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Spectroscopic diagnosis and progress toward understanding thermalization physics in low- to mid-atomic-number z pinches on the Z machine

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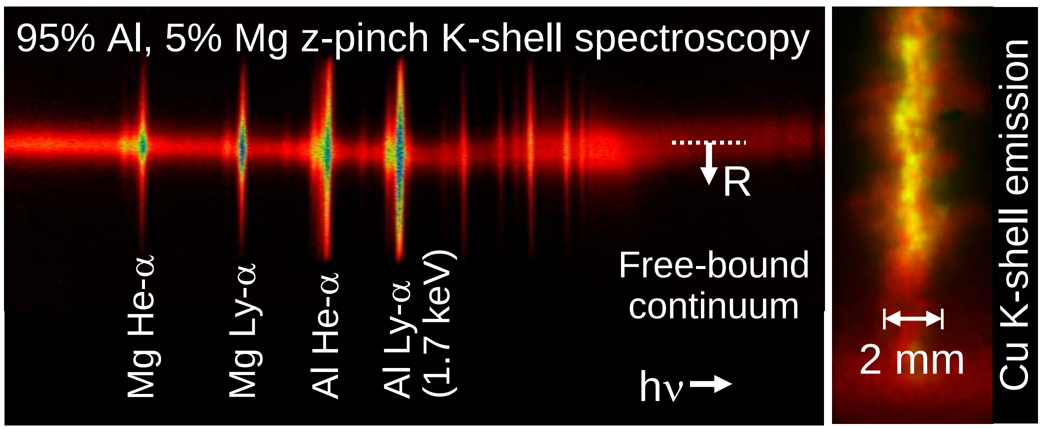

[1]Sandia National Laboratories
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[3]Ktech Corporation
[4]Naval Research Laboratory
[5]Berkeley Scholars
[6]Weizmann Institute of Science

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National Nuclear Security Administration

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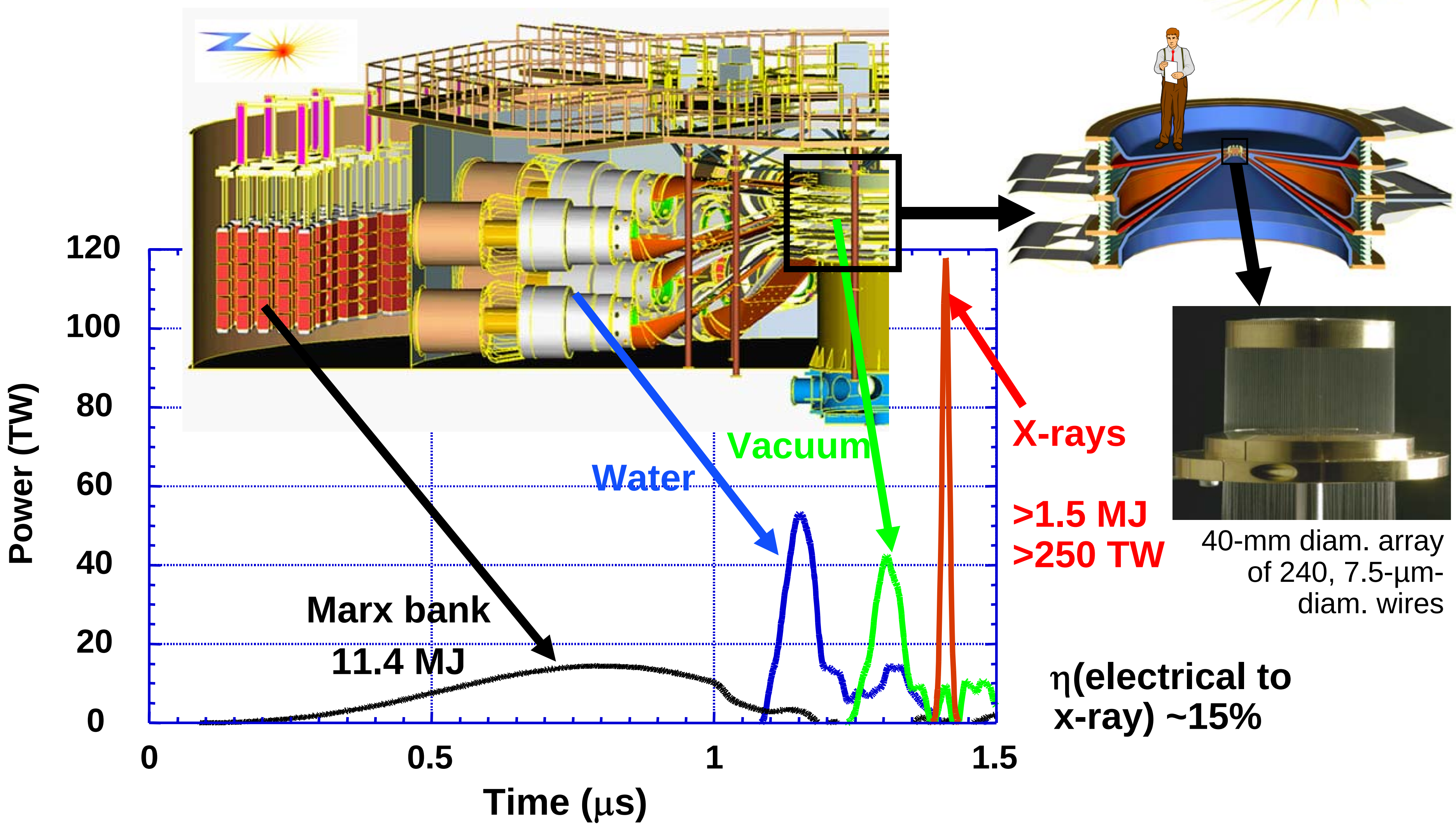
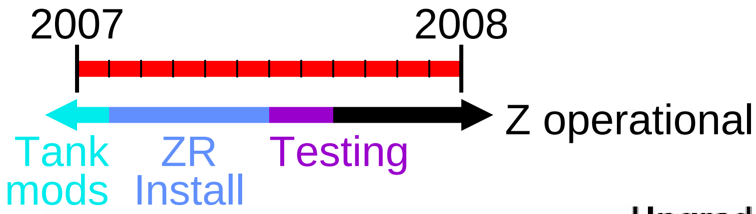
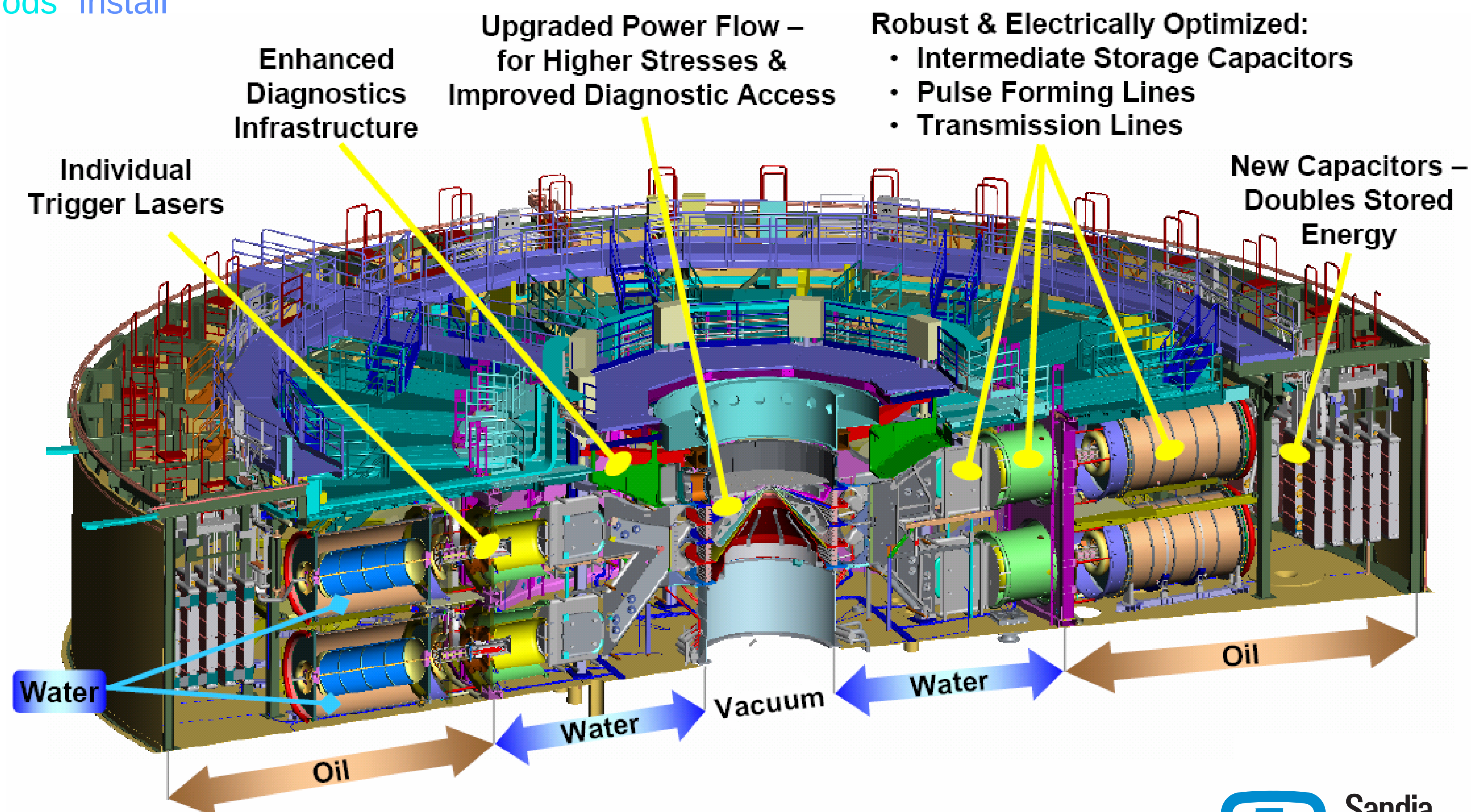
Sandia's Z machine produces intense x-ray radiation



