SAND2007-2058C

Implosion Energetics via Analysis of Mass Density Profile Evolution and Spectrally-Resolved Imaging

Brent Jones
Sandia National Laboratories

2007 Wire Array Workshop
Battle, UK – April 2-5, 2007

National Nuclear Security Administration

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

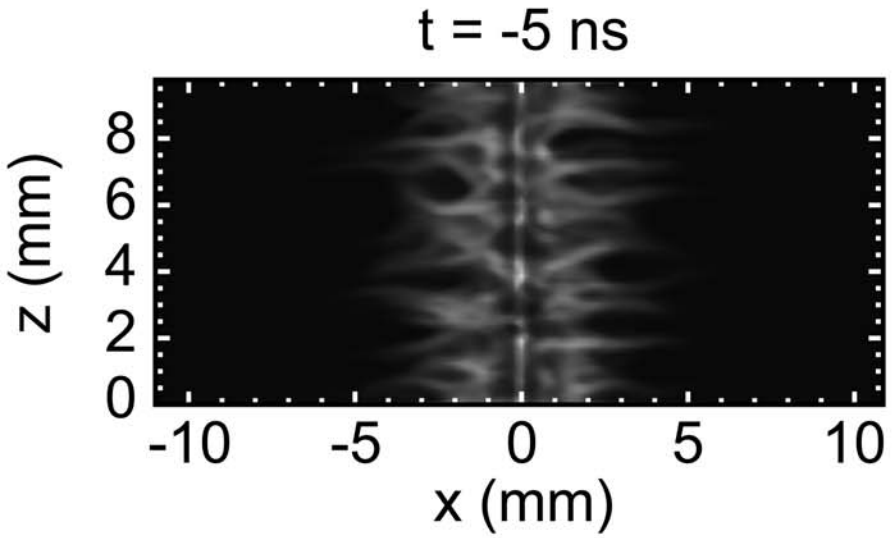
Sandia National Laboratories

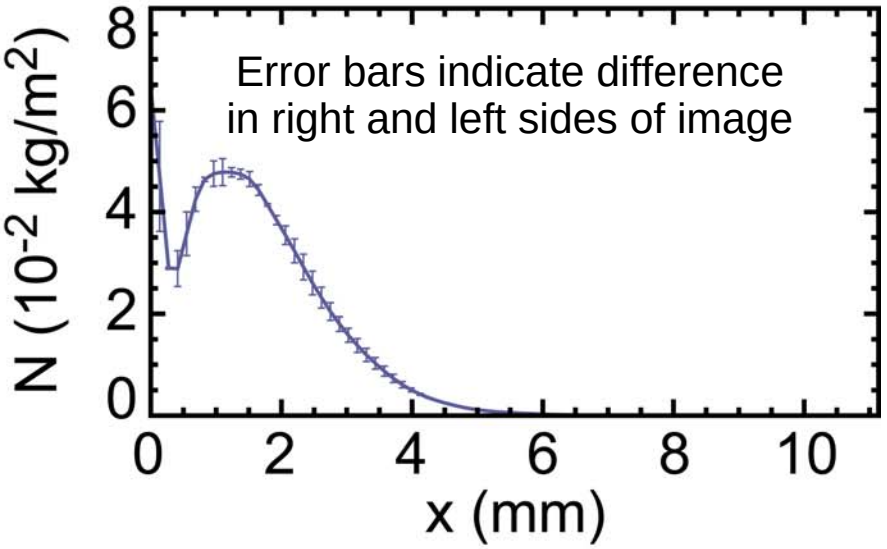
Overview

- How much information can we obtain through observation of the mass density profile evolution during z-pinch implosion?
  - Abel inversion of imaging data
  - Continuity equation analysis to obtain kinetic energy
- How can we measure $\rho(r,t)$ experimentally?
  - Multi-frame x-ray radiography
  - Time-resolved x-ray self-emission diagnostics
- K-shell spectroscopy of low-Z wire arrays
  - Doppler shift measurements can give velocity
  - Plasma parameters inferred in different regions, particularly on-axis where Abel inversion is most problematic

Sandia National Laboratories

2D areal density images from 3D MHD simulation (Jennings)

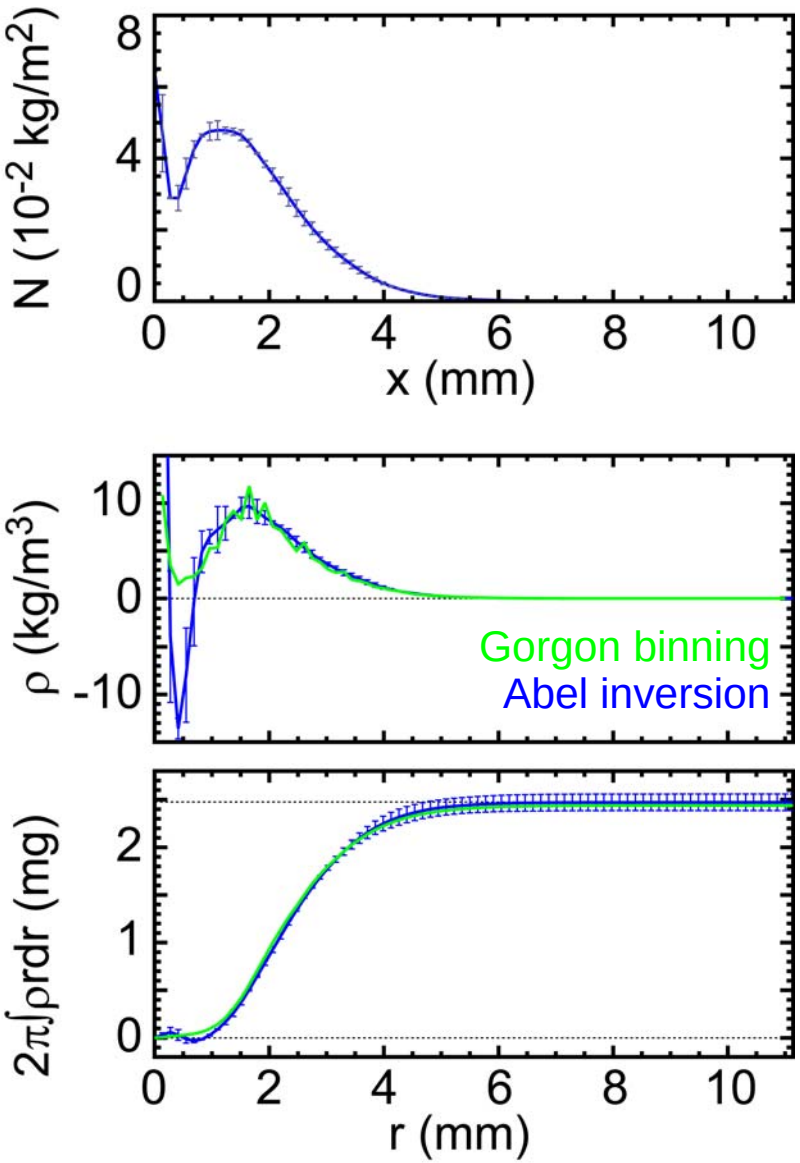


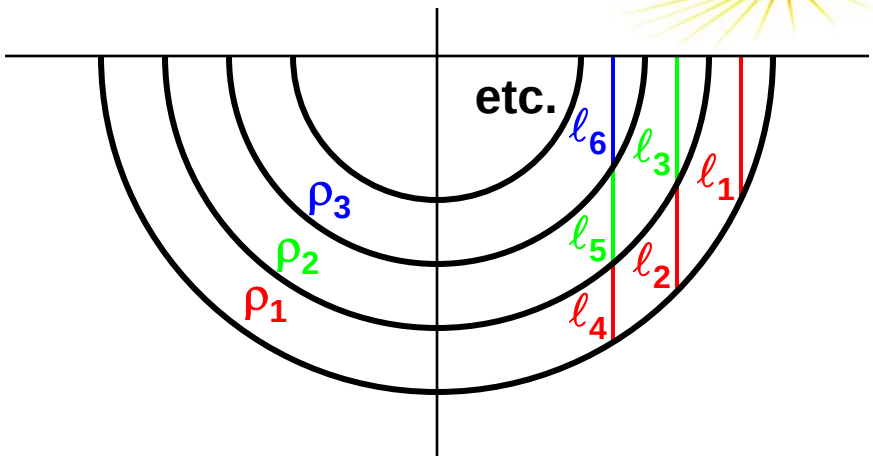


- 3D MHD Gorgon code, circuit model with shunting resistor
- 2.5 mg W wire array, 20 mm initial diameter, 120 wires, *ad hoc* perturbations to seed implosion instabilities
- 2D areal density map generated every 1 ns
- Center of image found by minimizing RMS difference between left and right sides
- Image is axially and left-right averaged to produce line-integrated density N(x)

Sandia National Laboratories

Mass density profile from onion-peeling Abel inversion

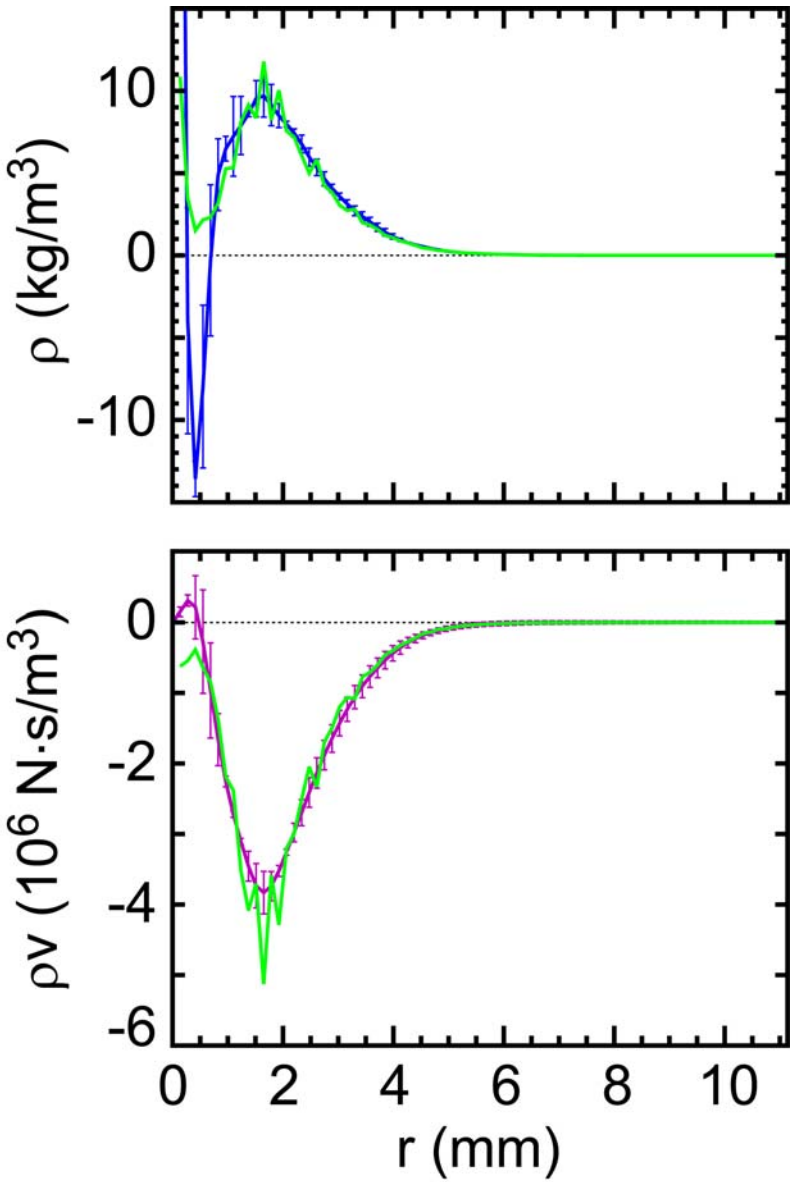




- Assumes cylindrical symmetry
- Numerical Abel inversion method
  - B. Jones *et al.*, IEEE T. Plasma Sci, **34**, 213 (2006).
- Onion-peeling does not handle noisy images well, but adequate for this case
- Average mass density profile from code calculated by summing xyz points in radial bins

Sandia National Laboratories

Momentum density profile inferred from continuity equation



$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{v}\right) = 0$$

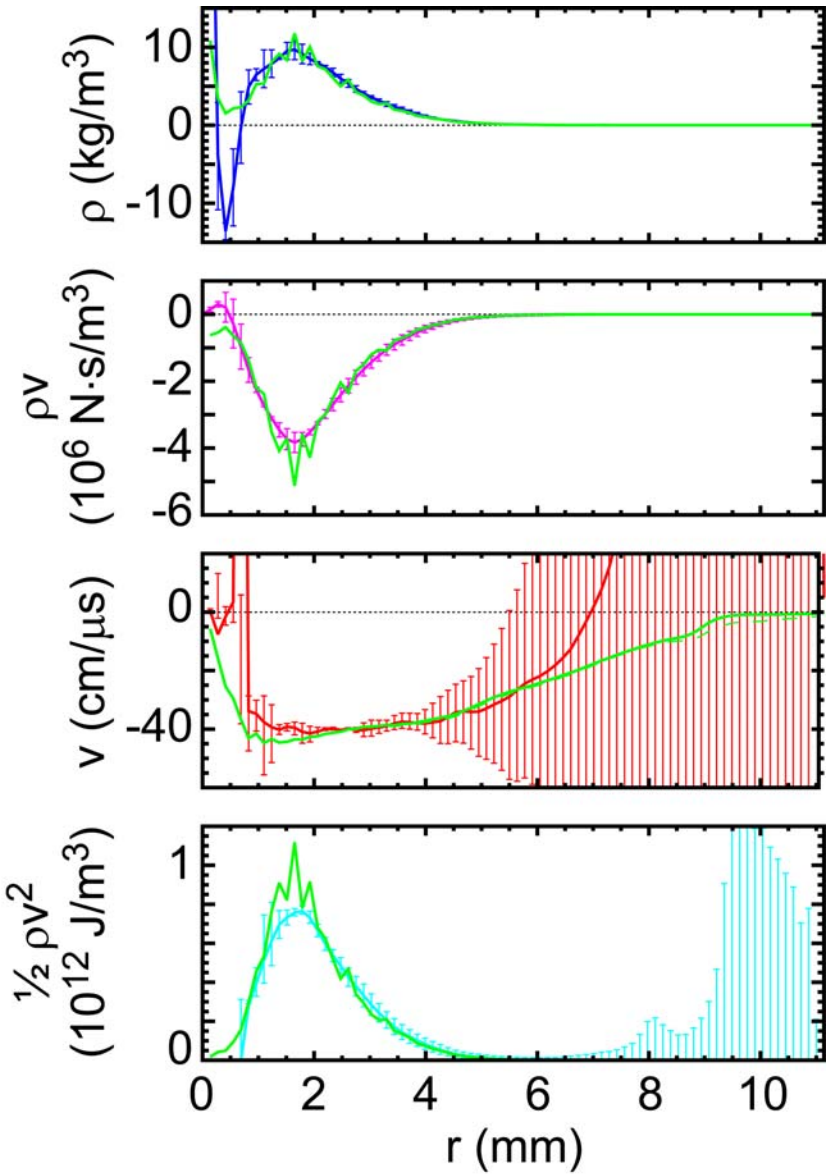
$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(r \rho v\right) = 0$$

$$\rho v = -\frac{1}{r}\int_0^r \frac{\partial \rho}{\partial t} r \, dr$$

- Assumes cylindrical symmetry with only radial motion
- Derivative in integrand calculated numerically from linear fit to three time points in $\rho(r,t)$ matrix
- Integration performed numerically over discrete r values

