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K-Shell X-Ray Generation on Sandia's Refurbished Z Machine for the Radiation Effects Sciences Program

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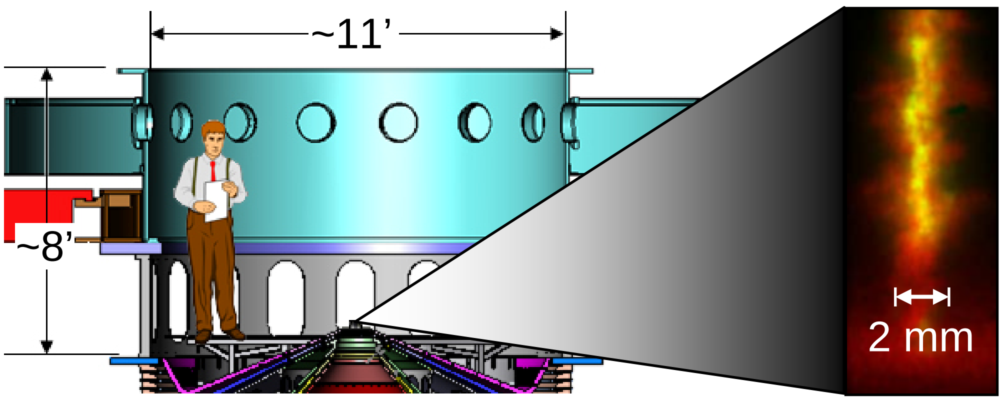

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NNSA Review Panel

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National Nuclear Security Administration

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Outline

- Programmatic motivations for performing the work at Z, and cold x-ray radiation source needs for nuclear survivability studies
- K-shell scaling physics, summary of Z results and predictions
- Five-year plan for the RES program on Z
- Z-pinch physics issues relevant to RES loads

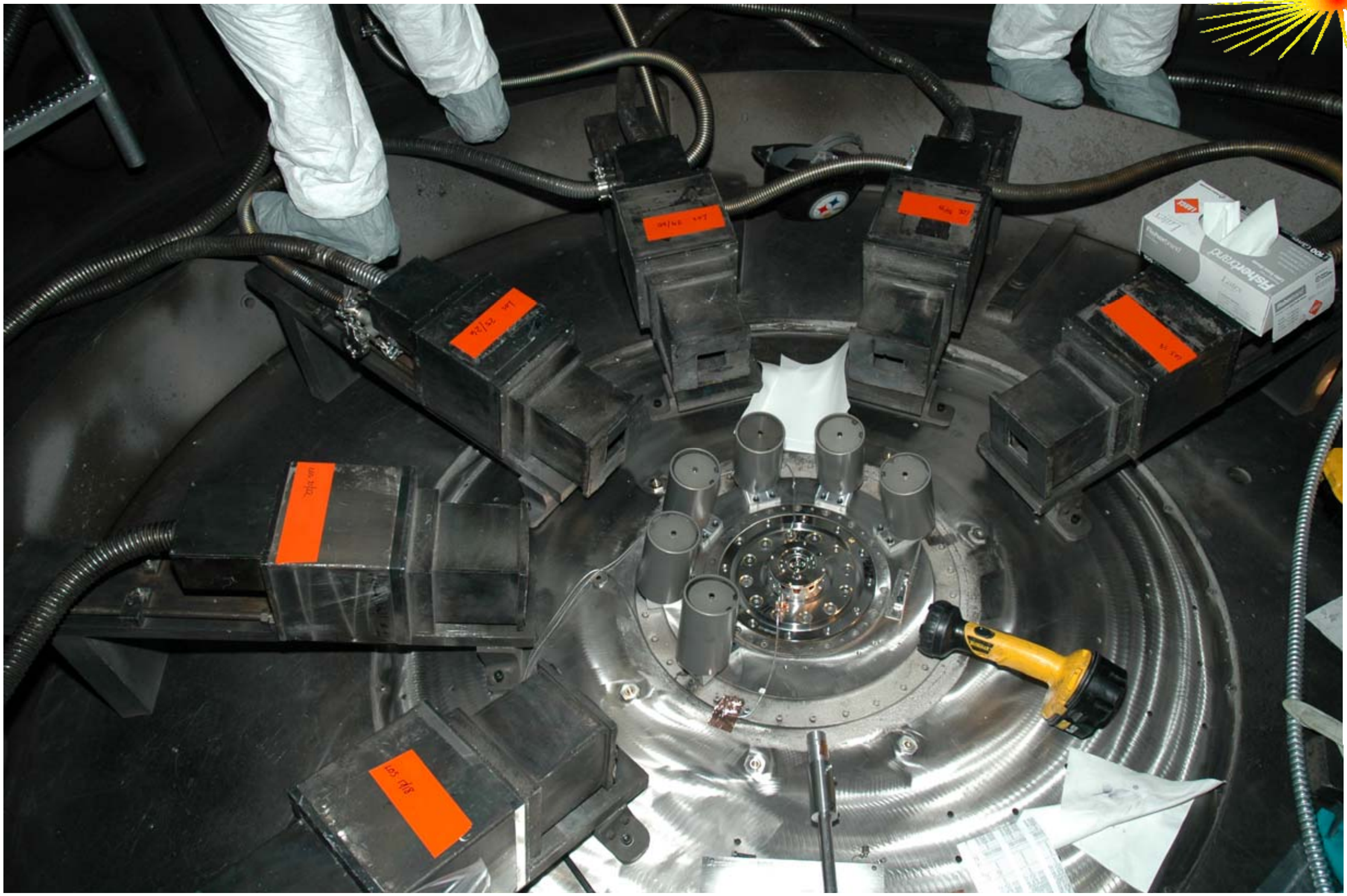
Stockpile needs motivate the RES program on Z

- NW programs motivate Z radiation effects studies in Sandia's Radiation Sciences Center
  - Reliable Replacement Warhead
  - Lifetime Extension Programs
  - Limited Lifetime Component Exchange and legacy stockpile issues
  - Collaborations: AWE, Work For Others (e.g. Missile Defense Agency)
- Scaled problems are used for code validation over a range of photon energies