Z Refurbishment underway—26 MA capability in 2007





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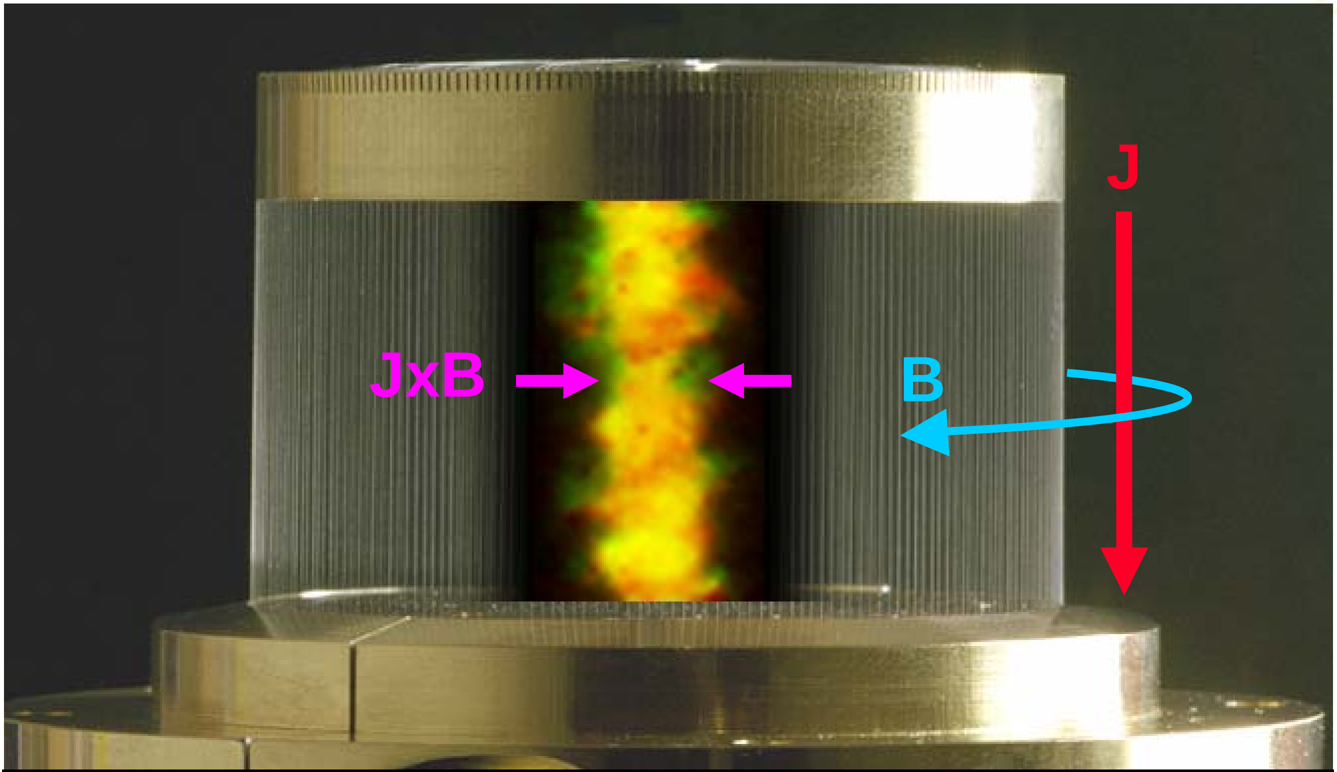
J x B pinches wire array into a dense, radiating plasma



Radiation Effects Sciences (C7) z-pinch sources

$n_i \sim 10^{20}$ cm^{-3}, $T_e \sim 1$ keV (non-LTE)

