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# Investigations of stagnated plasma conditions and opacity for K-shell x-ray sources at the Z accelerator

C.A. Coverdale[1], C. Deeney[2], J.P. Apruzese[3], B. Jones[1], P.D. LePell[4]

*[1]Sandia National Laboratories, Albuquerque, NM 87185 USA*
*[2]NNSA/DOE Headquarters, Washington DC 20375 USA*
*[3]Plasma Physics Division, Naval Research Laboratory,Washington DC 20375 USA*
*[4]Ktech Corporation, Albuquerque, NM 87123 USA*

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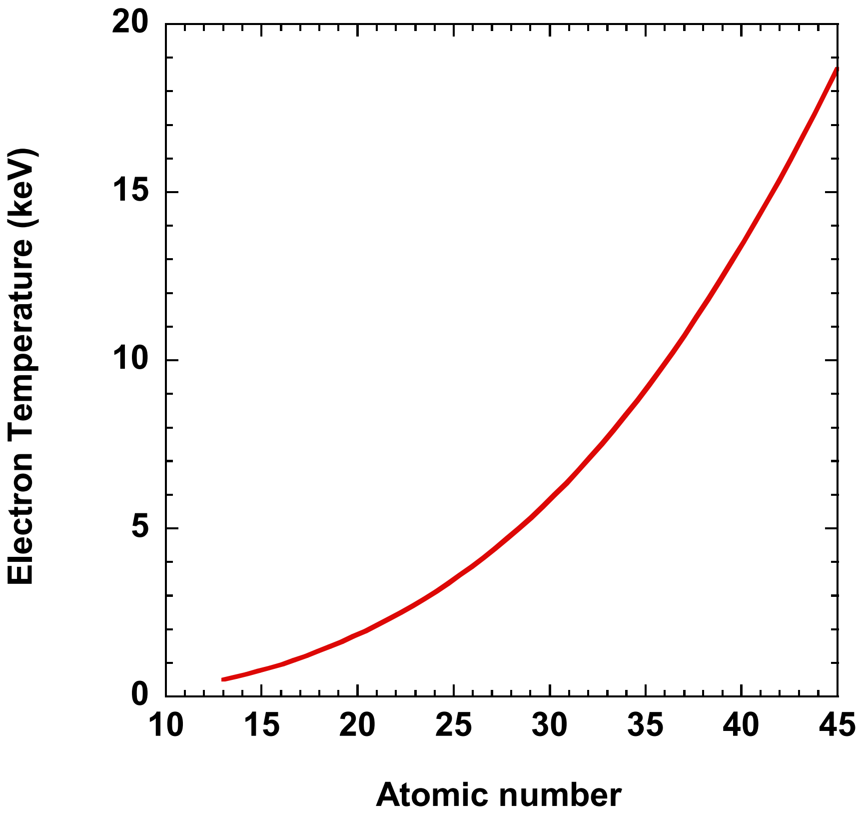
# Temperature requirements for K-shell emission from z pinches can be difficult to attain

- **K-shell scaling theories have shown that the temperature of the plasma necessary to produce the K-shell varies with atomic number**
  - **This suggests that for Cu, $T_e$ must be > 5 keV**




- As the load diameter increases, the jxB coupled energy is higher at comparable implosion times (lower mass)

- Designing loads that can take advantage of this energy to meet the $T_e$ necessary for K-shell is challenging


*K.G. Whitney et. Al., Phys. Rev. E 50, 2166 (1994)*
*J.W. Thornhill et. Al., Phys. Plasmas 1, 321 (1994)*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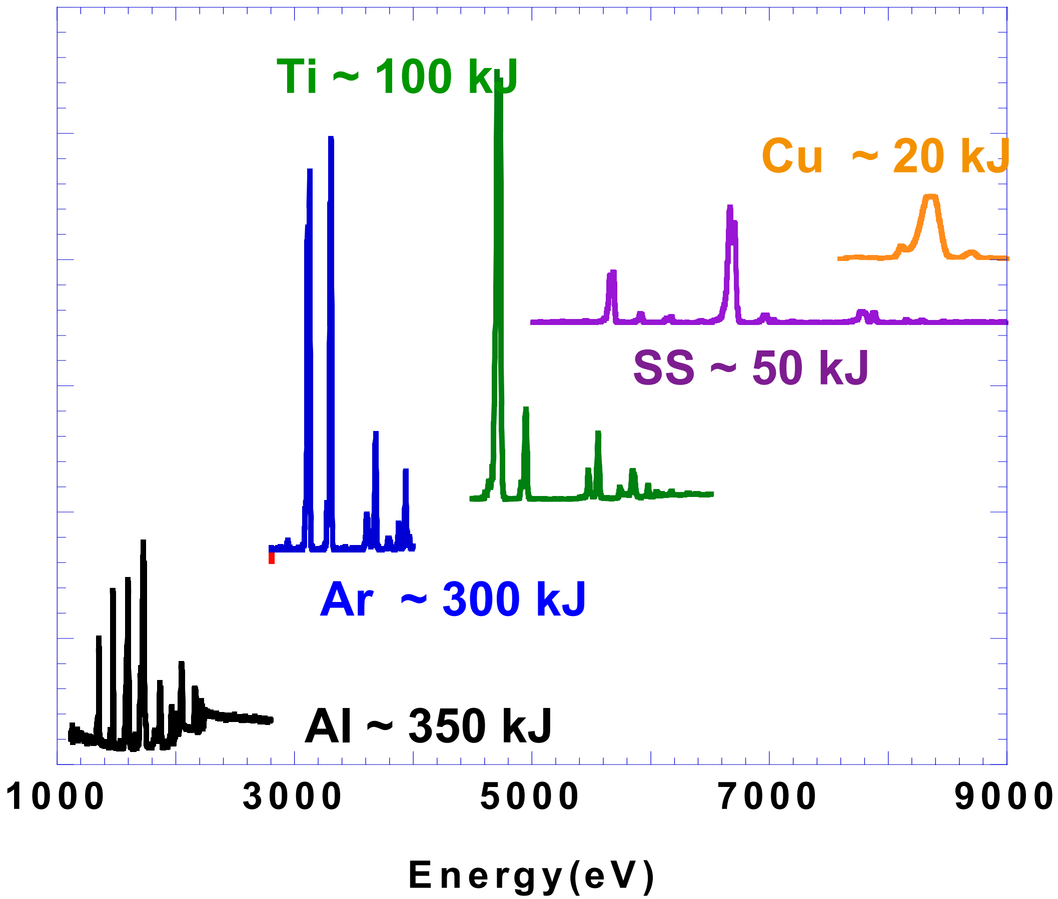
# Summary of the Z K-shell sources




- These are peak outputs
- Initial Load diameters:
  - Al: 40mm on 20mm nested
  - Ar: 1234 nozzle
  - Ti: 50mm on 25mm nested
  - SS: 55mm on 27.5mm nested
  - Cu: 60mm on 30mm nested


C. Deeney *et. al.,* Phys. Plasmas 6, 2081 (1999)
H. Sze *et. al.,* Phys. Plasmas 8, 3135 (2001)
B. Jones *et. al.,* J. Quant. Spec. 99, 341 (2006)
C.A. Coverdale, *et. al.,* JRERE 20-1 (2002)
C.A. Coverdale, *et. al.,* submitted to Phys. Plasmas.

# The K-shell x-ray sources can be used to study stagnated z-pinch plasmas through spectroscopy

- **Variety of K-shell z-pinch experiments have been performed**
- **Variations are observed in $T_e$ and $n_i$ from the different load materials**
    - **Plasma conditions are inferred from time-integrated, spatially-resolved spectra, and spatially-integrated, time-resolved spectra, in conjunction with radiated K-shell power and pinch diameter *(J.P. Apruzese et. al., J. Quant. Spectrosc. Radiat. Transfer 57, 41 (1997))***
    - **Measured $T_e$ confirm the scaling theory predictions, although in some cases the conditions are achieved only in isolated regions of the pinch**

- **The impact of opacity on the K-shell emissions has been directly observed by comparing the line intensities from low level dopant materials with those of the main load constituents**
    - **Al loads show significant opacity**
    - **Cu loads appear to be optically thin**