Source development goals

- High x-ray fluence is critical for driving radiation physics effects
- Warmer x-rays are desired for greater material penetration
- The Radiation Sciences Center requires Z sources at 4 photon energies by FY11
- The Pulsed Power Center will develop sources and x-ray diagnostics

Z is an essential resource for certifying non-nuclear components in the enduring stockpile



• Courtesy of C. A. Coverdale (1344)

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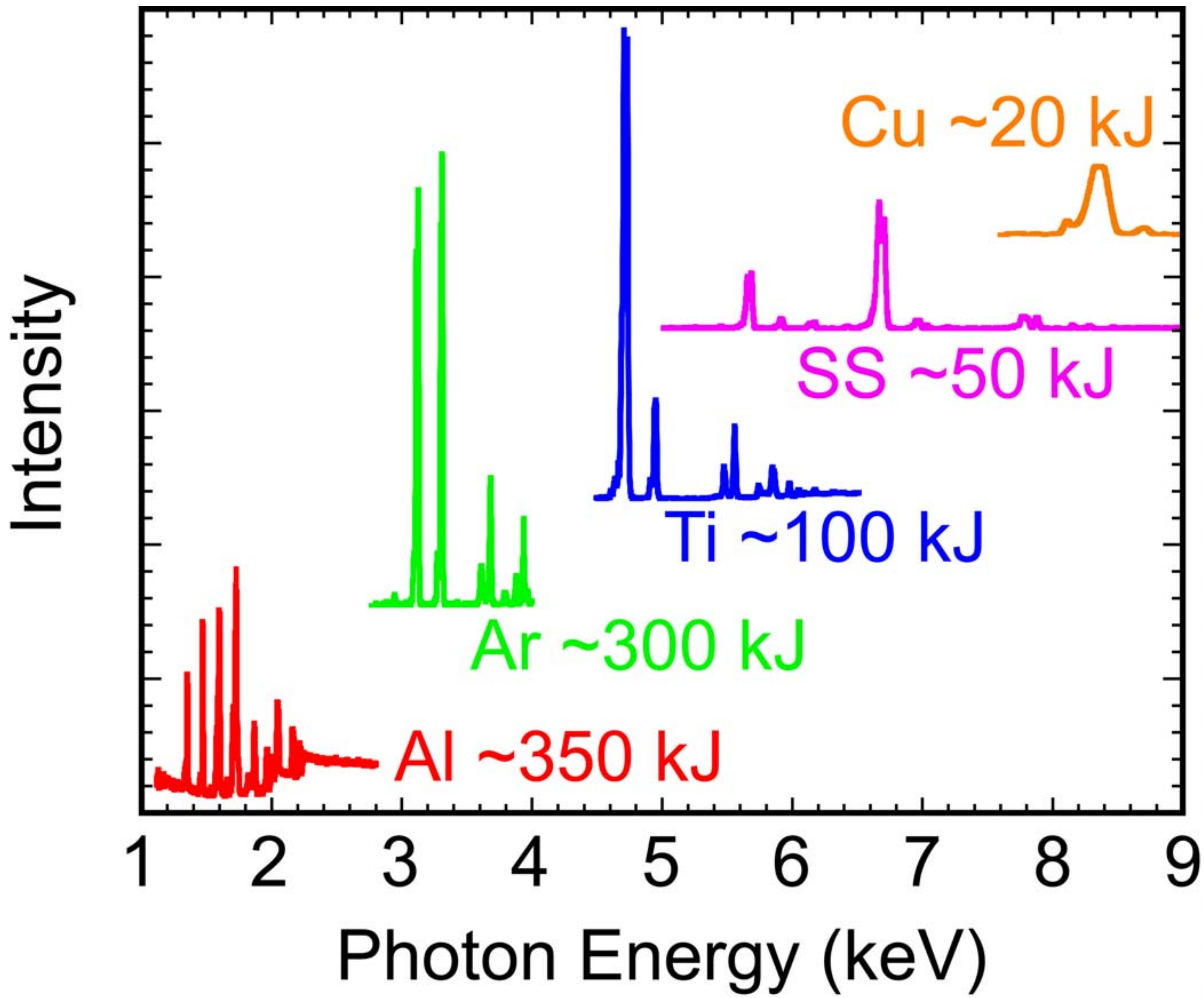
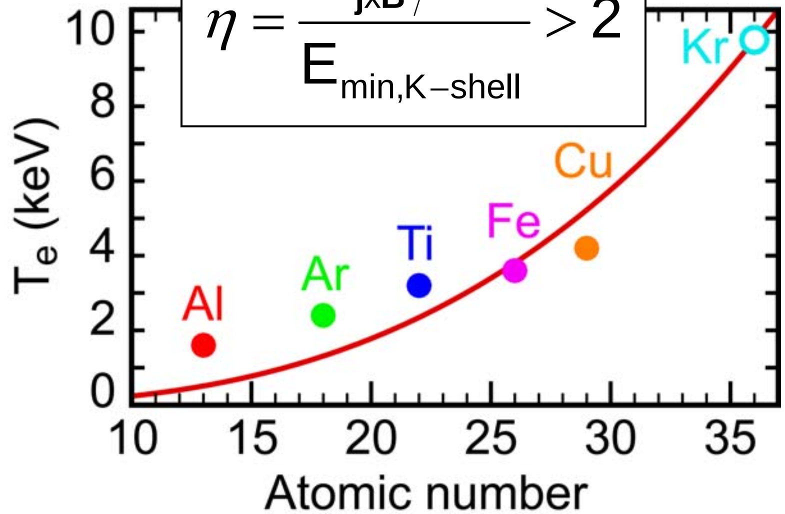
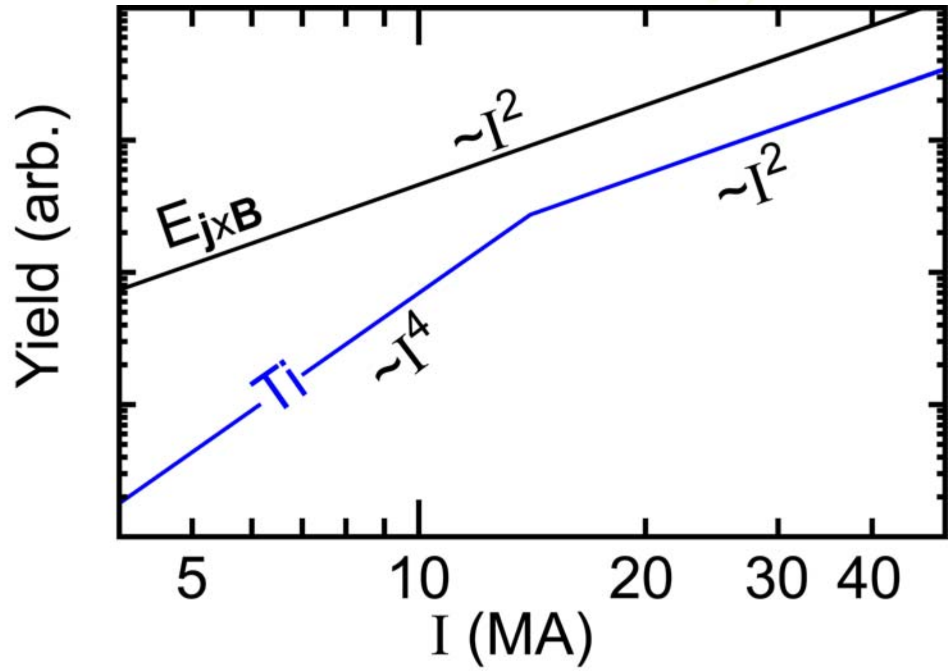
A variety of K-shell x-ray sources have been studied at Z