$P_{rad} \sim 100$ TW, $Y_{rad} \sim 1$ MJ, $Y_{rad,>1keV} \sim 100$ kJ

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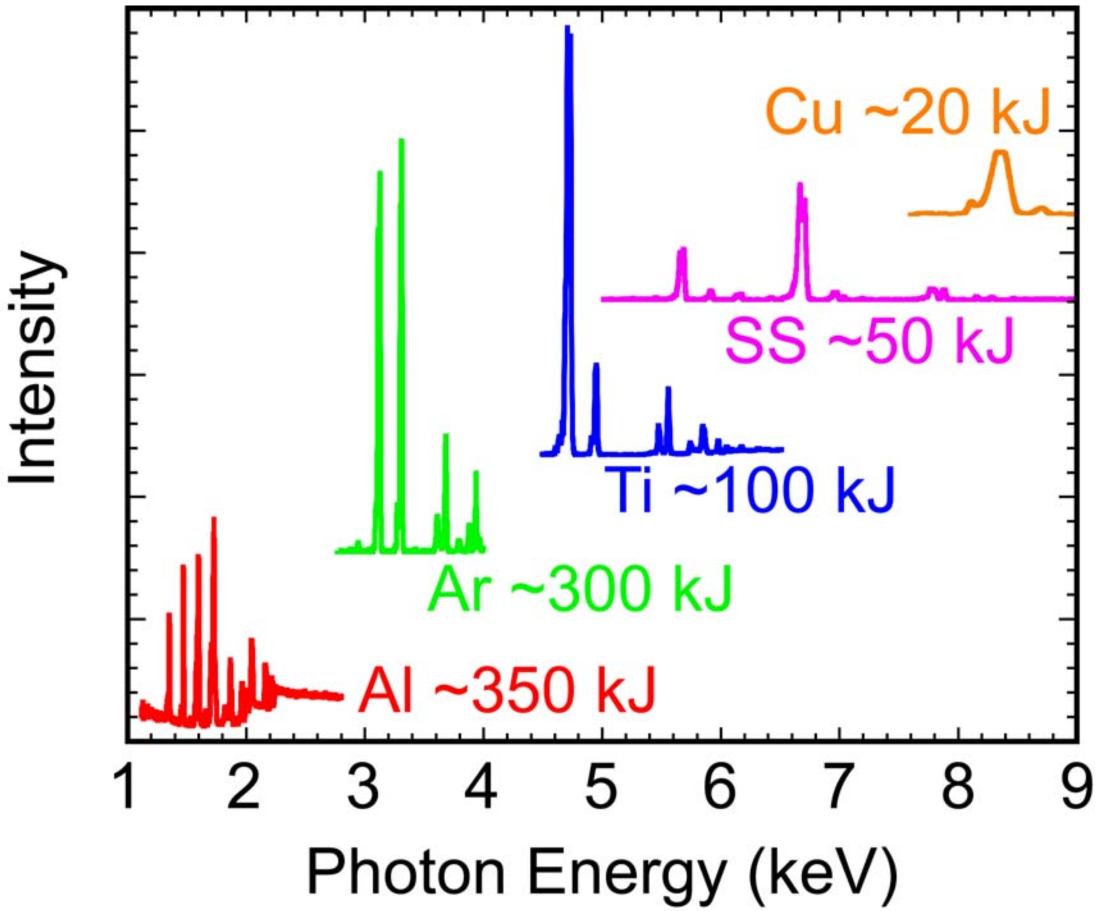
A variety of K-shell sources have been studied at Z for C7

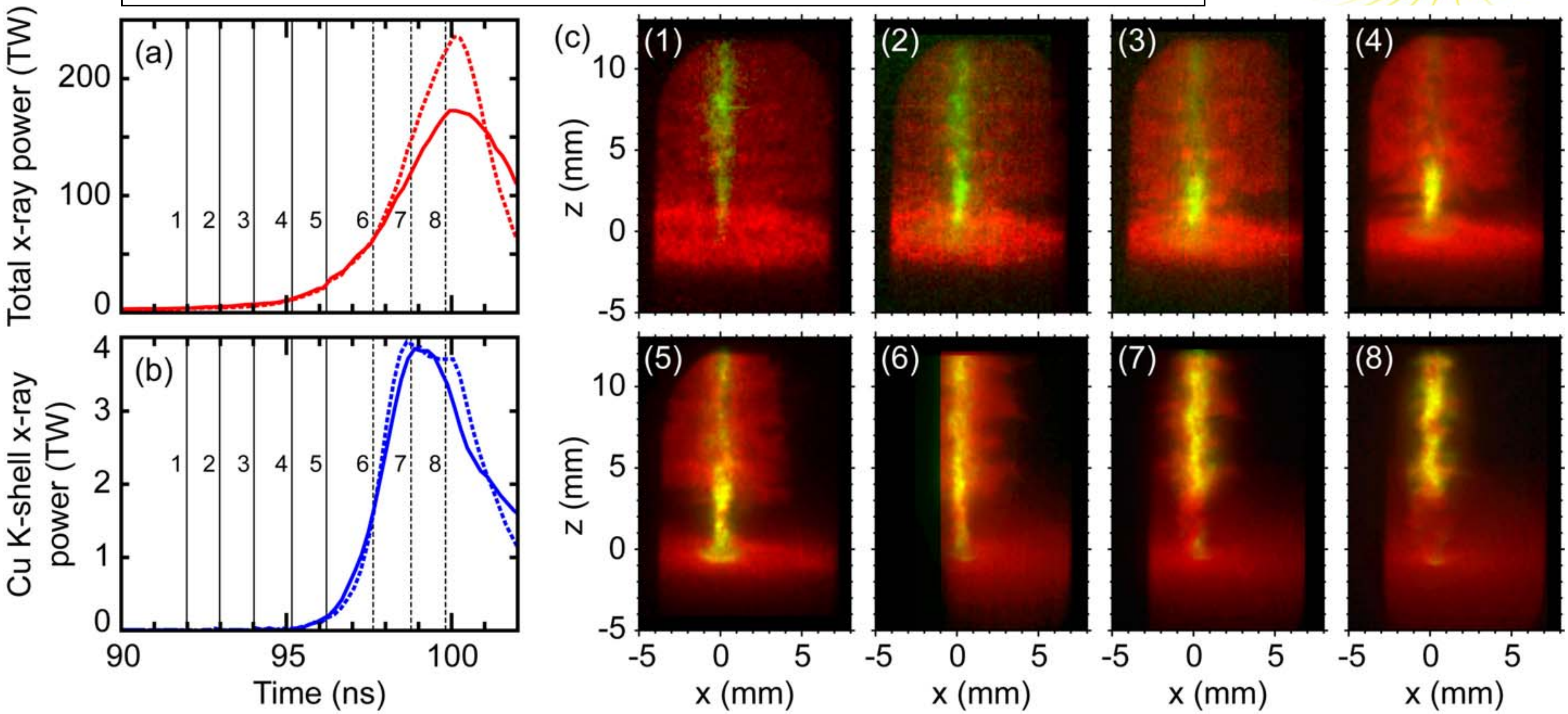


- Factor of 2-4 increases in yield expected on ZR
- Al: 40 on 20 mm dia. nested wire array
- Ar: L3 1234 nozzle gas puff Z pinch
- Ti: 50 on 25 mm dia. nested wire array
- SS: 55 on 27.5 mm dia. nested wire array
- Cu: 60 on 30 mm dia. nested wire array
- Pulse widths 5 to 25 ns, rise times 2 to 8 ns

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).
J.W. Thornhill *et al*., IEEE T. Plasma Sci. **34**, 2377 (2006).

Plasma heating and radiation excitation on ~1 ns time scale

Cu z pinch on Z (C.A. Coverdale); B. Jones *et al.*, APiP 2007 proc.



- Magnetic RT implosion instability broadens the radial profile
- Plasma accretes on axis, depositing kinetic energy
- e-i-rad thermalization in dense plasma on axis
  - K-shell emission from column where pinch is assembling
  - Details of shock heating are a topic of continuing interest

