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X-ray Spectroscopy of Plasmas on the Z Accelerator

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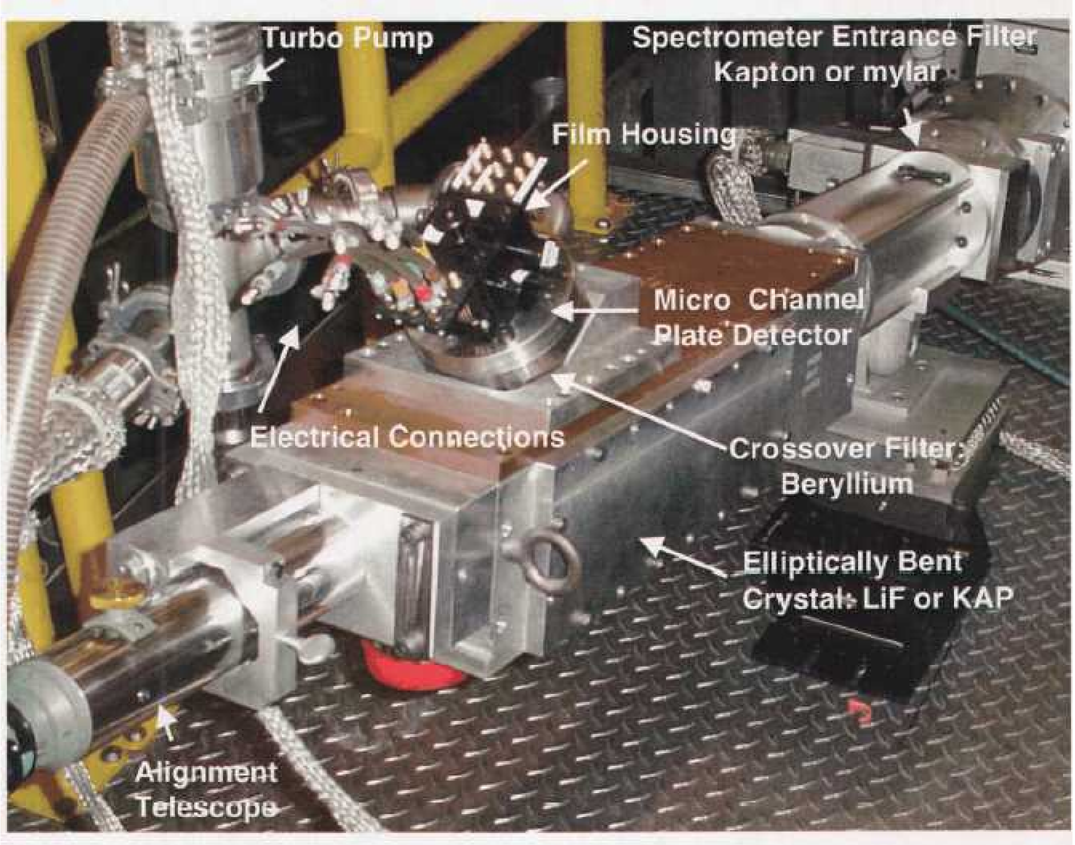
Introduction

- Z pinches are complicated structures with variations in temperature, density and opacity throughout the implosion
  - Spatial non-uniformities
  - Temporal evolution

- Spectroscopy can provide useful information about plasma conditions
  - Time integrated for averaged conditions
  - Spatially resolved to assess structural non-uniformities
  - Temporally resolved to study evolution of plasma conditions

- Spectroscopic techniques can be applied to primary components of plasma, or to dopant species in the plasma
  - Various line sources
    - Al, Ar, Ti, SS, Cu, etc.
    - Opacity is a particularly important issue for low Z materials
  - Dopant species includes intentional and contaminants

Time integrated and time resolved spectroscopy are fielded at Z



- Typically field axially and radially resolved time integrated spectometers

- Time and space (radially) resolved spectroscopy (TREX)

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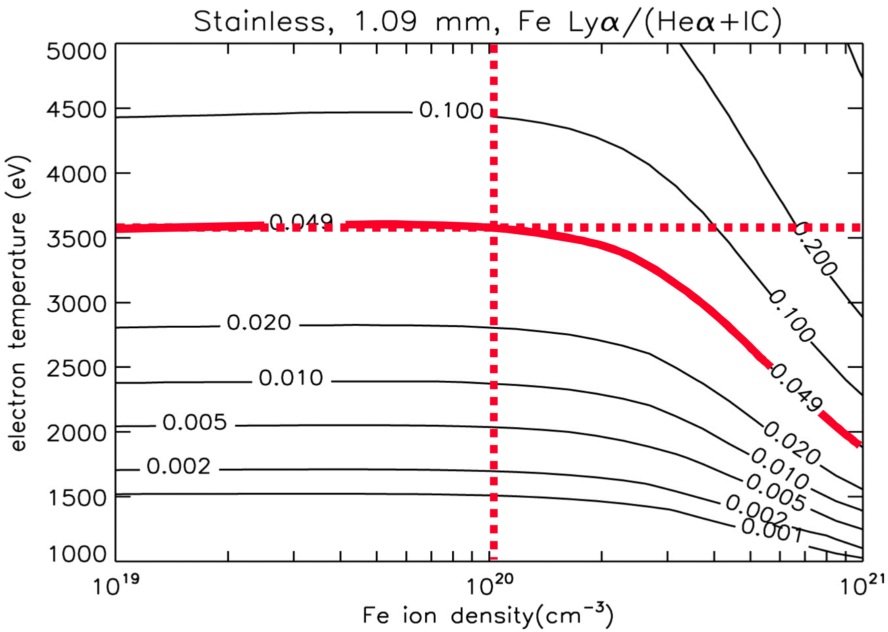
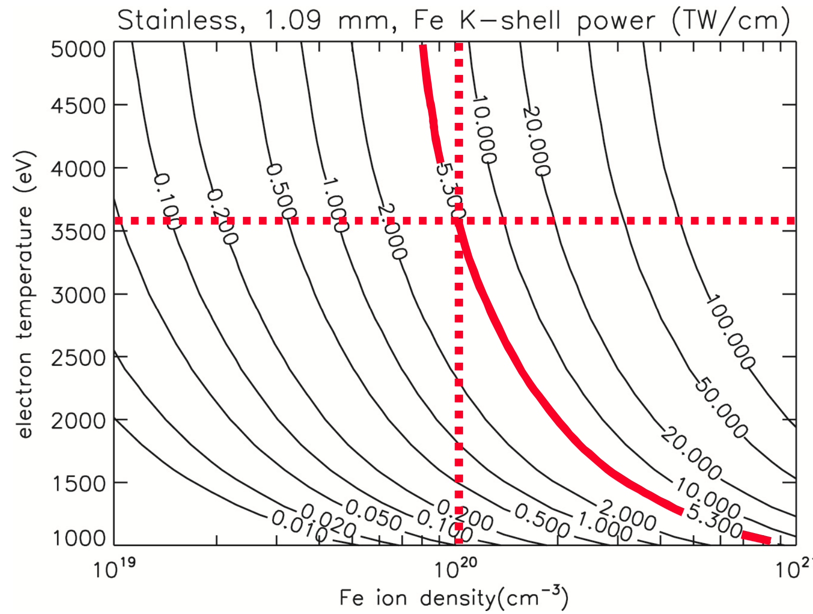
Methodology for inferring temperature and density from time-integrated spectra





- **Analysis of plasma conditions through collisional-radiative modeling**
  - **J. P. Apruzese *et al.*, JQSRT 57, 41 (1997).**
  - **Fe Ly-a/(He-a+IC) ratio primarily constrains T_e**
  - **K-shell power and pinch size primarily constrain n_i**