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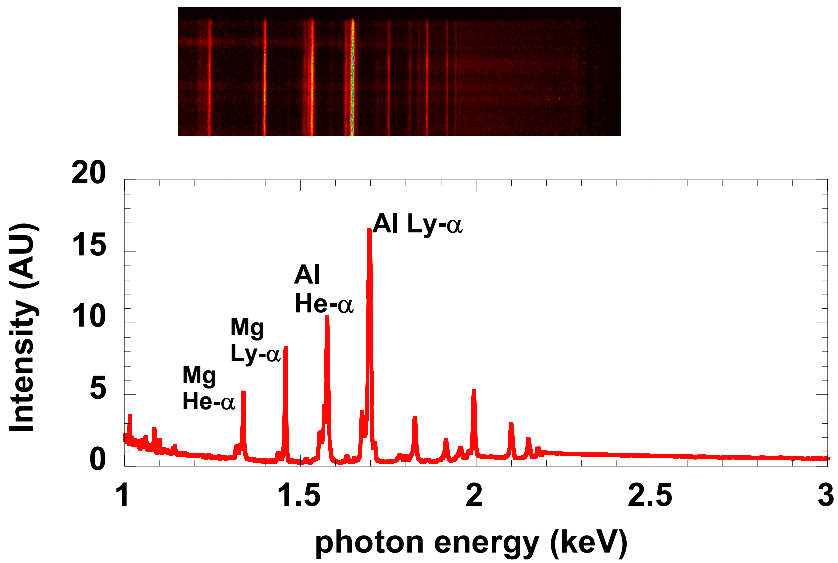
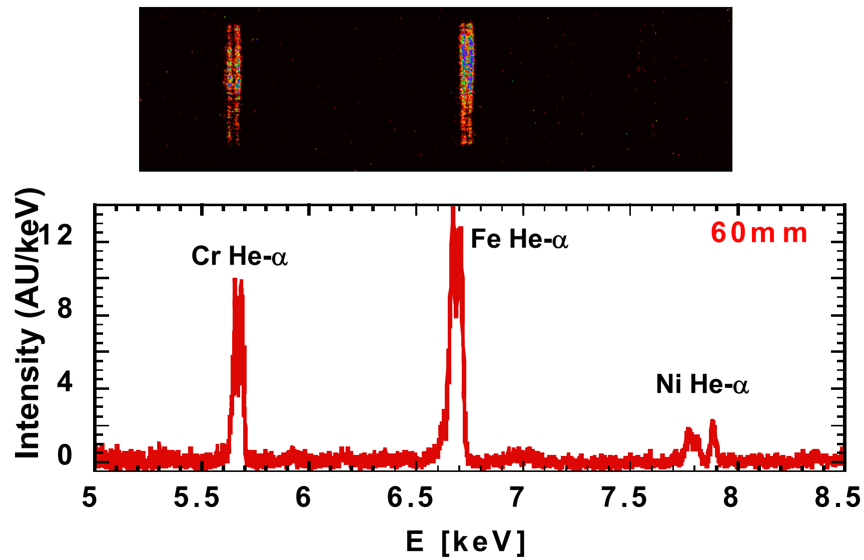
# K-shell sources offer opportunities to study plasma conditions through spectroscopy

Al (Al 5056), 40 mm nested




SS, 60 mm nested




**Lower Z materials show higher levels of uniformity along full length of pinch, as anticipated based on the less demanding plasma conditions necessary for production of the K-shell x-rays**

***Axially averaged spectra used to estimate plasma conditions***

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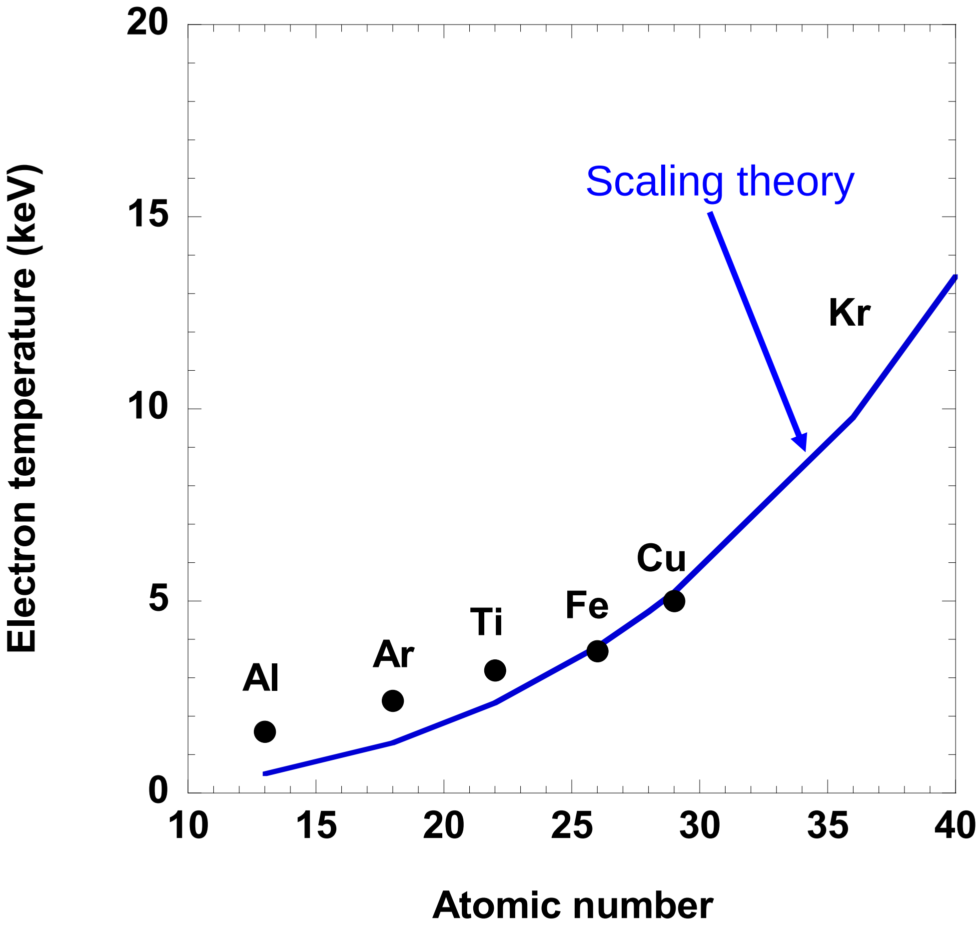
# Inferred electron temperatures agree well with scaling theory trend




**Scaling theory:**

$$T_e = 0.3 * Z^{2.9} \text{ eV}$$

**Electron temperatures are obtained from axially averaged, time-integrated spectral line ratios from "optimized" K-shell x-ray sources**

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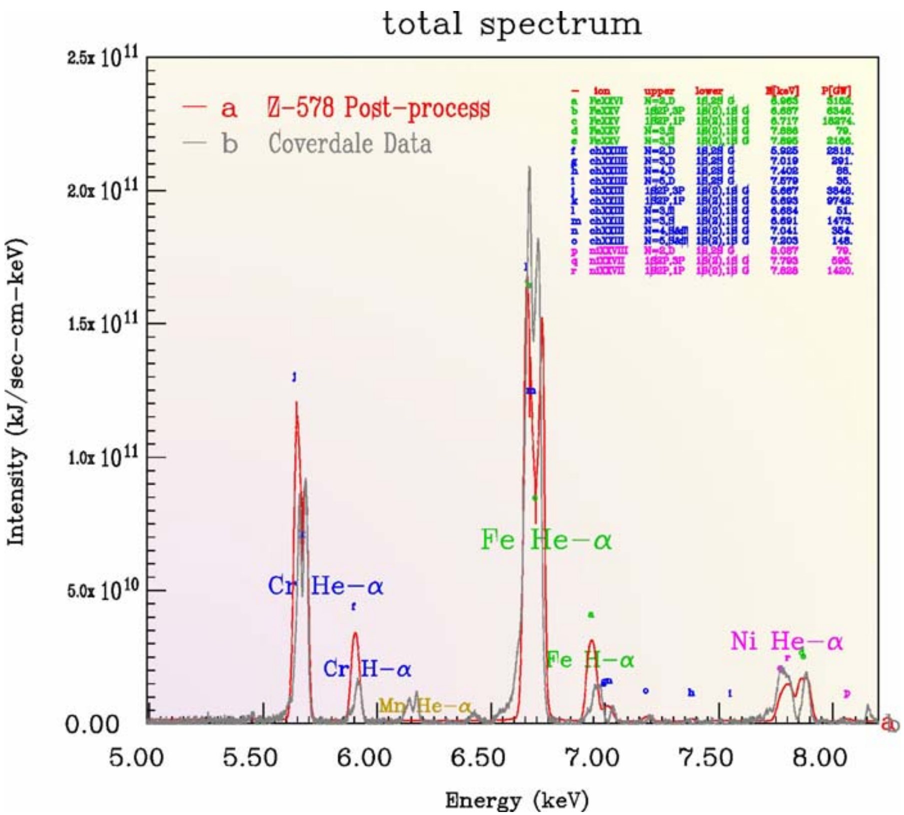
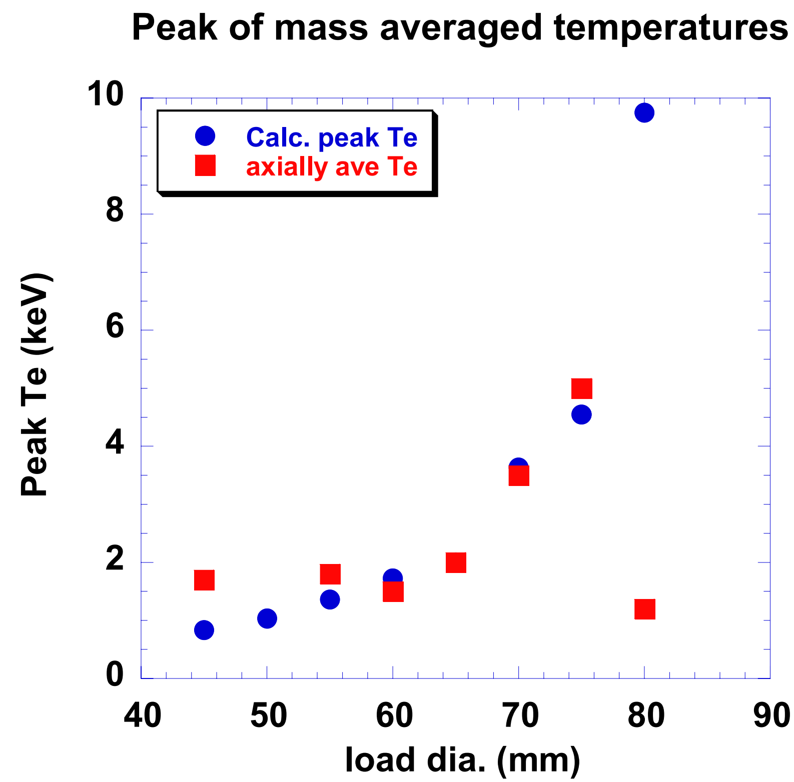
# 1-D calculations of SS variations fielded reproduce the measured spectra

