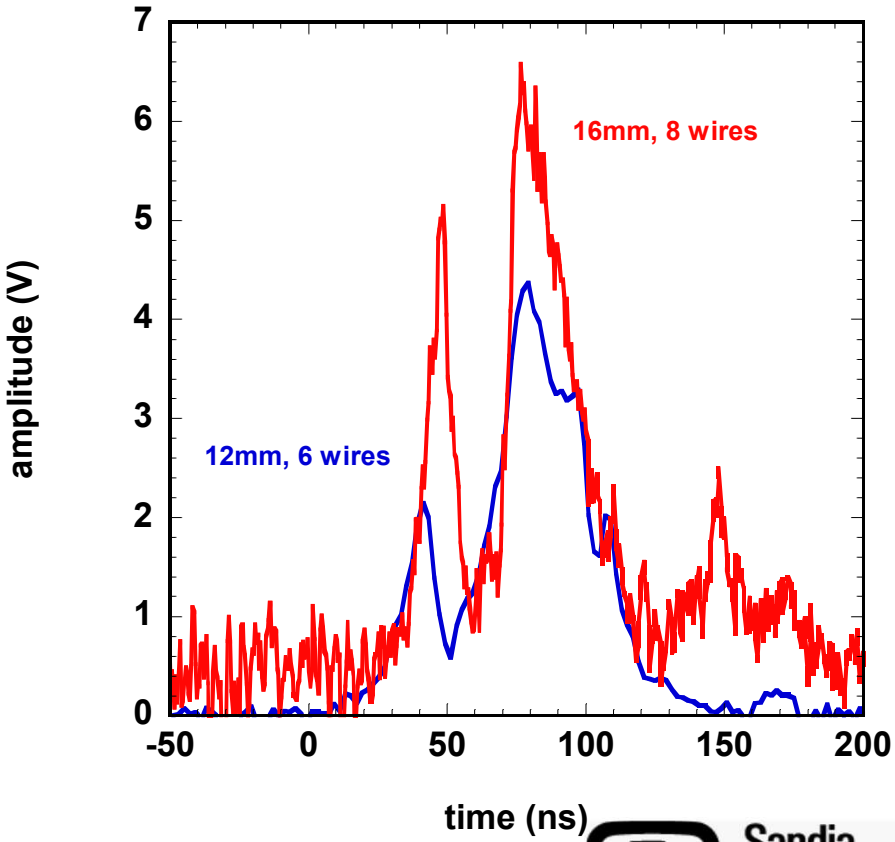


Precursor radiation is clearly seen in the x-ray output

Copper wire arrays



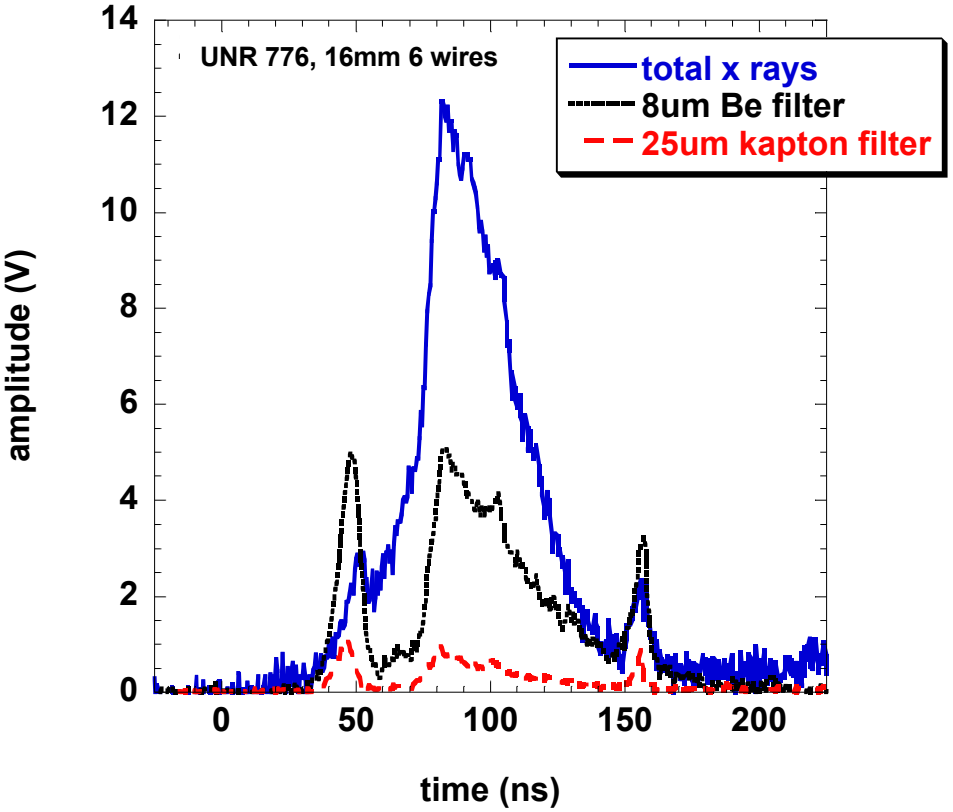
Stainless Steel wire arrays

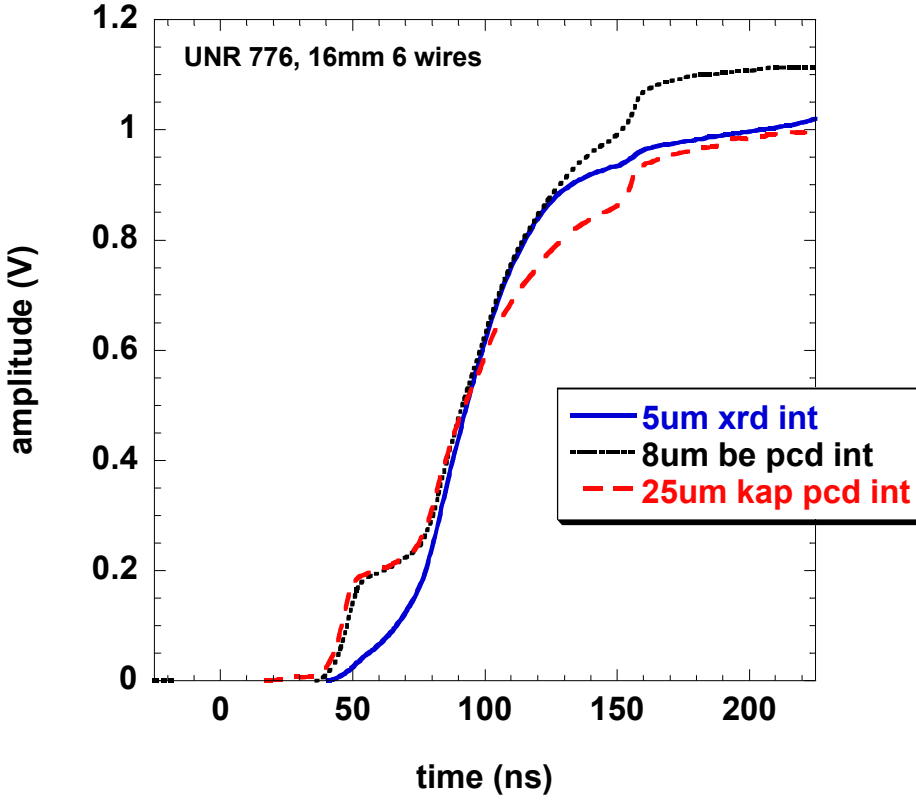


X-ray signals filtered with 8um Be

A significant amount of energy is present in the precursor

Copper wire array





- Energy in precursor is a significant fraction of radiation emitted, especially in harder x rays
- 16mm array, 100ns implosion requires ablation velocity < 10^7 cm/s for precursor formation