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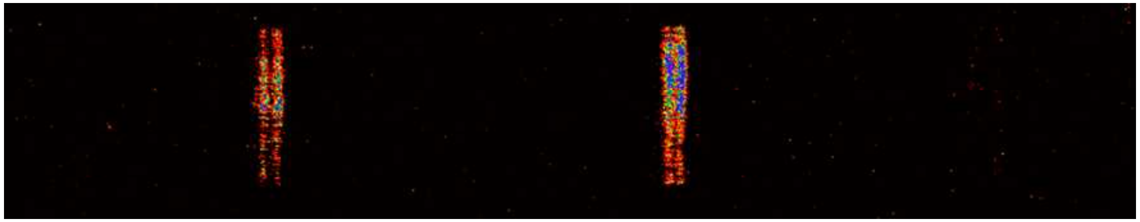
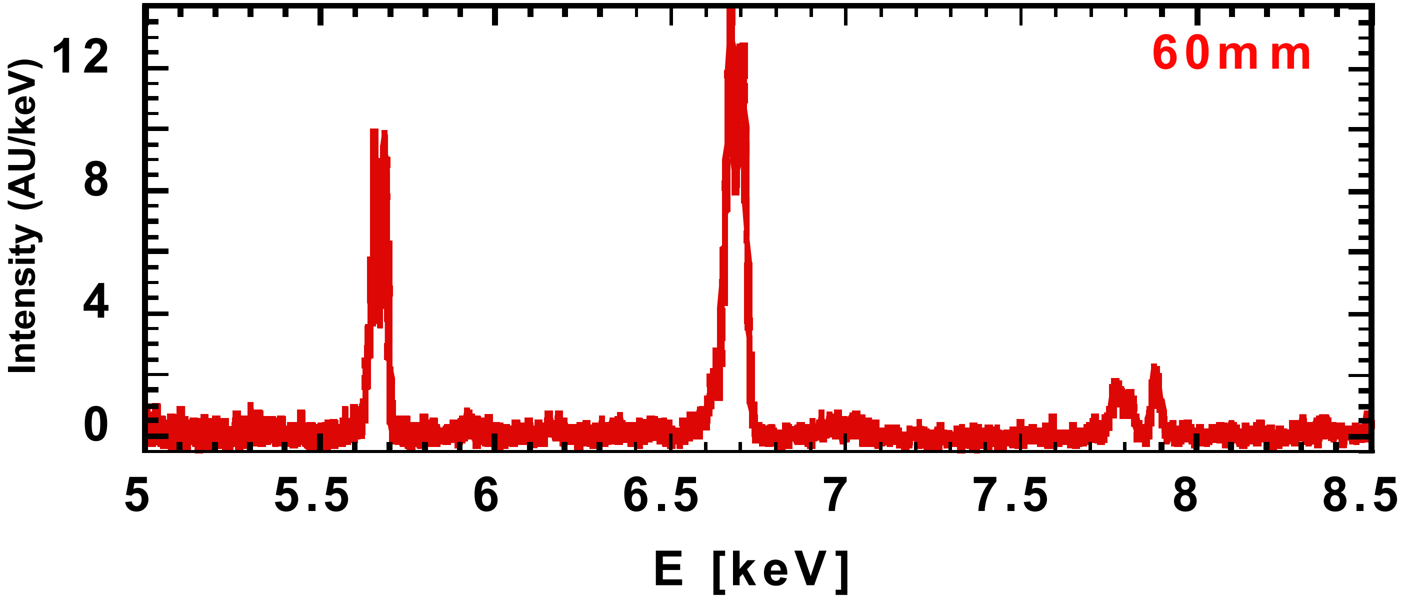
K-shell sources offer opportunities to study plasma conditions through spectroscopy





Axially averaged

Opacity plays a role, especially for lower Z materials

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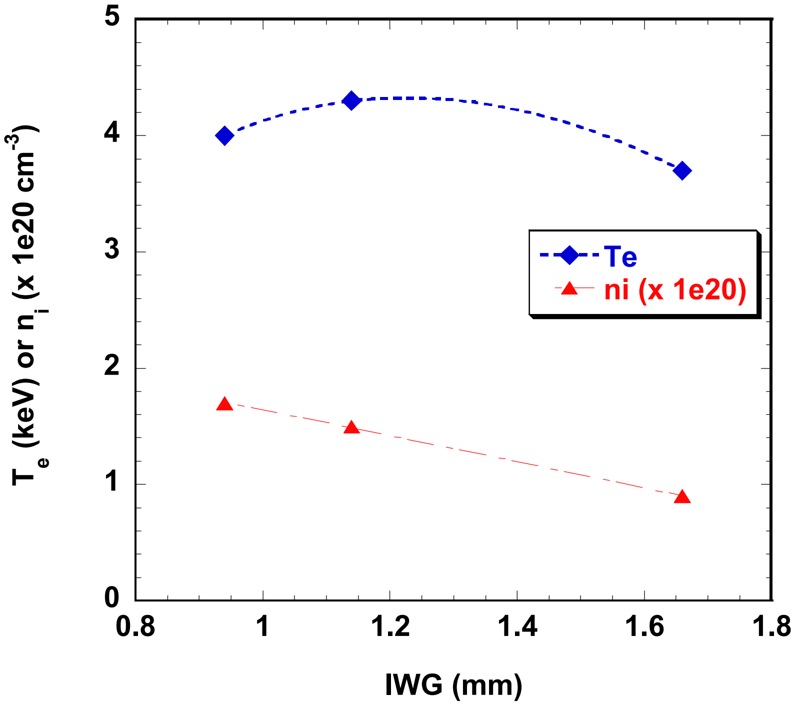
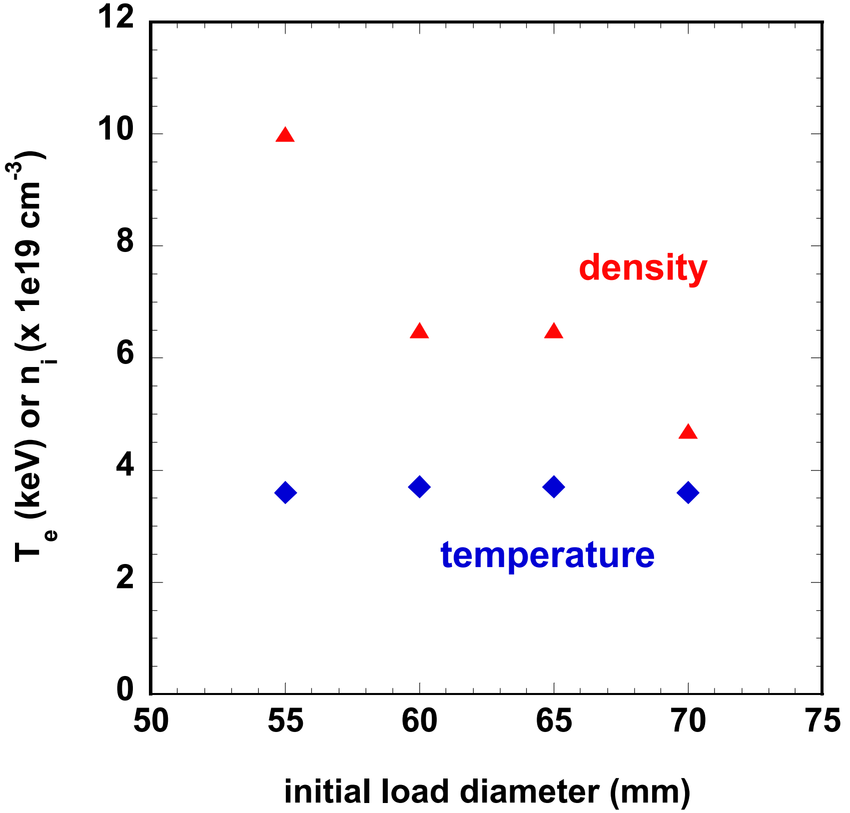
Time integrated spectra – variations with load configuration

55mm 2:1 mass and radius ratio





There was not a significant change in T_e over the range of wire numbers that could be fielded, but n_i increased with smaller wire number

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Variations on the inner array diameter of the load also show variations in plasma conditions

Shot	R_{outer}:R_{inner}	Fe Ly-α/ (He-α+IC) ±10%	K-shell power (TW/cm)	K-shell yield (kJ/cm)	T_e (keV)	n_i (10^{19} cm^{-3})
978	2:1	0.060	4.7±0.3	24±3	3.8±0.1	8±2
1084	4:1*	0.023	1.0±0.3	6±2	2.9±0.1	5±1
1308	4:1	0.040	5.1±0.5	20±5	3.3±0.1	9±3
1386	4:1	0.061	6.6±3.5	27±13	3.8±0.1	10±3

- **All arrays 55mm outer diameter**
  - **104 on 52 wires, ~ 10μm dia.**

- **Shot 1084 had non-simultaneous implosion of the inner and outer wire arrays**