Sandia National Laboratories

Velocity and kinetic energy profiles from ρ and ρv profiles



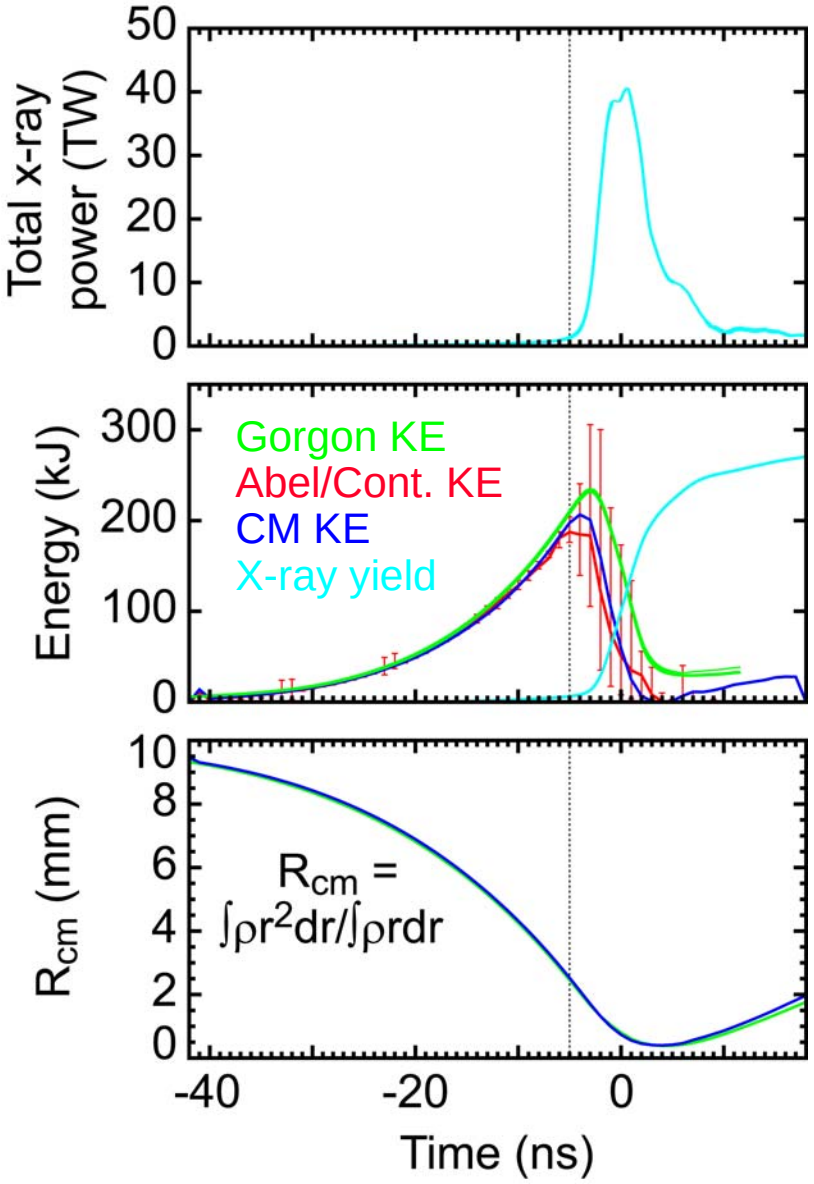
$$v = \frac{1}{\rho}\rho v$$

$$k = \frac{1}{2}\frac{(\rho v)^2}{\rho}$$

- Average kinetic energy density profile from code calculated by summing xyz points in radial bins
- Average velocity profile from code is from v = sqrt(2k/ρ)
- k(r) is valid except where ρ is very low; 1/ρ factor leads to errors

Sandia National Laboratories

Comparison of kinetic energy evolution



- Integrate k(r) to get KE(t)
  - Remove points with $\rho < 0.05\rho_{max}$ to avoid division by low numbers
- Compares well with Gorgon KE until just before peak KE
  - Abel inversion problems near the axis
  - Could be a lot of azimuthal non-uniformity (note right-left discrepancy)
  - Need to check if flow has azimuthal component near stagnation
  - Note early time discrete wire structures leads to Abel artifacts
- Velocity of the center of mass gives equivalent KE
  - All mass moving at nearly same velocity

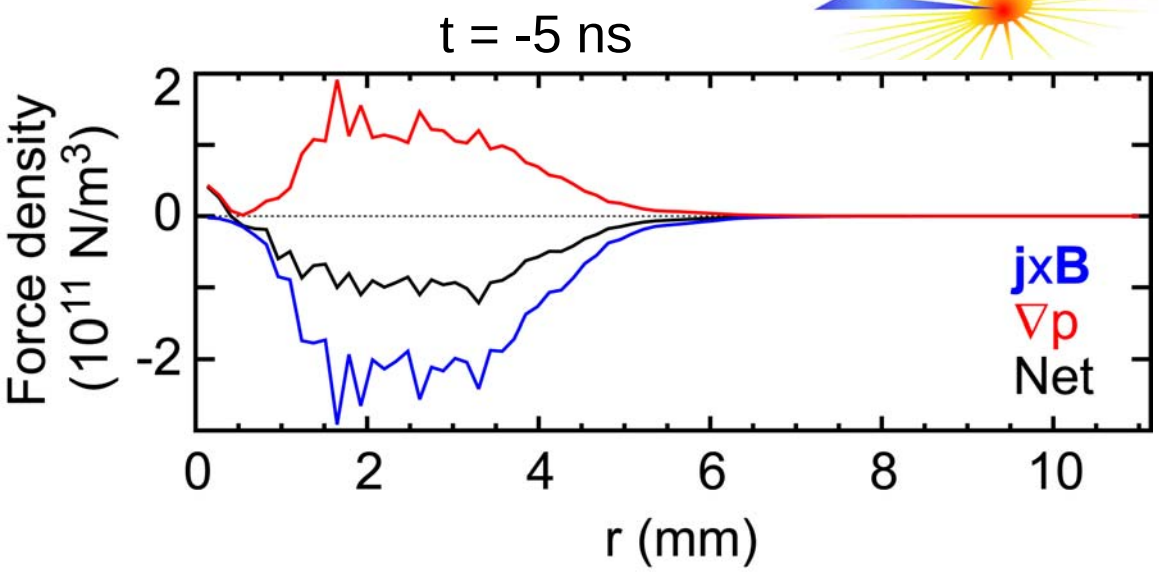
Sandia National Laboratories

Other energetics considerations near stagnation

Force density from momentum equation

$$f = \rho\left(\frac{\partial}{\partial t} + \vec{v}\cdot\nabla\right)\vec{v}$$

$$= \rho\left(\frac{\partial}{\partial t} + v\frac{\partial}{\partial r}\right)v$$



Compressional p·dV heating driven by jxB during deceleration/stagnation phase

$$\frac{\partial}{\partial t}\left(e_{\text{int}} + k\right)_{p\cdot dV} = -\nabla\cdot\left(p\vec{v}\right)$$

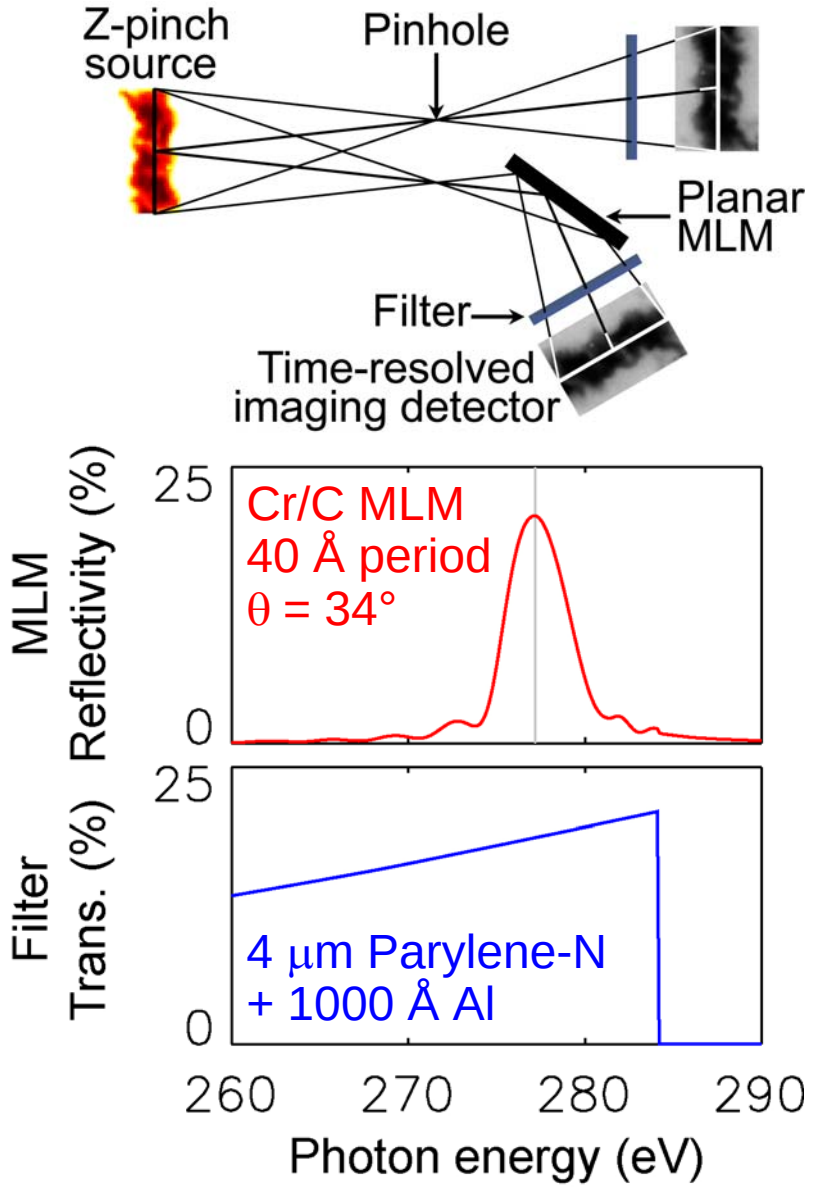
$$= -\frac{1}{r}\frac{\partial}{\partial r}\left(rpv\right)$$

$$p = n_e T_e + n_i T_i$$

- From Gorgon, ∇p force balances **j**x**B** force near stagnation
- Plasma decelerates but **j**x**B** can continue to do work
- Can we infer a strong ∇p from force density via ρ(r,t)?
- Would need v, n, T profiles to infer p·dV work

Sandia National Laboratories

MLM pinhole camera produces monochromatic images

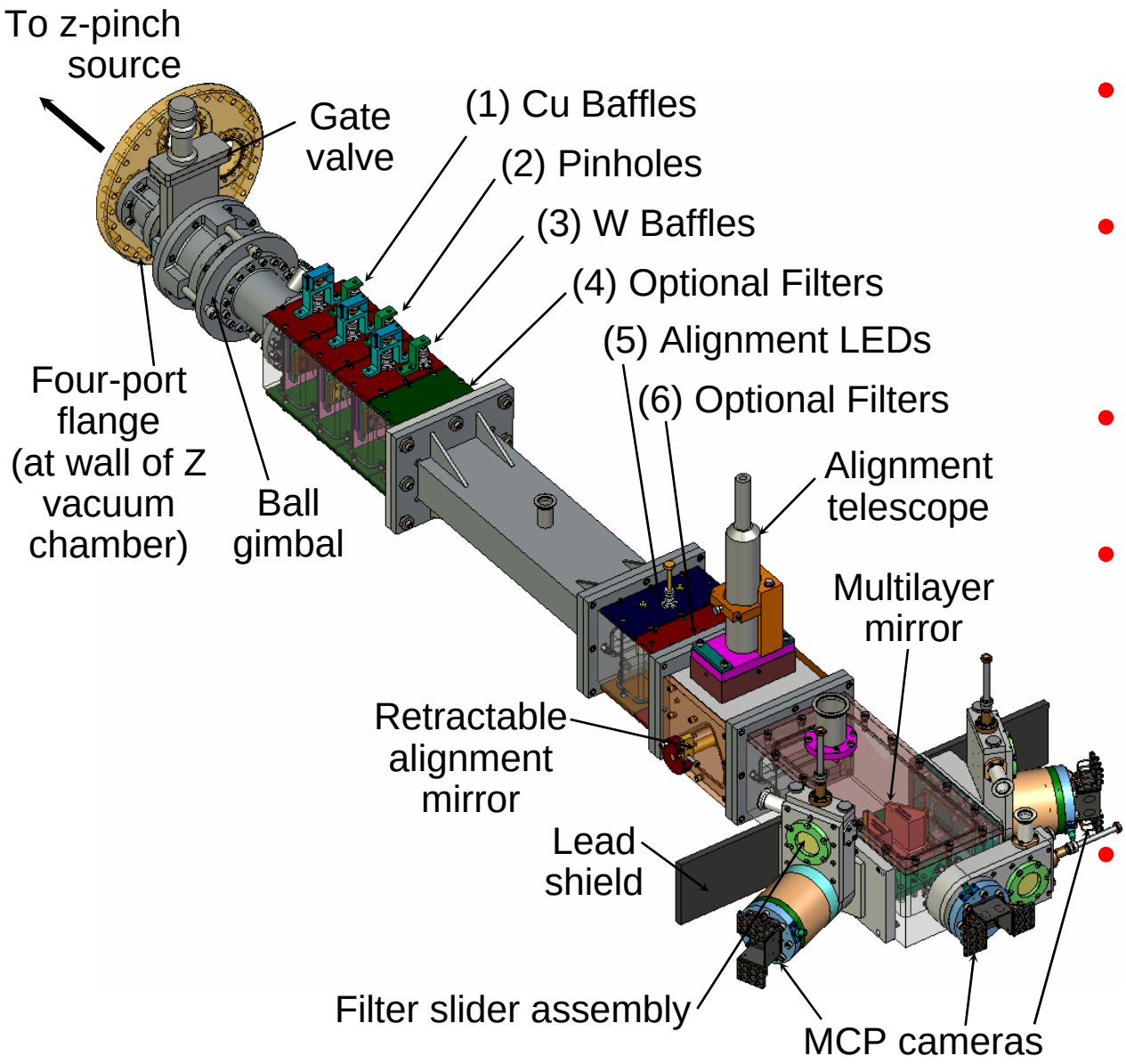


- Pinhole images are reflected from planar Cr/C multilayer mirror (MLM)
  - Calculated 20% peak reflectivity, ~5 eV photon energy bandwidth
  - 34° grazing angle allows shielding of detector from hard x-rays
- Thin filter blocks UV/visible light, suppresses second harmonic MLM reflection
- Instrument on the Z machine combines MLM-reflected and standard pinhole cameras (PHC)

B. Jones *et al*., IEEE T. Plasma Sci. **34**, 213 (2006).

Sandia National Laboratories

MLM pinhole imager has been fielded on the Z accelerator

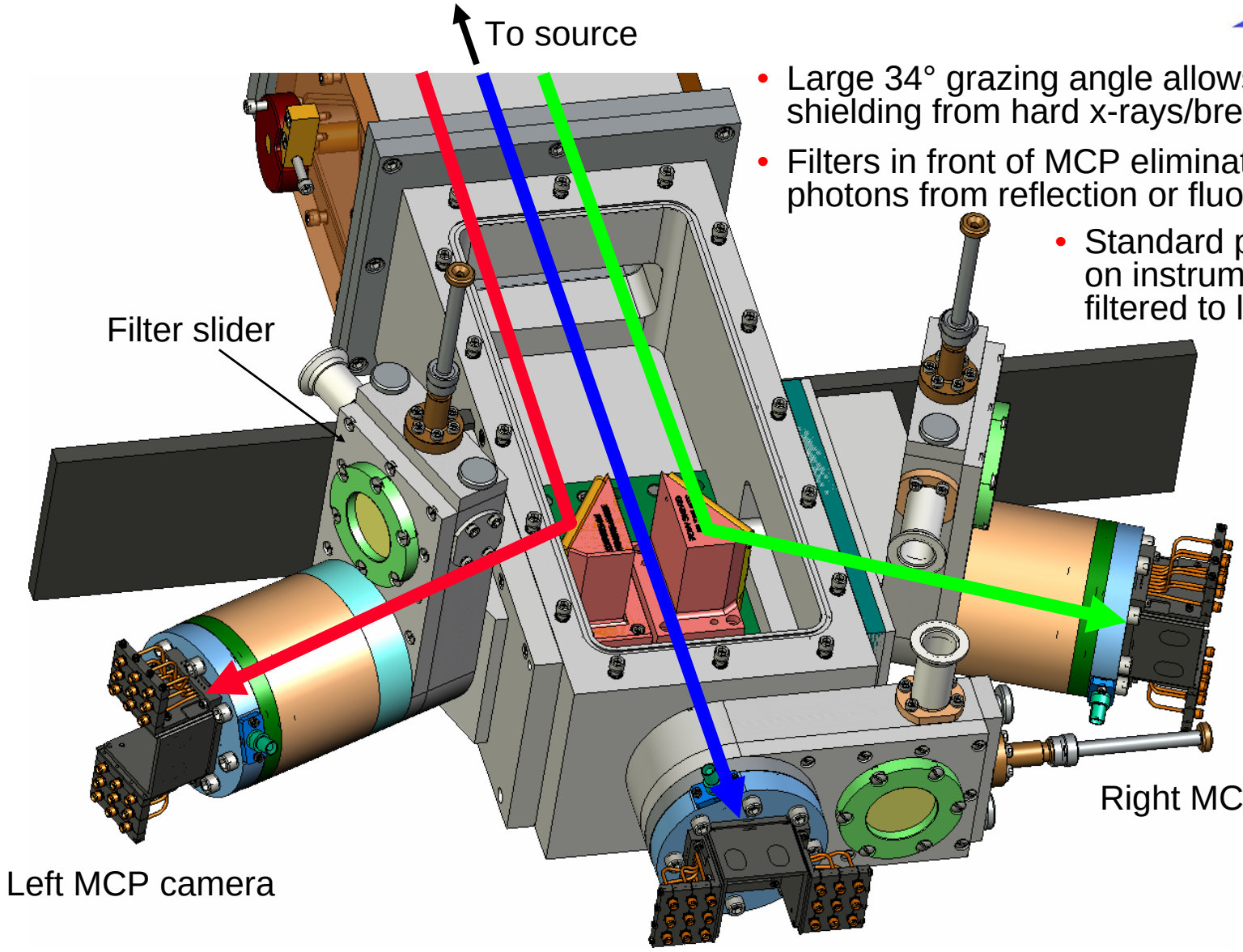


- Instrument mounts on 12° side-on LOS
- 3 PHCs can be fielded (one without mirror reflection)
- Ball gimble pivots to align with source
- Alignment under vacuum corrects for pipe sag and movement in Z load region
- Instrument is differentially pumped behind gate valve