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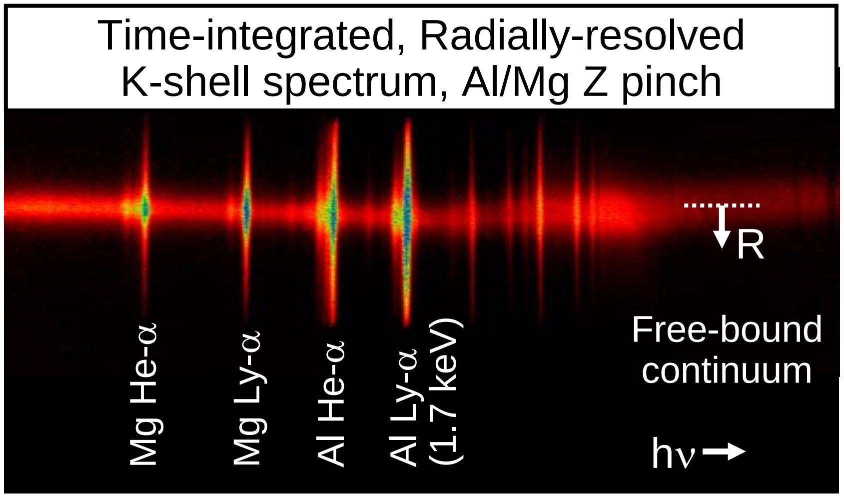
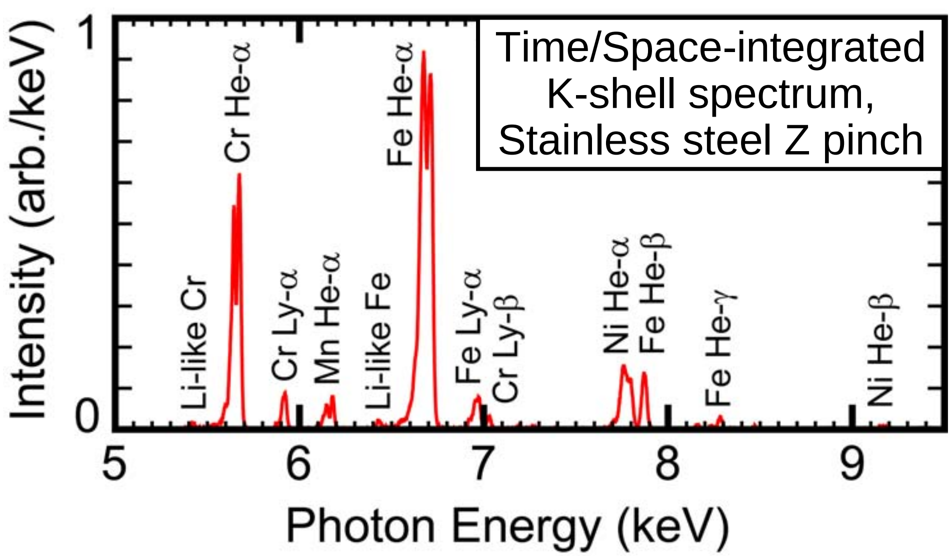
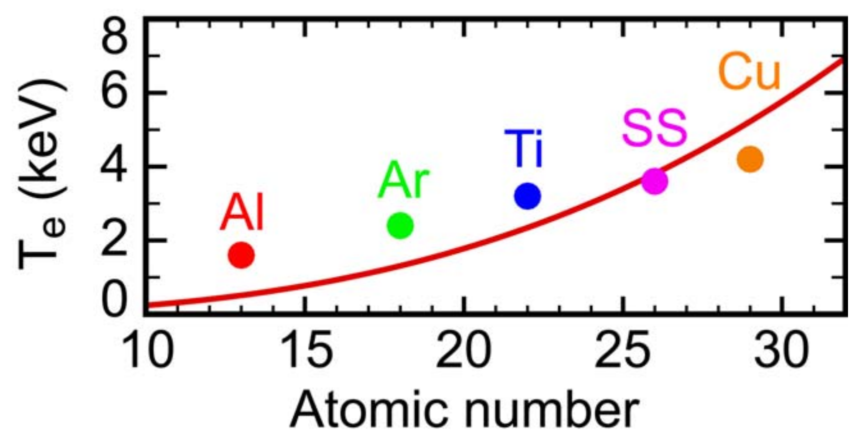
Load design provides T_e > 1 keV for K-shell excitation

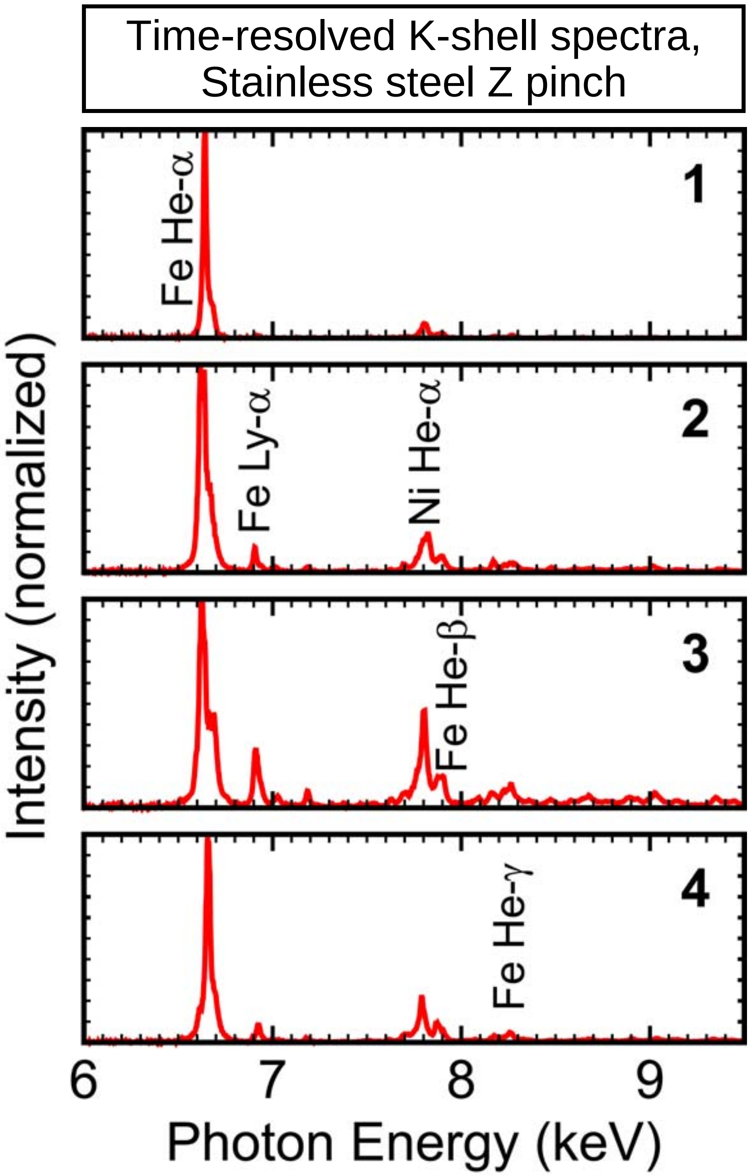


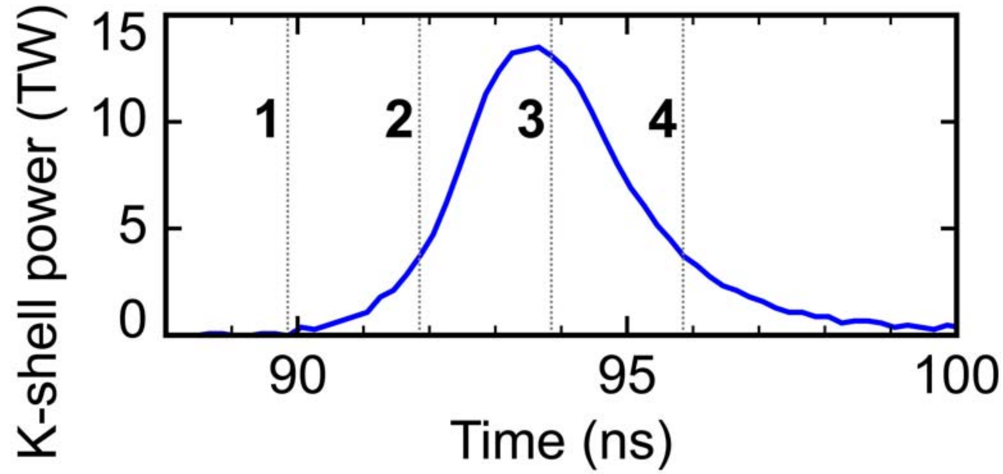


- Time-integrated crystal spectrometers fielded on all Z shots for K-shell survey
- Plasma conditions inferred through non-LTE collisional radiative modeling (NRL)
- Higher photon energy sources require higher T_e to ionize to the K-shell



Time-resolved x-ray spectra support thermalization studies





- Ni and high order Fe lines light up as n_e, T_e increase near peak K-shell x-ray power
- Time-resolved elliptical crystal spectrometers provide <1 ns resolution with low background
  - J. E. Bailey *et al.*, PRL **92**, 085002 (2004).