See B. Jones, CO2.00002

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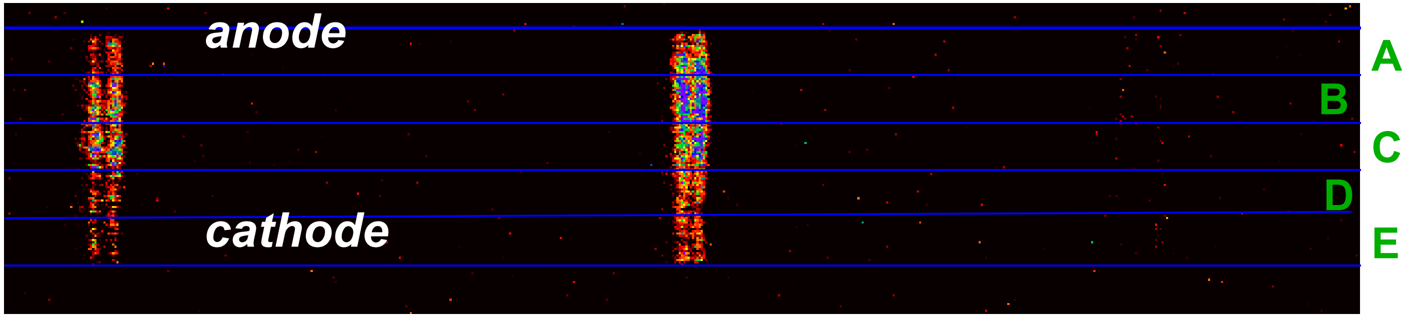
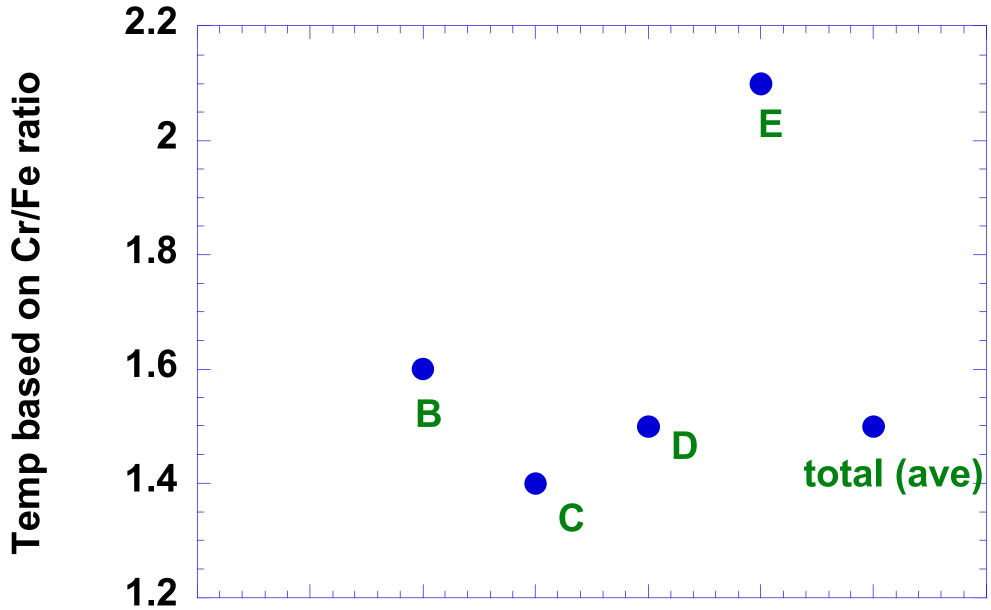
The temperature and density can vary along the axis of the z pinch

Data is axially resolved, can identify regions of brighter emissions

60mm





Axial average gives value similar to many bins, but does not represent well the highest temperature present

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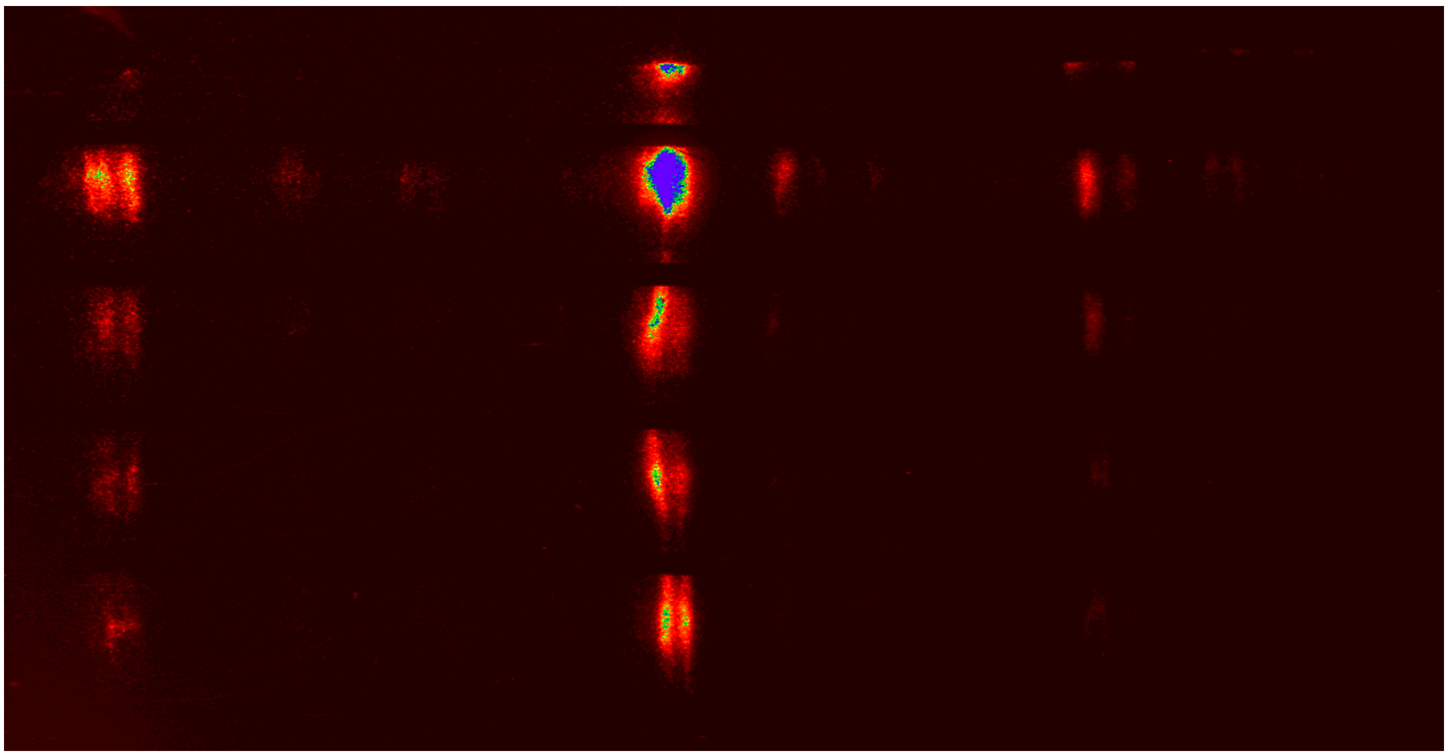
Time- and Space-resolved K-shell Spectra

Z1709 – 55mm nested SS wire array



- ***Radial resolution***
- ***Crystal defects appear as non-vertical lines***

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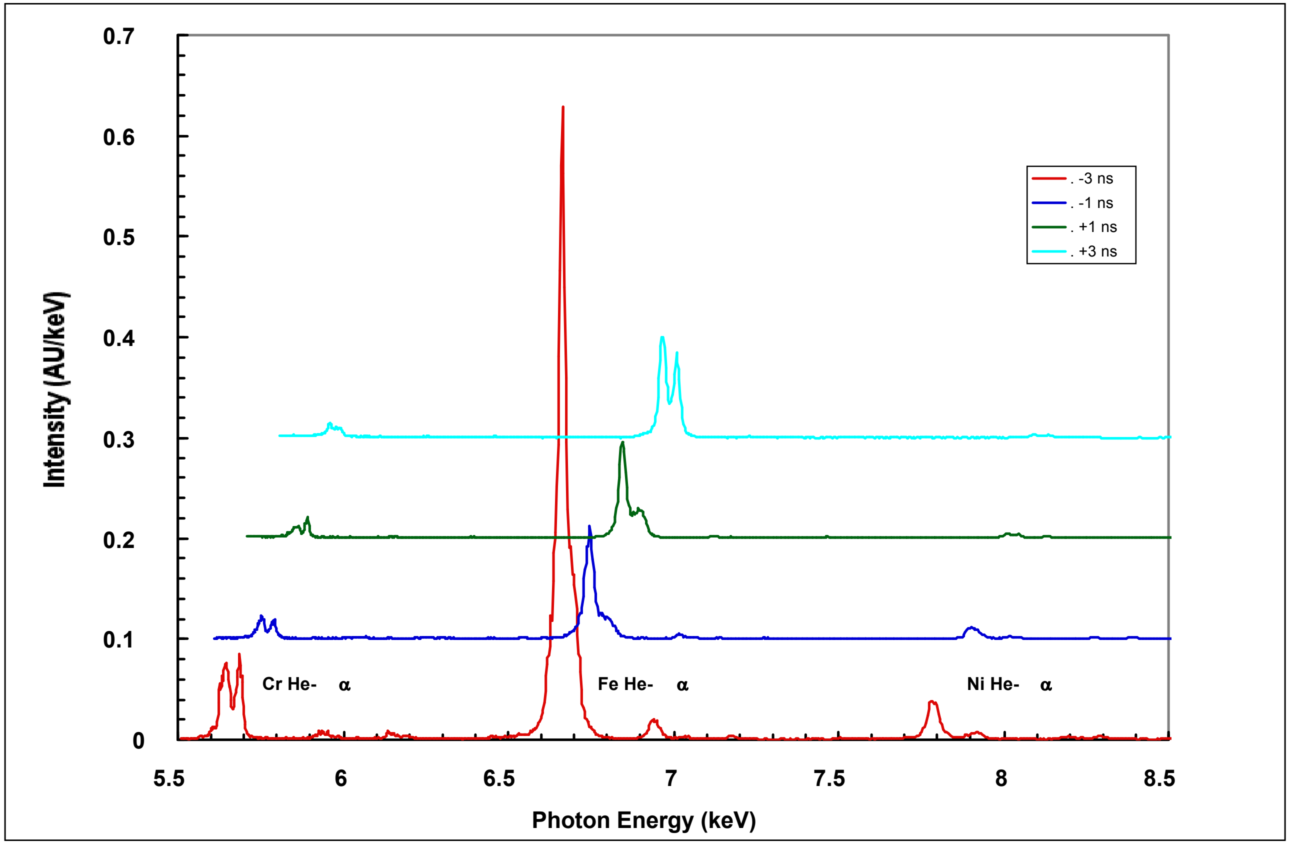
Time-Resolved K-shell Emissions from Cr, Fe and Ni