B. Jones *et al*., Rev. Sci. Instrum. **75**, 4029 (2004).

Sandia National Laboratories

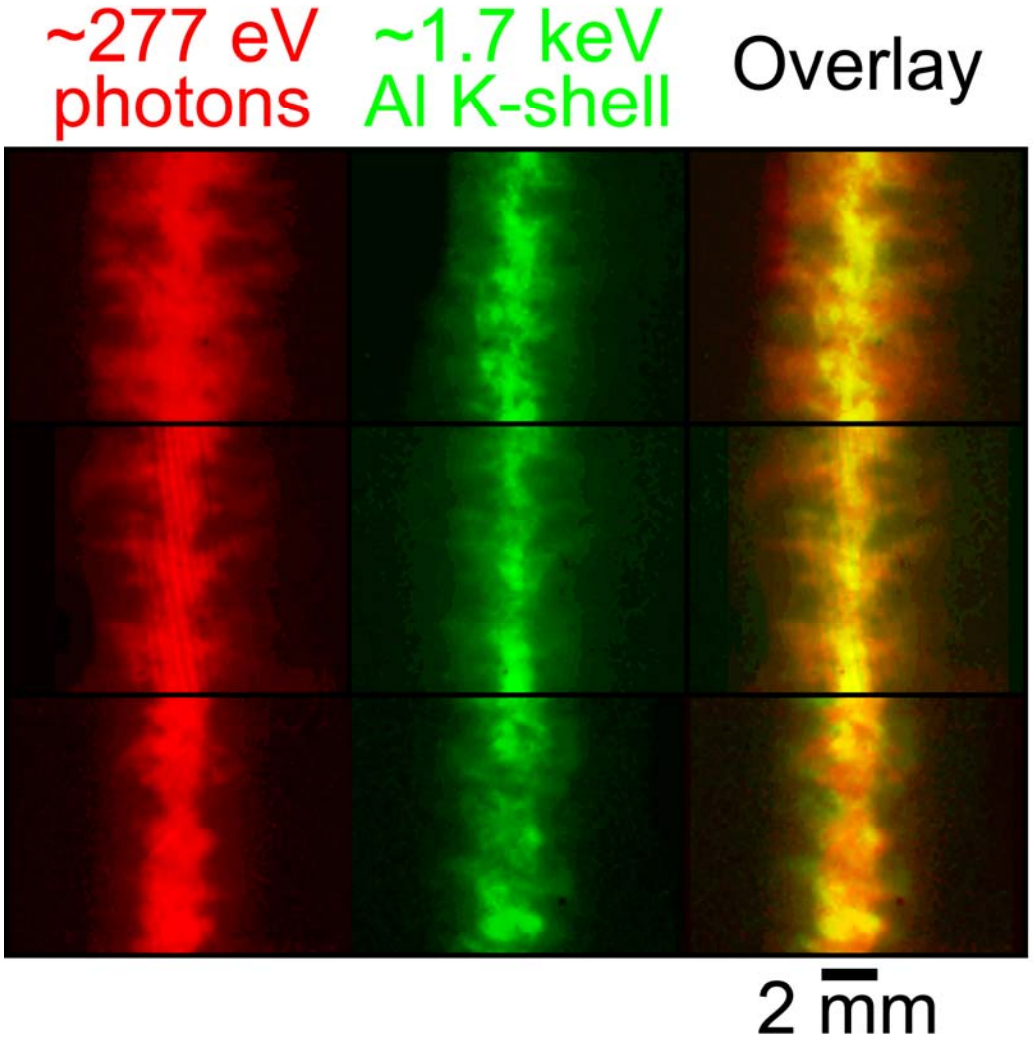
Three simultaneous 8-frame MCPs are now built for Z imager



- Large 34° grazing angle allows detector shielding from hard x-rays/brems
- Filters in front of MCP eliminate < 100 eV photons from reflection or fluorescence at MLM
- Standard pinhole camera on instrument axis can be filtered to look at >1 keV

Sandia National Laboratories

Z-pinch implosion structure imaged at multiple energies

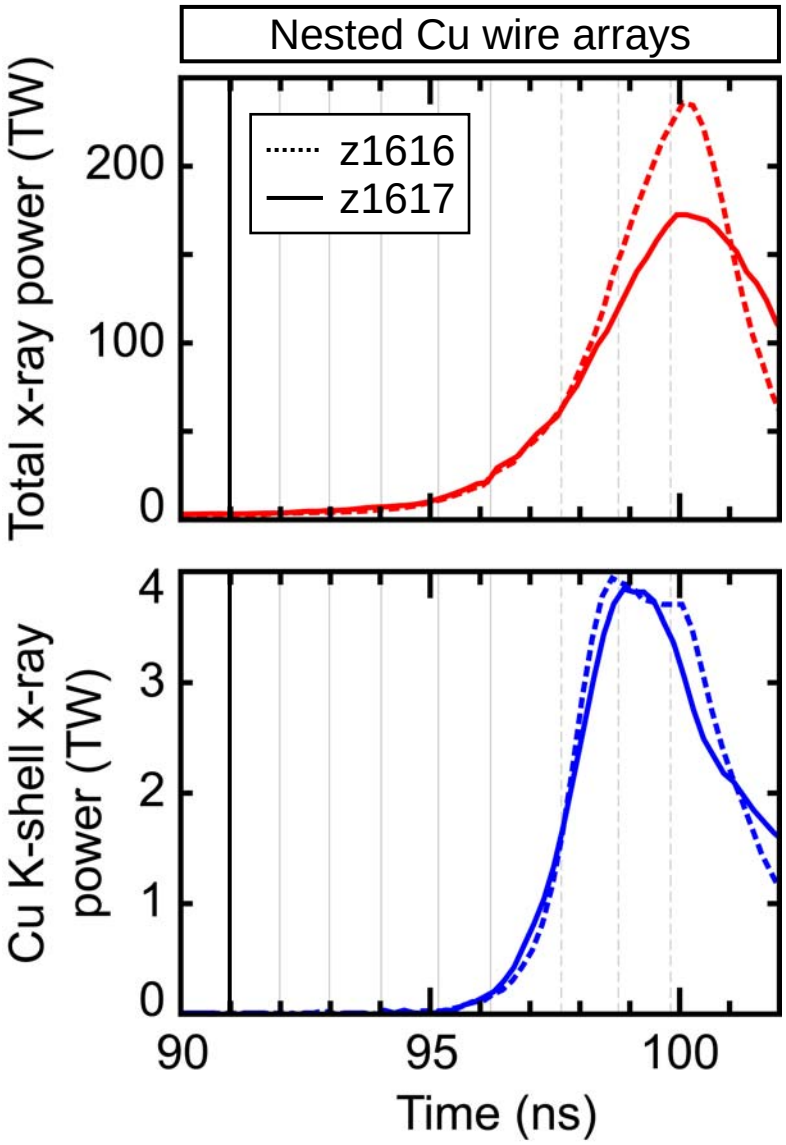


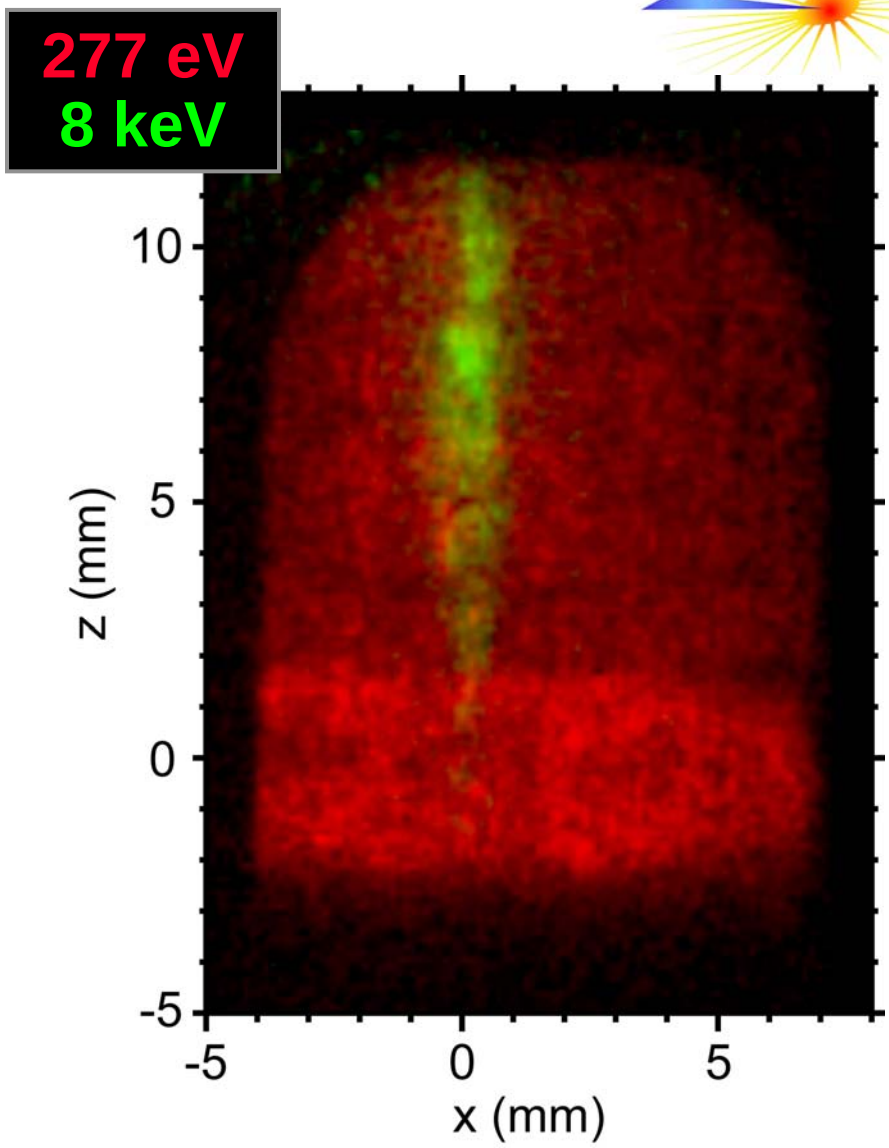
- Nested Al wire array z pinch
- Simultaneous imaging at two photon energies
- Imploding fingers of trailing cooler mass in ~277 eV images
- Al K-shell emitted from hot, dense column accreting on axis

- Opaque regions of cool plasma mask core after peak x-rays
- Striations on ~277 eV frame at -0.3 ns apparently due to MLM defect

Sandia National Laboratories

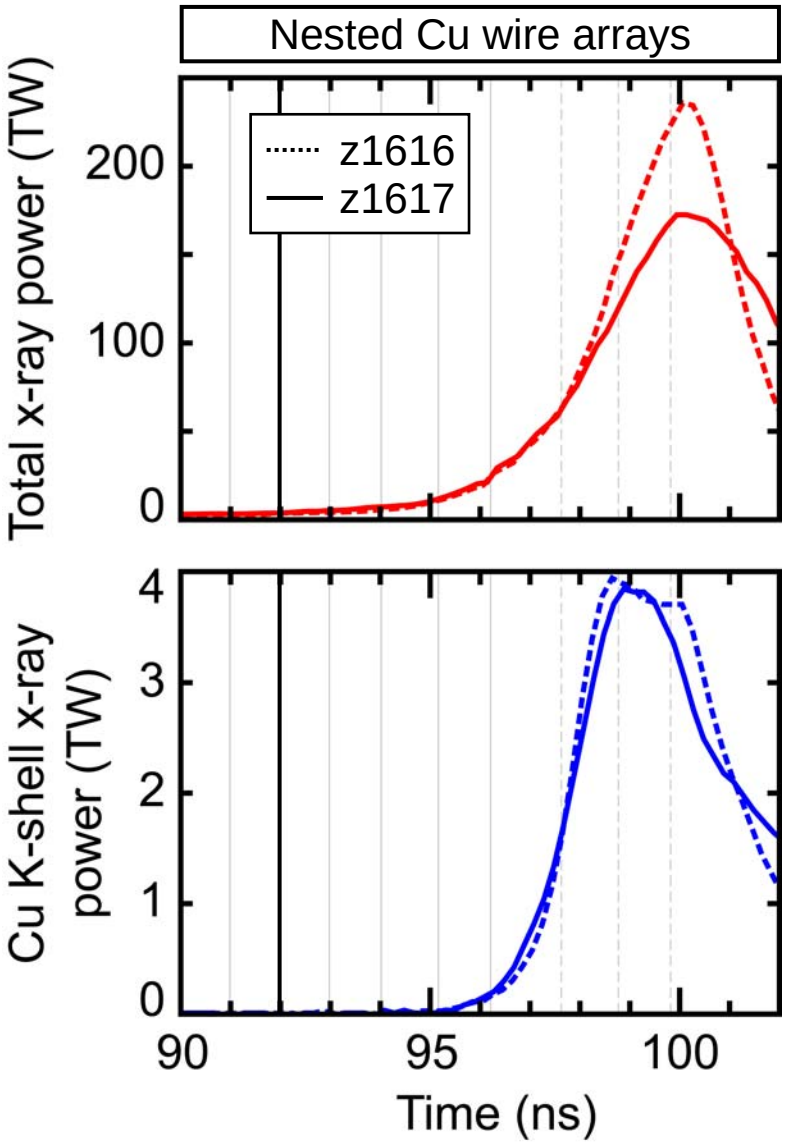
Z-pinch implosion dynamics and x-ray generation studied