*R. Clark & J. Davis, NRL*




- **Overlap of strong He-α with He intercombination line leads to higher emission on the low energy side of the lines**

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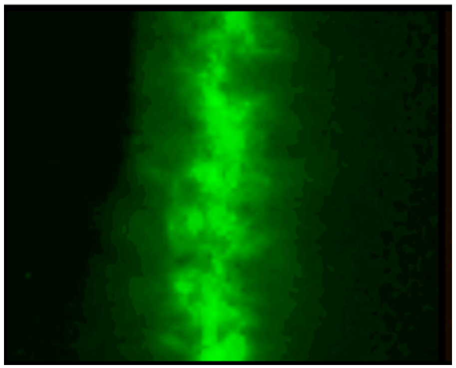
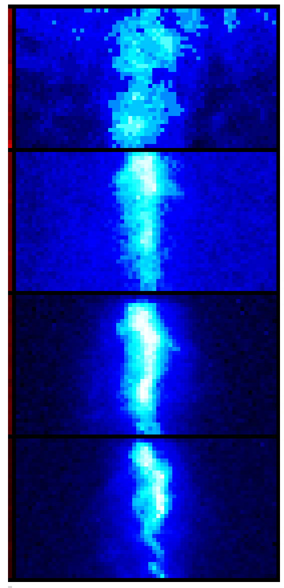
# Imaging of K-shell emission near peak radiated output show significant non-uniformity

**Al 40mm nested**



-2.3 ns

**SS 55mm nested**



-1 ns

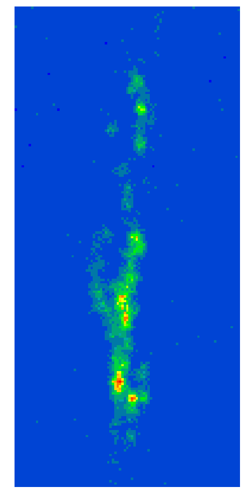
0 ns

+1 ns

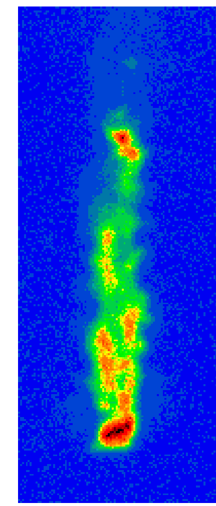
+2 ns

**Cu**

55mm single



55mm nested



- Lower Z shows instability and structure, but more uniformly distributed intensity along the pinch length
  - Higher Z materials show more substantial variations
- Use of a nested configuration clearly helps with K-shell emission for higher Z materials

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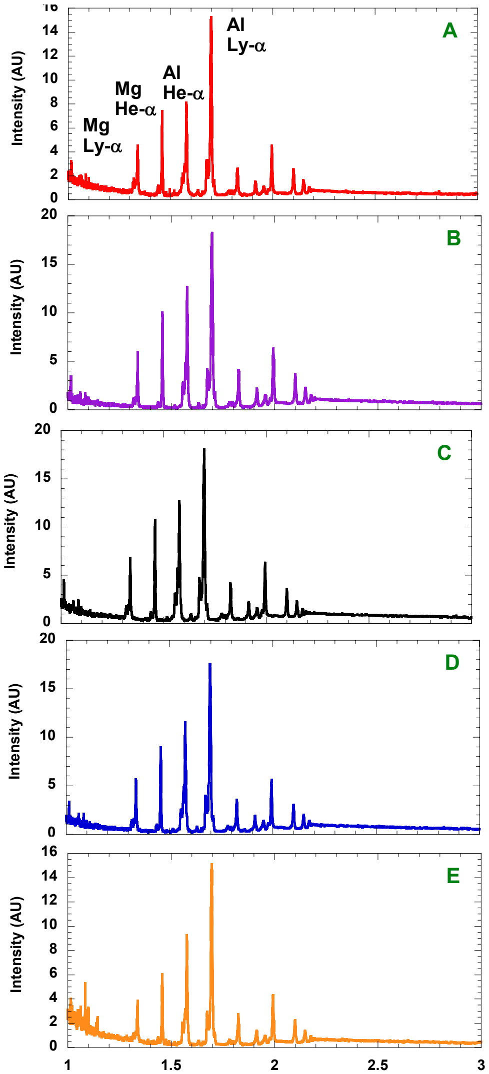
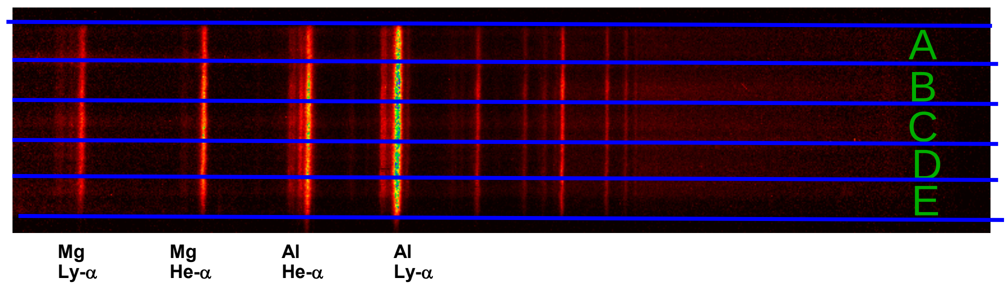
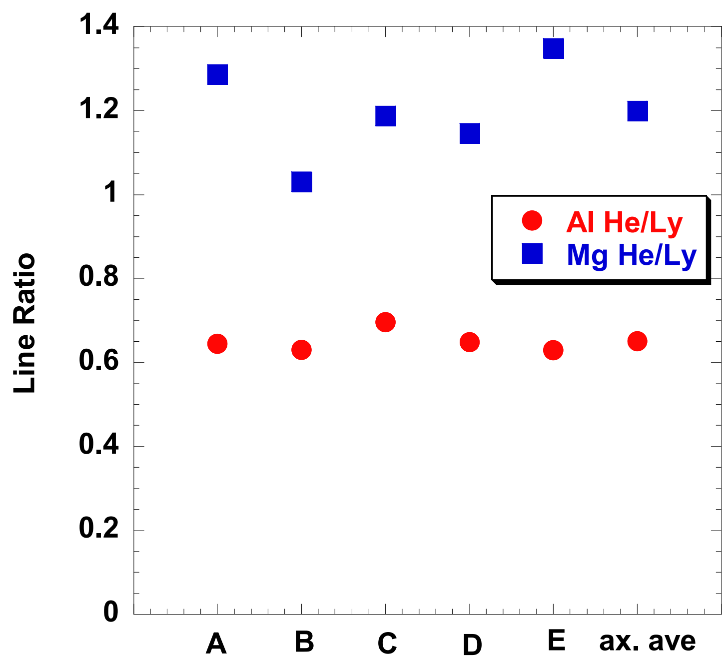
# Al z pinch is overdriven, and temperature and density vary little over the pinch length




## 40mm nested; Al 5056 (5% Mg)

Z1520, Al




- Brightest line is Al Ly-α
  - indicates overdriven plasma
- Analysis shows:
  - $T_e$ = 0.5 keV
  - $N_i = 2.4 \times 10^{20}/cm^3$
  - K-shell Mass Fraction = 20%