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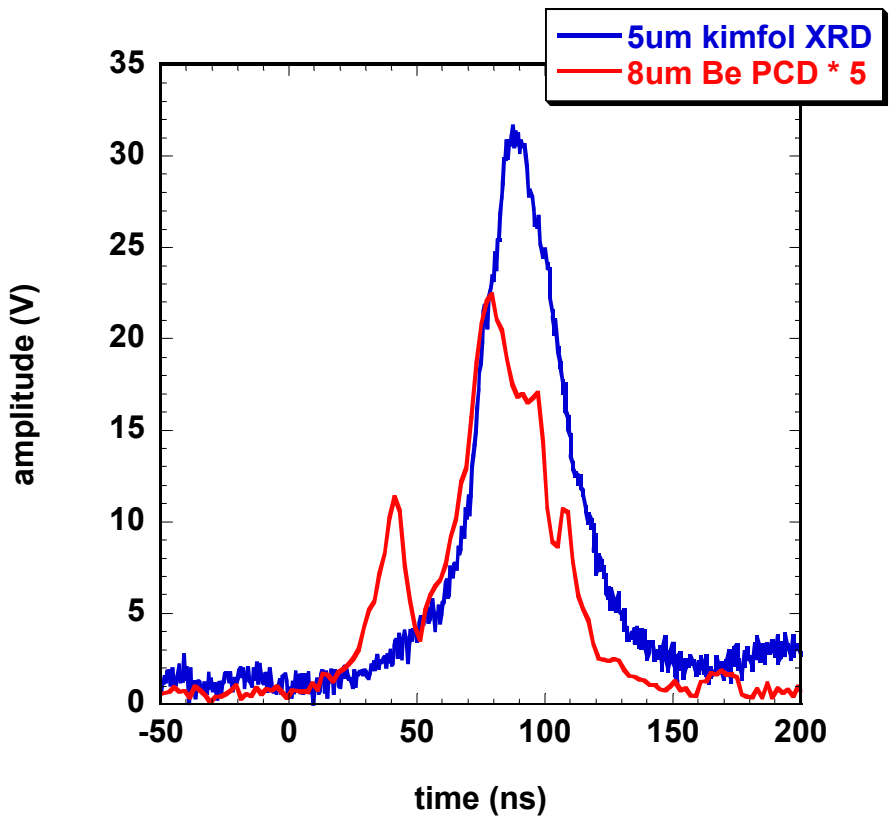
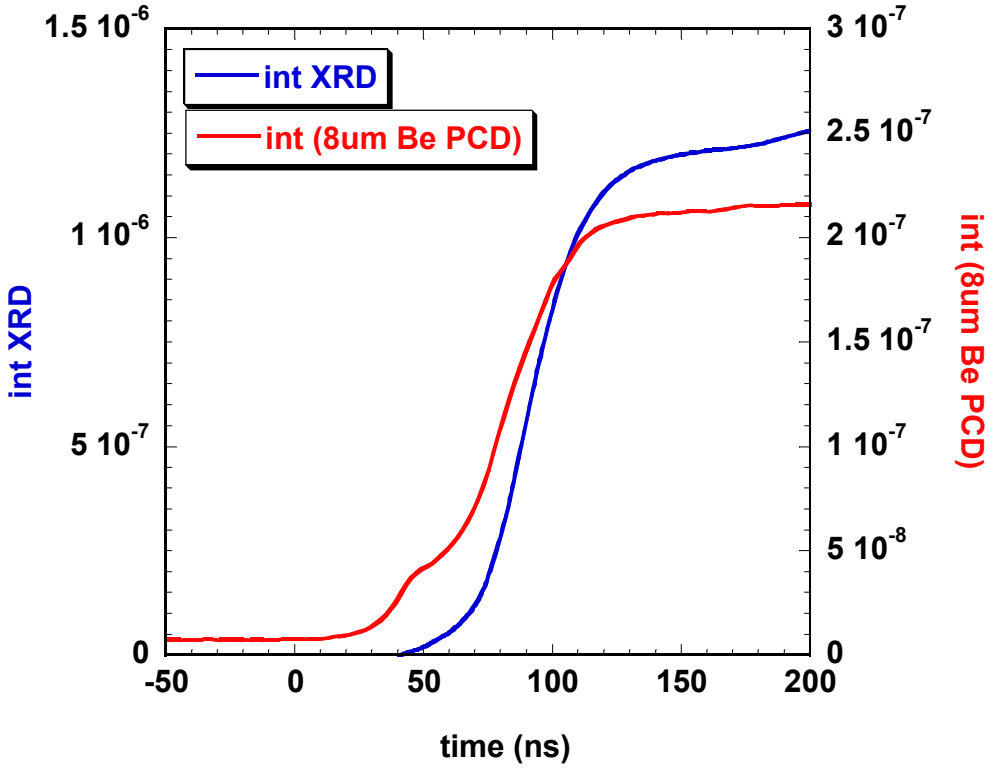
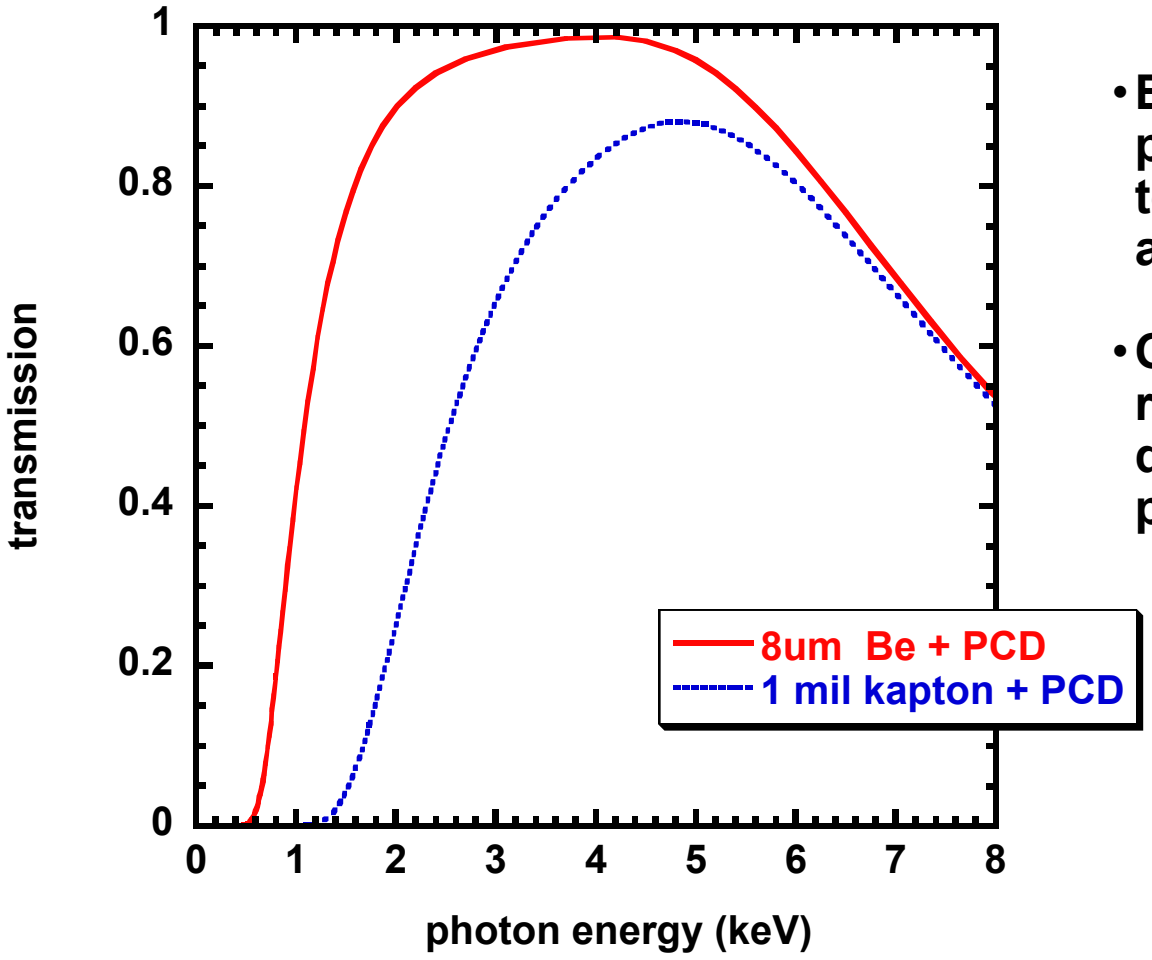
Significant precursor is also observed for SS arrays

Stainless steel, 12 mm dia., 6 wires





Significant radiation on filtered PCDs indicative of L-shell emissions



- Expected for main radiation pulse as appropriate temperature and density are achievable for L-shell emission
- Observation of precursor radiation on these same detectors indicates Cu and SS precursors are hot and dense