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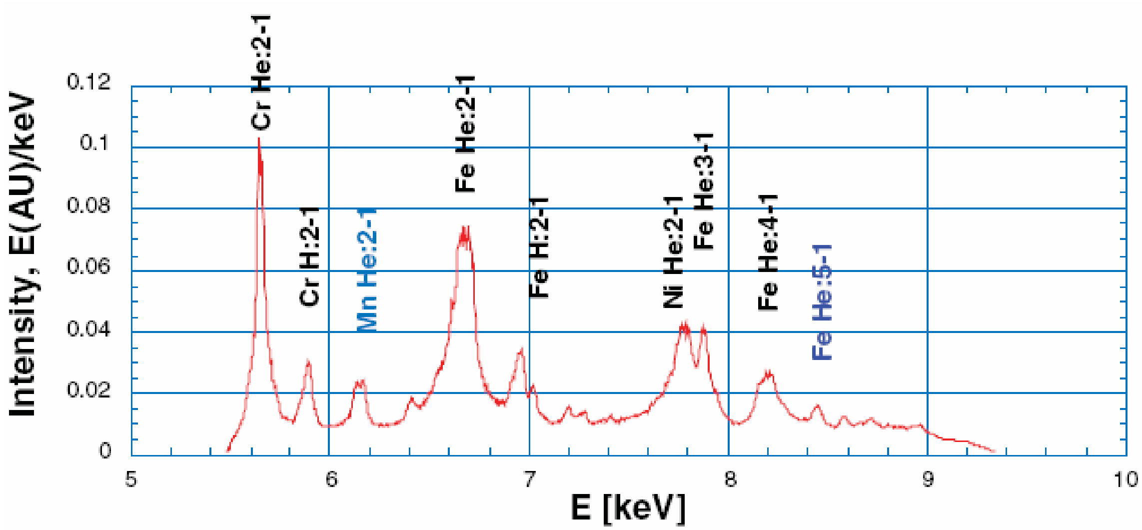
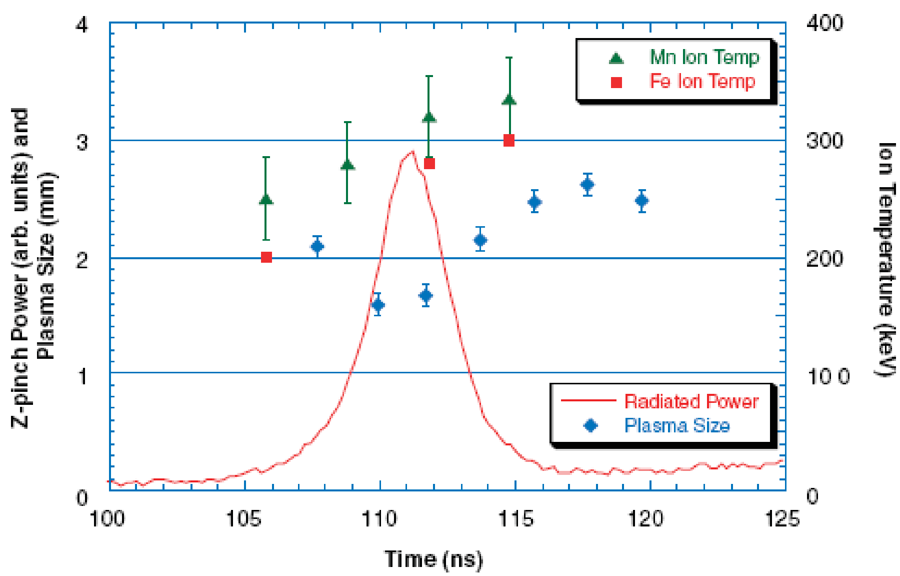
High ion temperatures are expected in z-pinch plasmas





- Ions carry KE; other heating proposed
- We have started to address ion heating in K-shell radiators (e.g. stainless steel)
- M.G. Haines *et al.*, PRL **96**, 075003 (2006): T_i > 100 keV inferred from Doppler-broadened line widths on Z
- Results are controversial—further study is desired
- E. Kroupp *et al.*, PRL **98**, 115001 (2007) also discusses > 1 keV ions in a small gas puff z pinch

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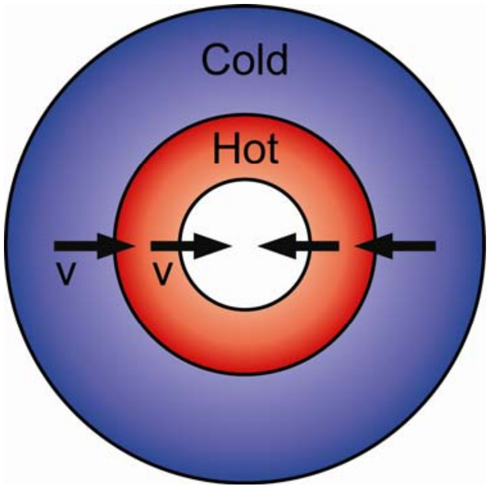
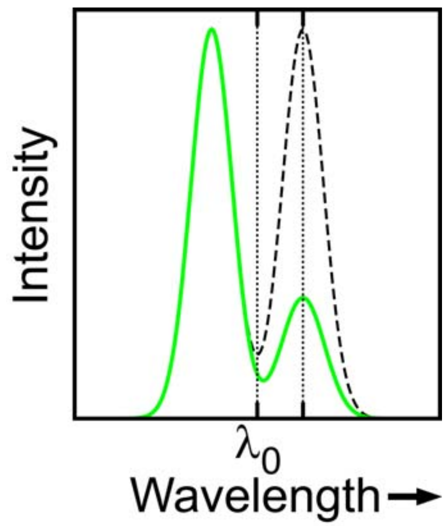
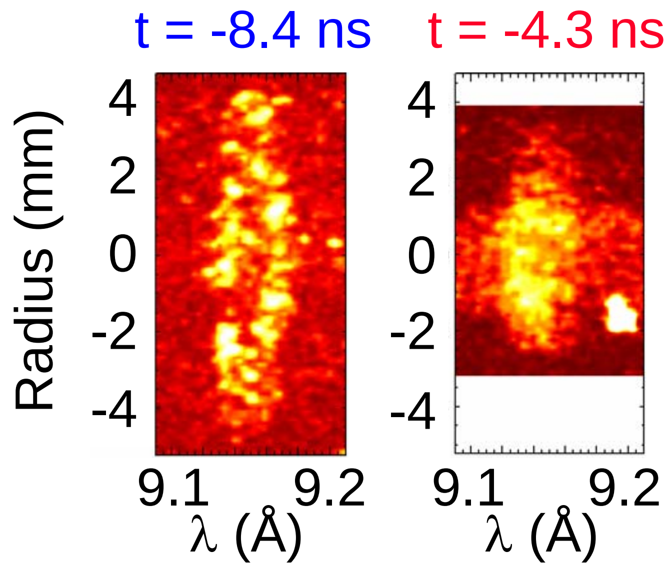
Optically thin Doppler splitting seen in low-mass Al wire array