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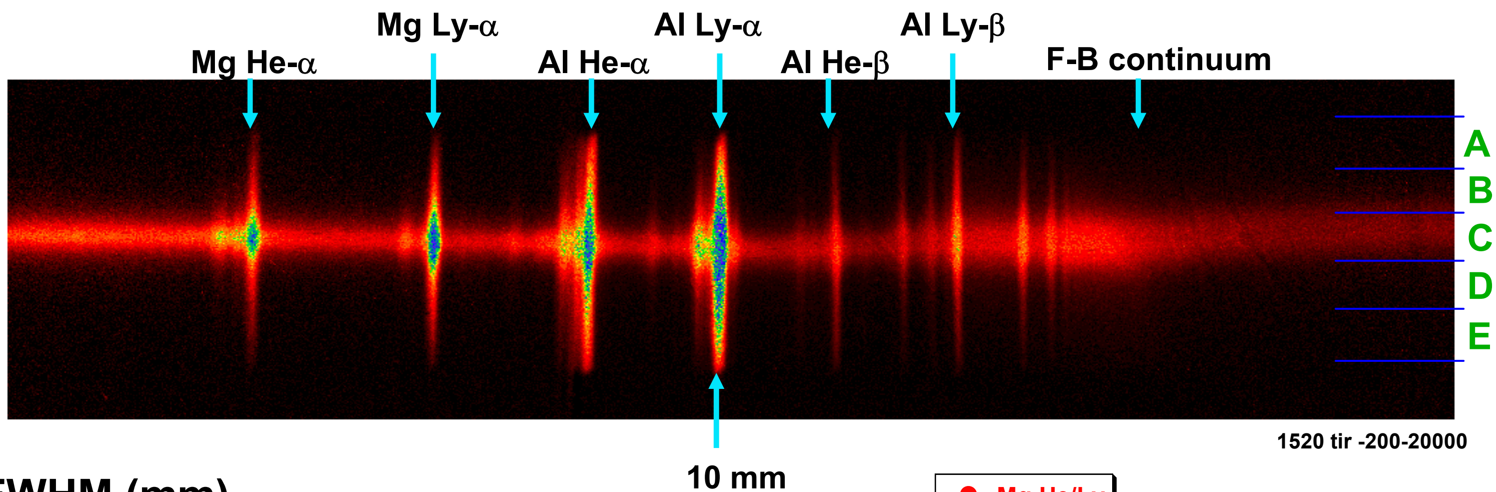
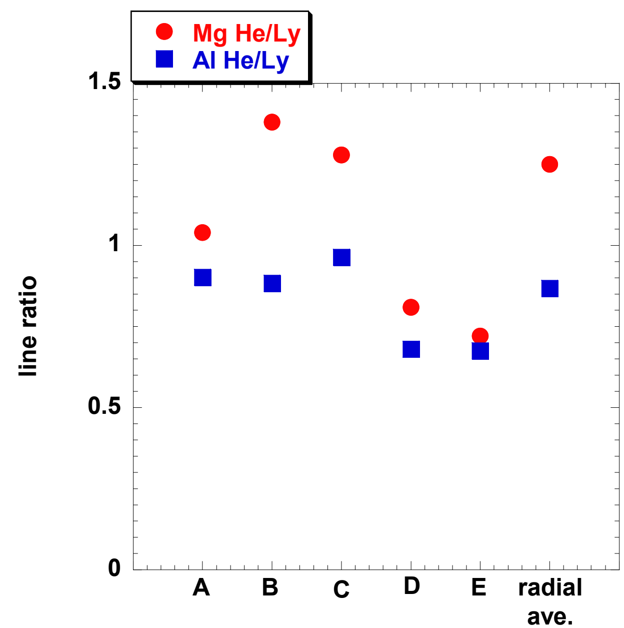
# Radially resolved Al5056 spectrum shows radial gradients exist

Z1520, Al




**FWHM (mm)**

| | |
|---|---|
| Al He-α: | 6.1 |
| Al Ly-α: | 8.0 |
| Mg He-α: | 2.7 |
| Mg Ly-α: | 3.4 |
| Free-Bound cont.: | 2.1 |




- Full viewing of the plasma is limited by the width of the slots in the current-return can.
- Lower density plasma may be resonantly scattering line radiation at large radii, but difficult to fully assess with time-integrated data

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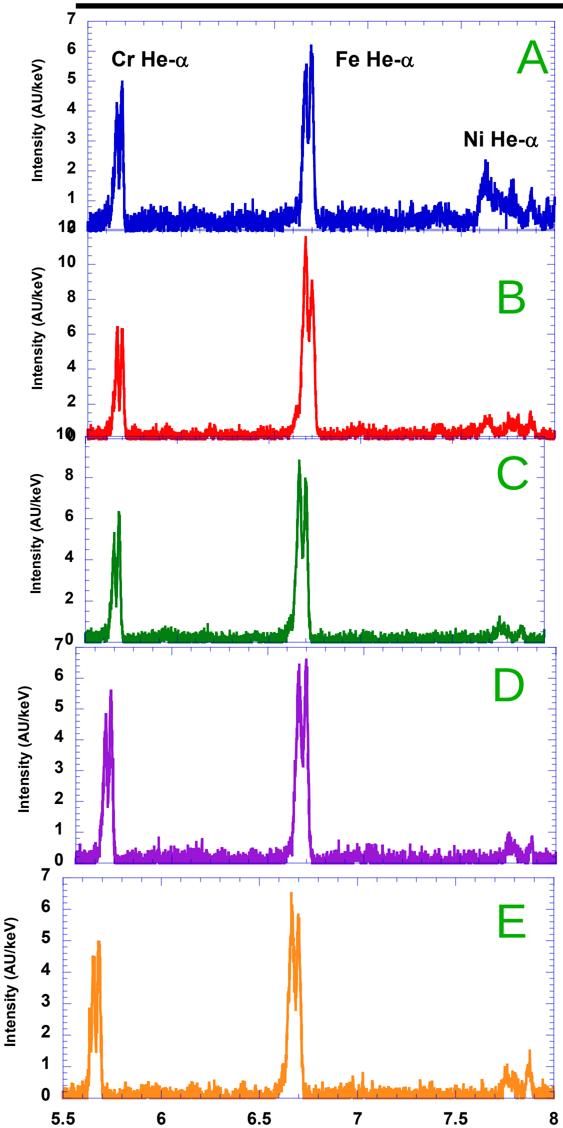
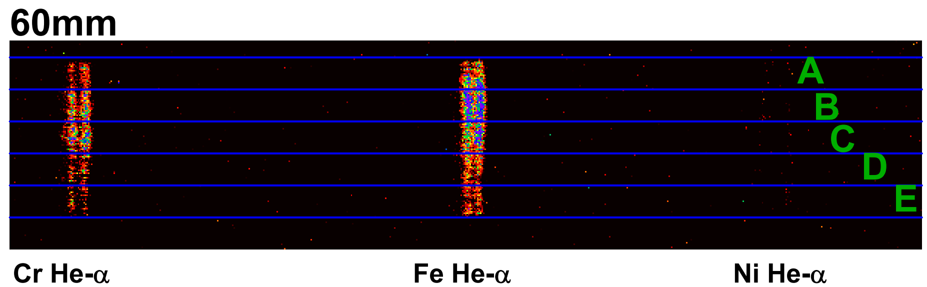
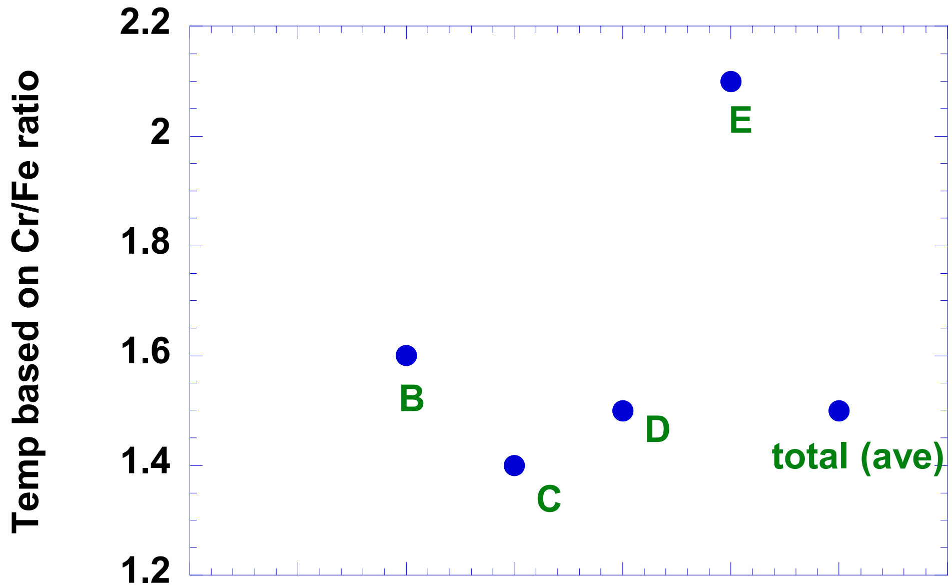
# More significant variation along the pinch length is observed for SS z pinches