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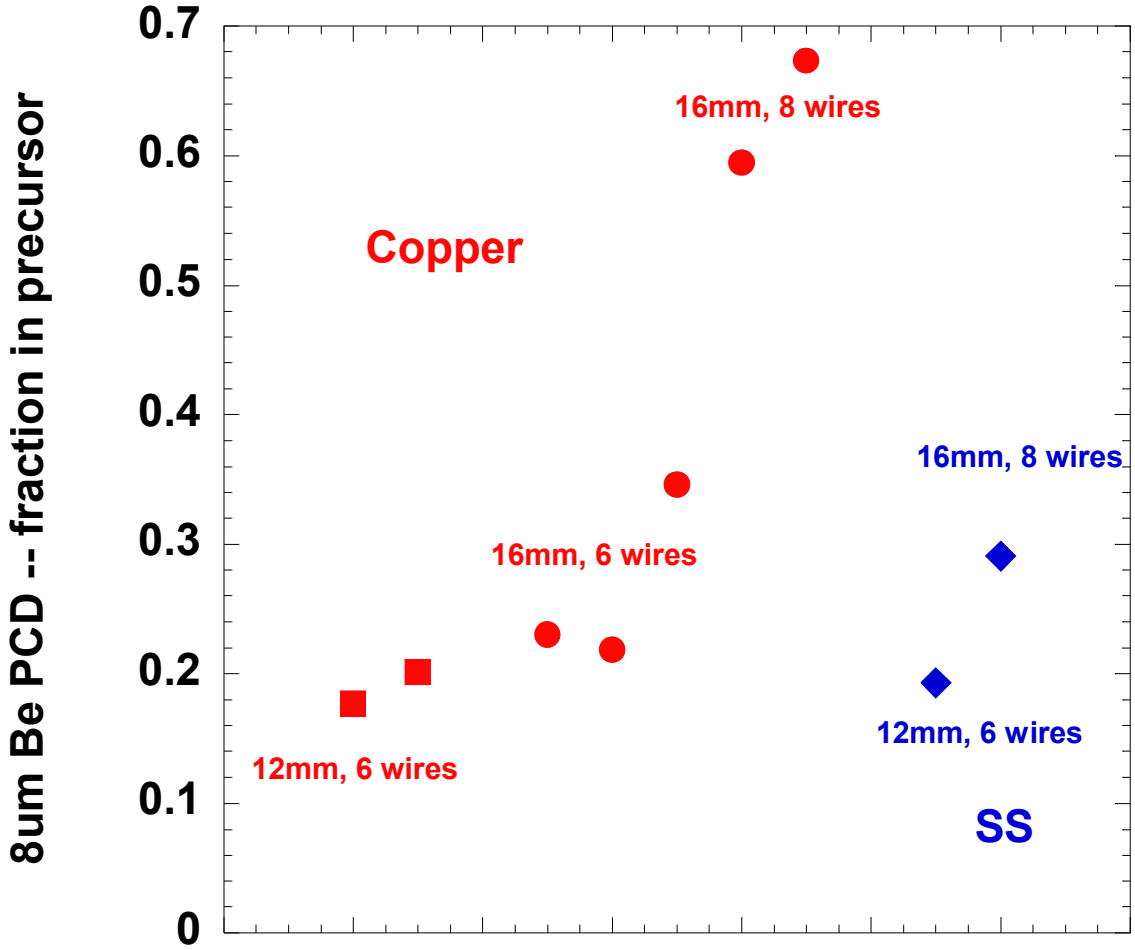
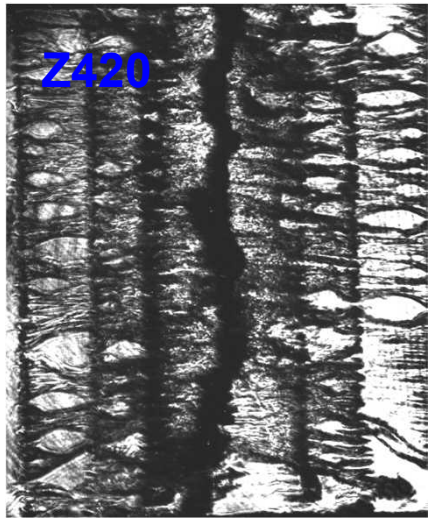
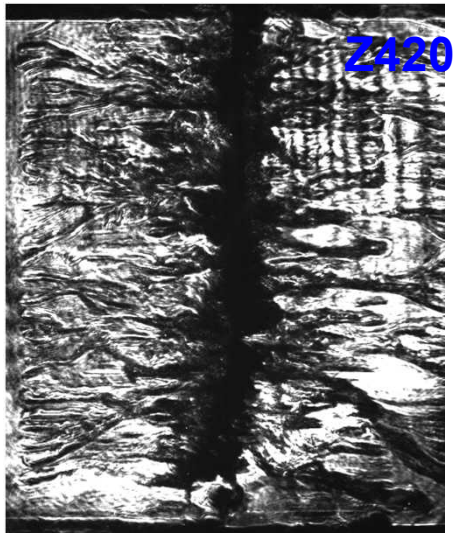
Fraction of output originating from precursor depends on initial load configuration



Structure observed in precursor is mirrored in time-integrated pinhole images

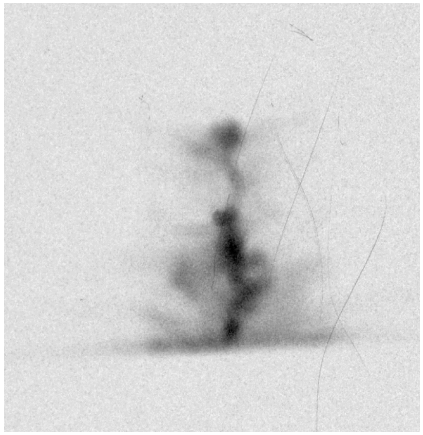
Time-resolved shadowgraphy



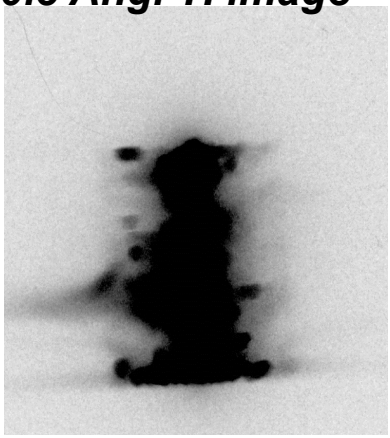


- Initial structure on precursor is partially smoothed by remaining imploding plasma
- Some features still apparent in stagnated plasma and TI images