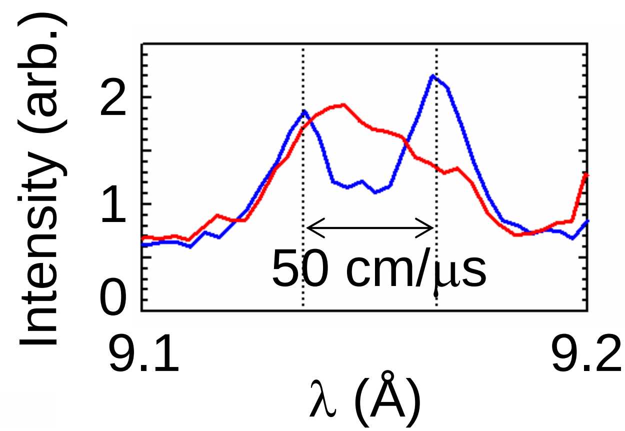
Z1520 (Coverdale), Mg He-α (Dunham)







- Oval shape—Doppler split seen on axis, but not in tangential view of shell
- At early time, red/blue-shifted lines are similar magnitude ⇒ optically thin
- Speckle could be azimuthal structure
- At later times, red-shifted line is attenuated by shell/trailing mass opacity
- Splitting not so obvious in Al lines—brighter precursor emission on axis?



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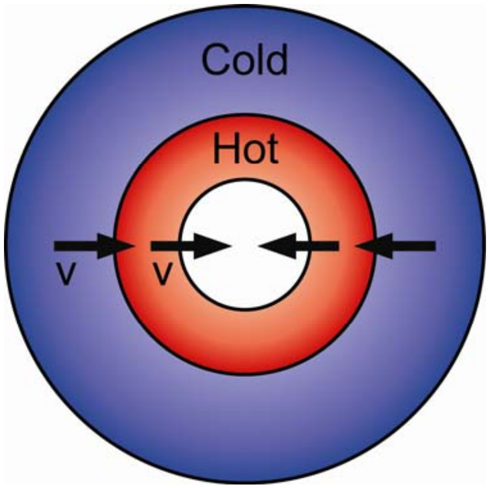
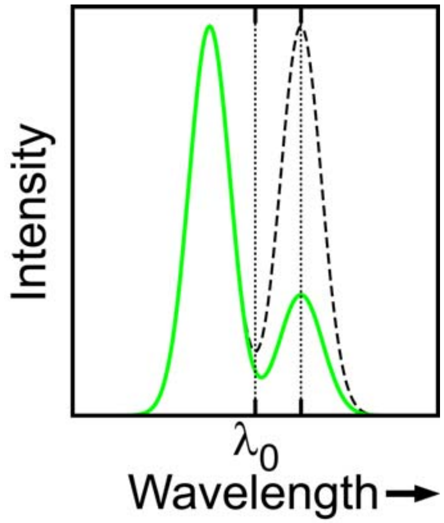
Doppler-shifted absorption seen in high-mass Al wire array