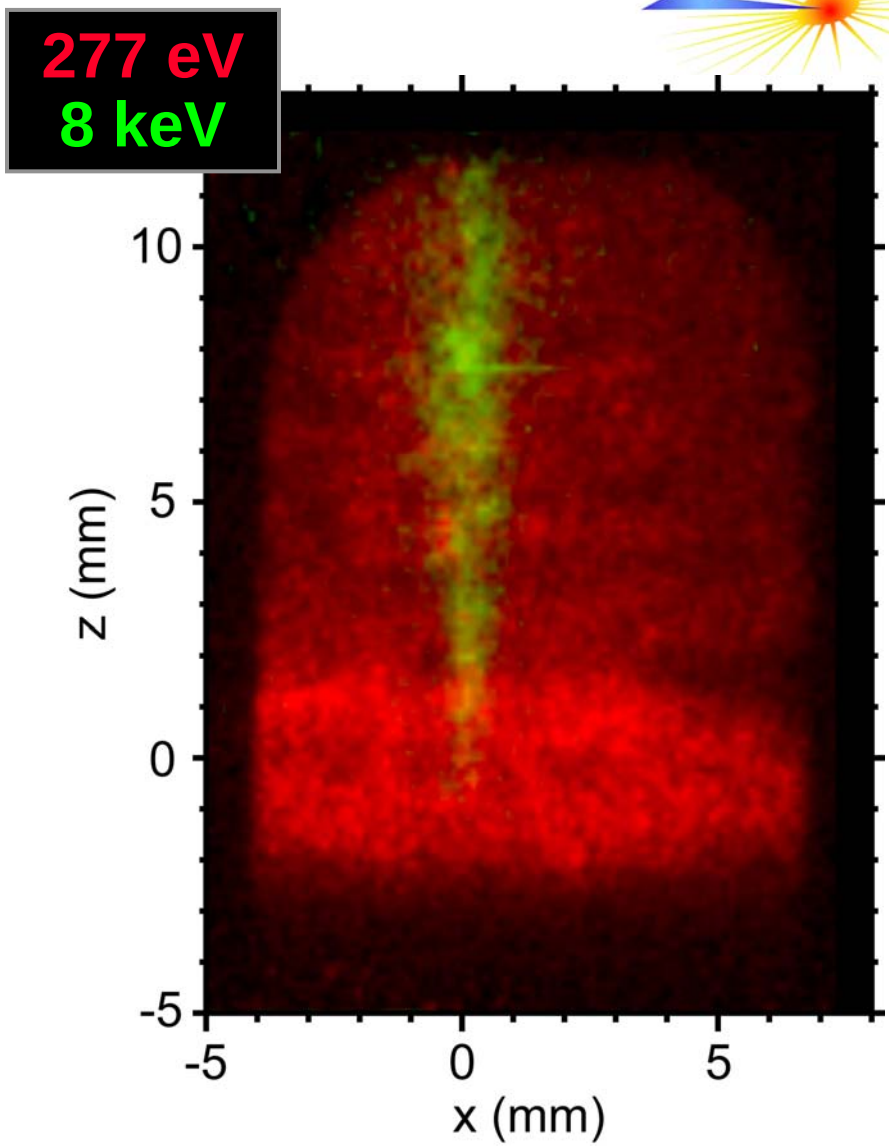




Sandia National Laboratories

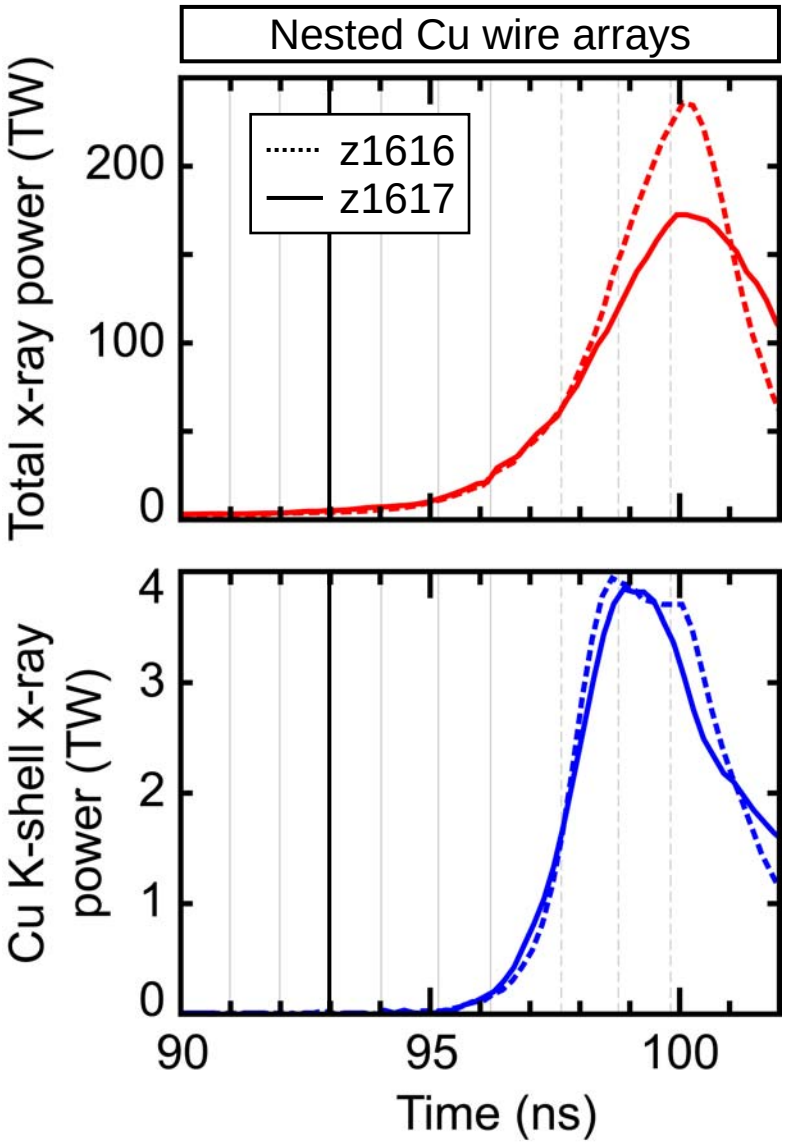
Z-pinch implosion dynamics and x-ray generation studied

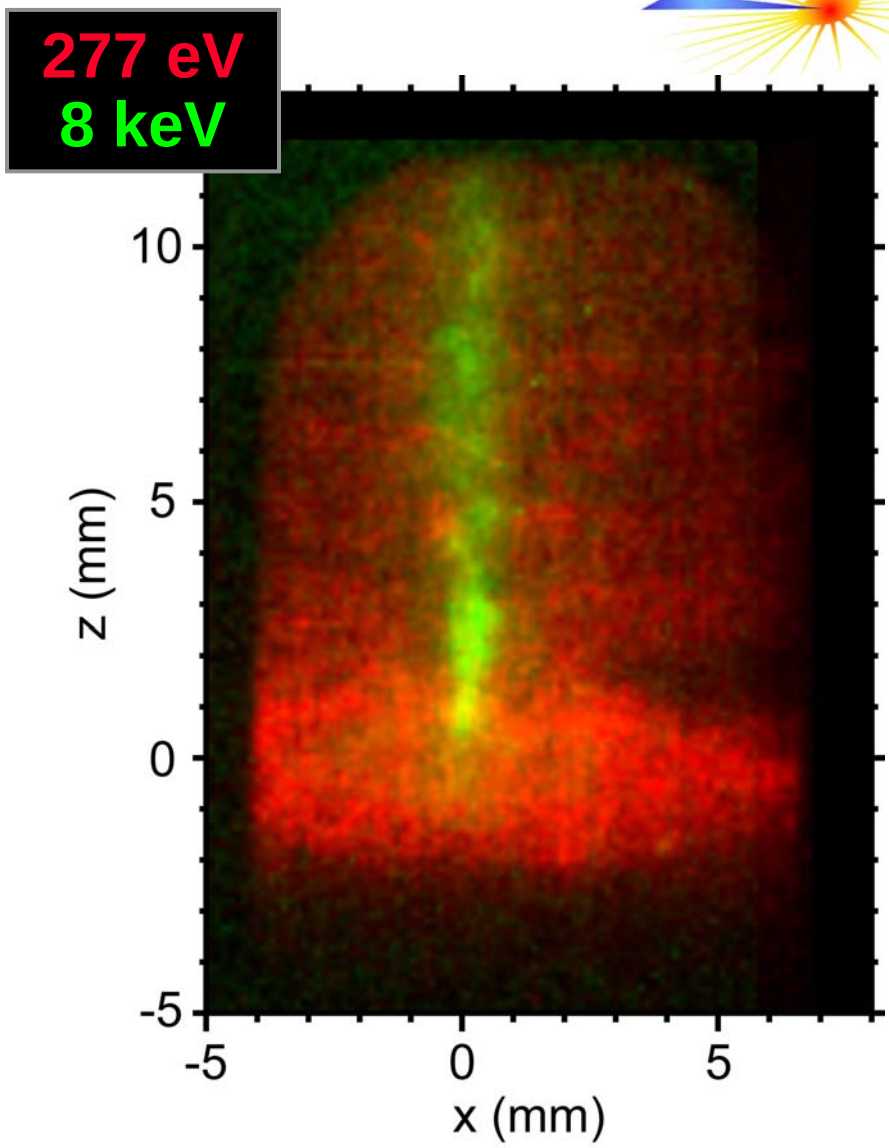




Sandia National Laboratories

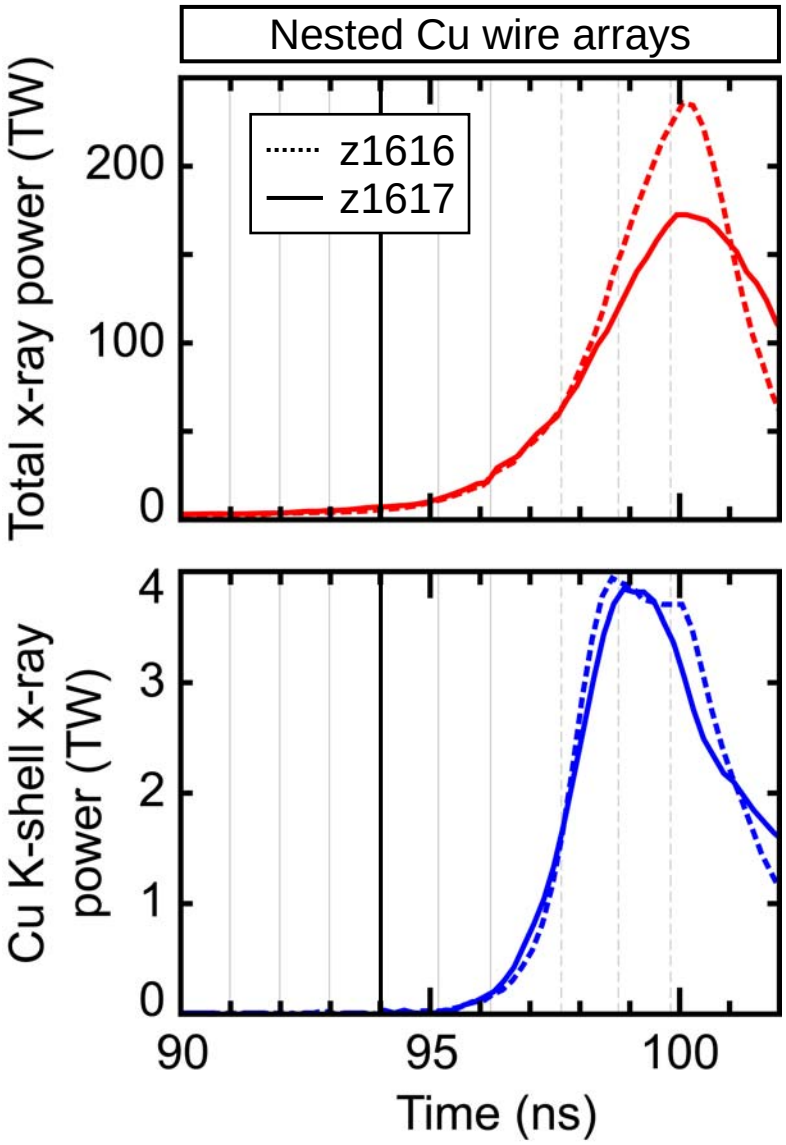
Z-pinch implosion dynamics and x-ray generation studied

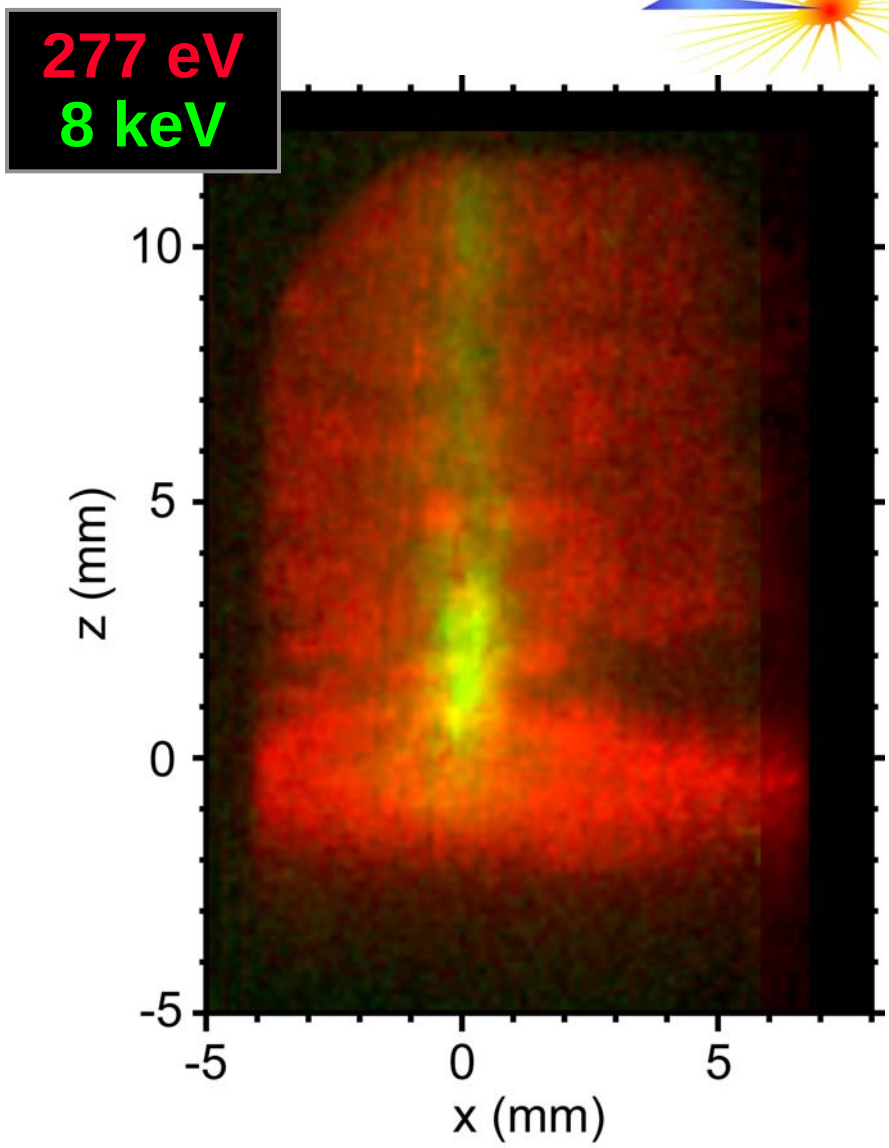




Sandia National Laboratories

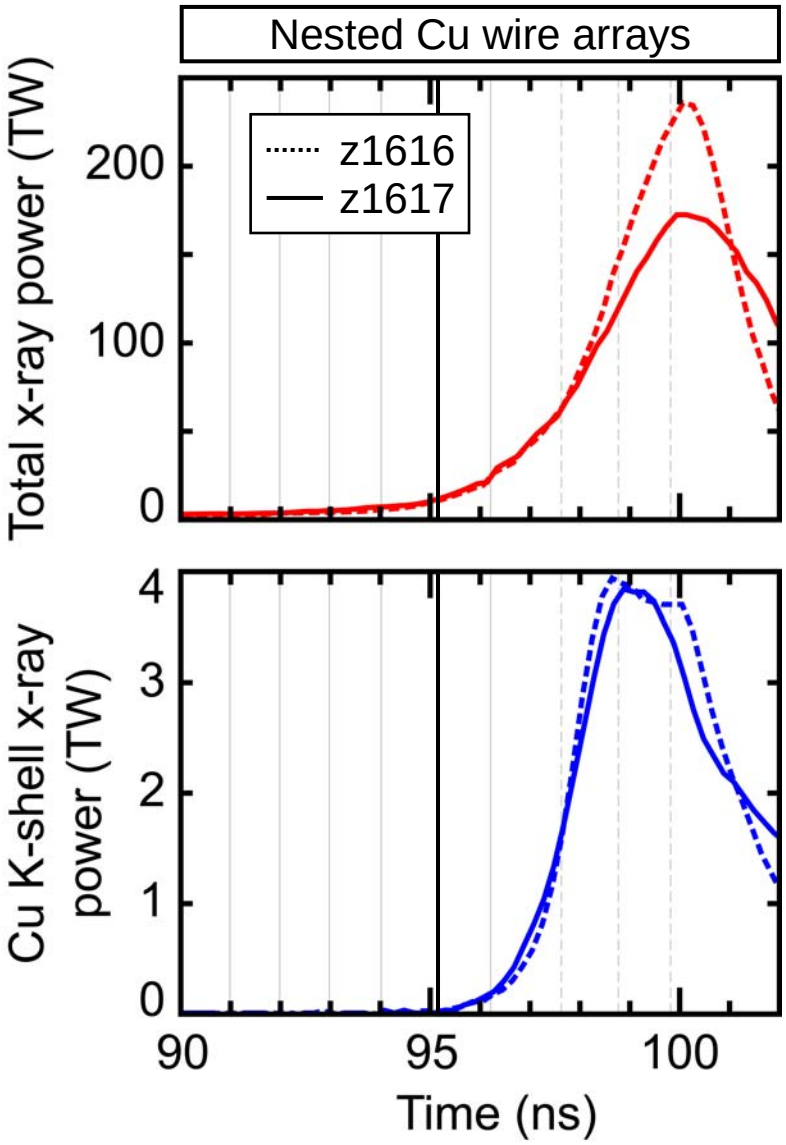
Z-pinch implosion dynamics and x-ray generation studied