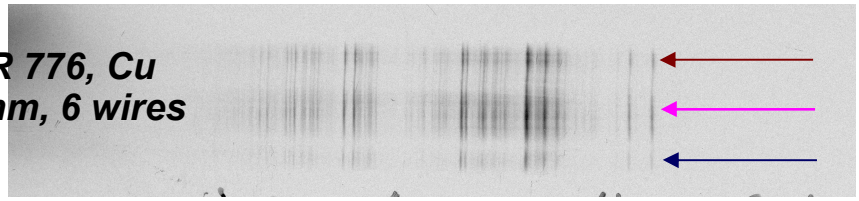
4.4 Ang. TI image



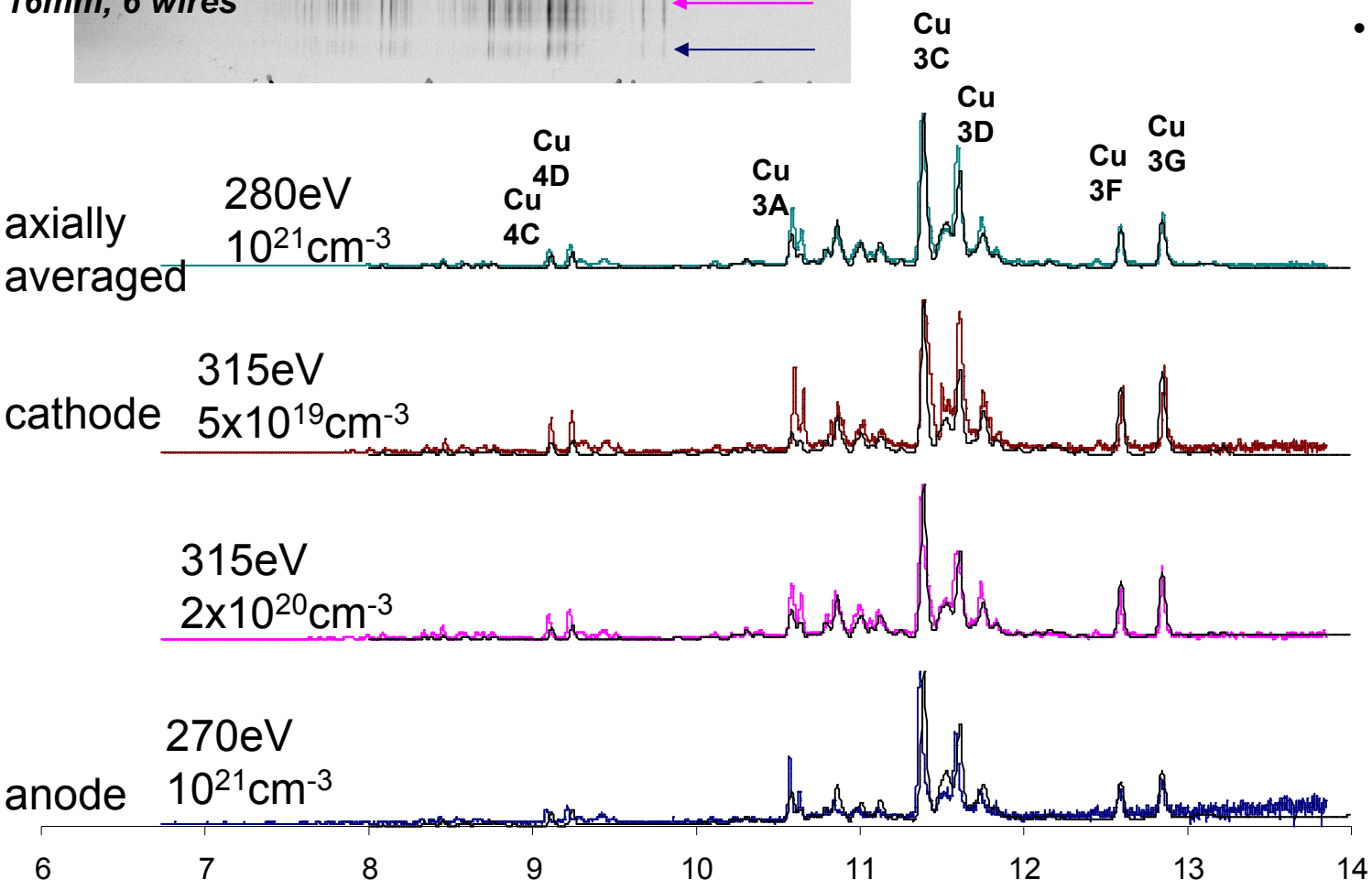
10.3 Ang. TI image



Analysis of the axially resolved spectra show different plasma conditions along the pinch length



UNR 776, Cu
16mm, 6 wires



- **Non-LTE kinetic modeling**

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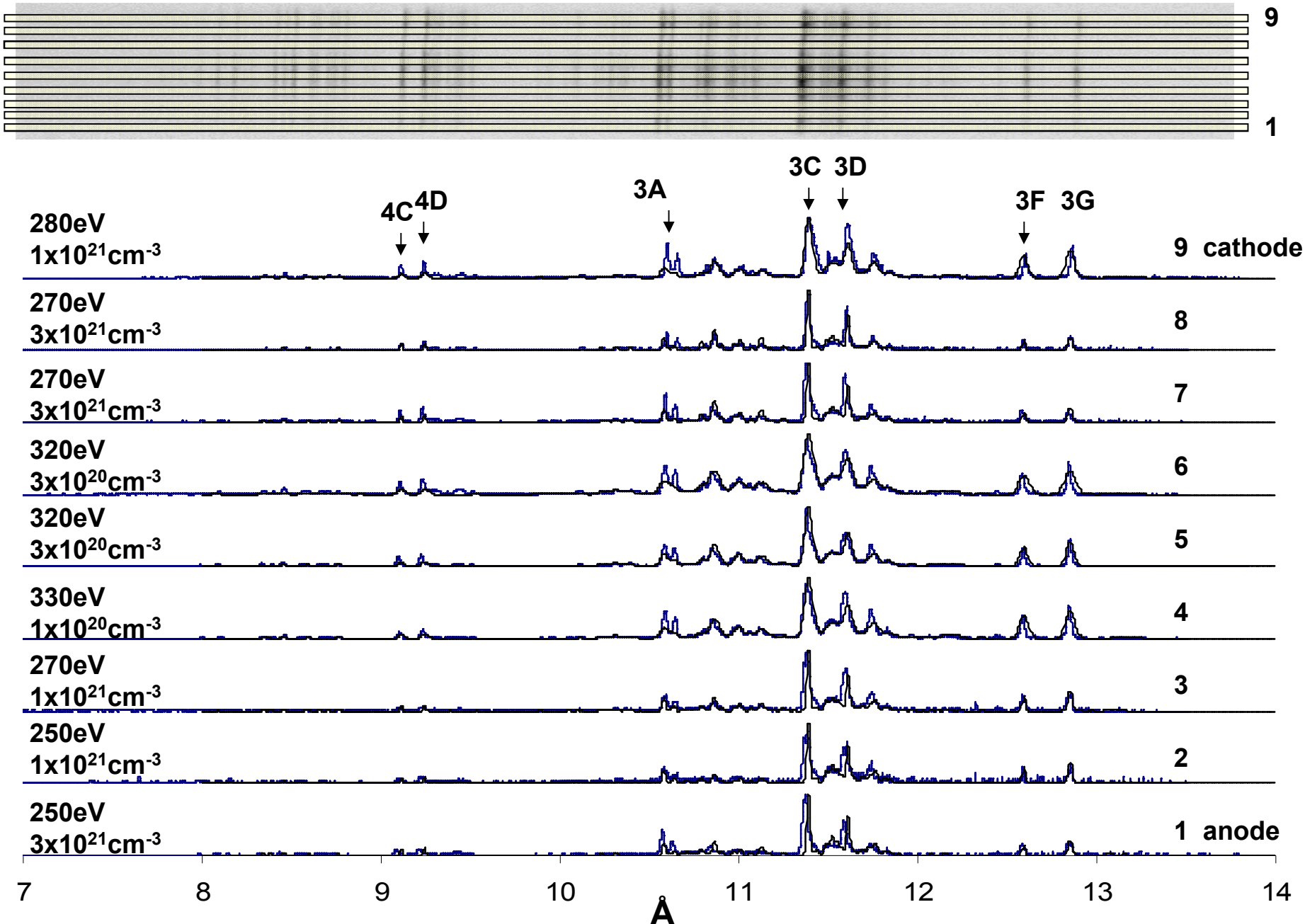
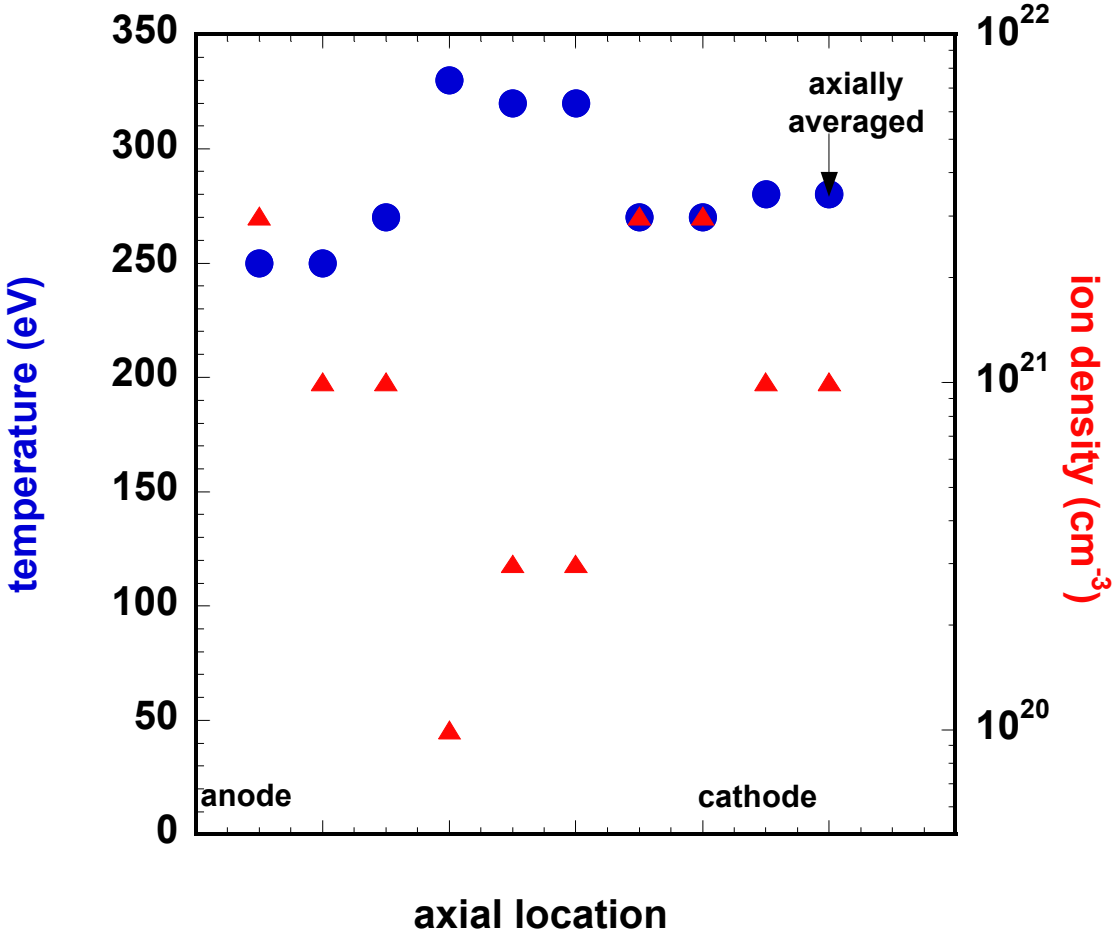
UNR 776, Copper 16mm, 6 wires