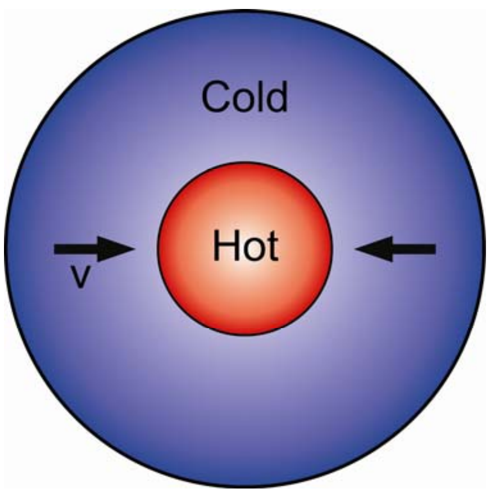
Can interpret as…

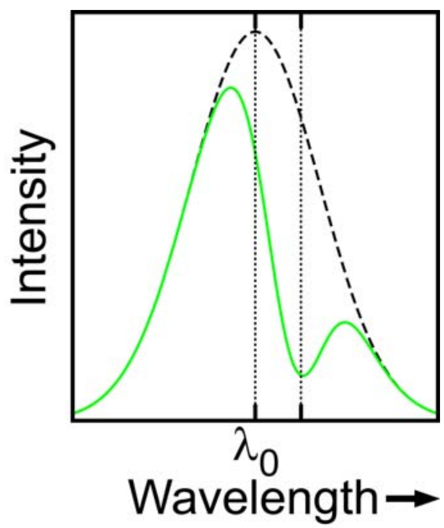


Opacity in cold trailing mass

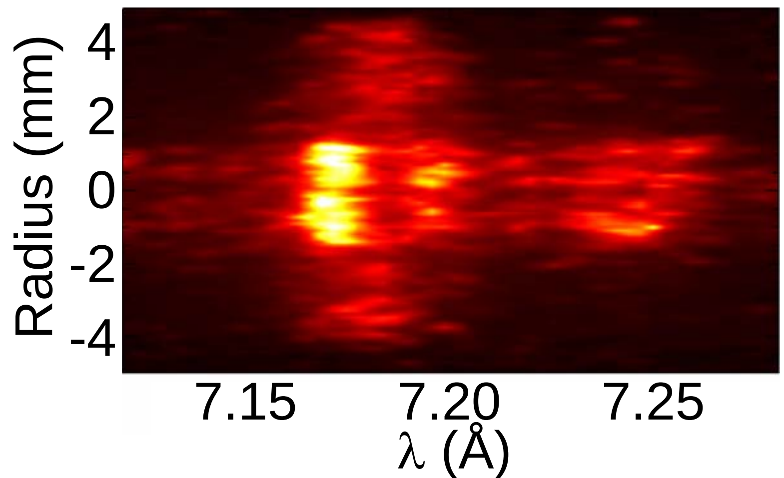


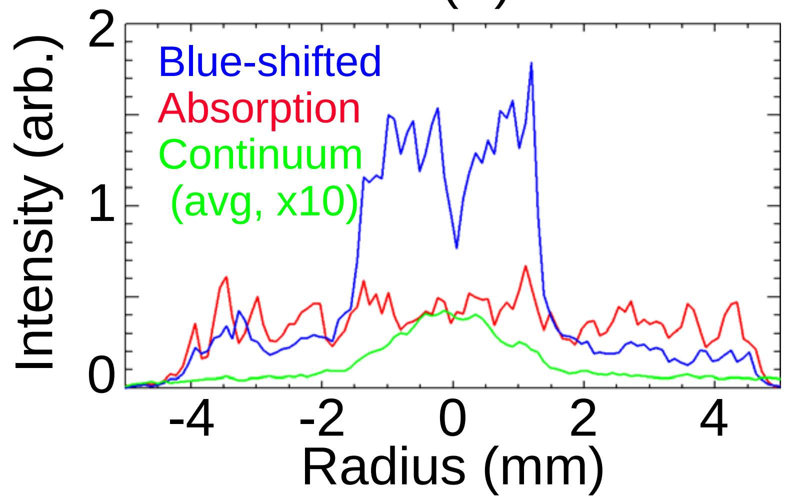
or as…





Z1518, Al Ly-α
t = -9.0 ns





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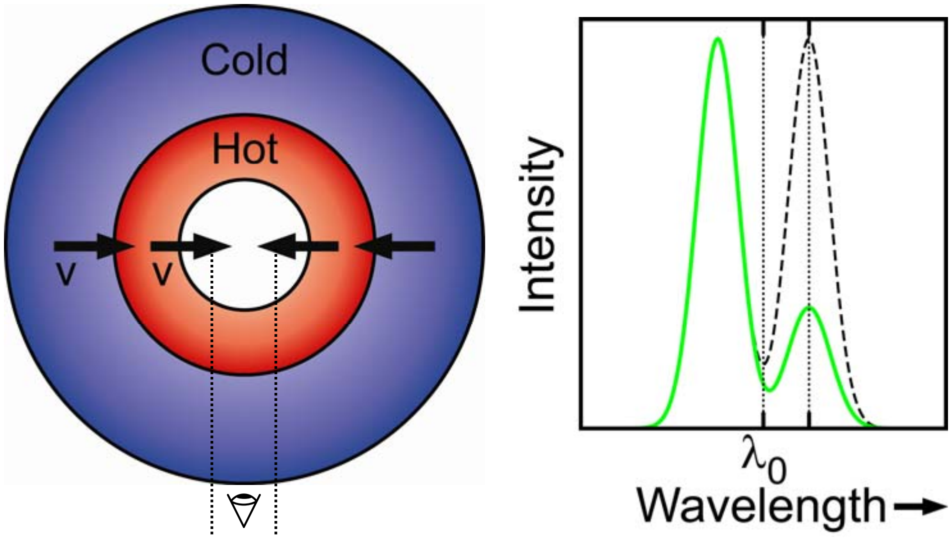
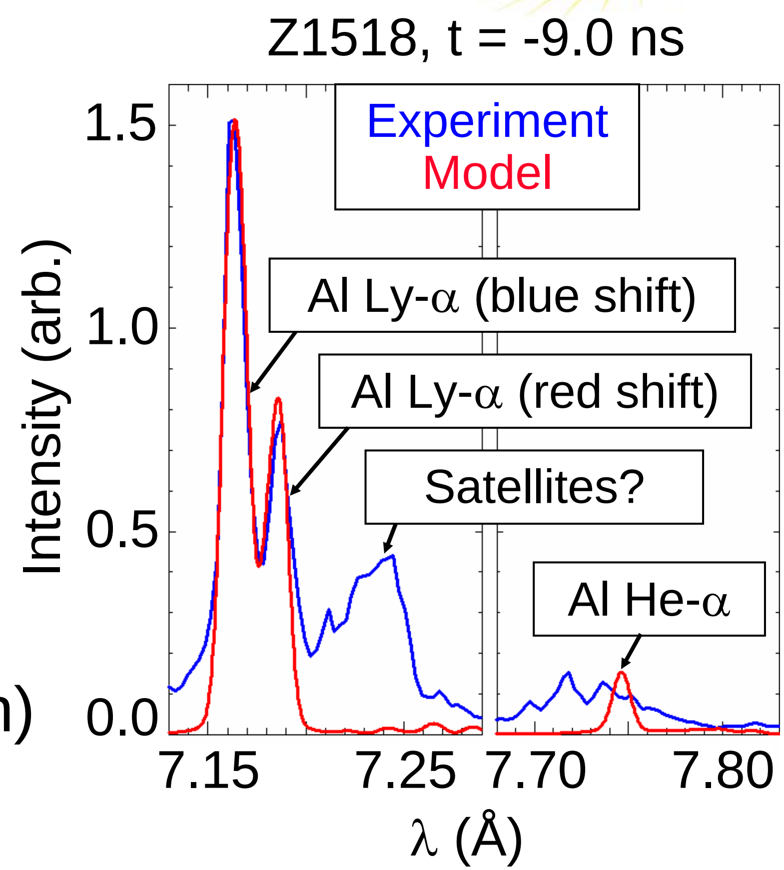
CR model with Doppler shifts/broadening is being developed

Opacity in cold trailing mass attenuates red-shifted Al Ly-α and He-α





- Collisional-radiative model, radiation transport in discrete zones (Y. Maron)
  - Hot: 1.5 mm < R < 2 mm
  - Cold: 2 mm < R < 9 mm
- Line shape calculations
  - Stark broadening (not dominant)
  - Doppler broadening/splitting (implemented for first time, $\delta v/v = 10\%$)
- Preliminary results (need to consider satellites):
  - Hot: $n_i = 5 \times 10^{19}$ cm^{-3}, T_e = 700 eV, v = 40 cm/μs
  - Cold: $n_i = 5 \times 10^{19}$ cm^{-3}, T_e = 150 eV, v = 30 cm/μs

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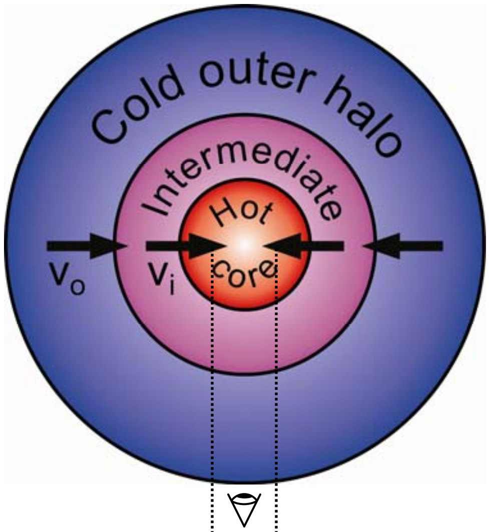
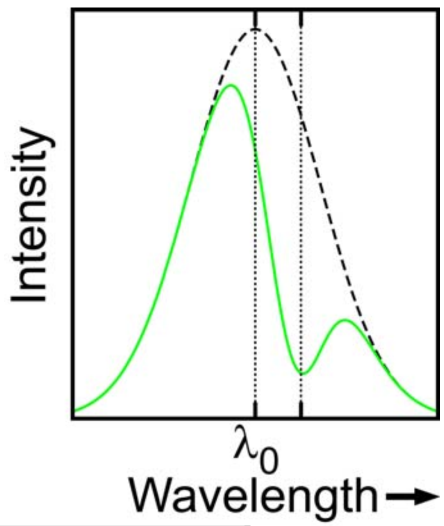
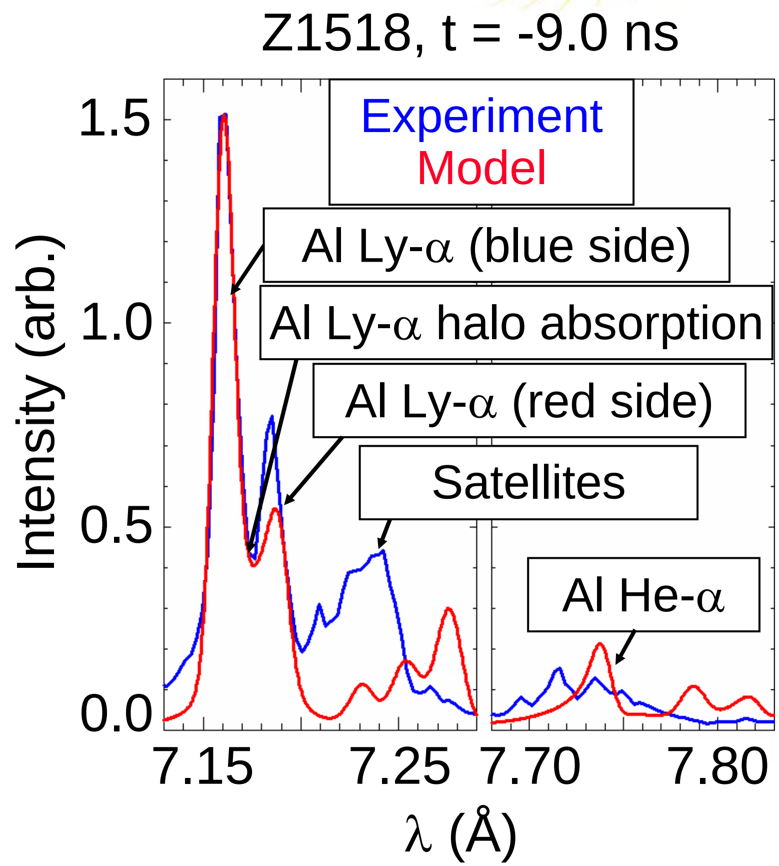
Matching spectral features constrains plasma parameters