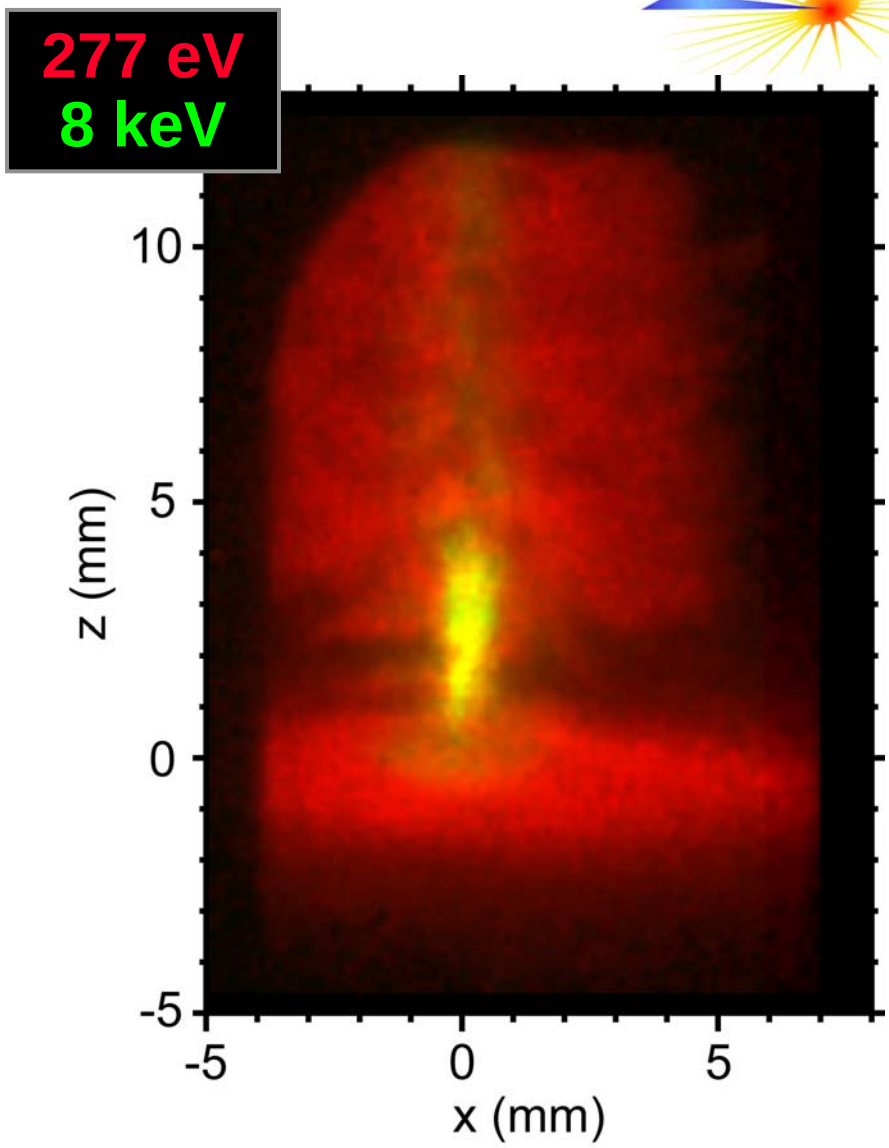




Sandia National Laboratories

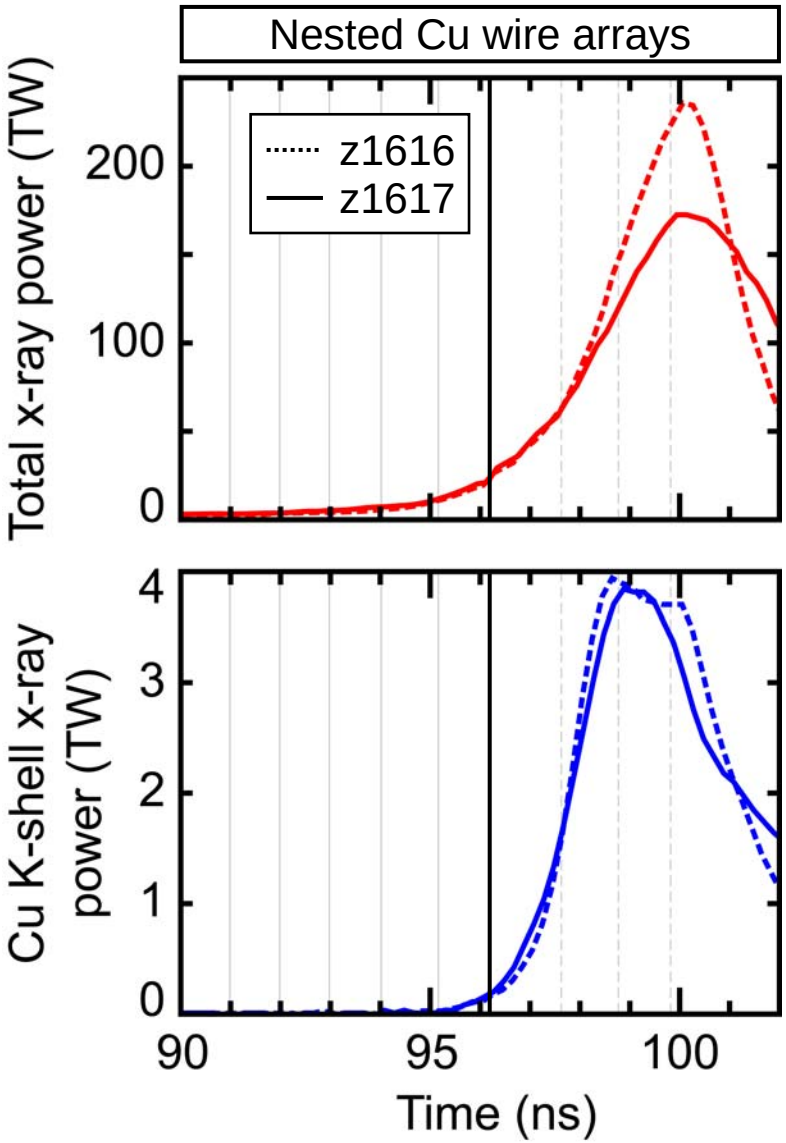
Z-pinch implosion dynamics and x-ray generation studied

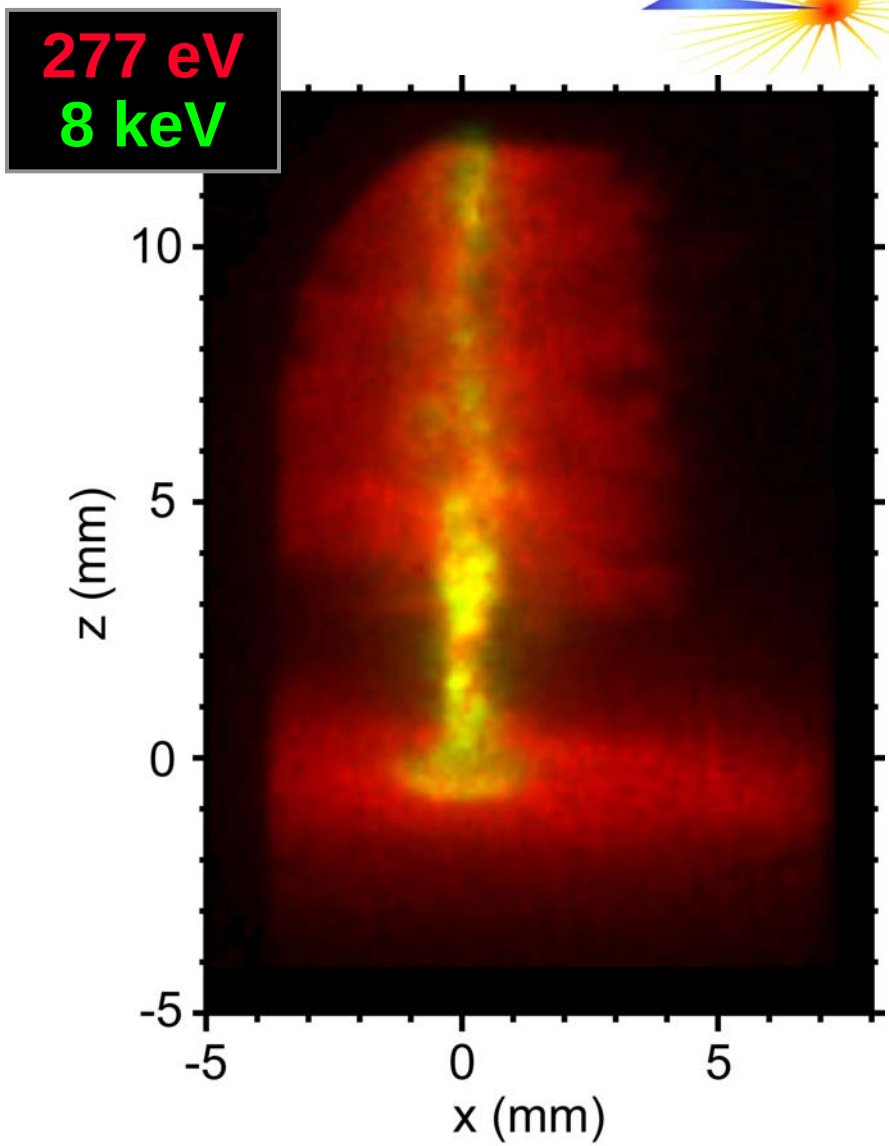




Sandia National Laboratories

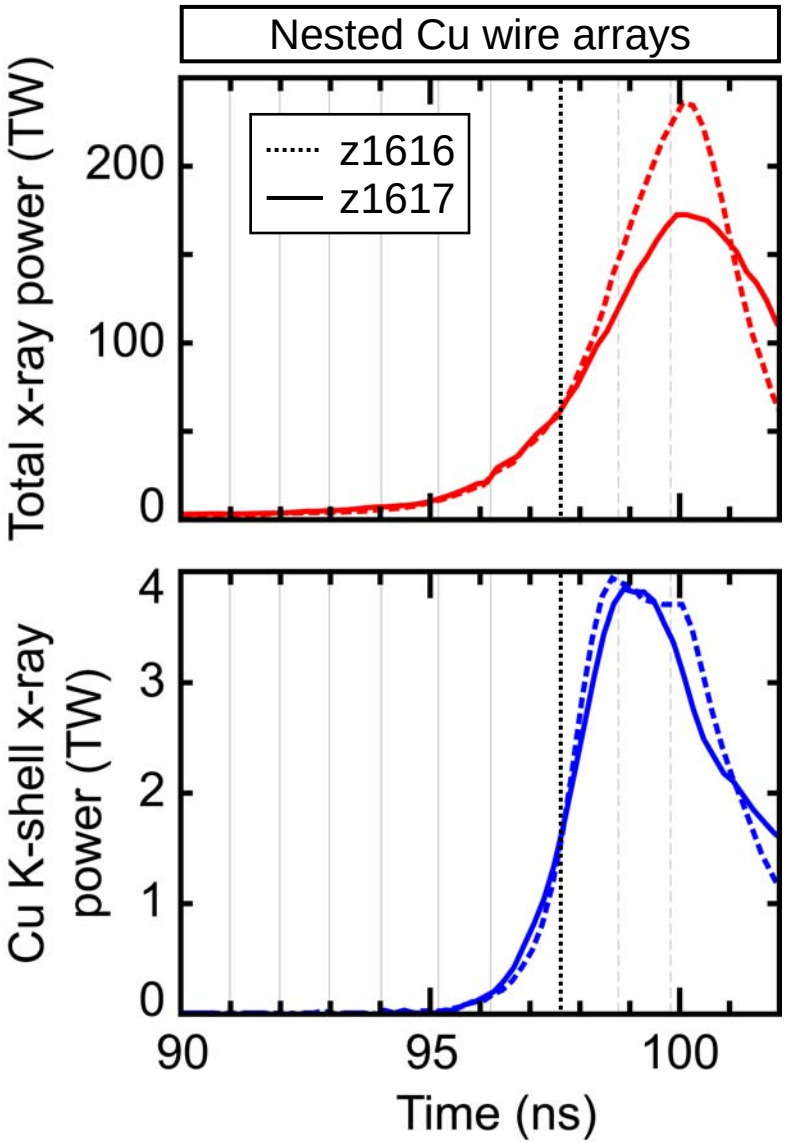
Z-pinch implosion dynamics and x-ray generation studied