Z1709 -- SS



- **Spectra offset for clarity**
- **Amplitude of all emissions varies with time**

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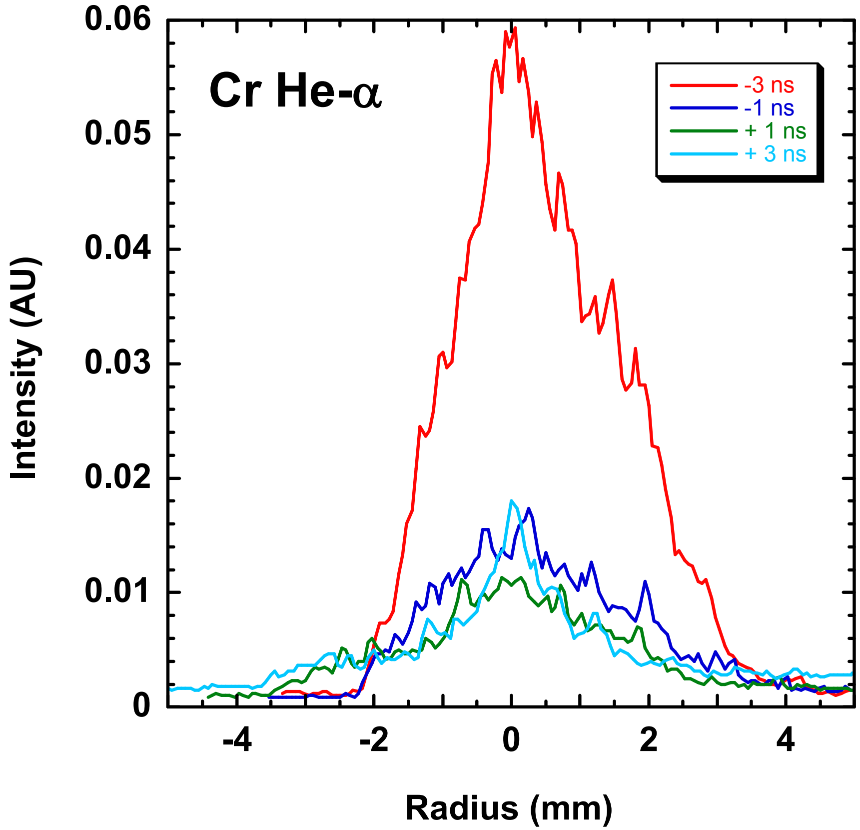
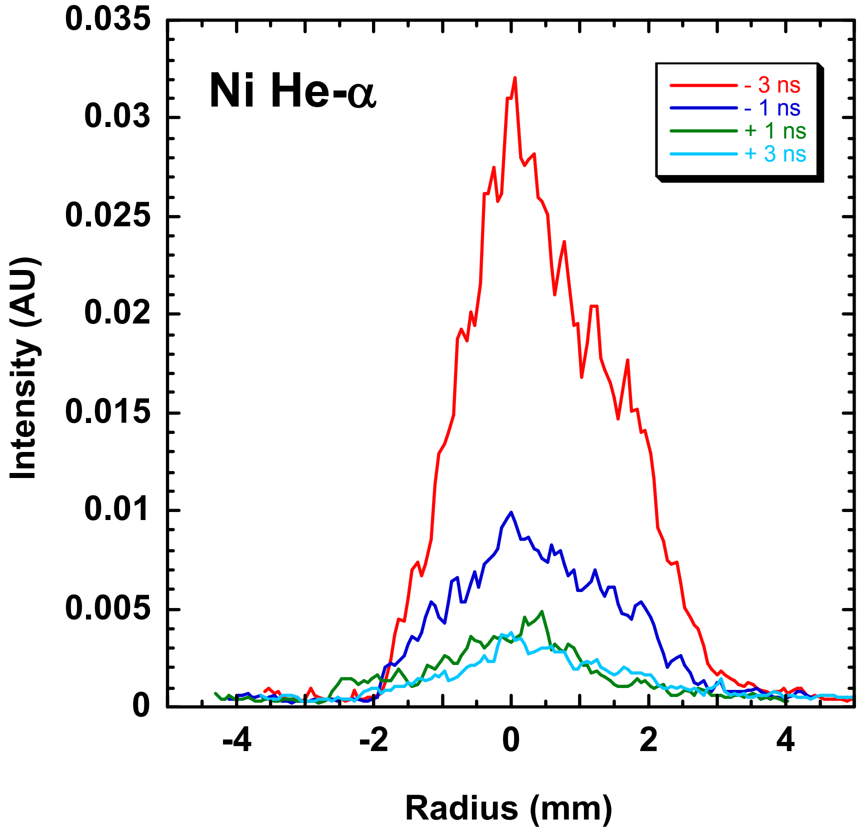
Radial Data Shows Similar Spatial Extent for Cr and Ni He-α Emissions

Z1709 -- SS





- Ni He-α shrinks faster than Cr He-α
  Not surprising since Ni requires higher T_e and n_i for emission