Opacity in cold trailing mass forms absorption dip in broad Al Ly-α line





	Core	Intermediate	Outer
T_e (eV)	400	250	100
R_{out} (mm)	1.5	3.5	10
n_i (cm^{-3})	4e19	4e19	4e19
v_r (cm/μs)	0	20	10
δv (cm/μs)	30	0	0



- Al Ly-α satellites can be better explained with dense core
- The δv in core may indicate T_i, turbulence, or ∇v
- Study required to determine how well plasma parameters can be constrained

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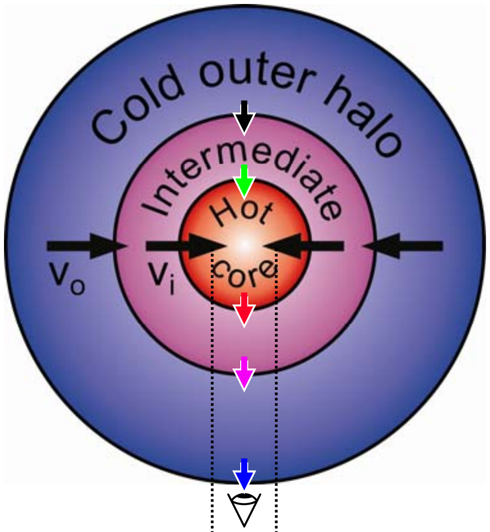
Radiation transport is tracked through each plasma region

Opacity in cold trailing mass forms absorption dip in broad Al Ly-α line



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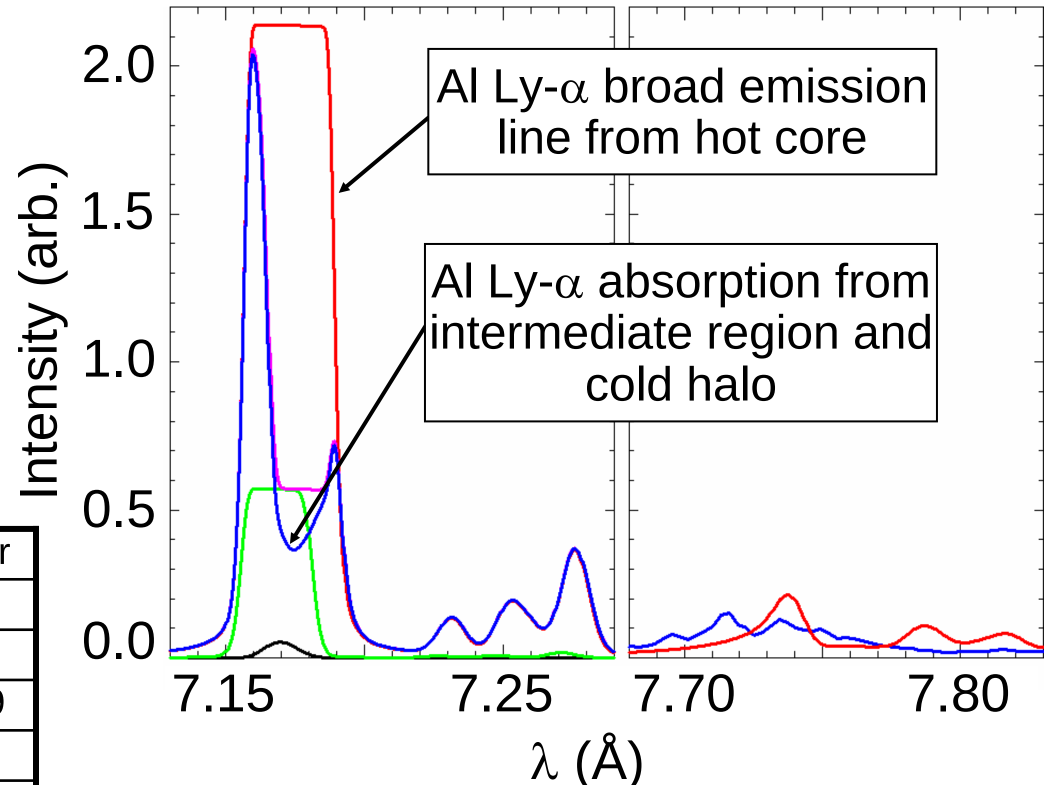
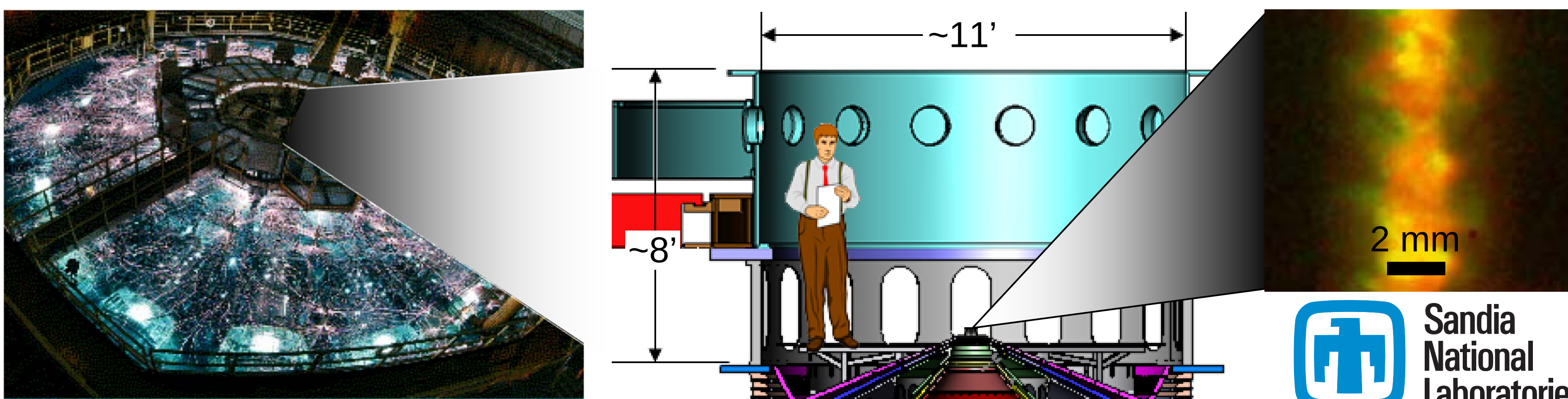


- Broad Al Ly-α line from hot core backlights the cold halo
- May be able to infer T_i in the core through this analysis
- Al Ly-α satellites originate in the hot core and will help constrain core density

Summary

- The Radiation Effects Sciences program at Sandia is developing 1-10 keV K-shell radiation sources (wire array and gas puff z pinches) on the Z machine
- Physics associated with conversion of ion kinetic energy to electron thermal energy, then radiation is important for z pinches of all classes
- Z-pinch physics, plasma heating and energetics will continue to be investigated via K-shell spectroscopy and other x-ray measurements on Z along with numerical and analytical theory



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