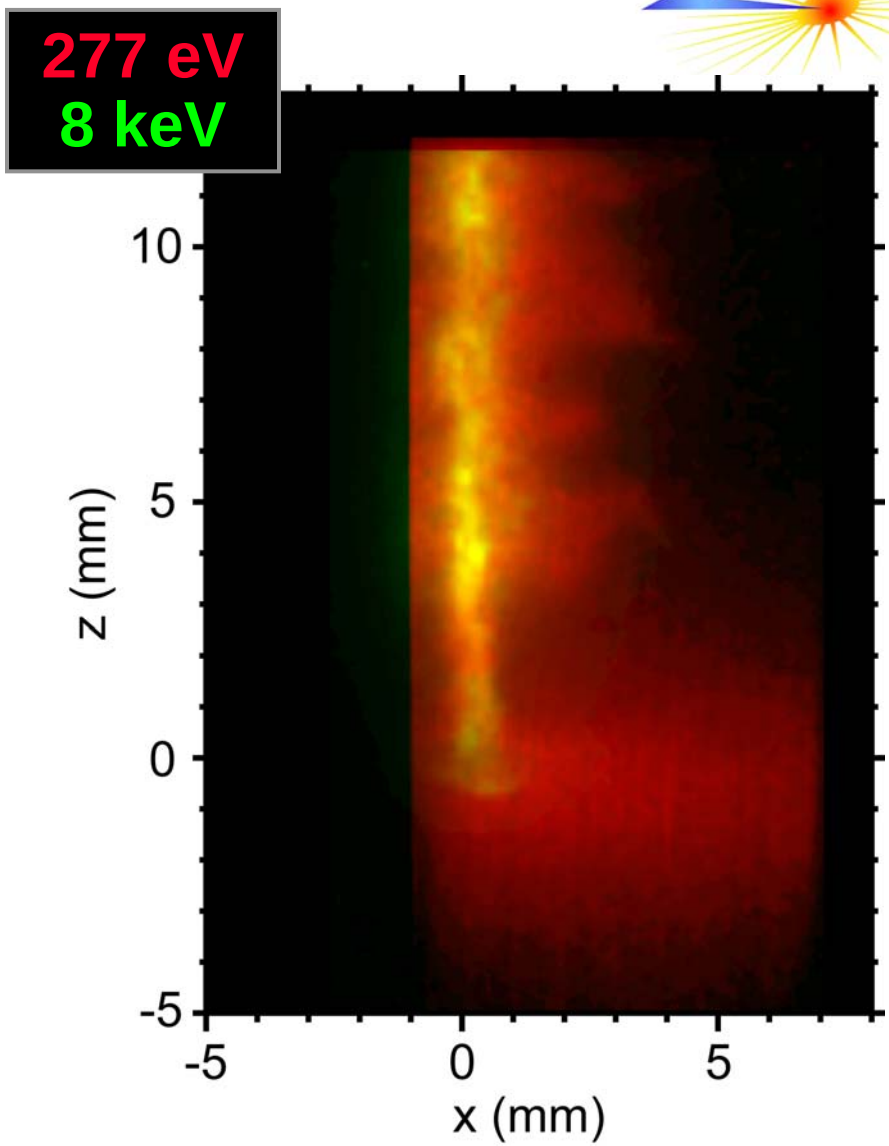




Sandia National Laboratories

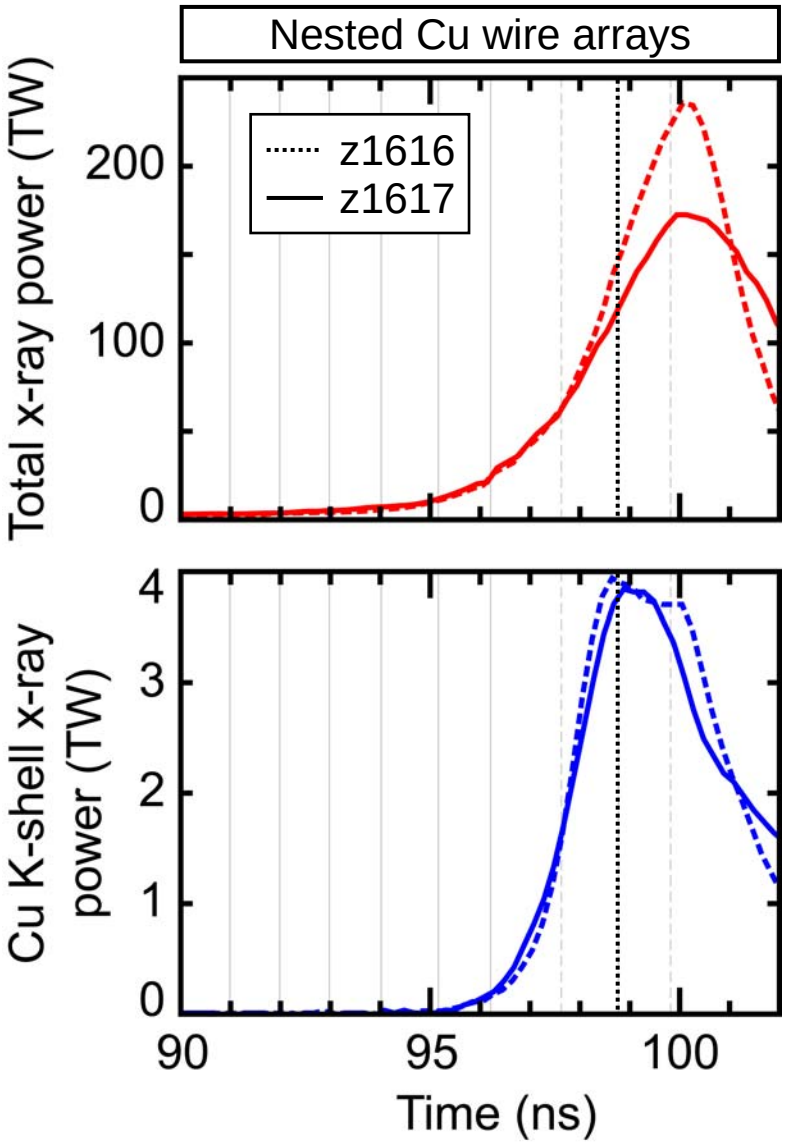
Z-pinch implosion dynamics and x-ray generation studied

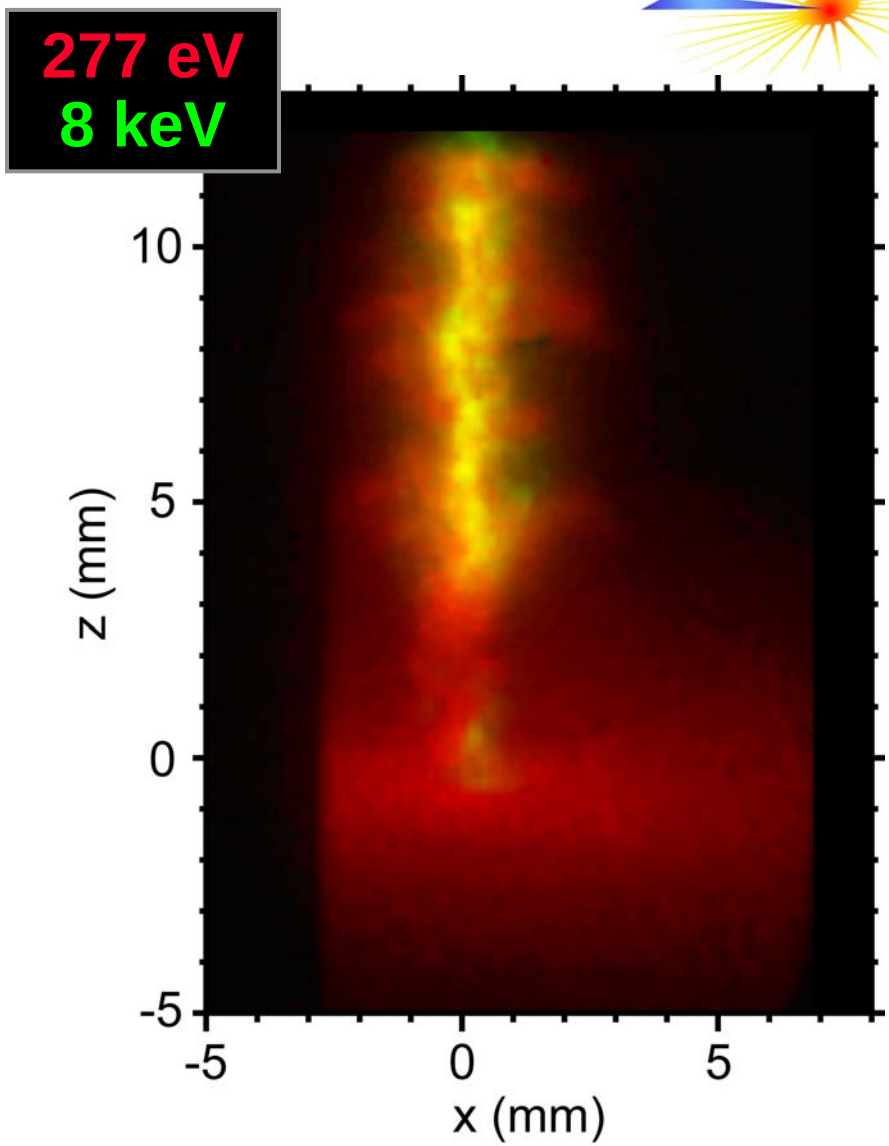




Sandia National Laboratories

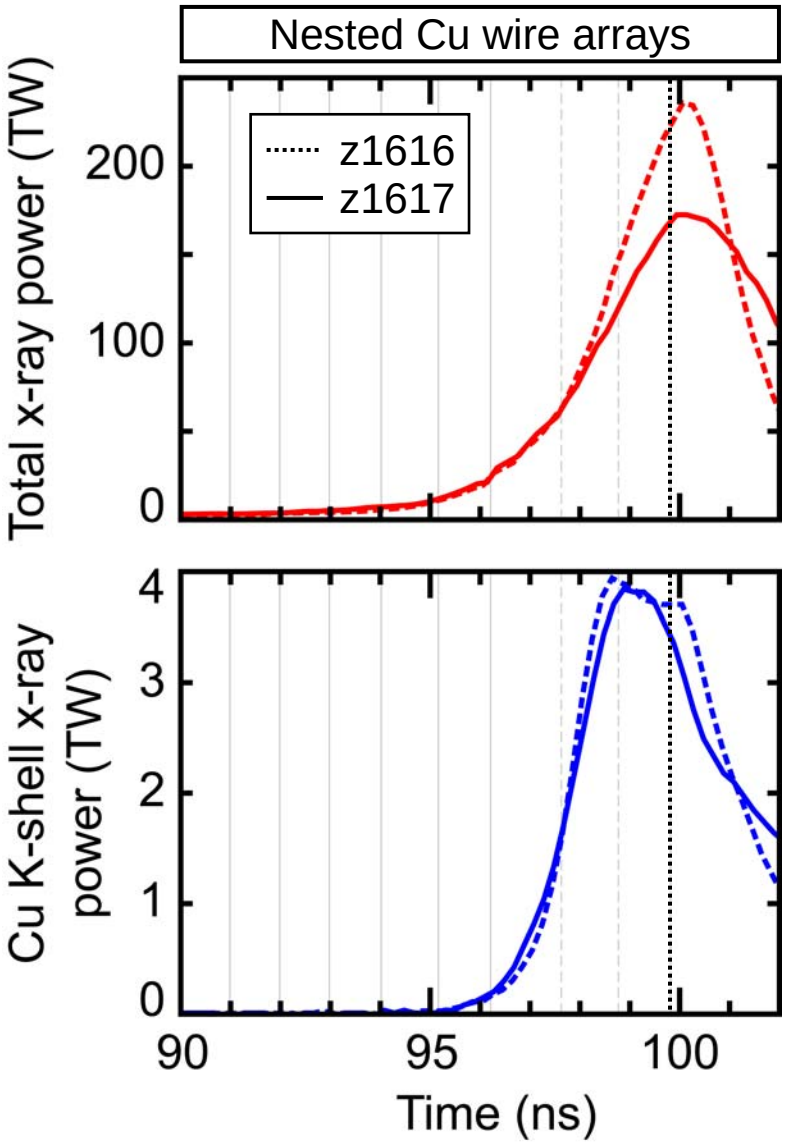
Z-pinch implosion dynamics and x-ray generation studied

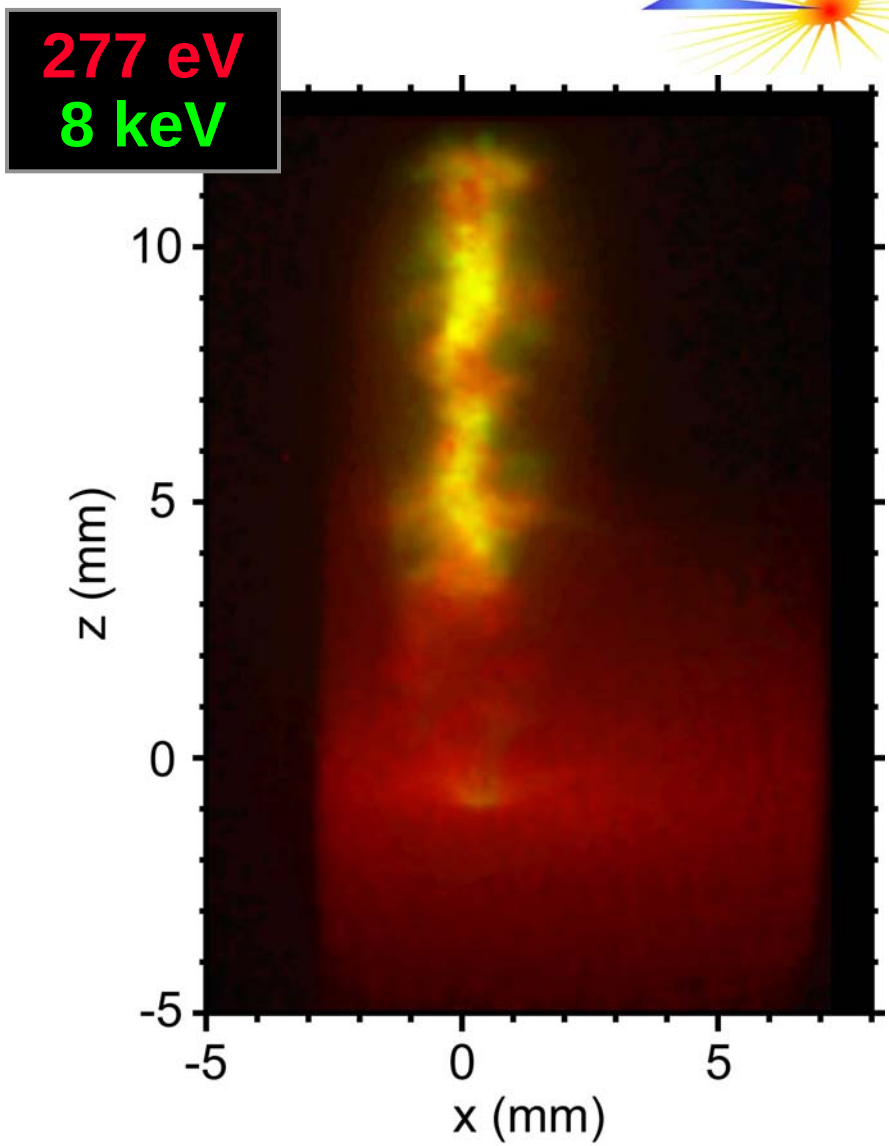




Sandia National Laboratories

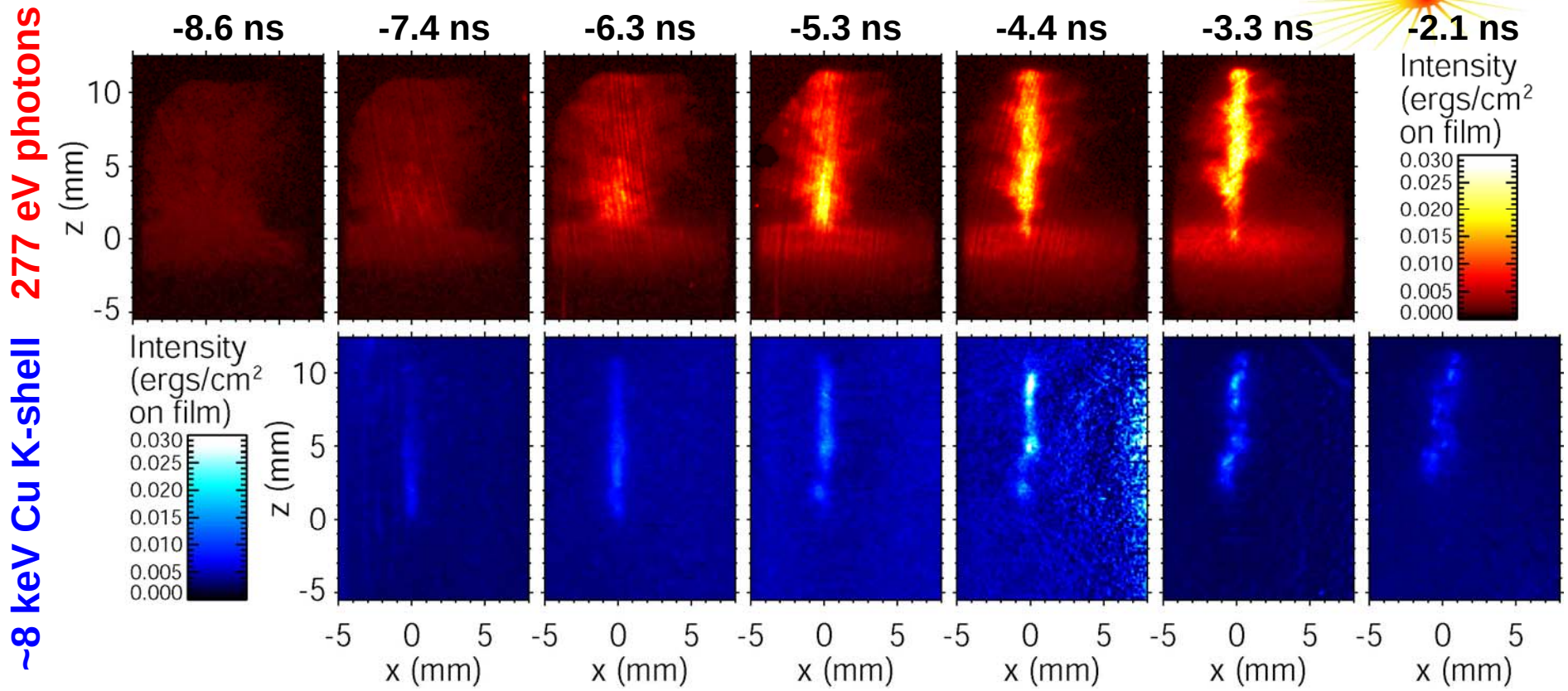
Z-pinch implosion dynamics and x-ray generation studied