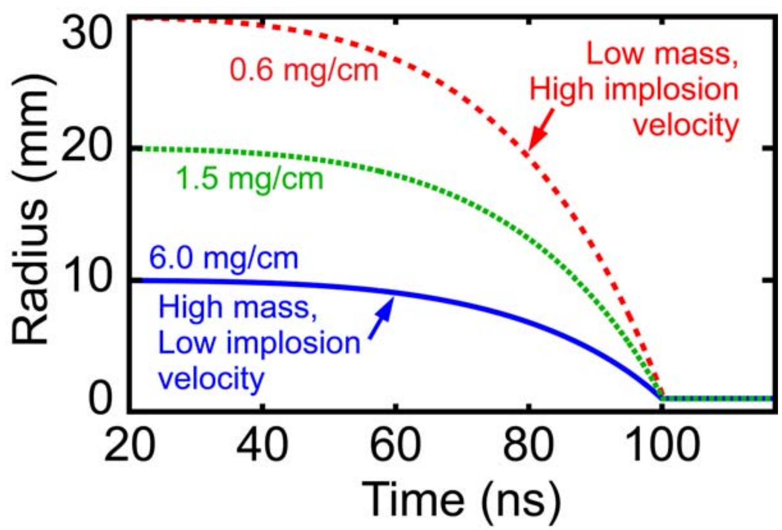


High temperature and density are required for K-shell x-rays

$$\eta = \frac{E_{\mathbf{jxB}}/\text{ion}}{E_{\text{min,K-shell}}} > 2$$







$$F = \mathbf{j}\text{x}\mathbf{B} = ma$$

$$I^2 \sim m$$

$$\varepsilon \sim n^2 \sim m^2 \sim I^4$$

$$Y_K = \varepsilon V \Delta t \sim I^4$$

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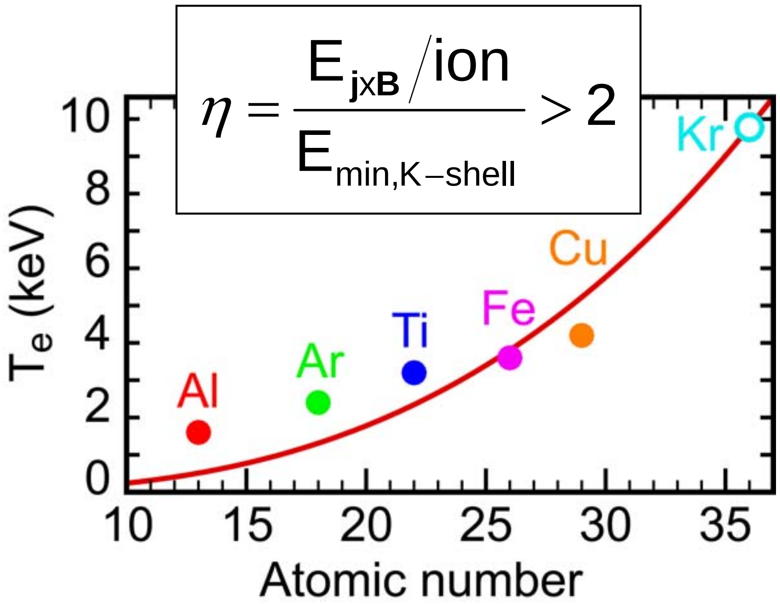
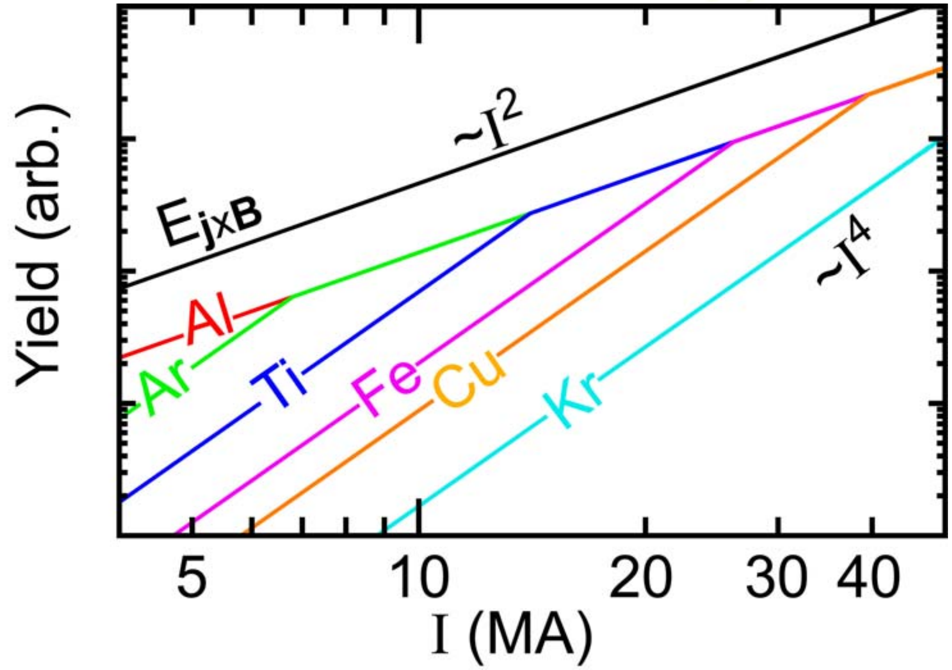
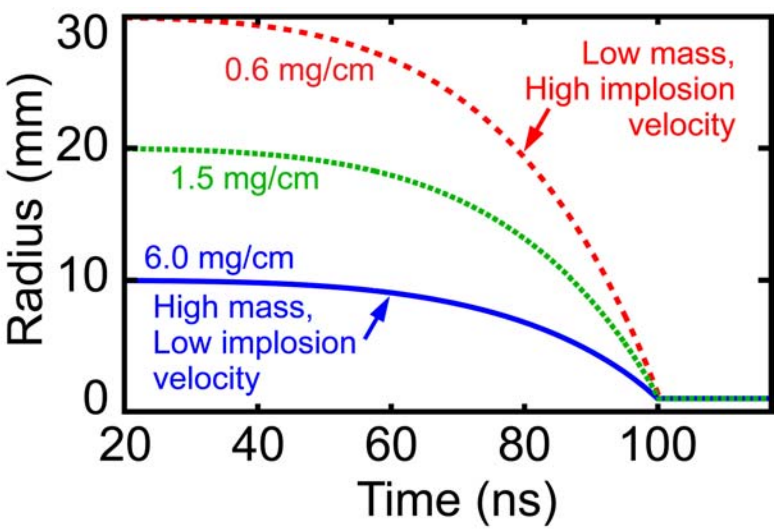