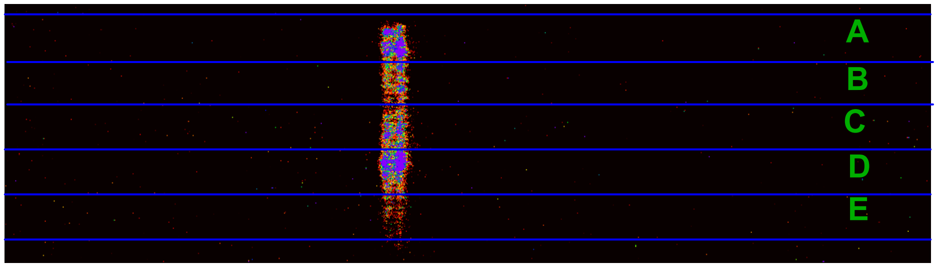


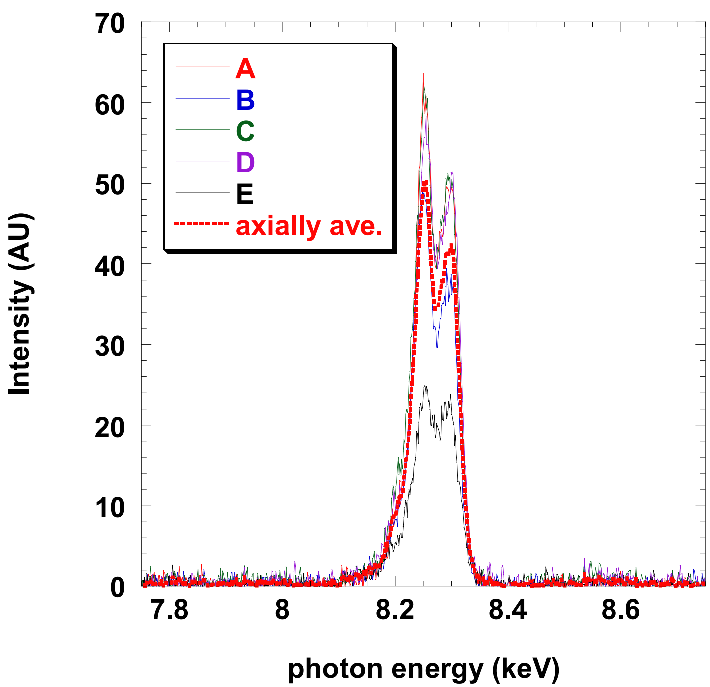



# Cu arrays also show substantial variation along the length of the pinch

Z1270, 60mm nested



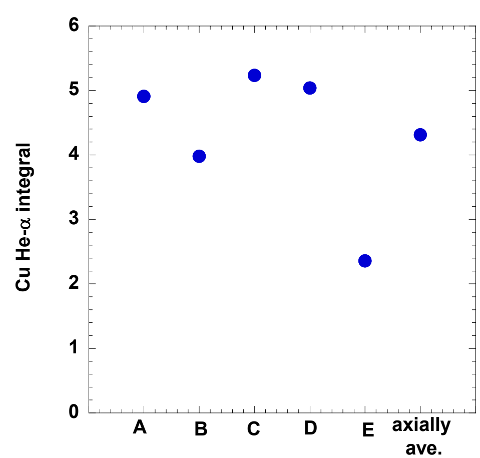

Cu He-α




Difficult to obtain Te, ni for this shot due to lack of other spectral lines

- Z1270: 2% Ni on inner array, pure Cu on outer array

- Note that other work at Saturn (C. Deeney et al., Phys. Rev. Lett. 8 155001 (2004)) and Z (C.A. Coverdale, in preparation) has shown that most of the radiation in the wire arrays originates from material on the outer array, which had no dopant for this array.

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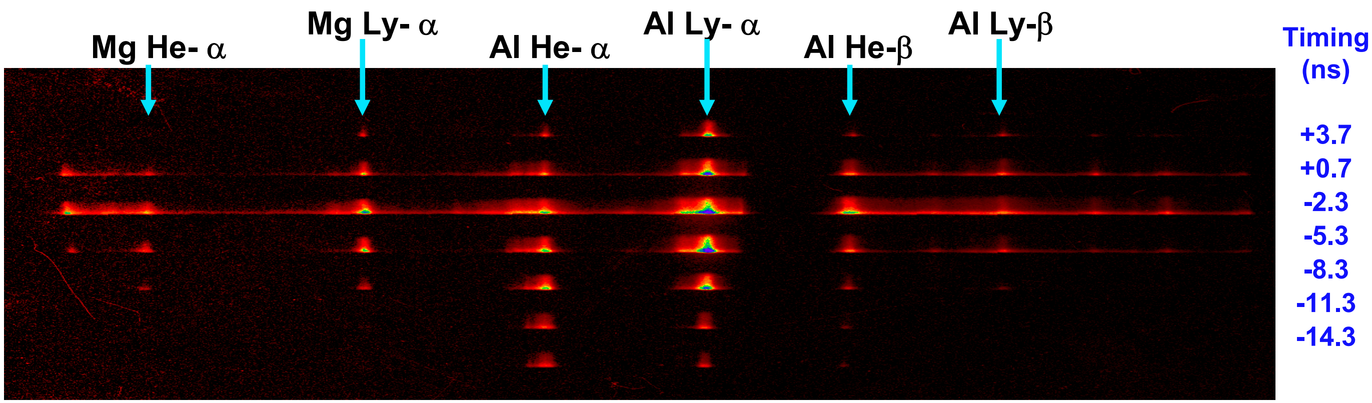
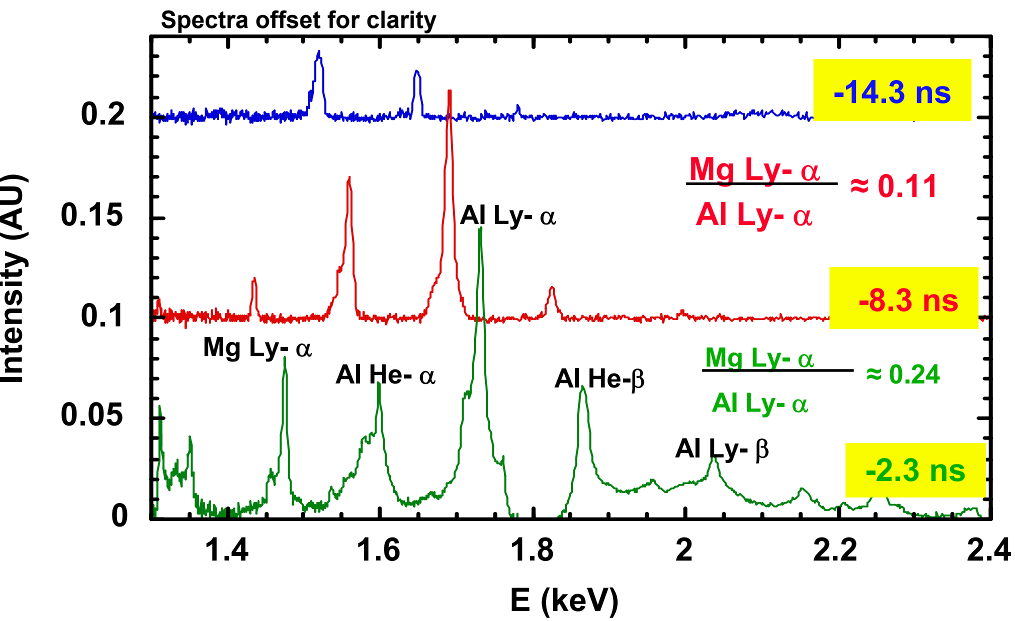
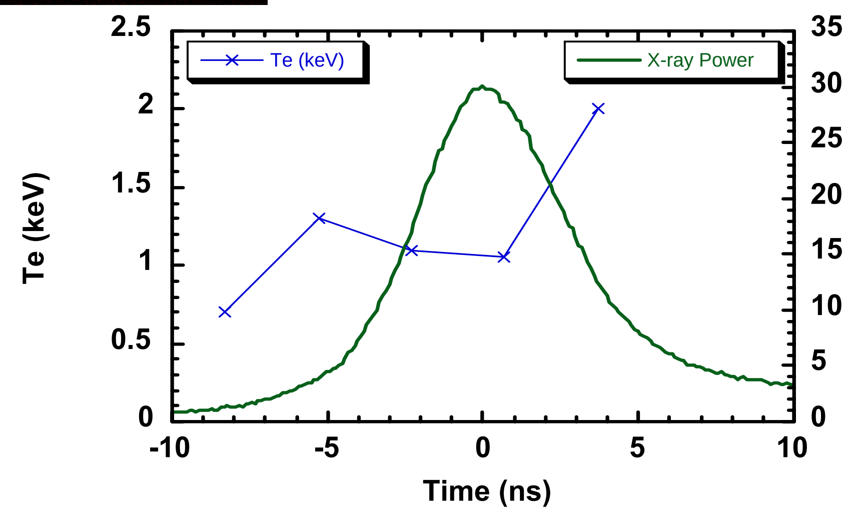
# Time-resolved Al5056 spectrum shows varying plasma conditions during the implosion