Sandia National Laboratories

Z1436 copper wire array implosion studied in detail

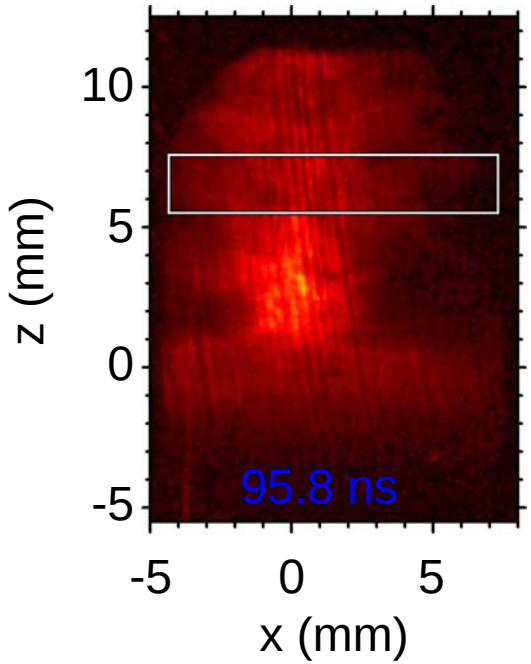


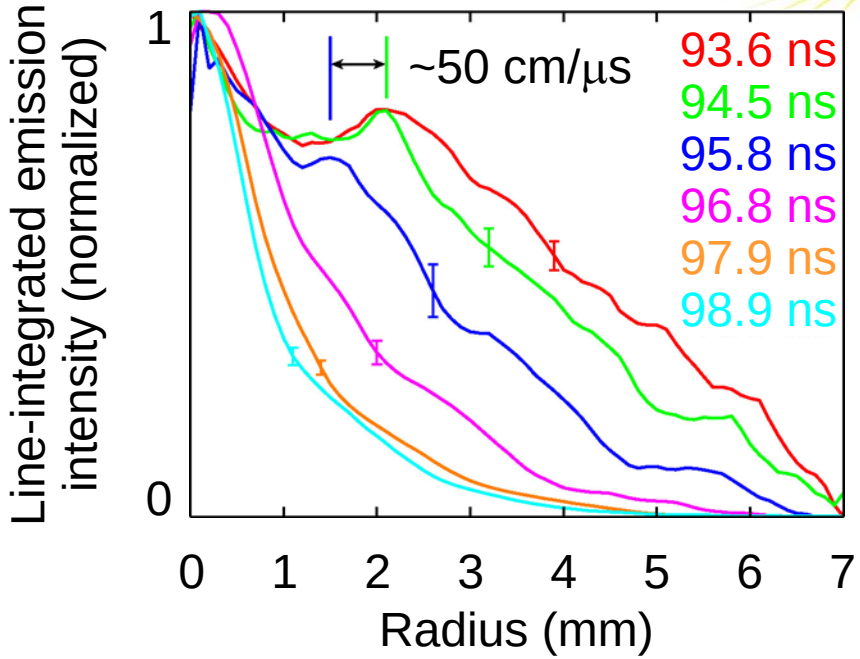
- Simultaneous imaging at ~277 eV and ~8 keV Cu K-shell
- Gradual accretion of mass on axis during ~5 ns x-ray pulse rise
- 3D structure: zipper at stagnation, trailing mass at large radius
- No brems background on MLM-reflected images

B. Jones *et al*., IEEE T. Plasma Sci. **34**, 213 (2006).

Sandia National Laboratories

Radial structure of imploding shell studied at stagnation

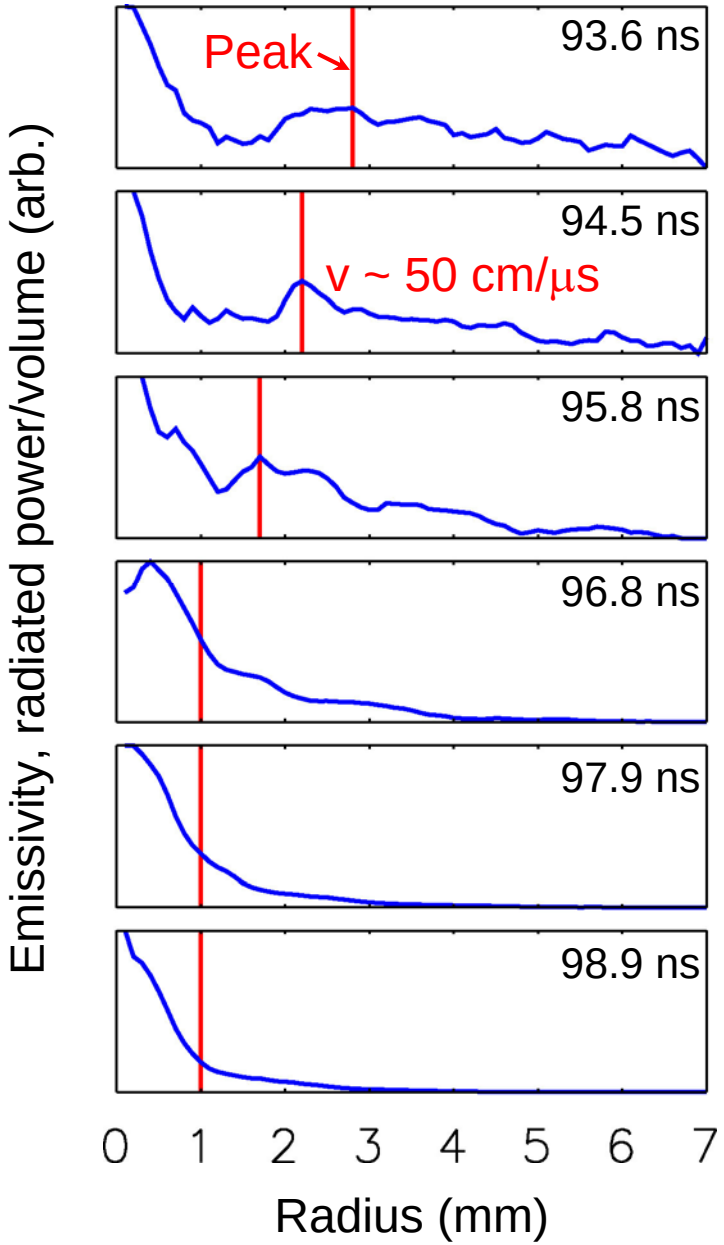


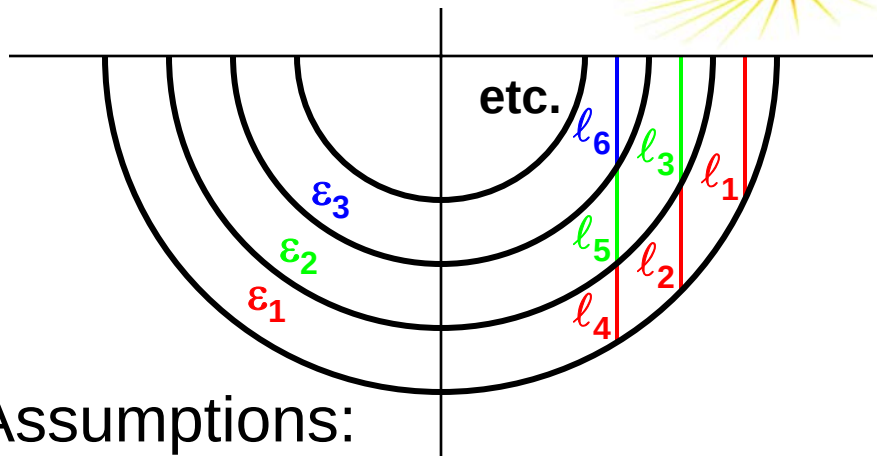


- Radial line-out taken across each 277 eV image
  - Average over axial structure, above cathode zipper and re-emission
  - Smoothed corresponding to 480 μm camera resolution
  - Error bars represent asymmetry from left to right of axis
- A diffuse shell appears to implode onto a column on axis
  - 60 cm/μs shell velocity << 110 cm/μs 0D calculation
  - Presence of hollow features implies opacity is not high

Sandia National Laboratories

Emissivity profiles inferred from Abel-inverted self-emission

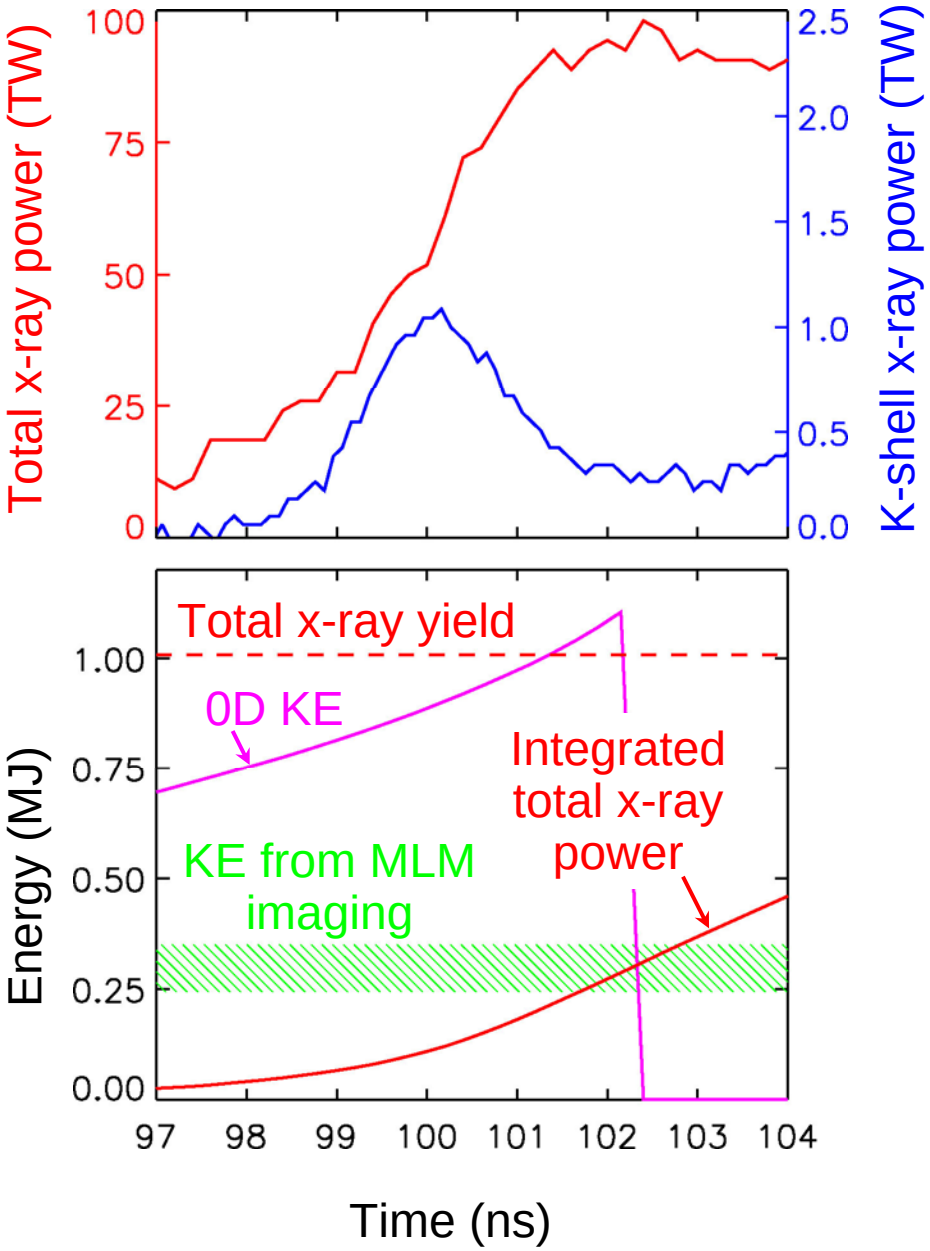




- Assumptions:
  - Emission is optically thin at 277 eV
  - Cylindrically symmetric geometry
- Numerical Abel inversion method
  - H. K. Park, Plasma Phys. Control. Fusion **31**, 2035 (1989).
- 50-60 cm/μs velocities, over 4-5 mm radial shell width
- ~4 mm/60 cm/μs ~ 7 ns, equal to measured FWHM of total x-ray pulse

Sandia National Laboratories

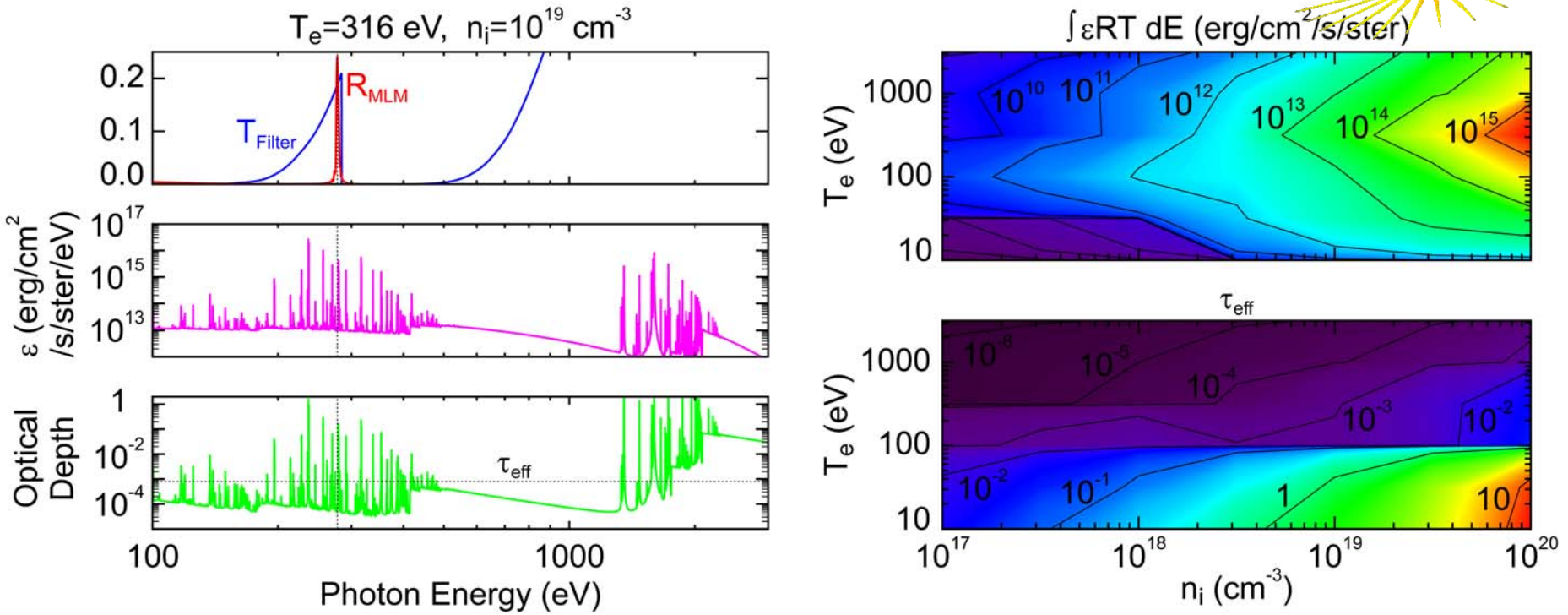
Estimated kinetic energy is inadequate to explain x-ray yield



- Kinetic energy is estimated assuming all of the mass is moving at 50-60 cm/μs
- KE can account for initial x-ray rise, but not total yield
- 2D and 3D MHD calculations predict p·dV work driven by **j** x **B** and Ohmic heating will dominate KE deposition
  - D. L. Peterson *et al.*, Phys. Plasmas **5**, 3302 (1998).
  - J. P. Chittenden *et al.*, Plasma Phys. Control. Fusion **46**, B457(2004).