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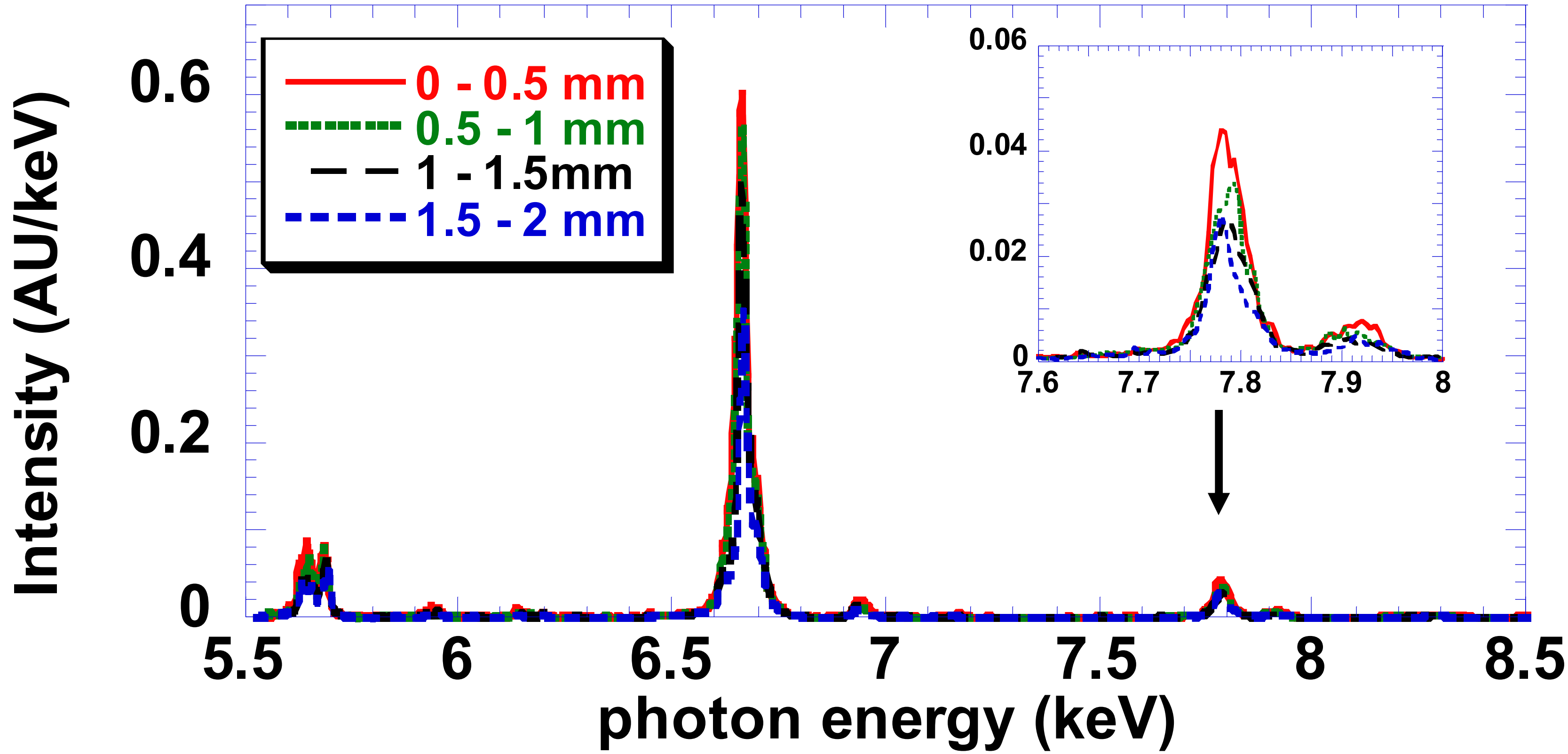
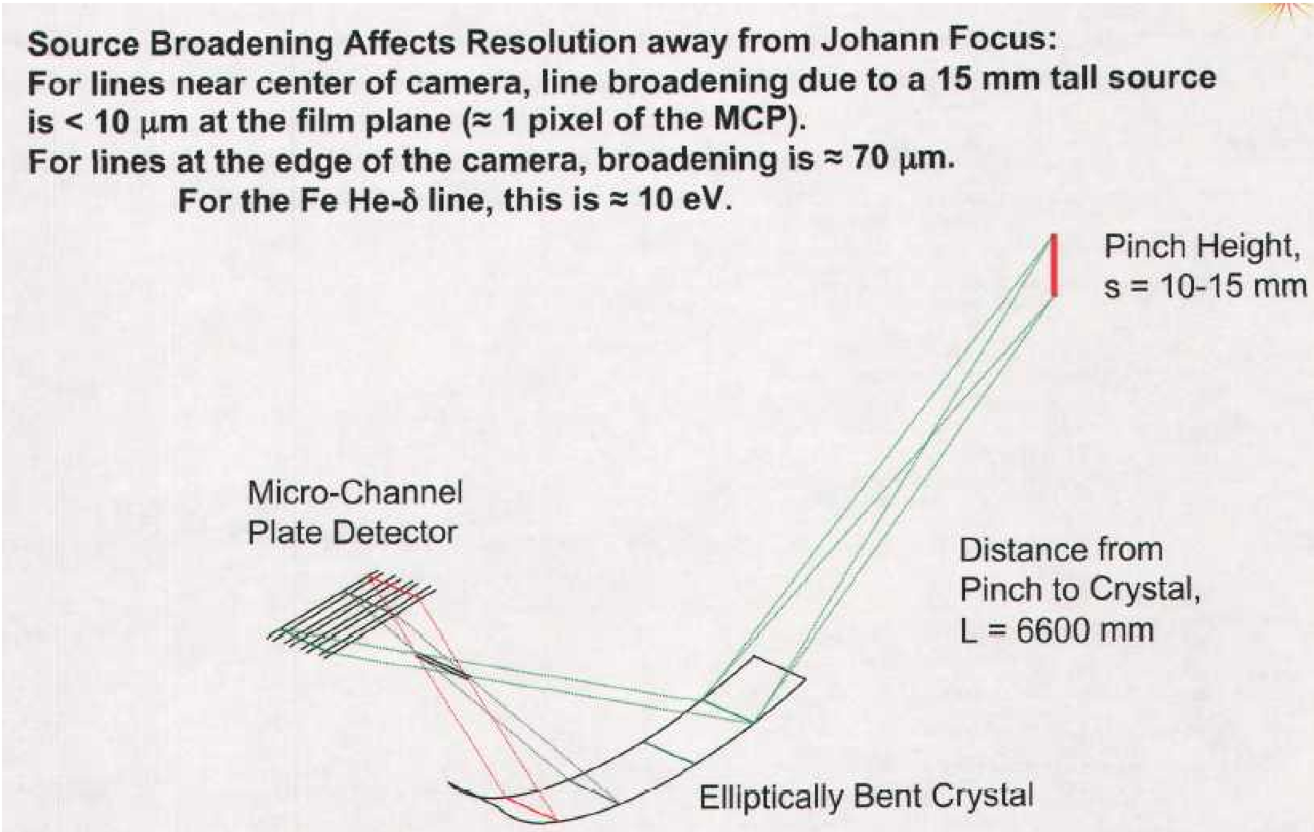
Time and space resolved spectroscopy can be used to further evaluate the stagnated plasma

Z1709 -- SS



Can get line ratios as a function of radial position to assess temporal gradients

The time resolved spectra can be used to estimate ion temperatures as well



Line broadening can then be used to infer an ion temperature

M. Haines et al., PRL 2005.

<u>Note:</u> spectral resolution of the camera is a large issue and has not been fully assessed at this time

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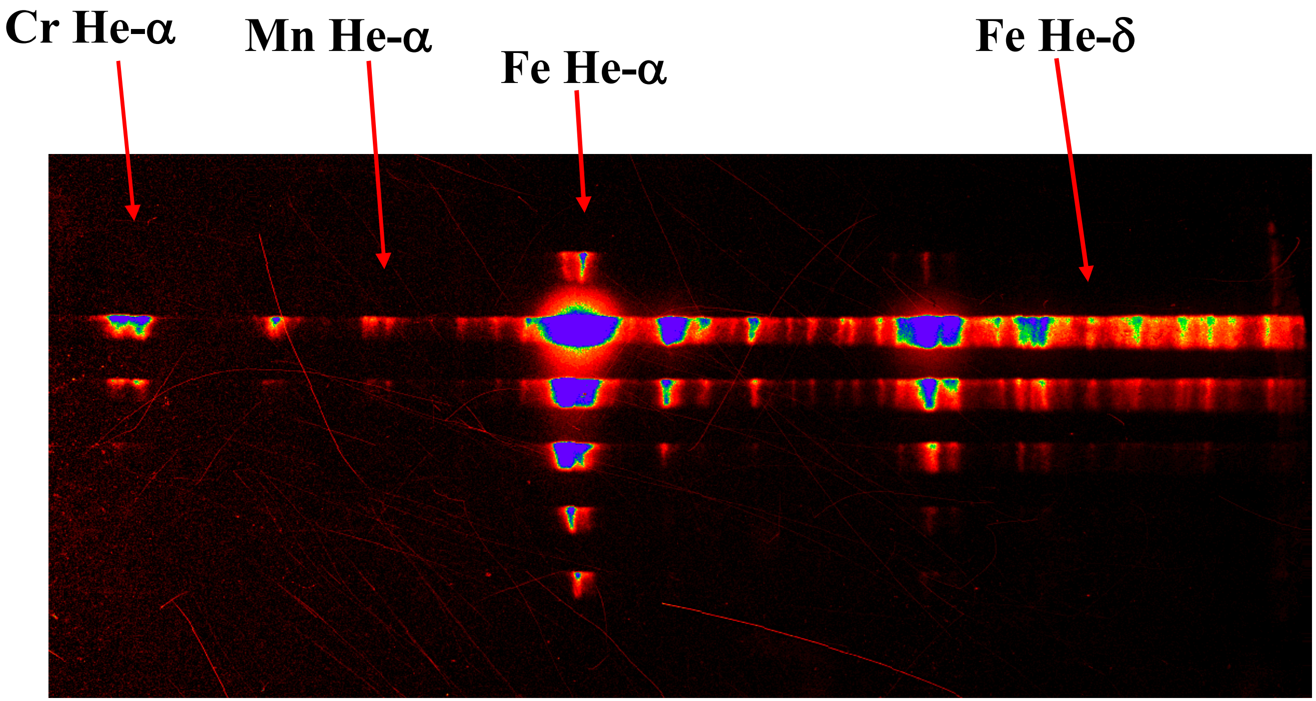
An ion temperature has been estimated from SS spectra



Fe He- δ	
Time	Ion Temp
-6 ns	n/a
-4 ns	200 keV
-2 ns	200 keV
0 ns	100 keV

Mg He-α	
Time	Ion Temp
-6 ns	n/a
-4 ns	150 keV
-2 ns	50 keV
0 ns	n/a

- Data is preliminary (see previous slide)
- Mn He-α and Fe He-δ lines assumed to be doppler-broadened and optically thin.
- Uncertainty in ion temperature is estimated to be ≈ 50 keV.