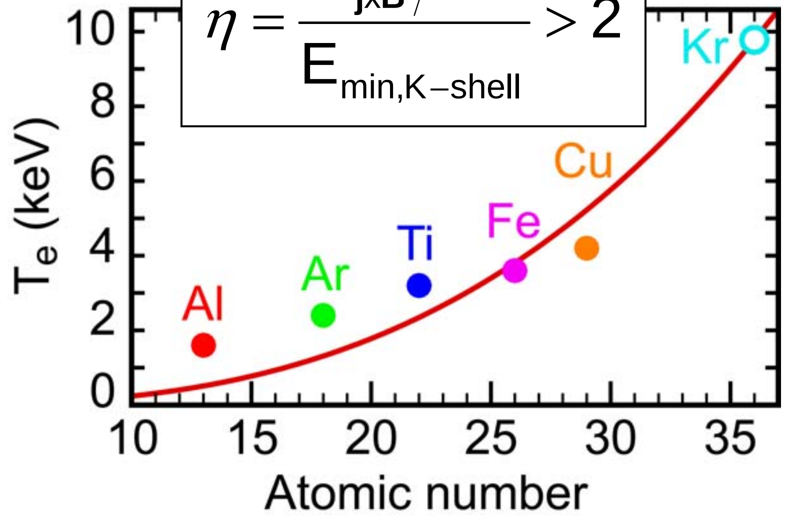


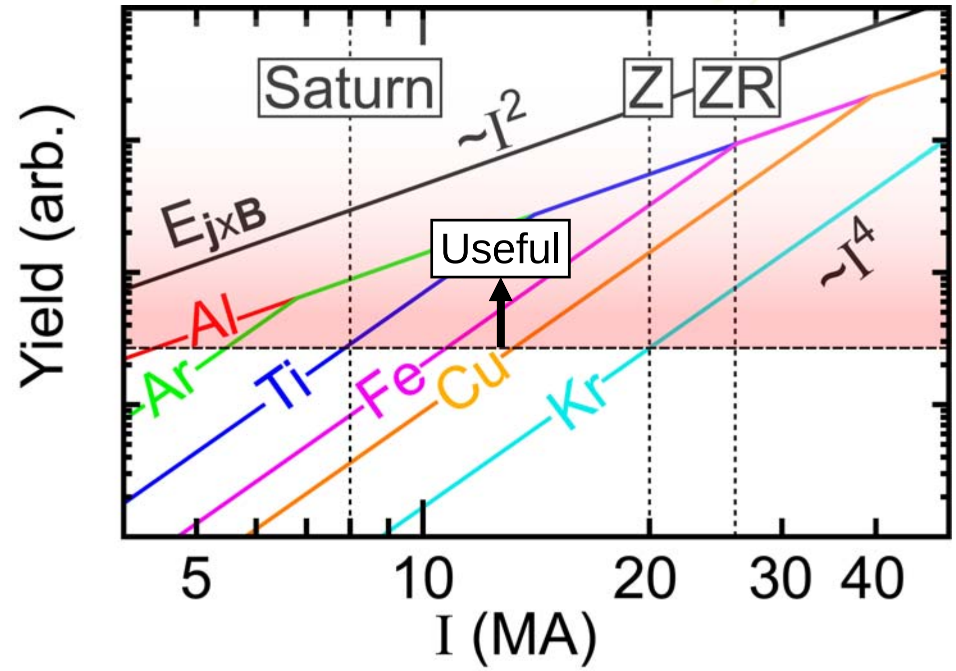


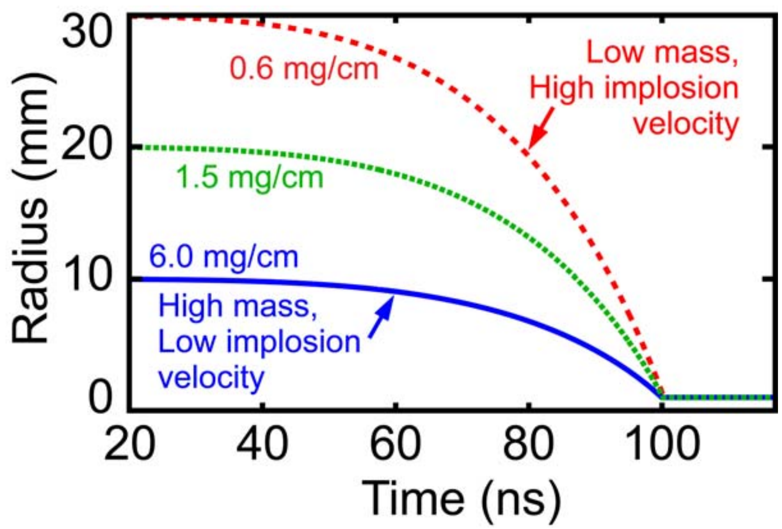
- It is more difficult to ionize higher *Z* materials to the K-shell at high mass

High temperature and density are required for K-shell x-rays

$$\eta = \frac{E_{jxB}/\text{ion}}{E_{\text{min,K-shell}}} > 2$$







Largest yields for efficient lower hν sources, e.g. Ar (3.1 keV)
Largest gains (~I⁴) for highest hν in transitioning to ZR: SS (6.7 keV), Cu (8 keV)
Kr (13 keV) is expected to become a useful source on ZR

C. A. Coverdale *et al.*, IEEE TPS **35**, 582 (2007).

RES 5-year plan: meet program goals, understand the physics