Z1520, Al




1520 tx3 0-6500

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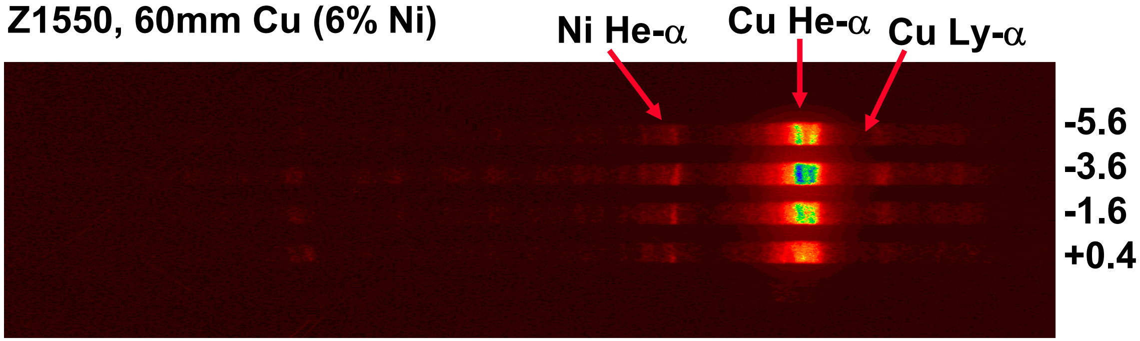
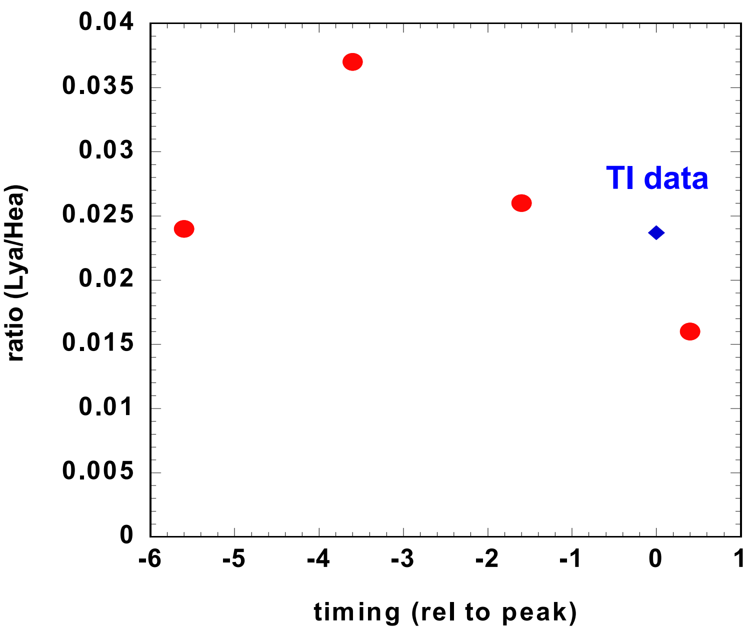
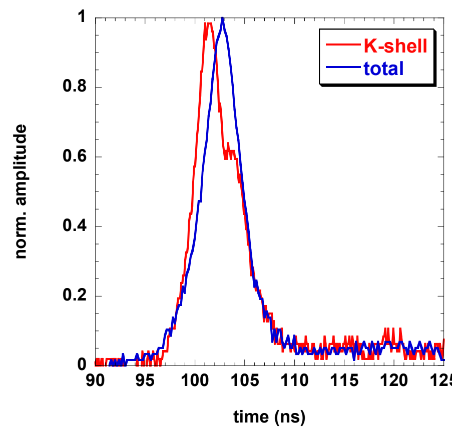
# The plasma conditions are also observed to evolve in Cu z pinches

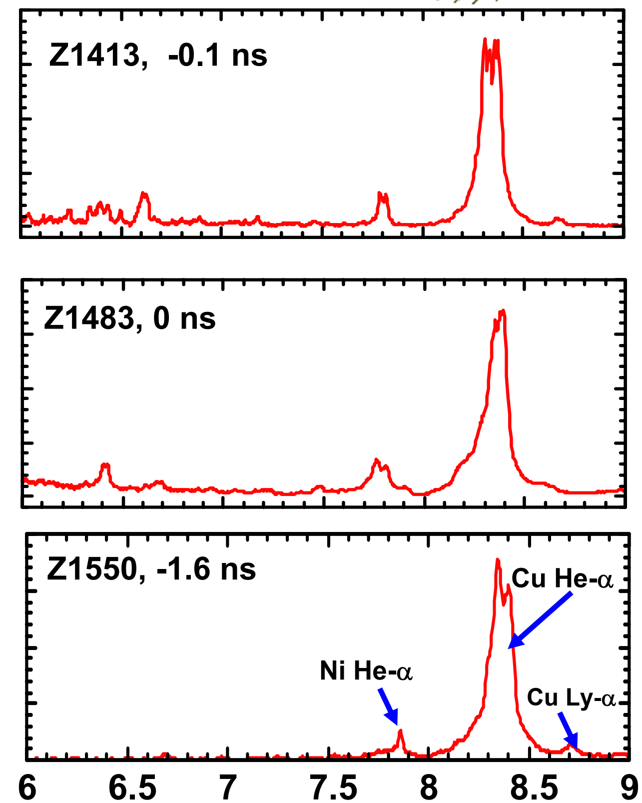
Z1550, 60mm Cu (6% Ni)



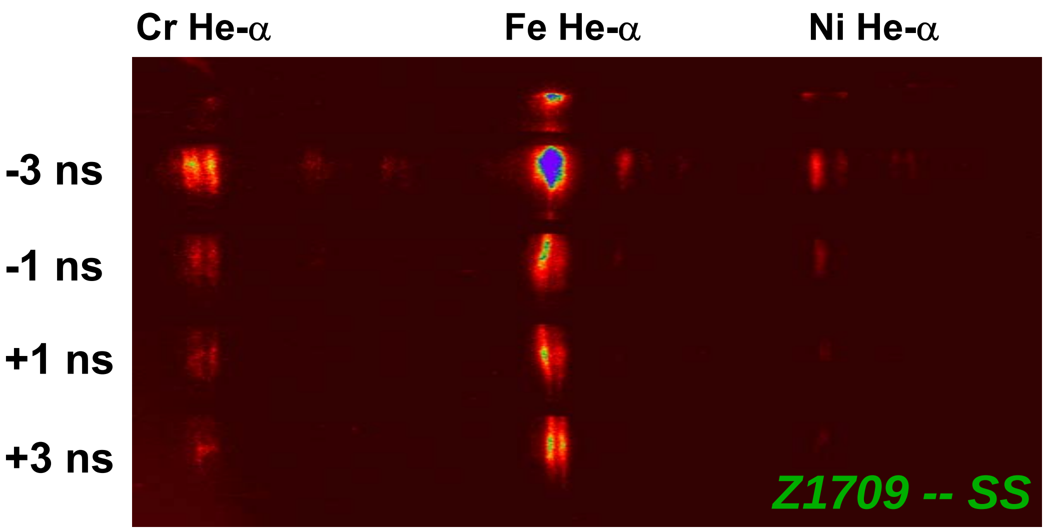



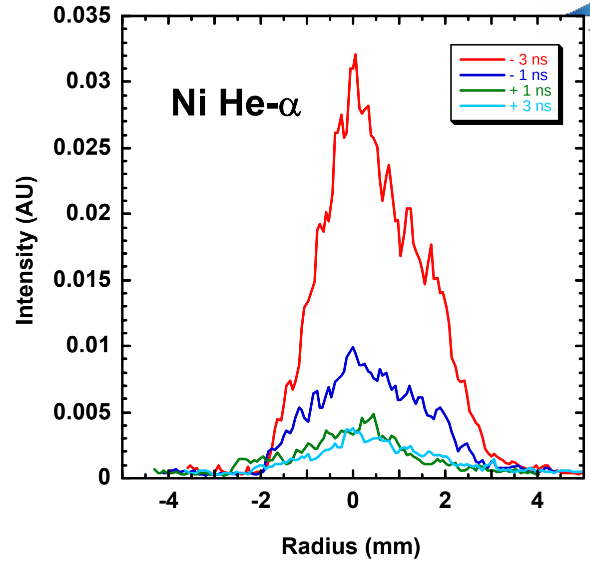

K-shell emission peaked ~1.7ns before total emission

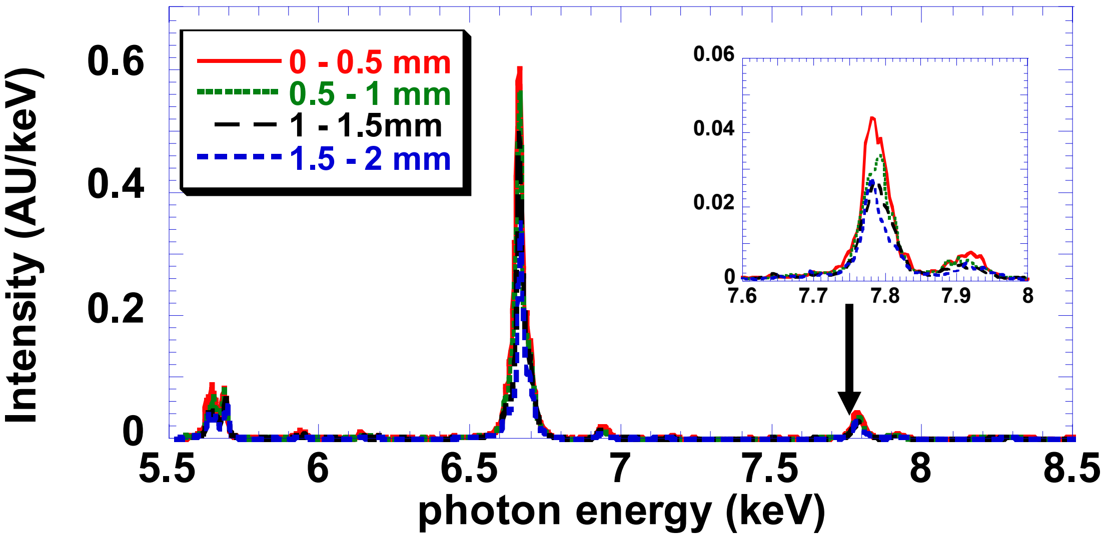


# Radial gradients are observed in SS pinches with time and space resolved spectroscopy




- Radially resolved data shows similar core size for Cr and Ni He-α emissions
- Ni emissions dissipate faster than Cr, however, due to higher $T_e$ needed to produce Ni