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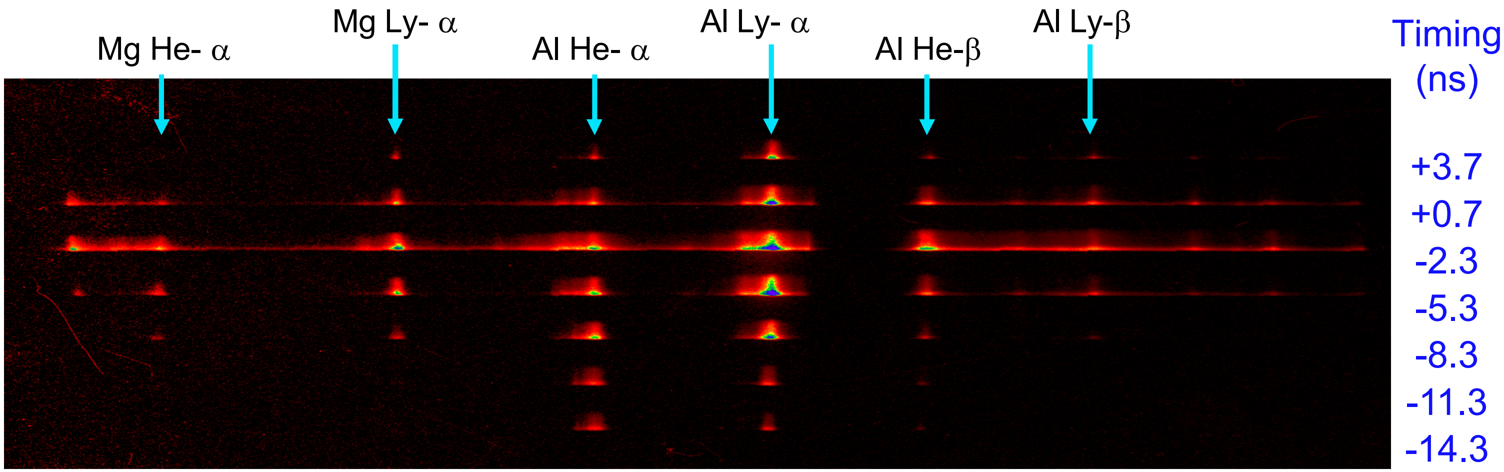
Opacity effects can complicate the understanding of plasma conditions

- **Opacity limits the radiation that escapes from the core of the pinch**
  - **Reduction of the emissivity of the Z pinch**
    - **The absorption process of line radiation removes photons from the emission, yielding higher energy electrons, but fewer x-rays**
  - **Transition from “volume” to “surface” radiator, as density and/or total pinch mass increases**

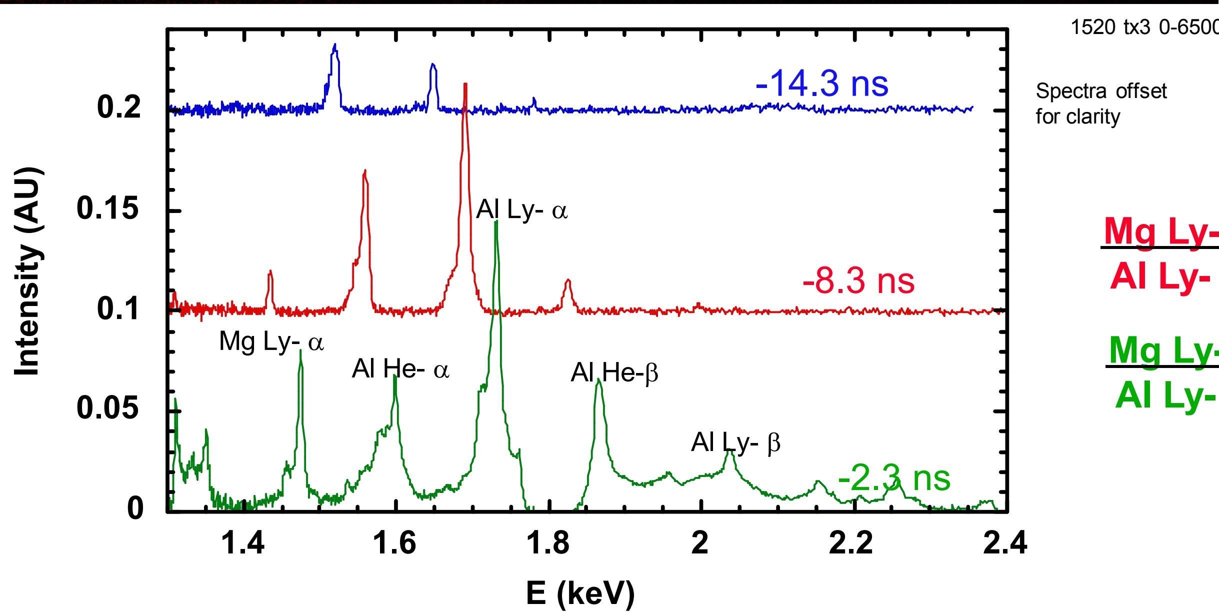
- **Pinch dynamics are altered by spatial redistribution of energy via emission and re-absorption within the plasma**

- **These processes affect the line ratios in the spectrum, which can lead to a misinterpretation of the temperature and density if opacity is not properly addressed**

Time-Resolved Al5056 Array Spectrum Shows Strong Ly-α Emissions from Al and Mg



Z1520
40mm on
20mm nested



Spectra offset for clarity

$$\frac{\text{Mg Ly-}\alpha}{\text{Al Ly-}\alpha} \approx 0.11$$

$$\frac{\text{Mg Ly-}\alpha}{\text{Al Ly-}\alpha} \approx 0.24$$

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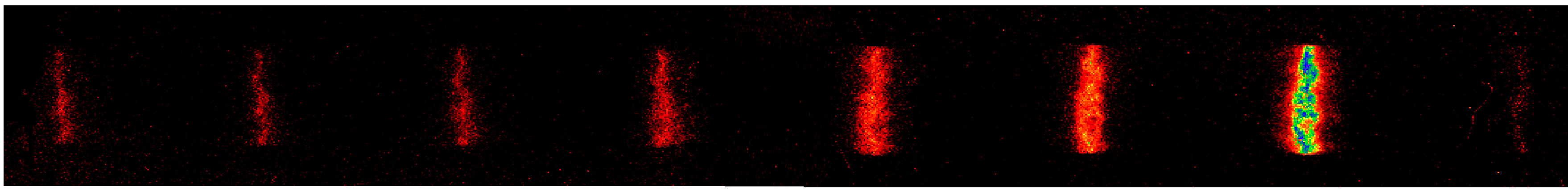
Time-Resolved Pinhole Camera Images Show Axial Plasma Well Before Peak Output

Timing (ns), relative to peak output

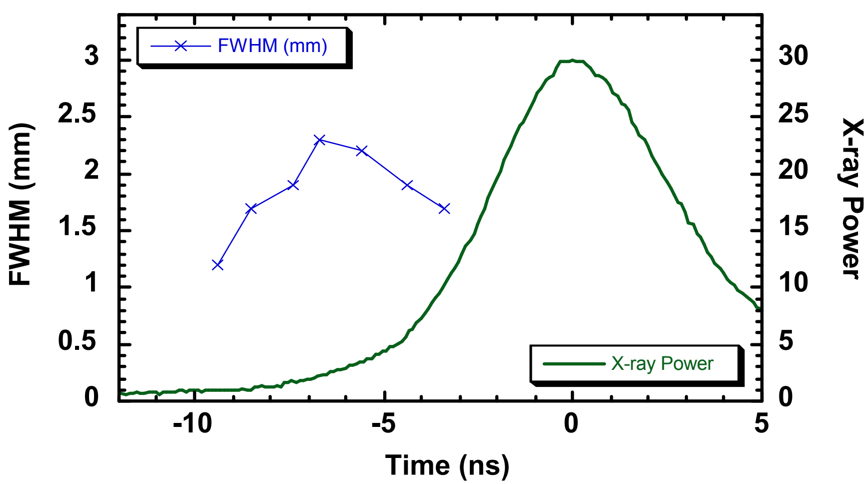
-9.4 -8.5 -7.4 -6.7 -5.6 -4.4 -3.4 TI



1520 mlm0 550-
1350

1.2 1.7 1.9 2.3 2. 2 1.9 1.7 1.4

FWHM (mm)



- Timing of camera captures evolution before peak output is reached.
- Full height of the plasma is limited by 12 degree viewing angle and aperture.
- Image height is 9.6 mm, ≈ 50% of actual plasma height.