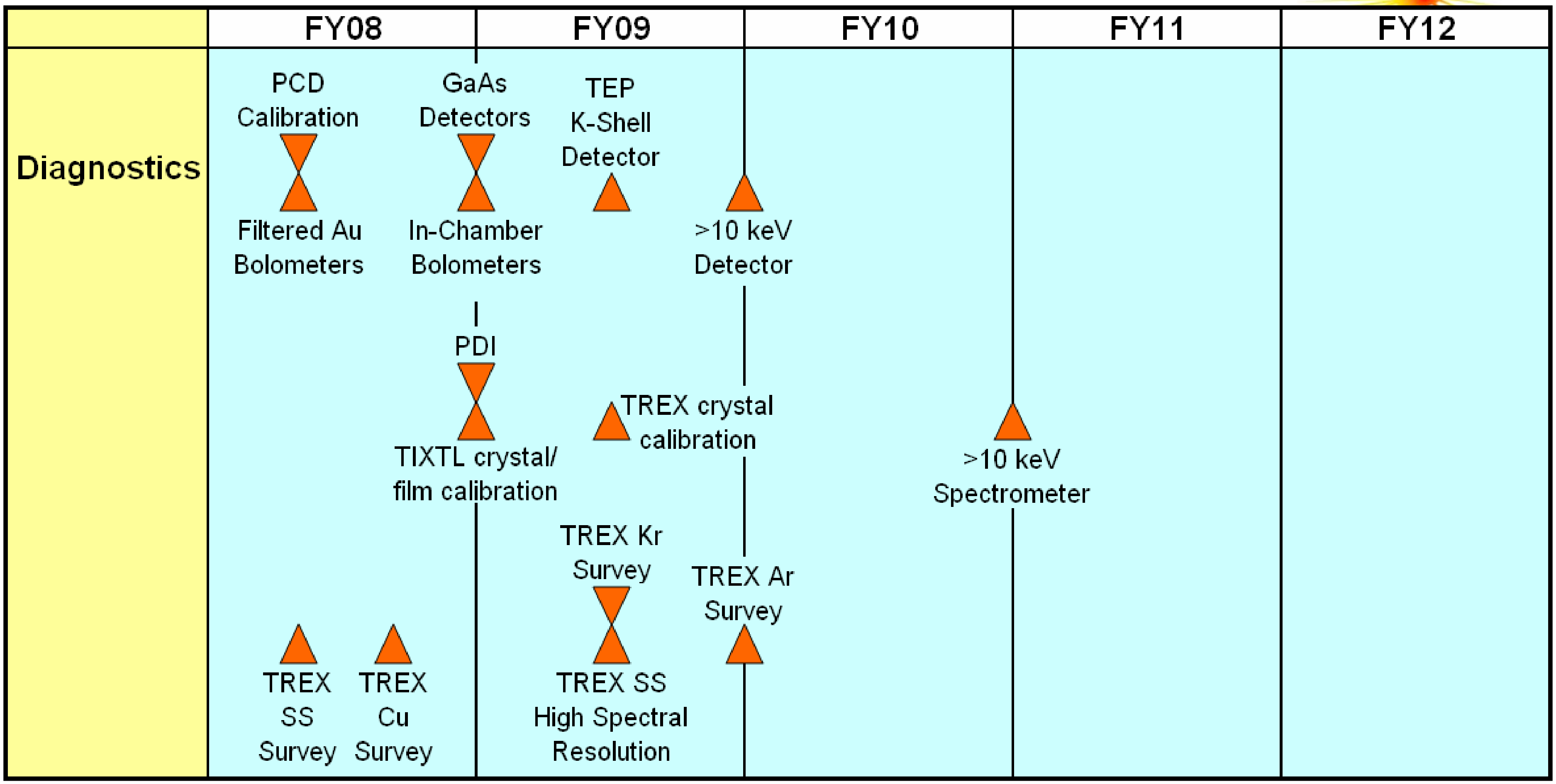
	FY08	FY09	FY10	FY11	FY12
Z Shots	20	30	40	30	30
Campaigns	4.8 keV Ti Current Scaling				
	6.7 keV SS Development			6.7 keV SS Long Pulse Exploration	
	8.4 keV Cu Development				8.4 keV Cu Long Pulse Exploration
		13 keV Kr Exploration / 13 keV Kr Development			
		3.1 keV Ar Exploration	3.1 keV Ar (or 4.8 keV Ti) Development		
		8-13 keV Exploration	8-13 keV Wire Array Development		
			>13 keV Source Exploration	>13 keV Source Development (K-shell, or continuum)	
	Rad. Effects Ride-ons	Radiation Effects Physics Experiments (Radiation Sciences Center) With Available Sources			