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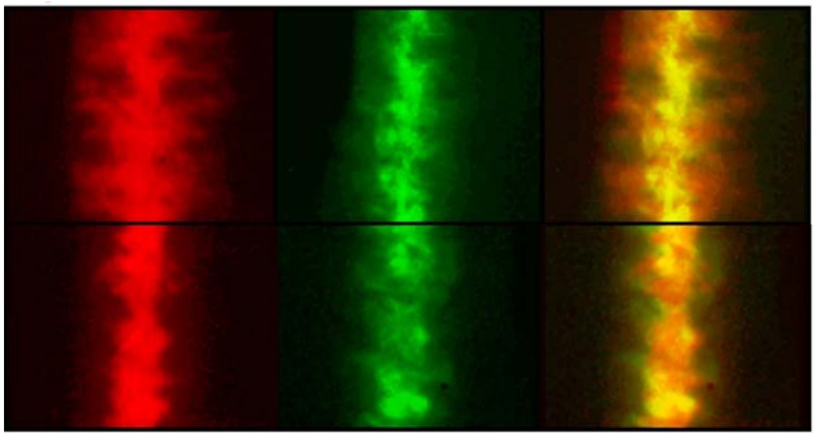
# Observance of hot cores surrounded by cooler blankets suggests that opacity can be studied

277 eV | 1.7 keV Al K-shell | Overlay

Z1519, Al



-2.3 ns

+3.2 ns

- MLM images show hot, dense column emitting K-shell on axis with colder material still imploding

**Radially resolved spectra shown earlier for Al and SS illustrate variations in line emission moving radially outward from central pinch axis**

**High temperature, dense cores observed with Al arrays at Saturn by T.J. Nash *et al.* (J. Quant. Spectrosc. Radiat. Transfer 60, 97 (1998))**

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# Sources of opacity, with approximate cross sections ($cm^2$), in order of importance

**1. Strong lines (oscillator strength ~ 0.5):**

$\sigma$(line center) $\approx 6 \times 10^{-18} Z^{0.55}/[h\nu(\text{keV})]$

-- assumes Doppler broadening with $T_{ion}$ = 20 keV

(reasonable for most cases, based on

J. S. Levine *et al.*, Phys. Plasmas 8, 533 (2001)

M.G. Haines et al. Phys. Rev. Lett. 96, 075003 (2006))

-- Since $h\nu \sim Z^2$, $\sigma \sim Z^{-1.45}$

**2. Bound-free (photoionization per valence electron):**

$\sigma$(at threshold) $\approx 1.2 \times 10^{-17} Z^{-2}$

-- above threshold $\sigma \sim (h\nu)^{-n}$, n > 1, typically, n ~ 3

**3. Free-free (bremsstralung, Gaunt factor of 1):**

$\sigma \approx 7.6 \times 10^{-28} N_i(10^{20}\ cm^{-3}) Z^3 T_e(\text{keV})^{-1/2}[h\nu(\text{keV})]^{-3}$

-- assumes $N_e = N_i Z$

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# Absorption and reradiation of photons

- **The absorption process of line radiation removes photons from the emission, yielding higher energy electrons, but fewer x-rays**
  - **Step 1:** The photon excites an ion of the same species that emitted it, raising an electron from the ground state to an excited level. **Example:** Al (1s) + h$\nu$ → Al (2p)
  - **Step 2:** The excited ion is then de-excited by superelastic collision(s), restoring the photon's energy to the electron pool. Example: Al (2p) + e- → Al (1s) + e-

- **Reradiation to the ground state before collisional de-excitation does not remove photons (scattering), no energy loss.**
- **These two processes compete, but absorption increases with increasing density, eventually dominating.**
  - **Step 1:** The probability that a line photon is intercepted by a K shell ion varies as the cross section: $Z^{-1.45}$
  - **Step 2:** The probability of electron quenching is the collisional de-excitation rate divided by the spontaneous decay rate. The collisional rate varies as $Z^{-3}$; the radiative decay rate as $Z^{4}$, giving an overall variation as $Z^{-7}$ !

*The sharp dependences of the underlying atomic physics factors can produce large variations in K-shell opacity for relatively small differences in Z*

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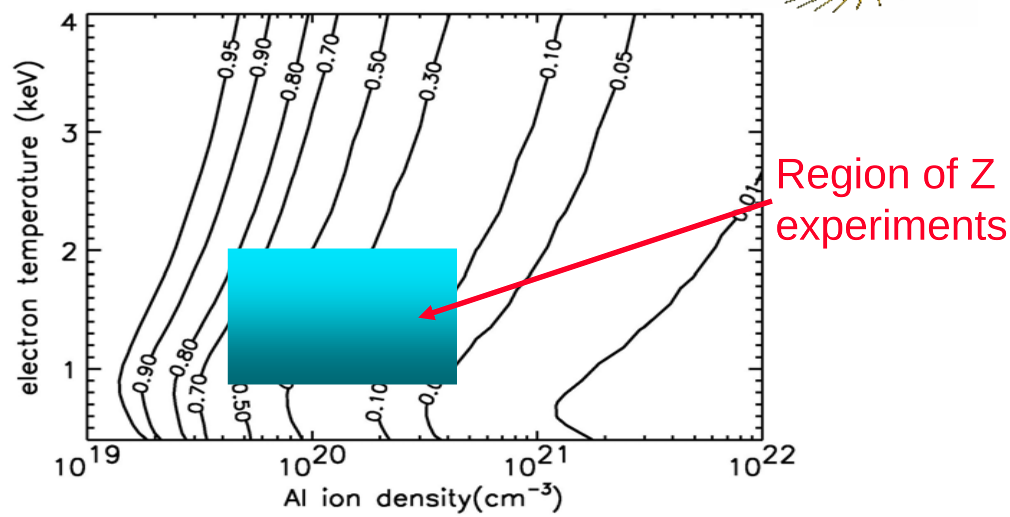
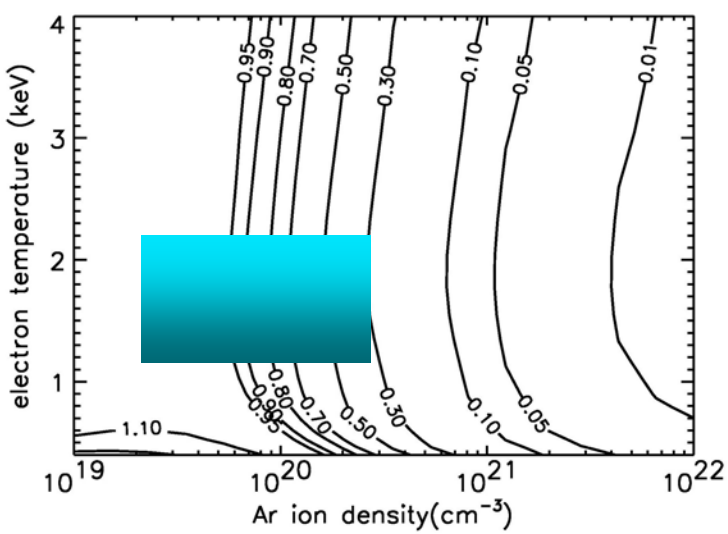
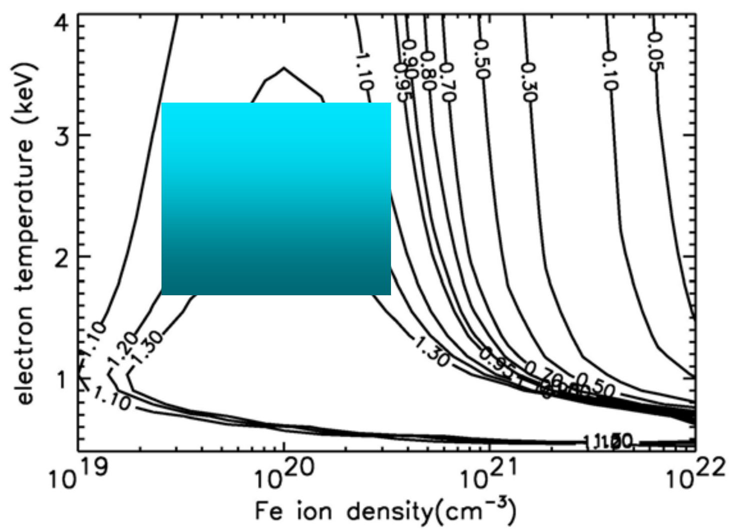
# Thick-to-thin power ratio for K-shell α lines show effects of increasing opacity

- A value of 0.10 indicates an optically thick plasma radiates only 10% that of an optically thin plasma