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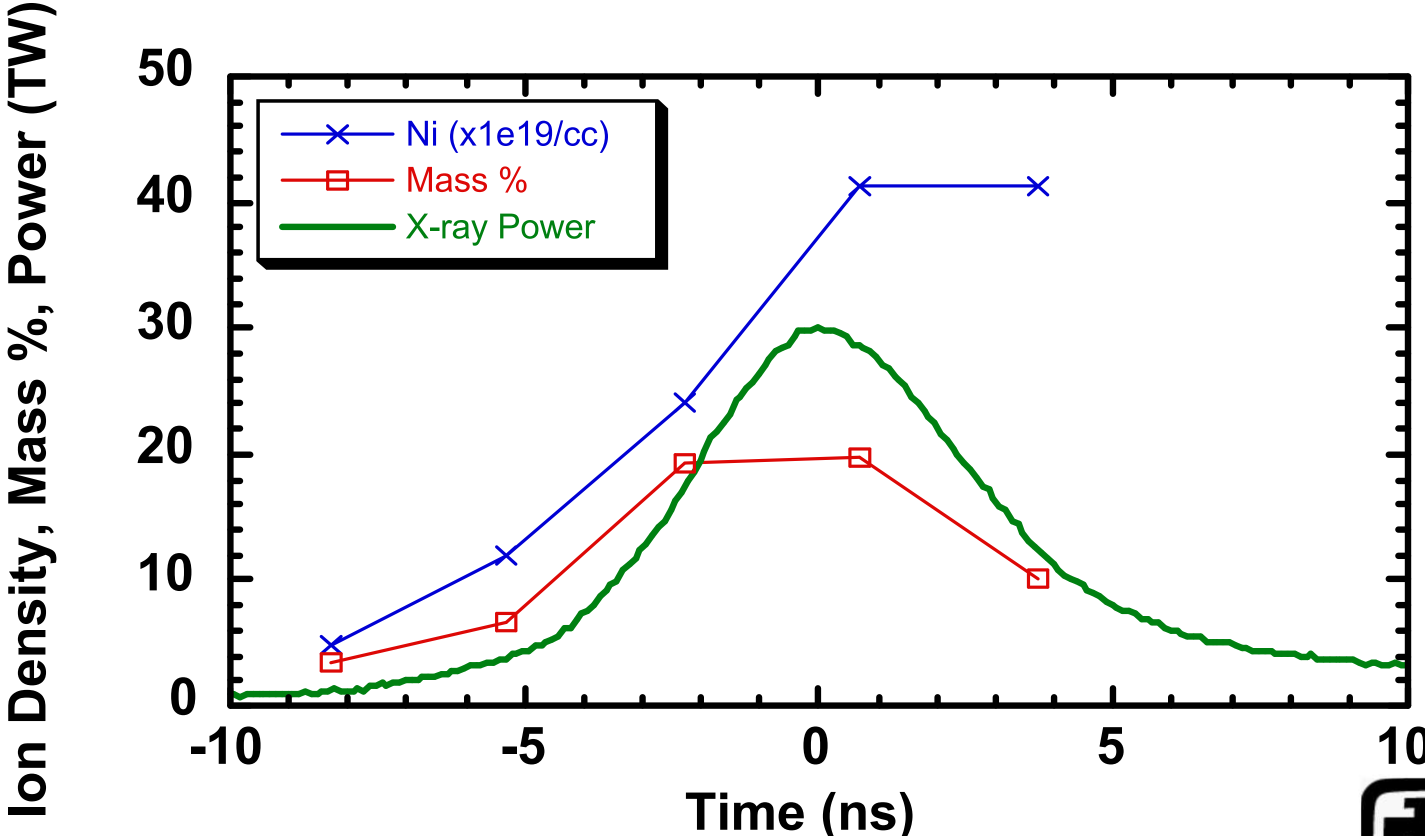
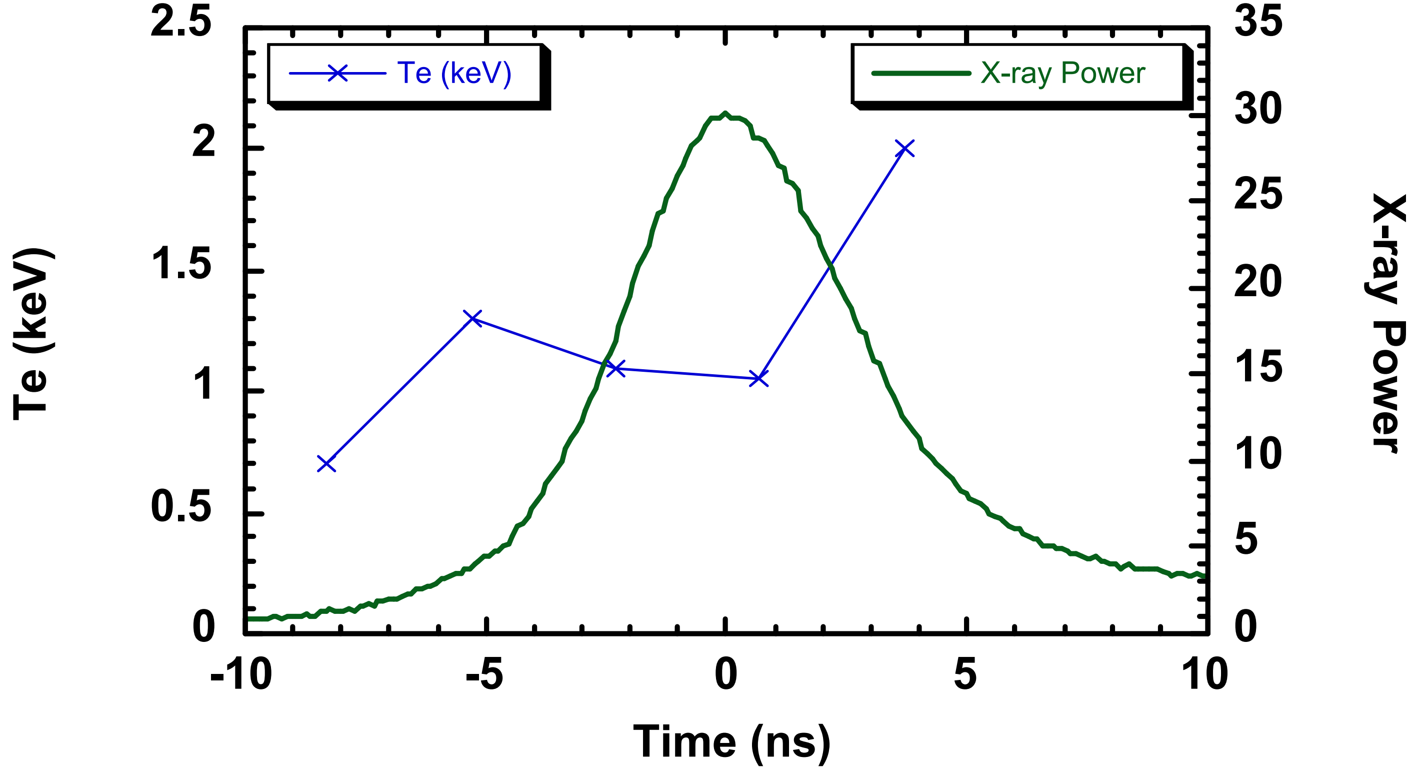
Analysis Shows Density Variation and Mass Fraction Correlate with X-ray Power