▲ Large diameter convolute (start of FY09)

▲ Decision on gas puff development (start of FY09)

▲ 4 sources available (start of FY11)

K-shell diagnostics will be developed in step with sources



- Accuracy of x-ray power/yield measurements has a direct bearing on code validation error analysis—development and calibration of multiple independent diagnostics will be pursued
- Time- and space-resolved x-ray spectroscopy is key to studying basic z-pinch dynamics

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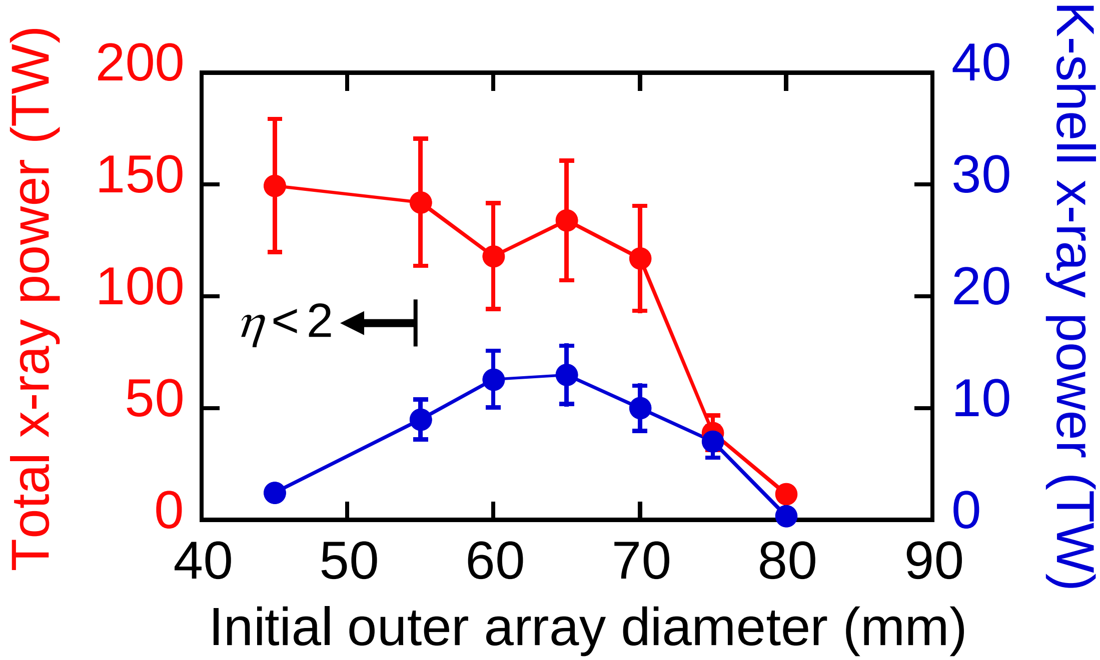
Instability may worsen with increasing array diameter

C. A. Coverdale *et al.*, submitted to Phys. Plasmas



- Drop in total and K-shell power and yield observed on Z with nested stainless steel array diameters >70 mm
- ZR will require larger diameter arrays to achieve high implosion velocities for higher atomic number materials

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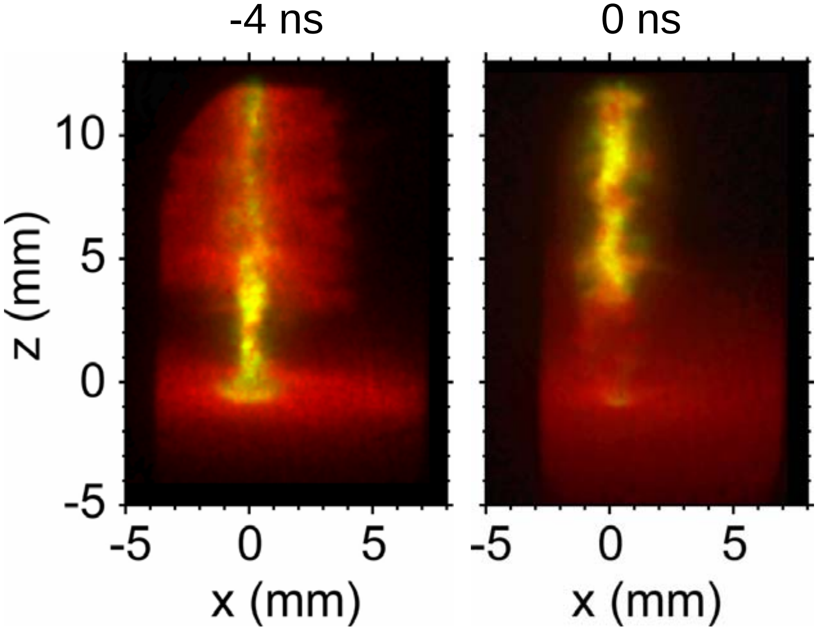
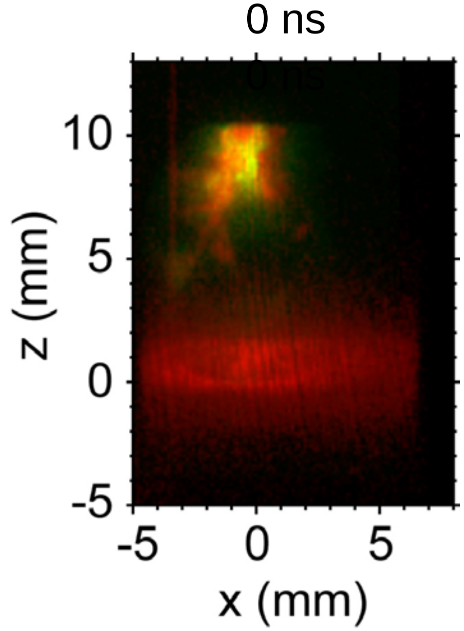
Large scale cathode instability can spoil large diameter loads