Variation in temperature and density is consistent with axial structure observed

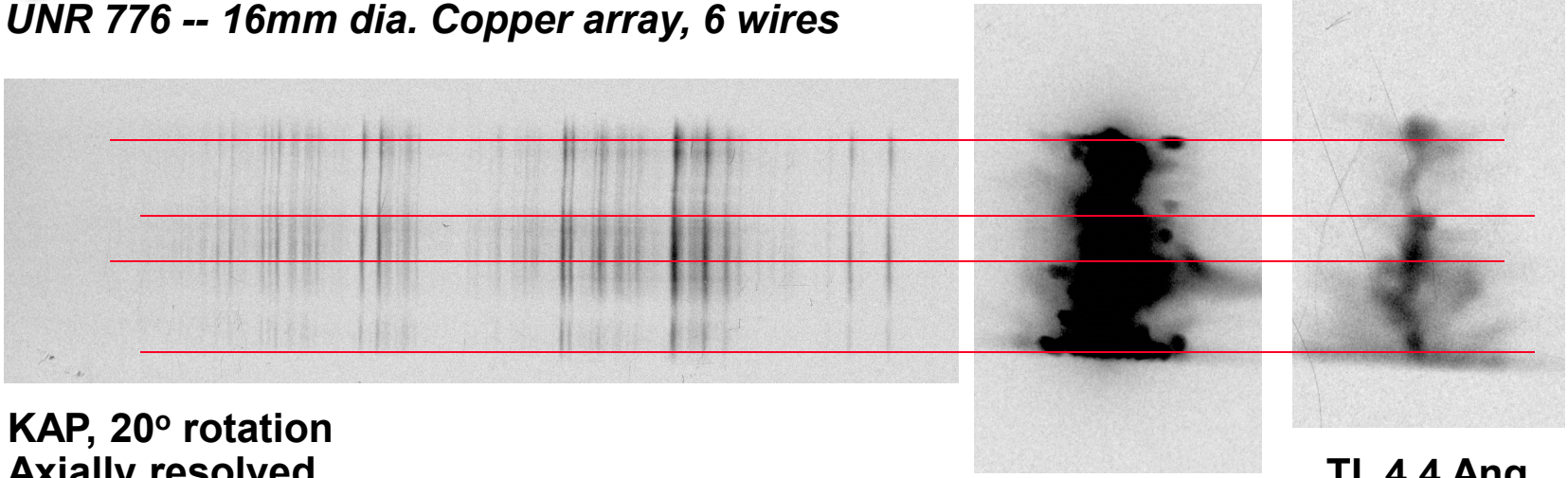
UNR 776 -- 16mm dia. Copper array, 6 wires



- Temperature relatively stable, although some variation observed between anode and cathode
  - Mirrors structure observed in pinhole images
- Density variation is pronounced

Variations in axially resolved spectra are correlated to structure in pinhole images

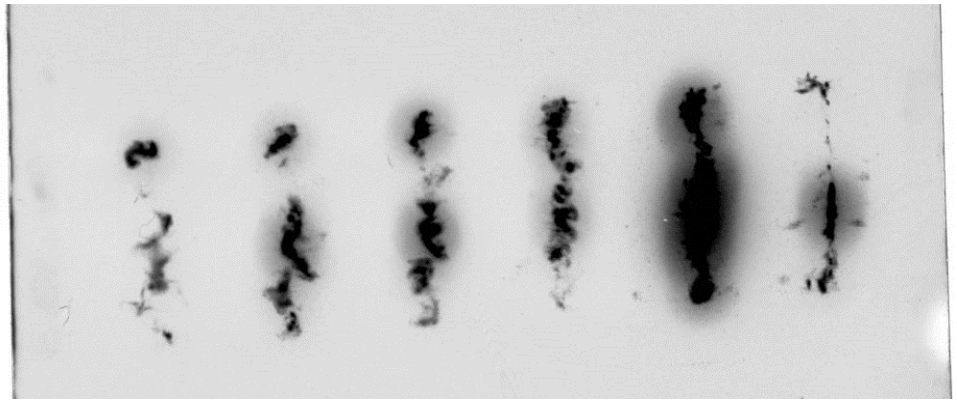
UNR 776 -- 16mm dia. Copper array, 6 wires



KAP, 20° rotation
Axially resolved
0.5 mm slit

Tl 10.3 Ang.

Tl 4.4 Ang.



Time gated images
Interframe time = 5 ns

Similar to Al data documented by G.N. Hall et al., Phys. Plasmas 13, 082701 (2006)

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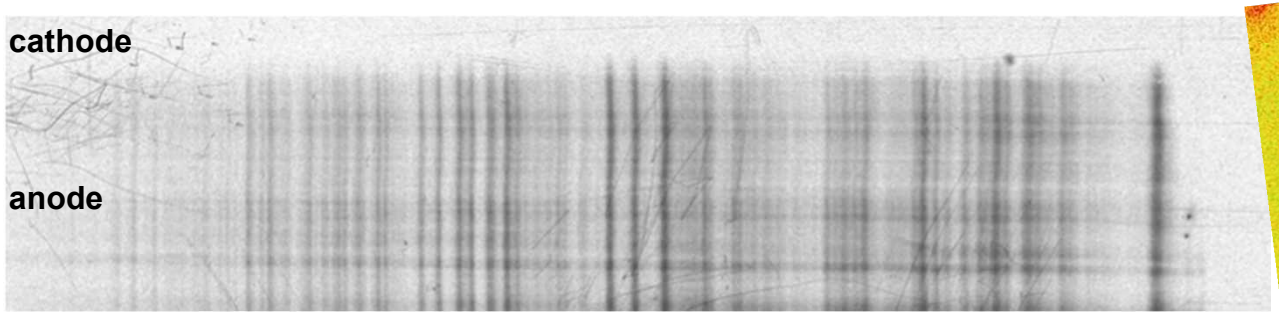
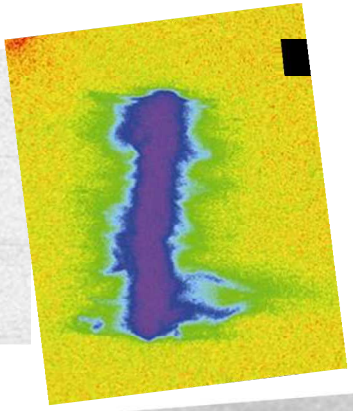
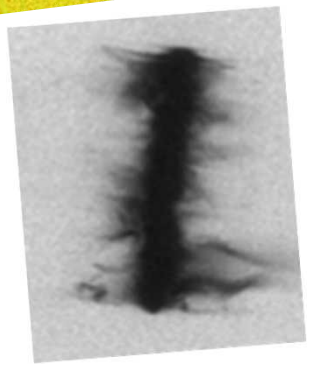
Similar correlation is evident for the stainless steel arrays