Sandia National Laboratories

CR simulations to relate emissivity to plasma conditions

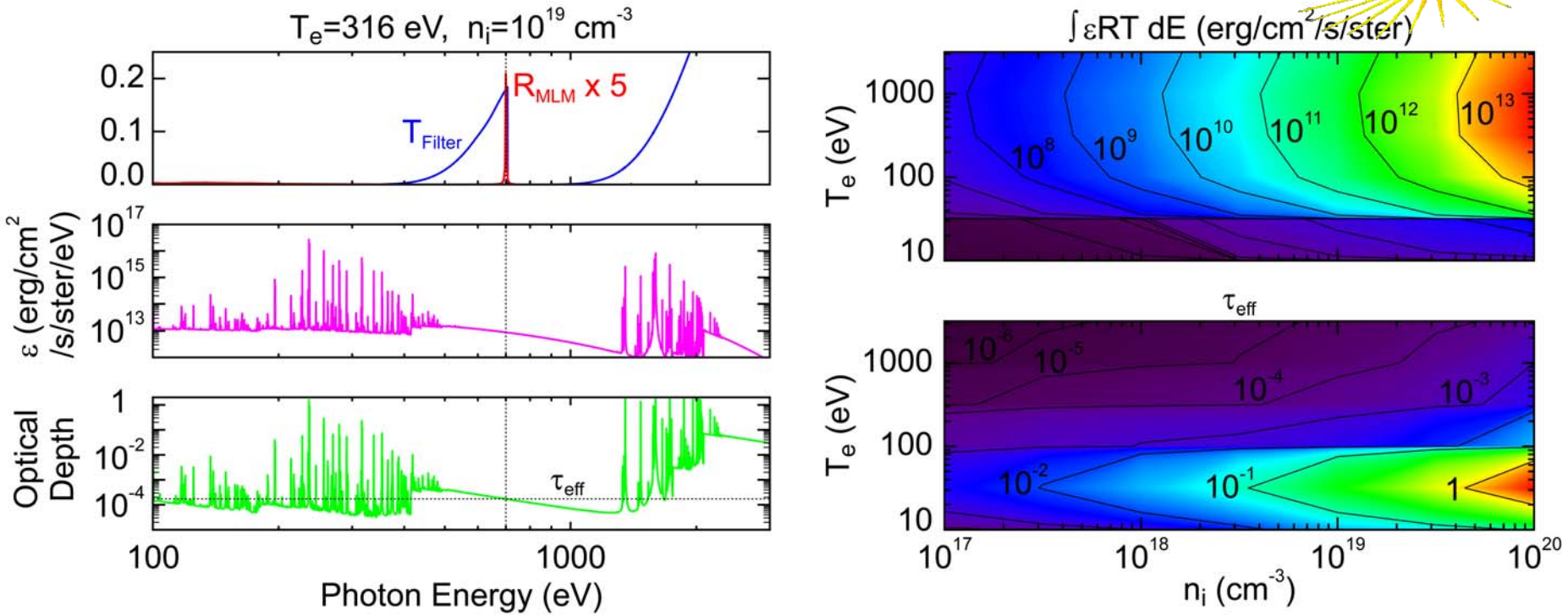


- Non-LTE PrismSPECT collisional-radiative code*
- 95% Al, 5% Mg over range of n_i, T_e
- All atomic levels for B-like through H-like; all ground state levels
- 1D radiation transport with 1 mm path length
- Optically thin emission evident for T_e>100 eV

*J. J. MacFarlane *et al.*, Proc. IFSA 2003, 457 (2004).

Sandia National Laboratories

L-shell continuum imaging may be more simply related to n_i

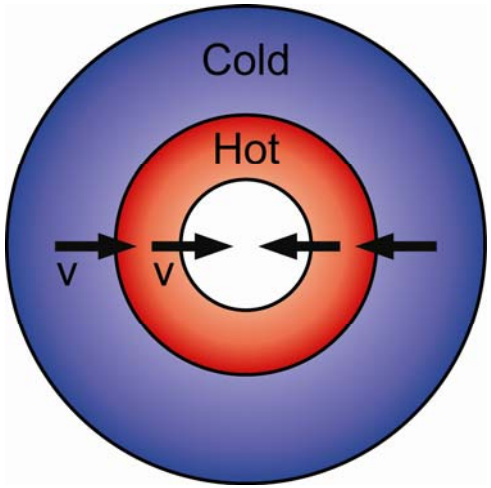


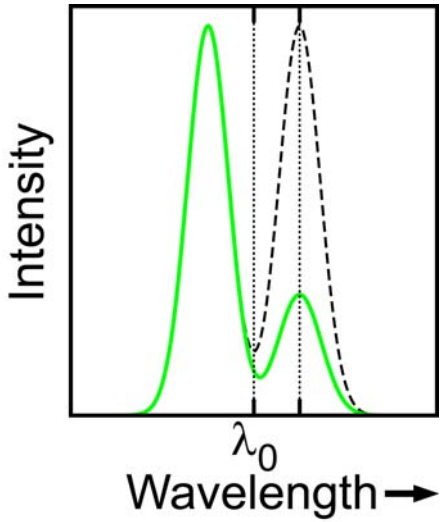
- Non-LTE PrismSPECT collisional-radiative code*
- 95% Al, 5% Mg over range of n_i, T_e
- All atomic levels for B-like through H-like; all ground state levels
- 1D radiation transport with 1 mm path length
- Optically thin emission evident for T_e>100 eV

*J. J. MacFarlane *et al.*, Proc. IFSA 2003, 457 (2004).

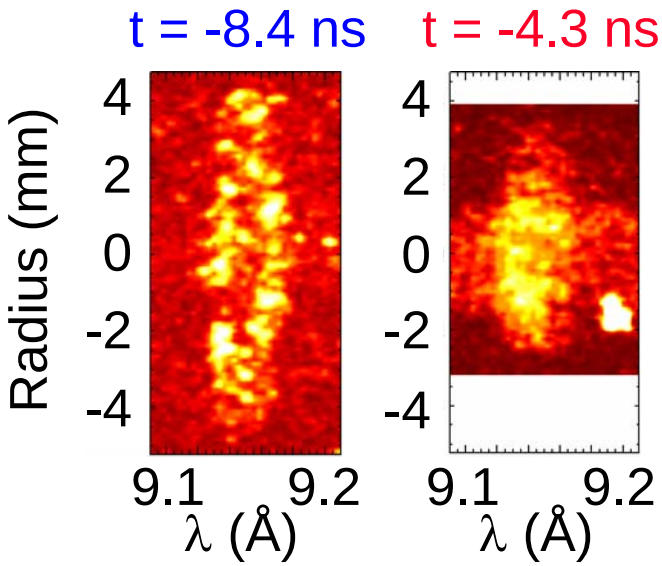
Sandia National Laboratories

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

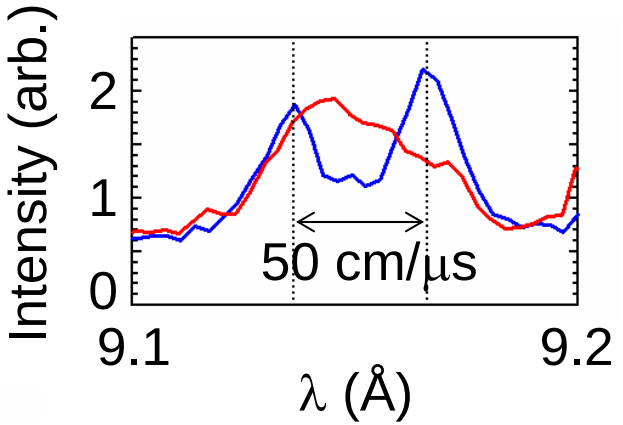




Z1520 (Coverdale), Mg He-α (Dunham)

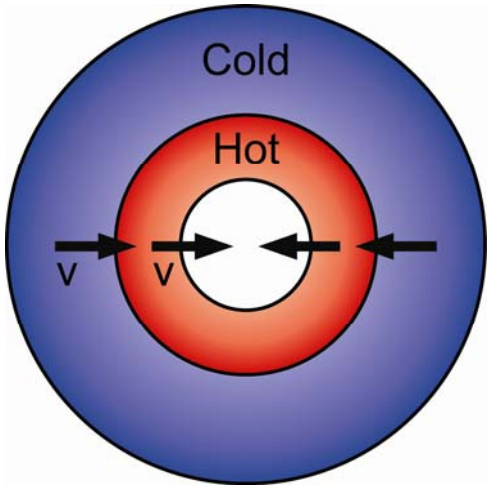


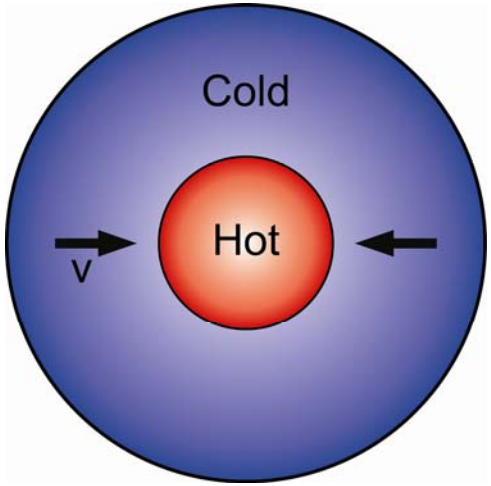
- Oval shape—Doppler split seen on axis, but not in tangential view of shell
- At early time, red/blue-shifted lines are similar magnitude ⇒ optically thin
- Speckle could be azimuthal structure
- At later times, red-shifted line is attenuated by shell/trailing mass opacity
- Splitting not so obvious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



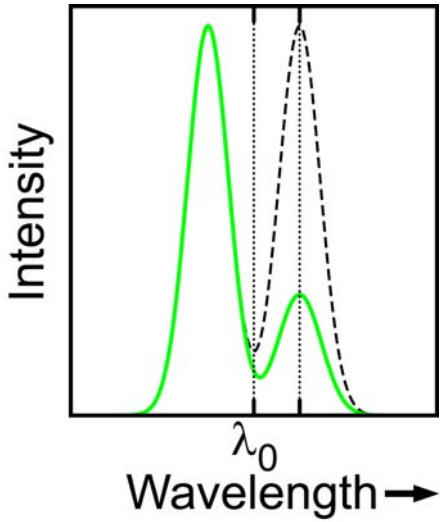
Sandia National Laboratories

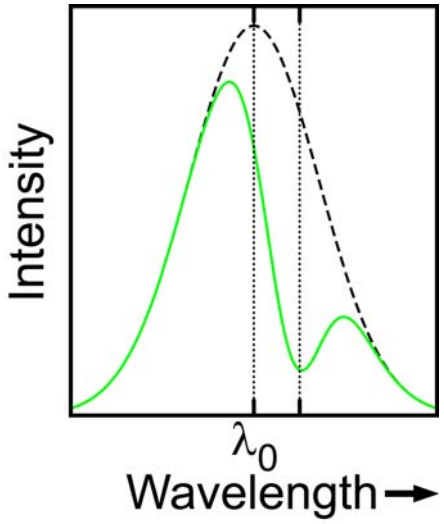
Doppler-shifted absorption seen in high-mass Al wire array



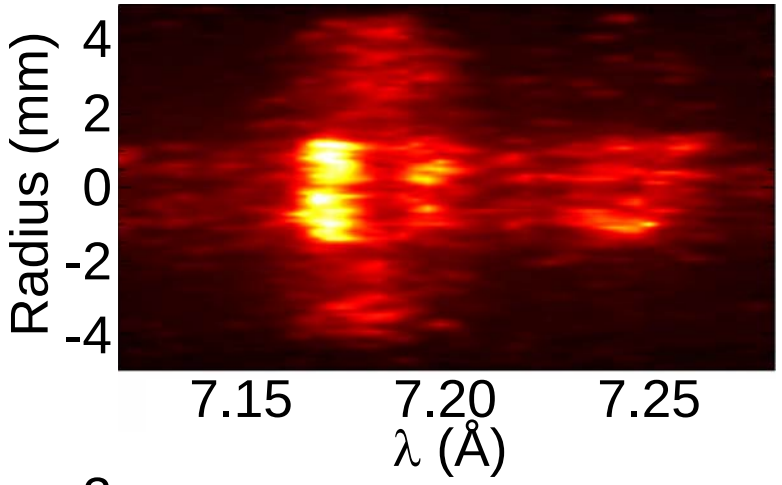


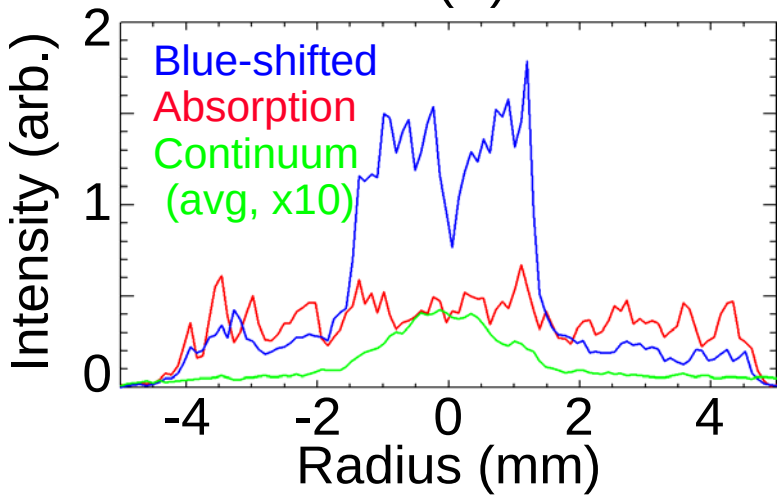
Opacity in cold trailing mass





Z1518, Al Ly-α
t = -9.0 ns

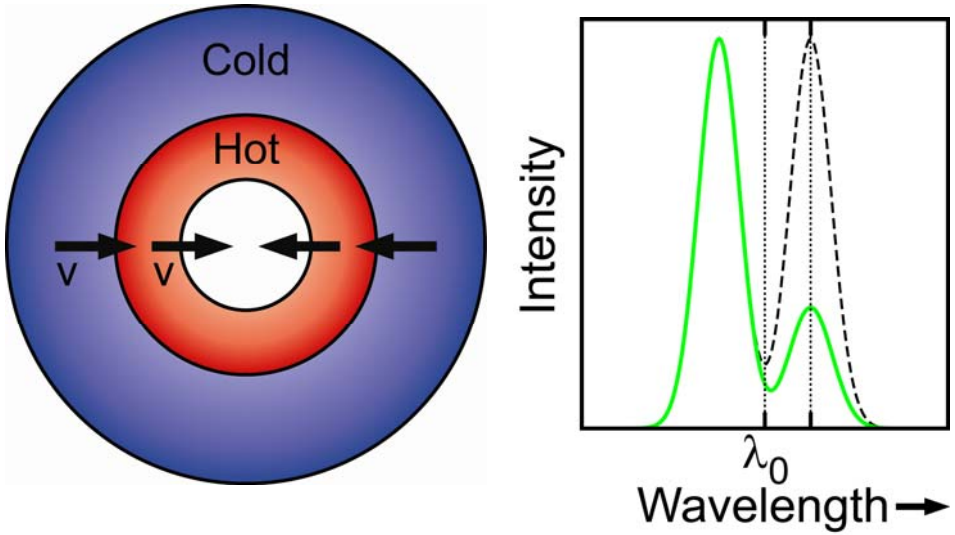


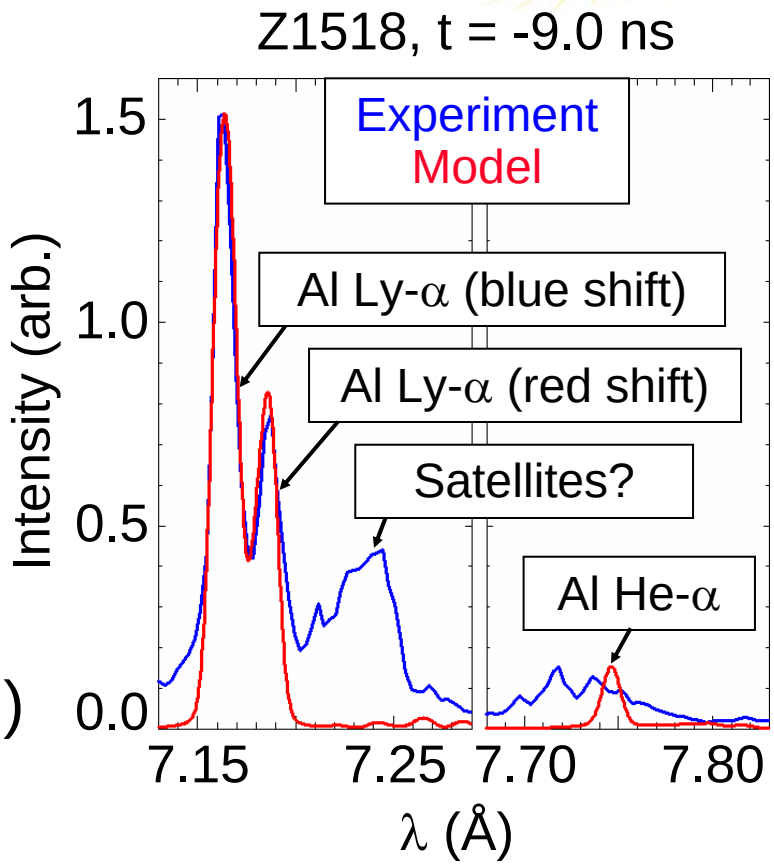


Sandia National Laboratories

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

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

Sandia National Laboratories

Summary

- Abel inversion yields physically relevant information despite deviation from cylindrical symmetry
- Continuity equation approach offers a technique for inferring plasma momentum and kinetic energy
- Several independent possibilities for measuring density profiles
- Spectroscopic techniques can offer independent velocity measurement, and plasma n, T information (especially in stagnated pinch)
- Temperature profiles are needed in addition to say more about compressional heating, thermalization rates, energy partitioning, etc.

Sandia National Laboratories