Multi-color self-emission imaging, Ø60 mm Cu nested arrays

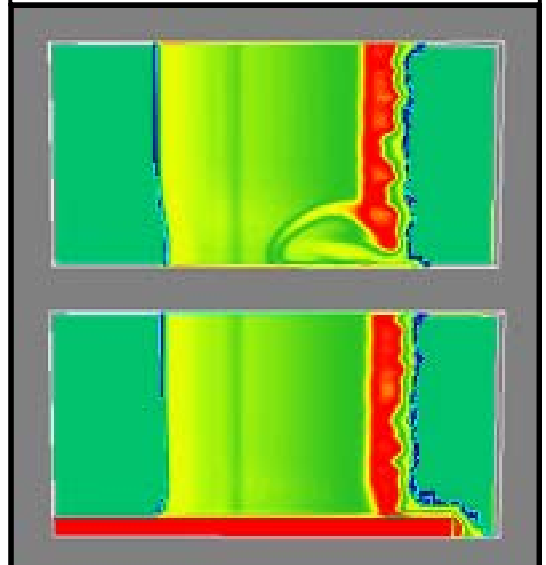
277 eV 8 keV



Most of Ø75 mm SS nested array viewed at 12° LOS is disrupted



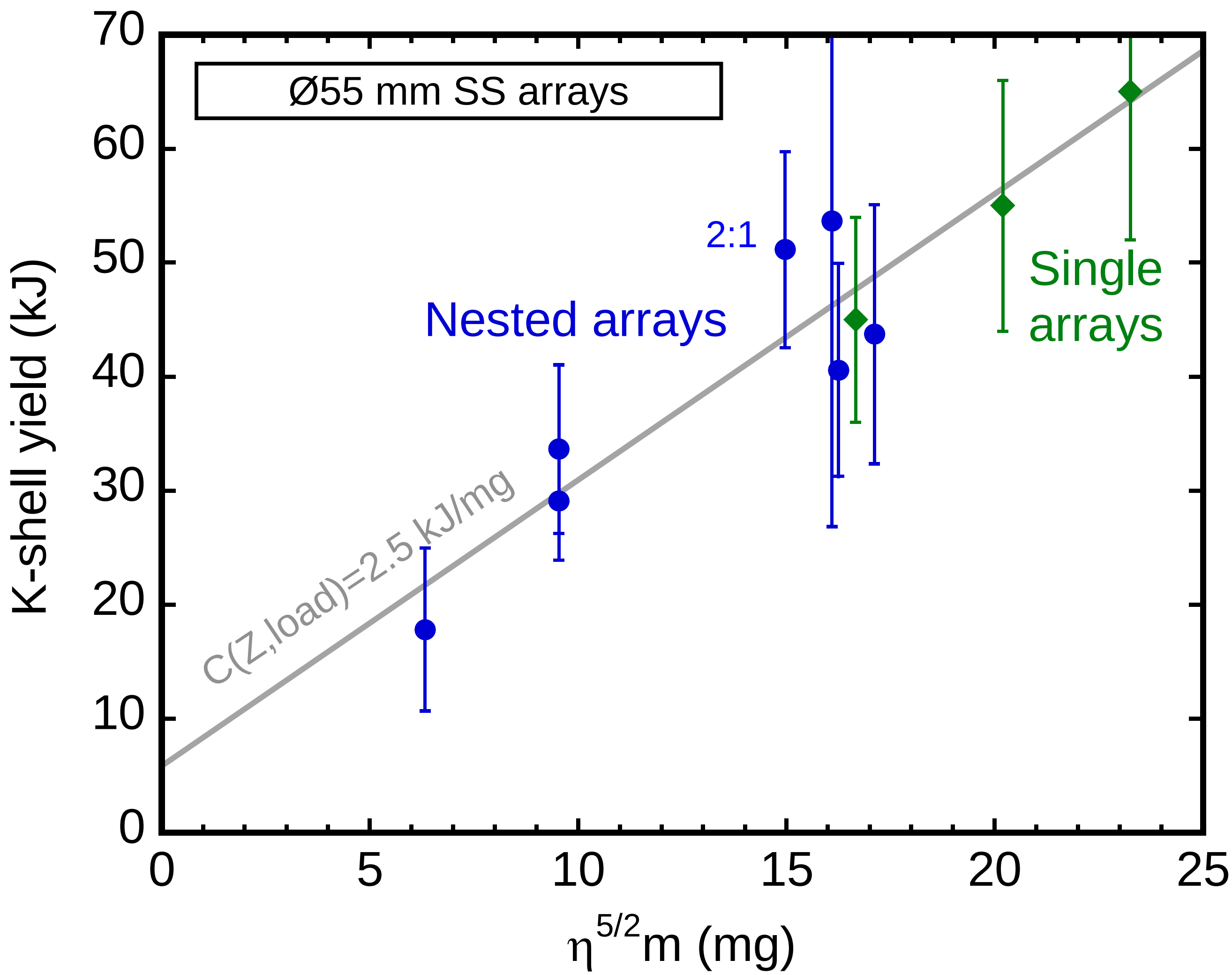
Cathode step (red) mitigates instability



3D MHD models courtesy of C. A. Jennings

- Cathode end can disrupt prior to peak x-rays
- Mitigation by cathode step or prepulse proposed (C. A. Jennings, J. P. Chittenden)
- Initial Saturn tests of step look promising (D. J. Ampleford)