UNR 605 Stainless steel
16mm dia., 8 wires

10.3 Ang. filter



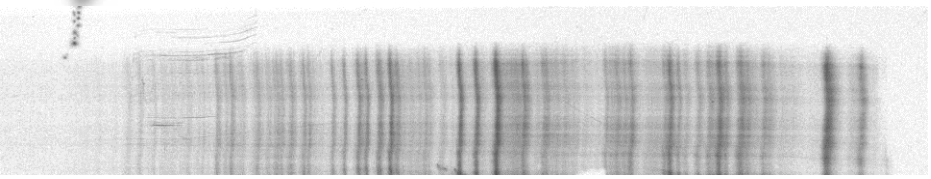


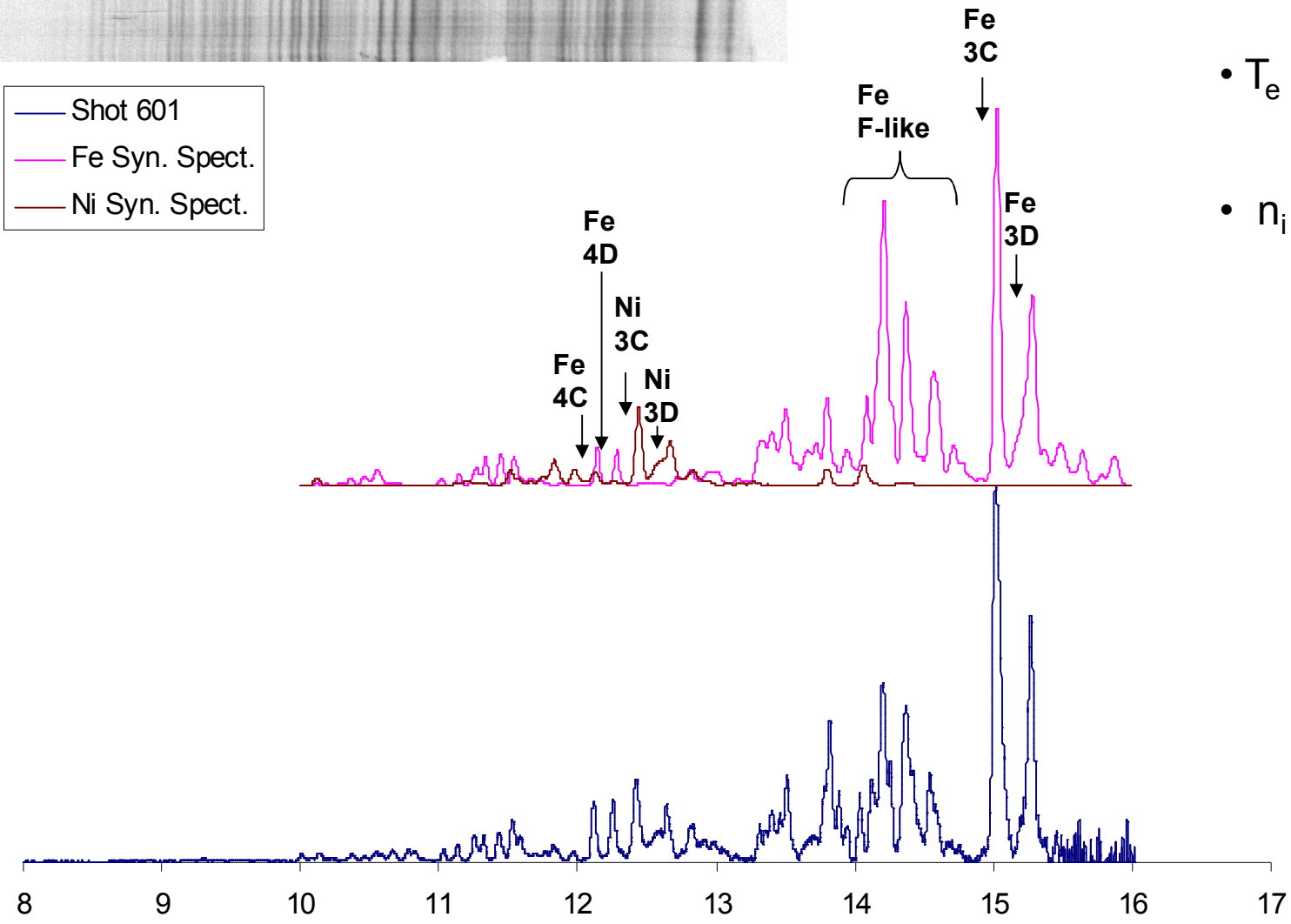


KAP, 20^{o} rotation
Axially resolved
1mm slit

- **Regions with higher continuum background likely tied to brighter regions in pinch, although not evident in these pinhole images due to saturation**

Temperature and density observed for SS are similar to those seen for Cu





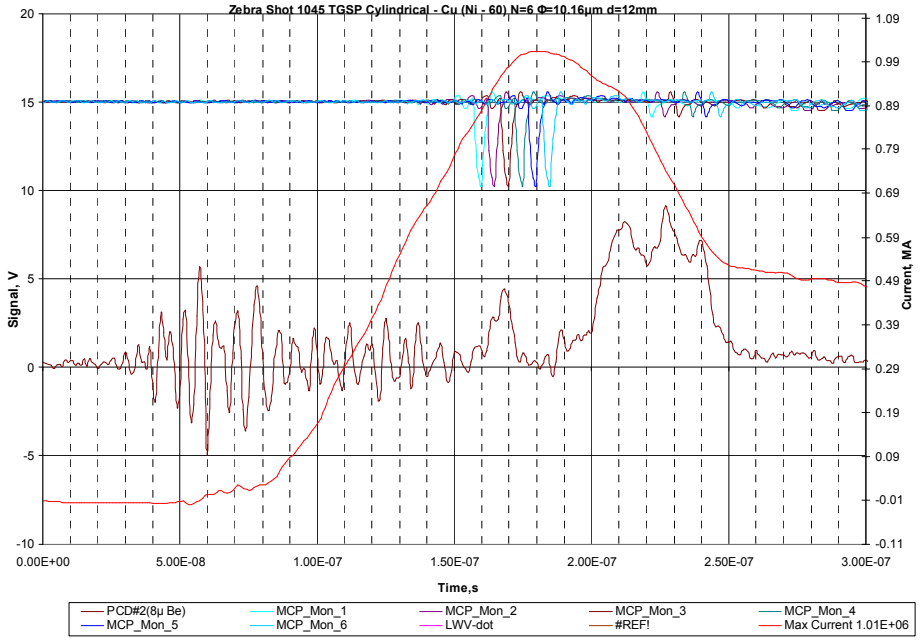
- T_e = 200 eV (Fe)
  250 eV (Ni)
- $n_i = 10^{21}$ cm^{-3}

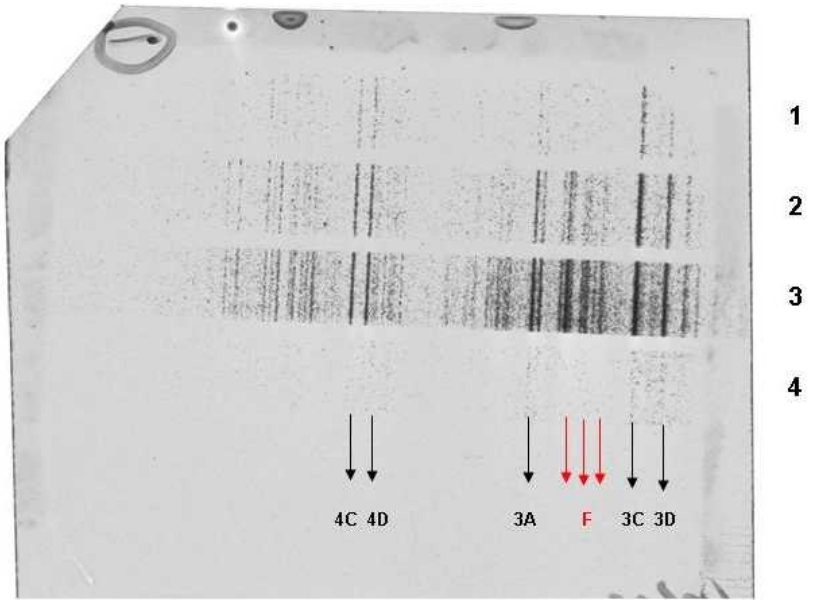
Radiated output and TI spectra suggest precursor plasmas are hot

- Previous work (G. Hall, DZP 2005 and Phys. Plasmas 13, 082701 (2006)) has noted several of the same observations noted here:
  - Correlation of spectral structure with hot spots in images
  - Shadowgraphy of precursor formation
- Work by S. Bott et al. (Phys. Rev. E 74, 046403 (2006) has studied in detail the dynamics of the precursor formation with various materials
  - Previous work by S.V. Lebedev (Laser Part. Beams 19, 355 (2001)) used XUV spectroscopy to estimate plasma temperature for an Al precursor column
- Time histories of L-shell radiation show significant yield in the precursor
- Modeling of the TI spectra requires for many cases either the assumption that multiple sources contributed to the spectra, or hot electrons were present
- Time-resolved spectra has been collected on Cu shots to verify plasma conditions associated with precursor radiation