- **X-ray power rises with increasing density.**



Analysis of Time-Resolved Spectra Shows Rising Electron Temperature



Essentially constant during pulse, followed by a sharp rise after peak output

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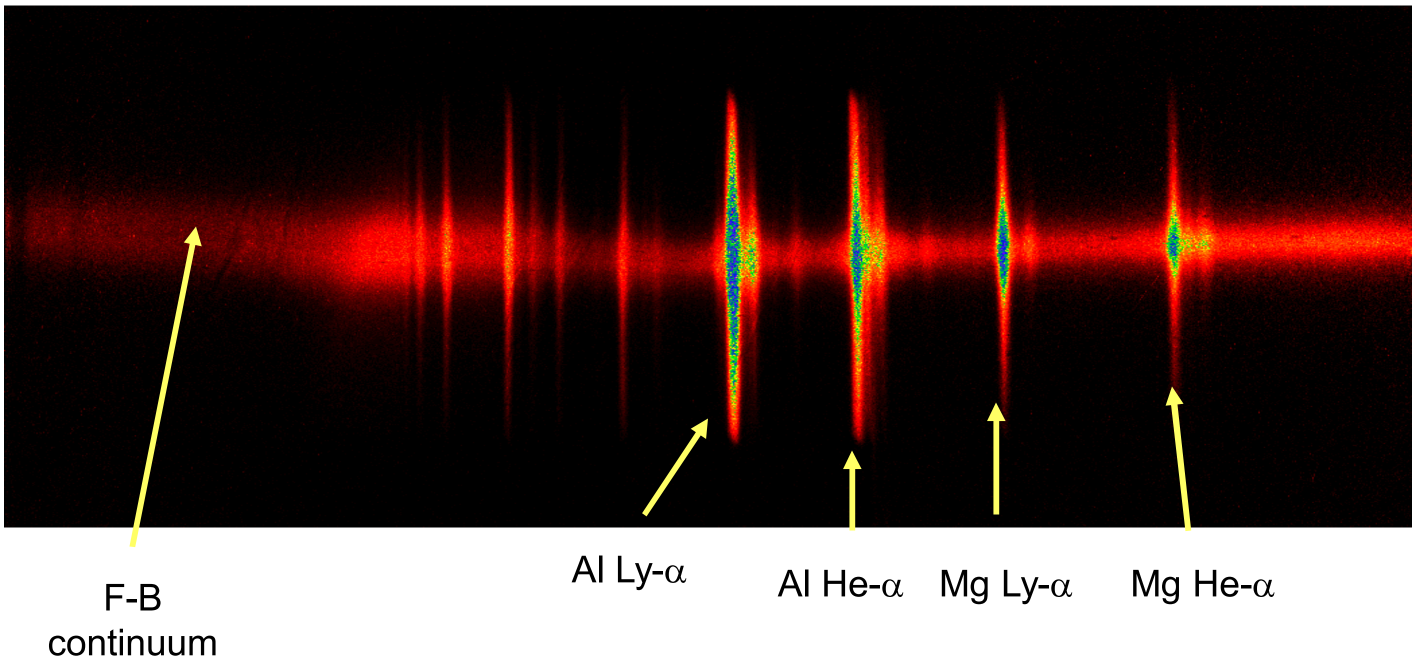
Scattering of line photons from the outer regions of the pinch plasma is observed

Z1520, time integrated radially resolved spectrum



FWHM (mm)	
Al He-α:	6.1
Al Ly-α:	8.0
Mg He-α:	2.7
Mg Ly-α:	3.4
F-B cont.:	2.1

Full viewing of the plasma may be limited by the width of the slots in the current-return can.

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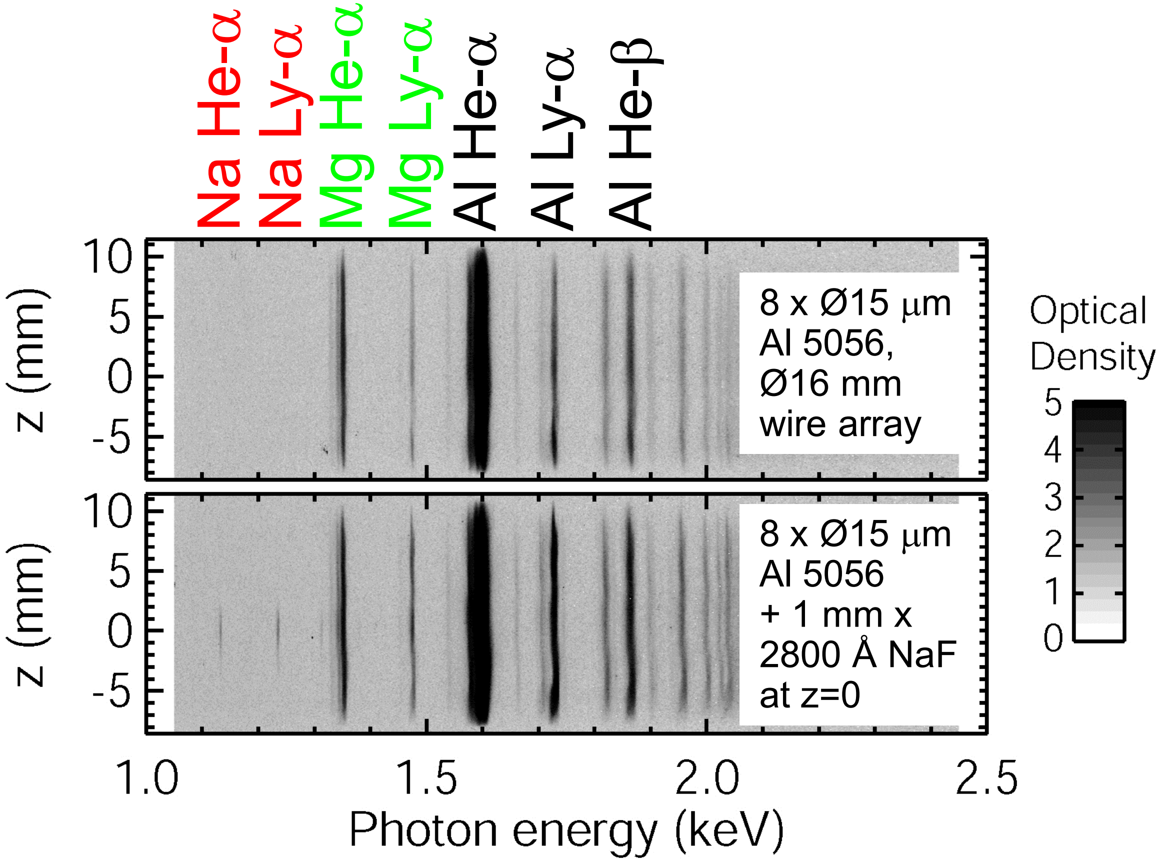
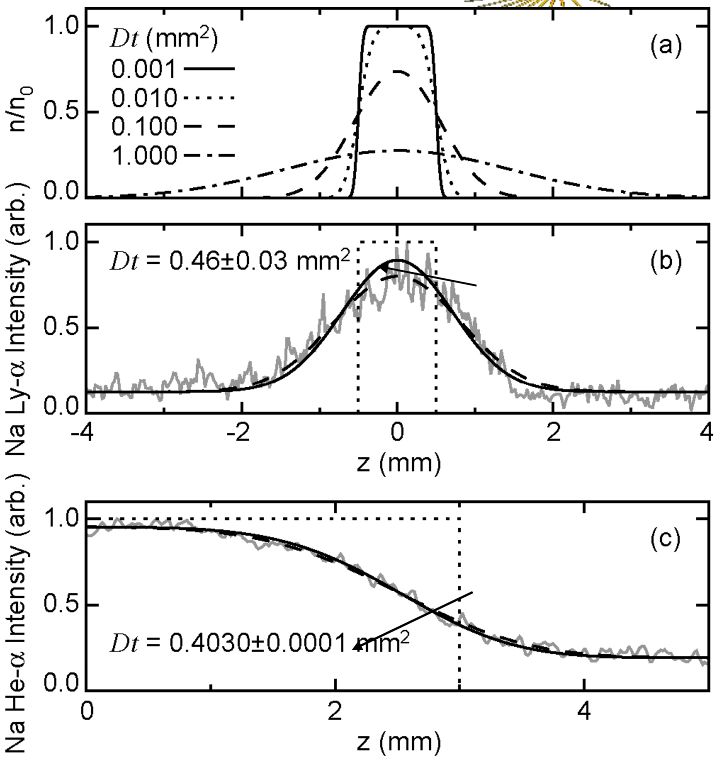
Dopant spectroscopy has been used to study particle transport





- NaF coated Al/Mg wires shot on 1 MA Zebra at UNR
- Na K-shell spectroscopy shows axial diffusion of material, perhaps indicating plasma turbulence

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Summary

- Spectroscopy is a useful tool for assessing plasma conditions
- Spatially resolved, time-integrated spectra has shown varying temperatures and densities along the length of the z pinch
- Temporally resolved spectra show the evolution of the temperature and density, and can be used to infer ion temperatures as well
- Temporally and spatially resolved spectra illustrate the spatial gradients present in the z pinch
- The effects of opacity appear most strongly in the low Z plasmas, but are also a factor for mid Z materials as well
  - The high ratio of Mg Ly-α to Al Ly-α relative to their proportionality in the alloy is an indicator of the impact of the opacity
- Continued experiments and analysis will further enhance the understanding of z pinches

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