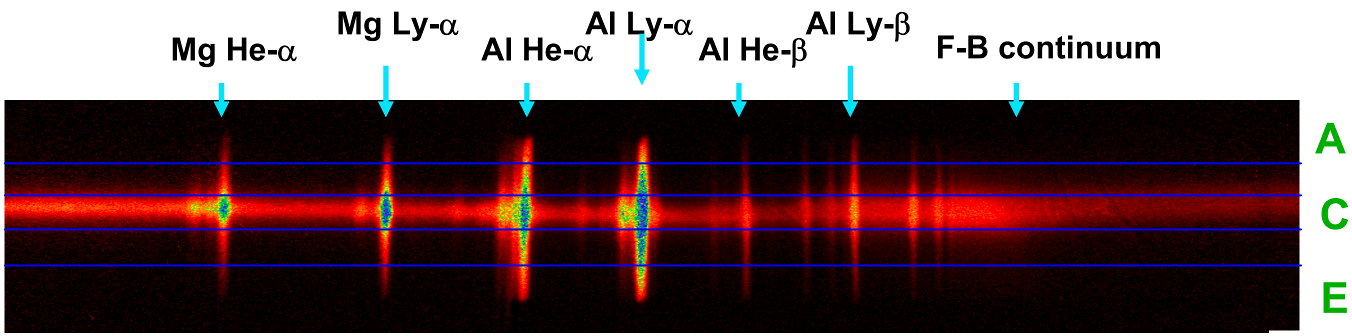
- Al plasmas on Z show these effects; higher Z materials (Ar, Fe) do not
    - In fact, ladder ionization at low density can produce a ratio > 1



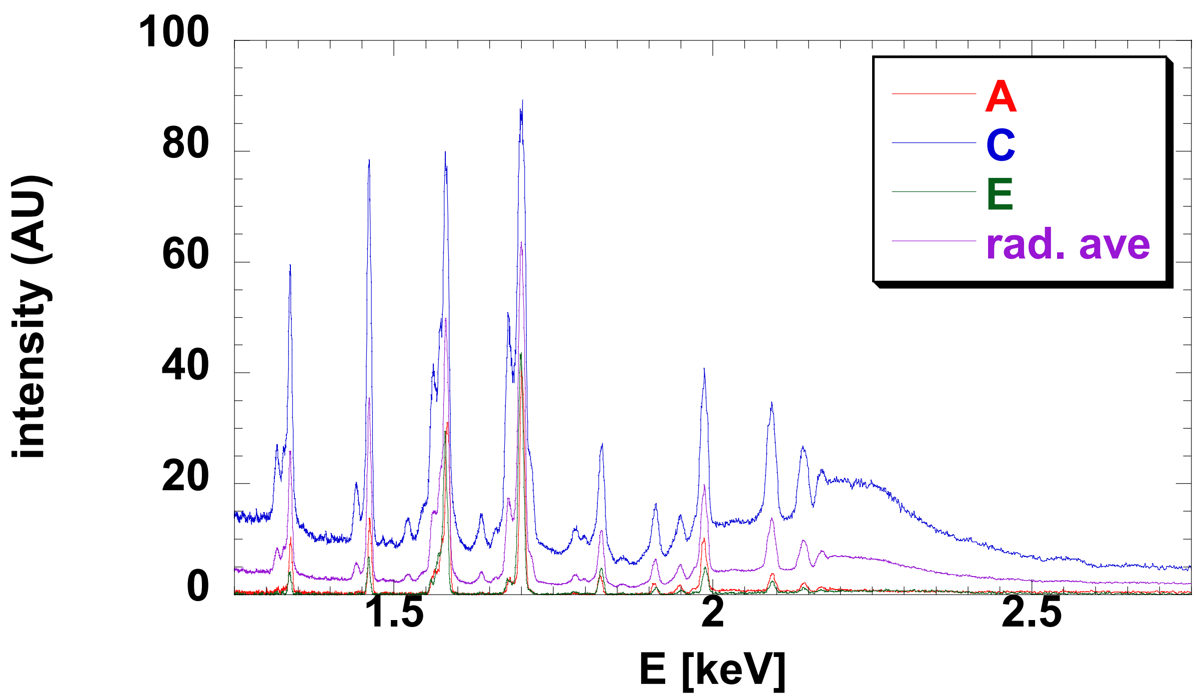



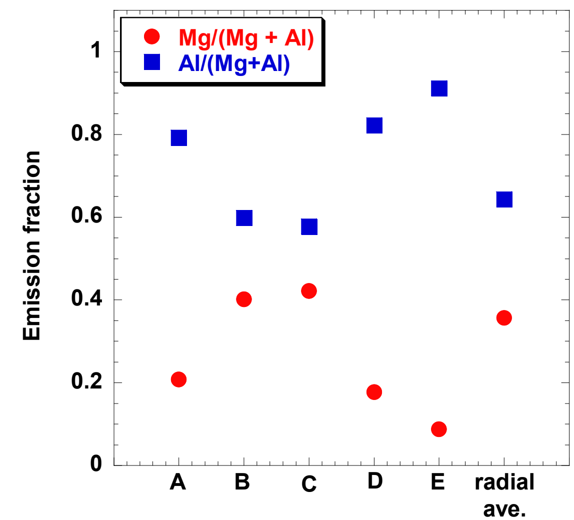
# Al data (time-integrated, radially resolved) shows effects of opacity




1520 tir -200-20000

**Easier for photons produced in cooler blanket to escape**

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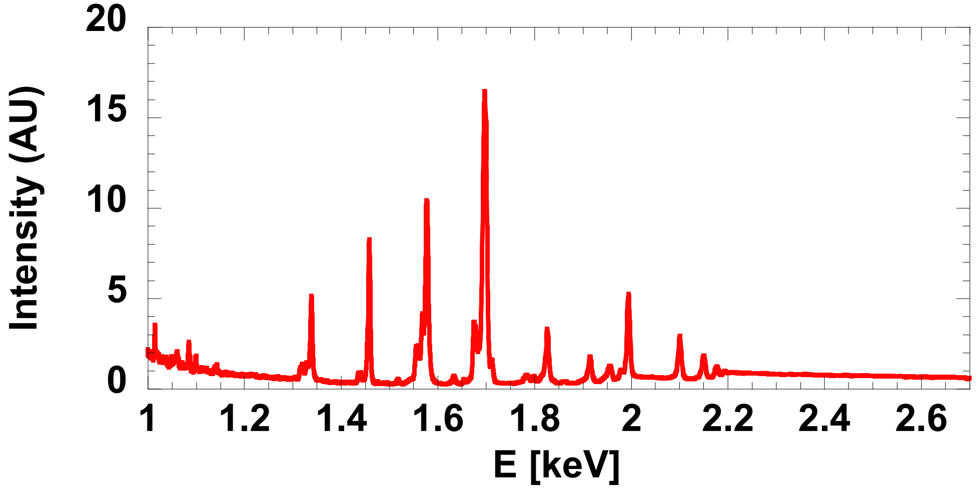
# The impact of opacity is evident experimentally in time-integrated spectra; Atomic number trend is consistent with theory

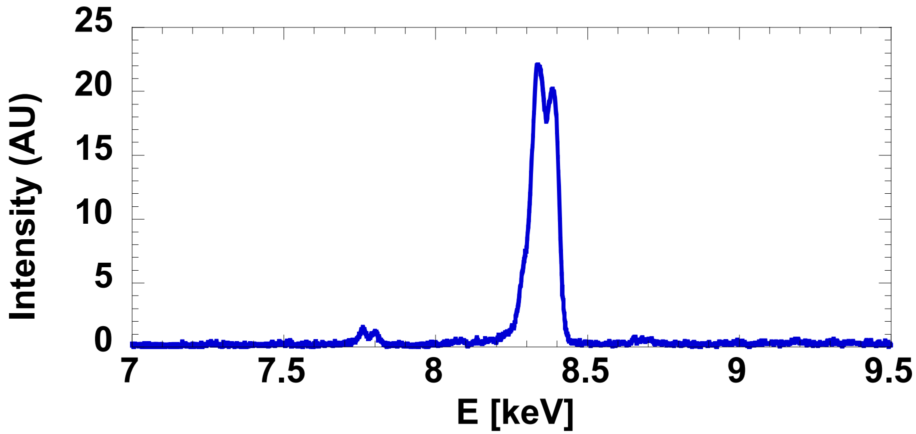
**Al (40 mm nested); Al 5056 (5% Mg) on both arrays**




Amplitude of Mg relative to Al suggests that mass distribution is ~30% Mg, ~70% Al
- clear evidence of opacity issues for Al at Z

**Cu (60 mm nested); 94% Cu / 6% Ni on both arrays**

Z1550




Amplitude of Ni relative to Cu suggests that mass distribution is ~ 10% Ni, 90% Cu
- Clearly little if any opacity impact here

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# Summary

- A variety of K-shell sources have been fielded at Z
  - Wide range of photon energies fielded
  - Assessment of K-shell scaling theories on required temperatures possible
  - Study of temperature gradients possible (axial, radial, and temporal)
- Temperature and density gradients observed
  - Pinhole images suggest significant axial structure present
  - Axially resolved spectra show peak temperature generally higher than axially averaged temperature for higher Z materials
    - Consistent with images showing brighter regions of emission
  - Radially resolved spectra show hot core with cooler surrounding blanket
  - Temporally resolved spectra show varying pinch conditions during radiation pulse
- Effects of opacity clearly evident in measured spectra
  - Opacity comes into play due to atomic physics of absorption and reradiation
  - Expected to be more severe with lower Z
  - Al data clearly shows impact of opacity
  - Cu data appears to be optically thin

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