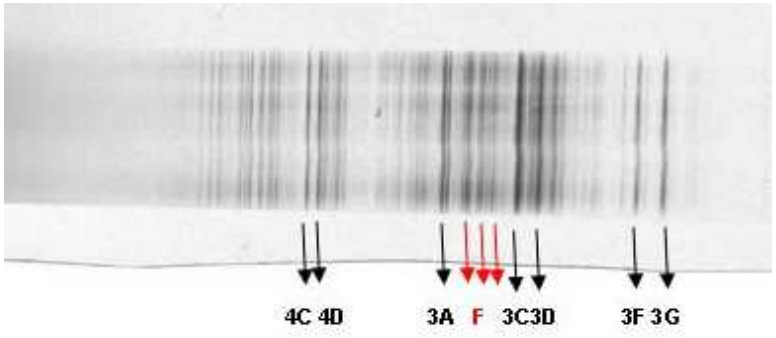
Time-gated spectra have been recently collected to assess precursor plasma conditions

UNR 1045, Copper 12mm dia. 6 wires





Interframe time = 5 ns, 3ns gate



F-like Cu lines (red) manifest high Te (>300 eV)

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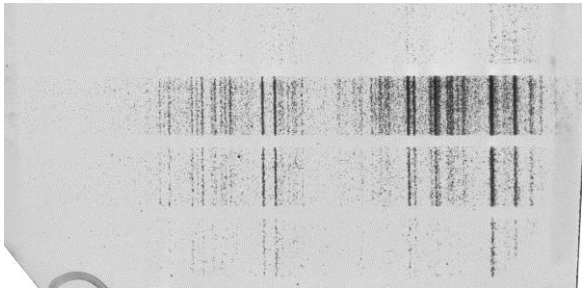
Temperatures and densities measured are highest reported to date from precursor plasmas

UNR 1045



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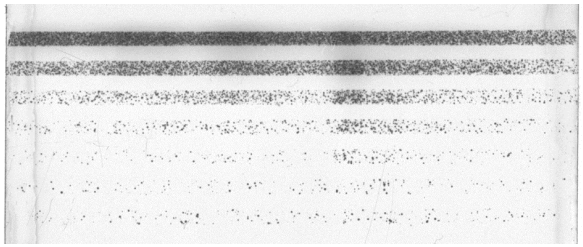
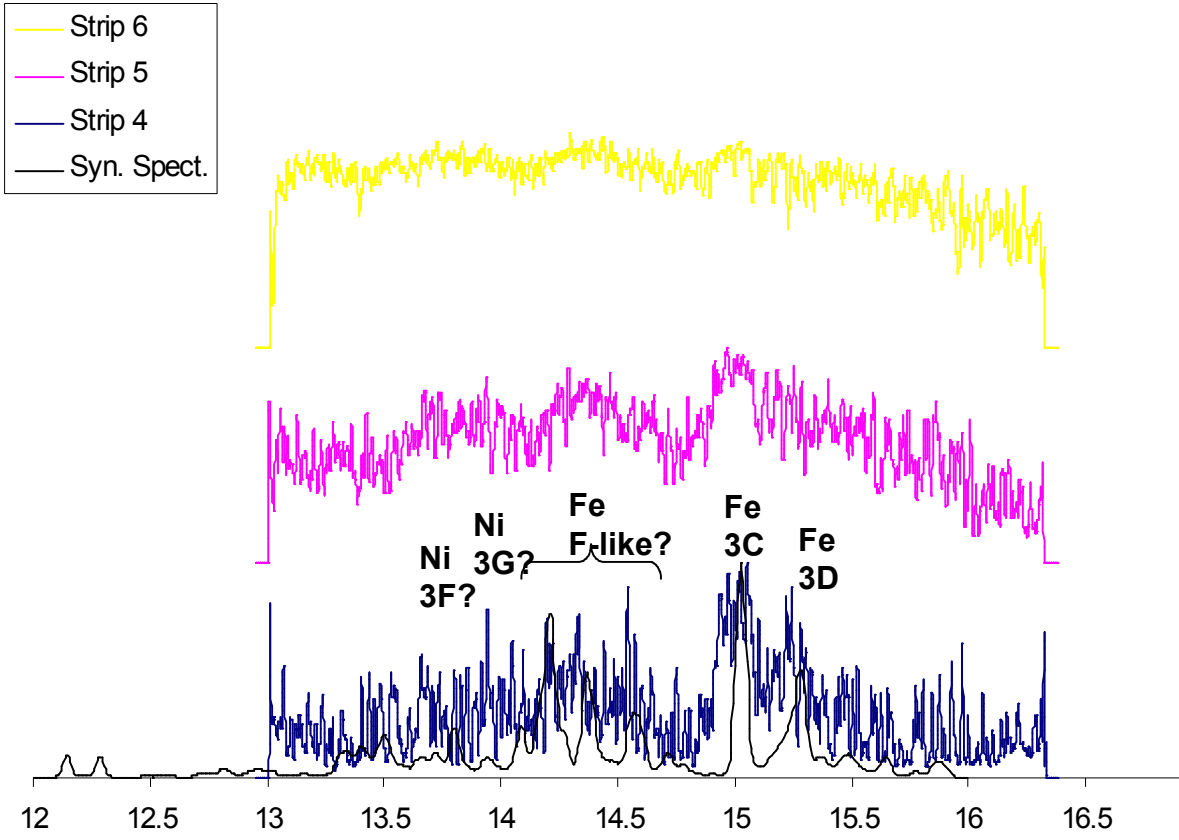
Time-gated spectra have also been collected for SS precursor





- Setup on TG spectrometer not ideal
- Signal to noise not good
  - Presence of lines suggests hot precursor

Summary

- Significant quantities of L-shell radiation (> 700 eV) have been observed with Copper and Stainless Steel wire arrays have been fielded at Zebra

- Shadowgraphy provides detailed information on initiation, precursor formation, and implosion
  - Additional analysis necessary

- Axially resolved spectral data can be used to assess plasma conditions
  - T_e and n_i are higher near cathode
  - Higher T_e and n_i is correlated to regions with higher continuum
    - Evidenced in spectra, correlate to time-integrated pinhole images

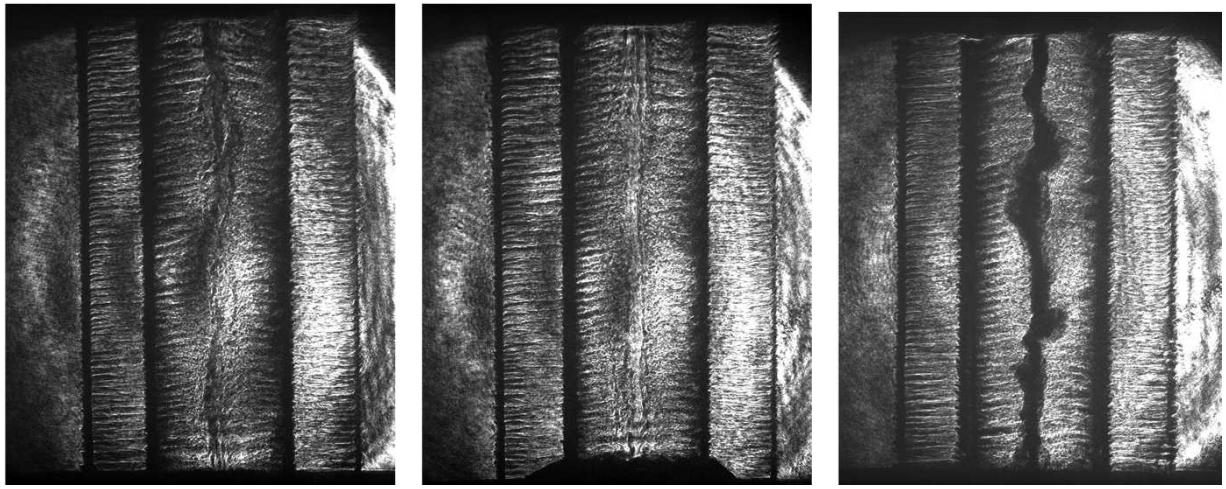
- Time-resolved data provides evidence that precursors are hot and dense
  - Highest temperature and density measured in precursors to date

- For other interesting work from Zebra, see also:

2P104 2P117
2P113 2P118
2P115 4A6

Early phase of the precursor formation can also be studied

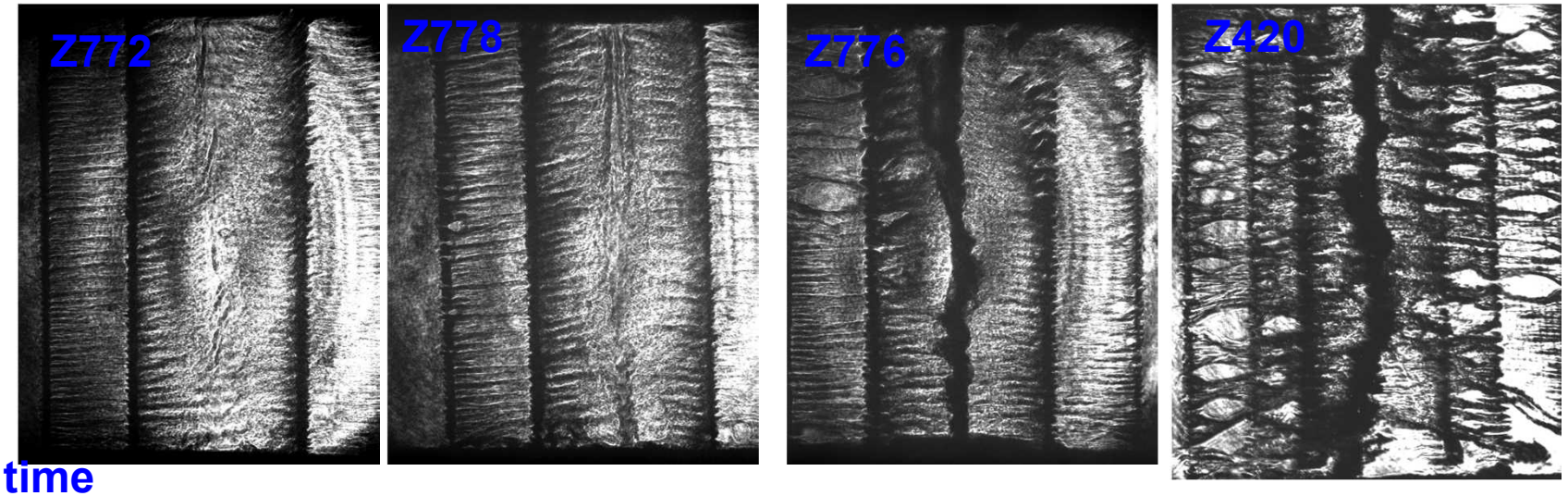
12mm, 6 wires



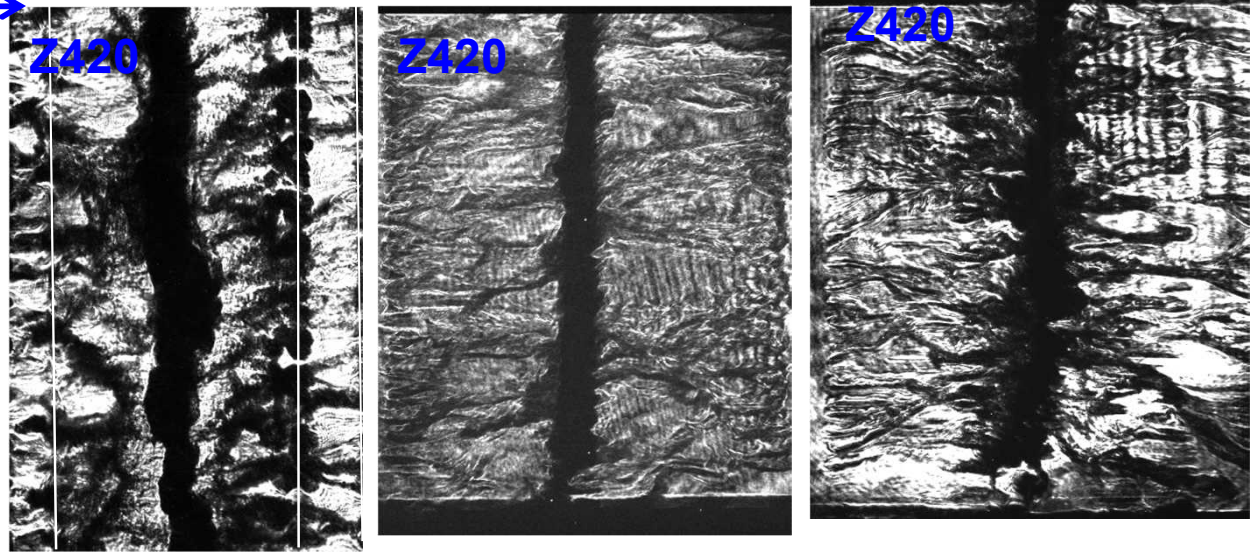
This initial column is narrower than the precursor plasma that emits significant radiation

- **Useful to compare this initial formation with radiating precursor and main x-ray pulse**
  - **Is thermal pressure from the precursor limiting later pinch diameter?**
- **Collection of Faraday rotation data will help assess fields involved in the precursor (V.V. Ivanov)**

Similar behavior is observed for larger diameter Cu array (16mm, 6 wires)



time



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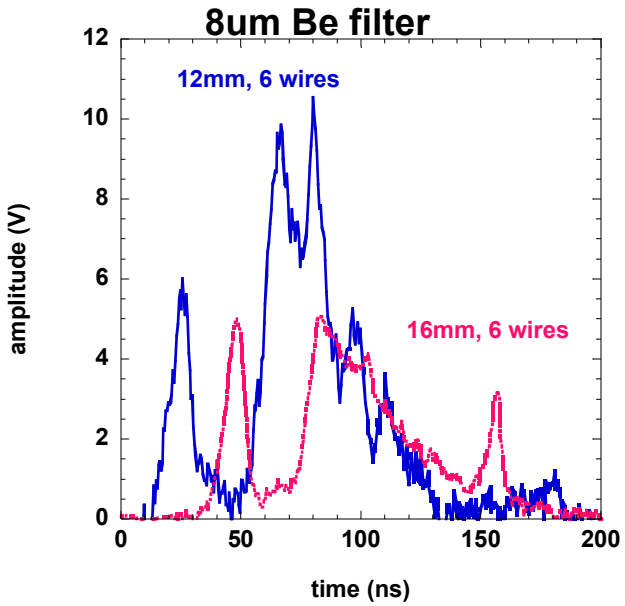
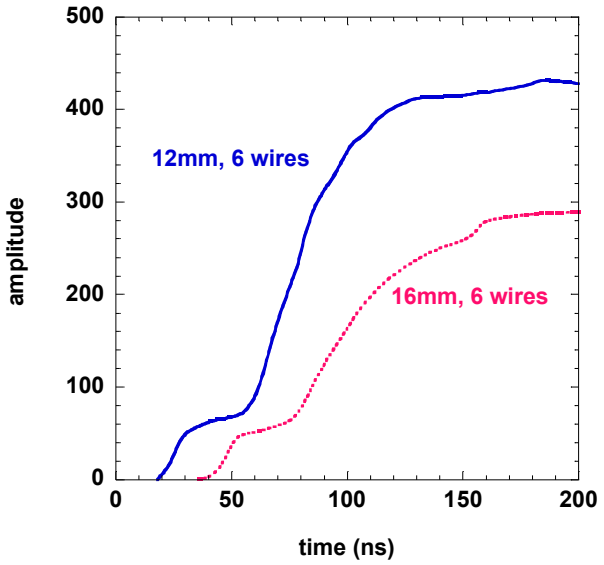
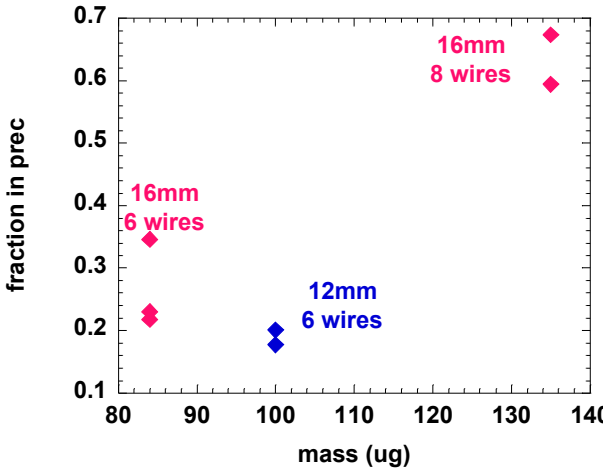
Modeling is more complicated for the 12mm arrays

- Similar approach as previously used (non LTE kinetic modeling)
- Modeling does not appropriately describe both Na and F-like lines
  - Different temps and densities necessary to describe
- Invoking hot electron argument does not improve the modeling
- Could this be result of intense precursor?
  - Precursor intensity is higher for 16mm case, however







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A similar approach was applied to the 12mm array to evaluate spatial variations

UNR 771
12mm, 6 wires