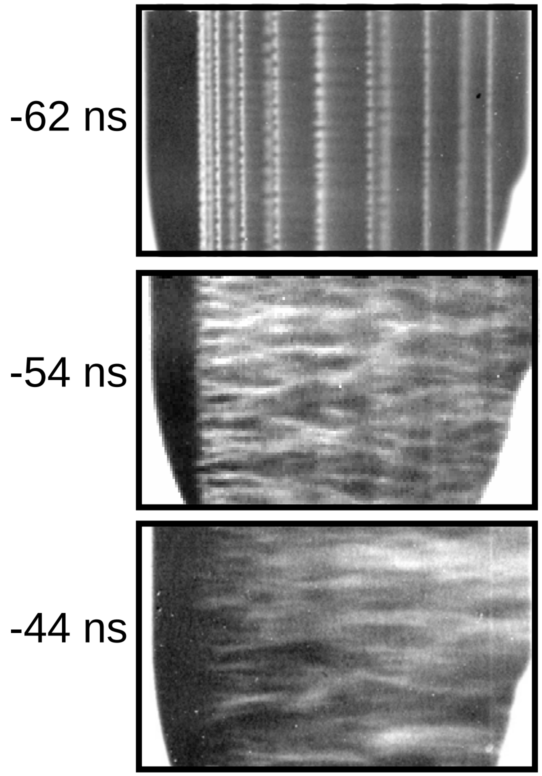
Scaling model benchmarked to Z guides future load design



- Y_k(kJ) = C(Z,load) $\eta^{5/2}$ m for the SS regime on Z (Thornhill)

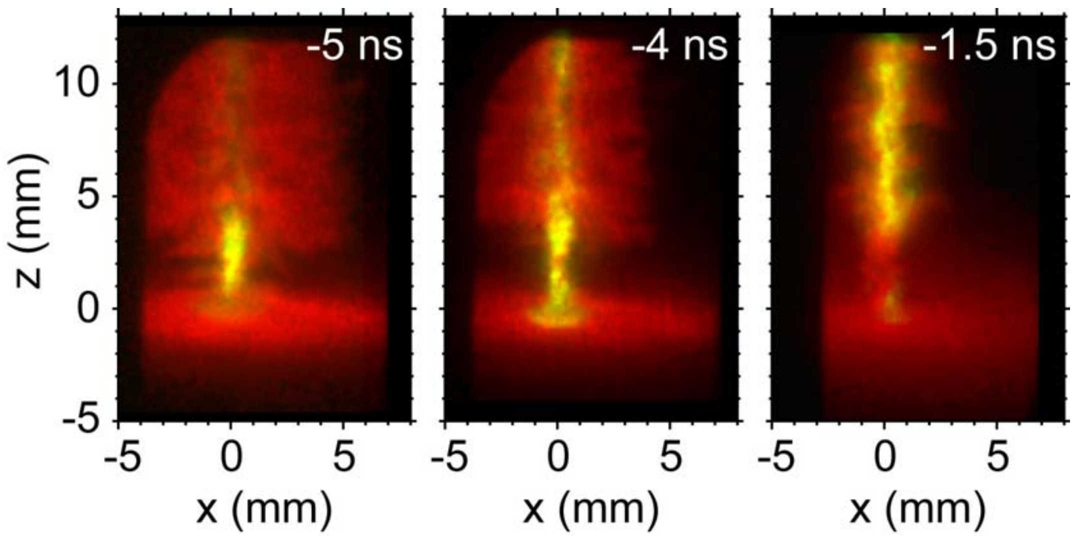
J. W. Thornhill *et al.*, IEEE TPS **34**, 2377 (2006).

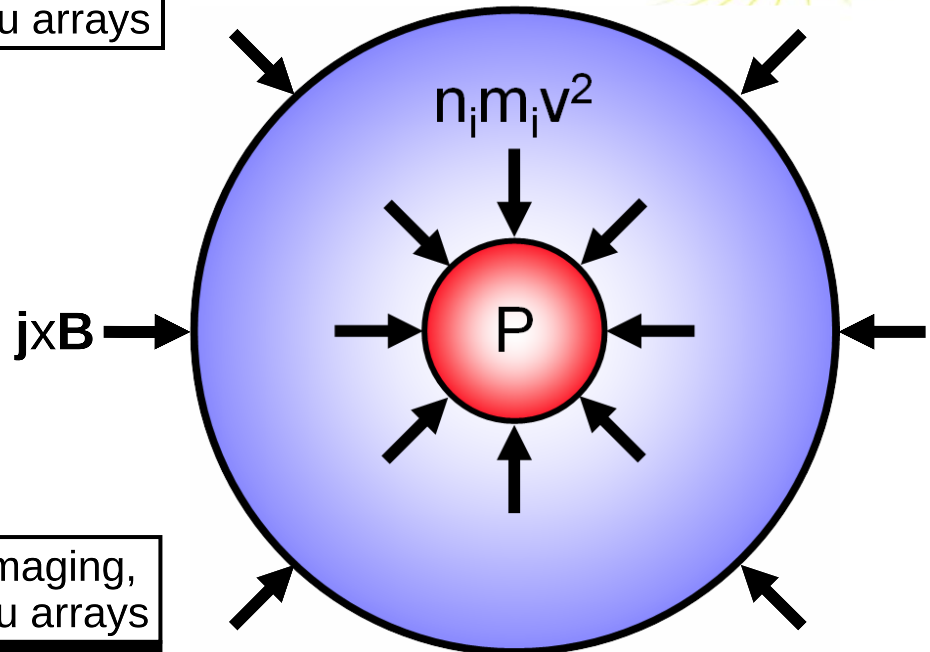
Dynamics are not 0D—distributed mass accretes on axis



1.865 keV radiography,
Ø60 mm nested Cu arrays

Multi-color x-ray imaging,
Ø60 mm nested Cu arrays
277 eV 8 keV

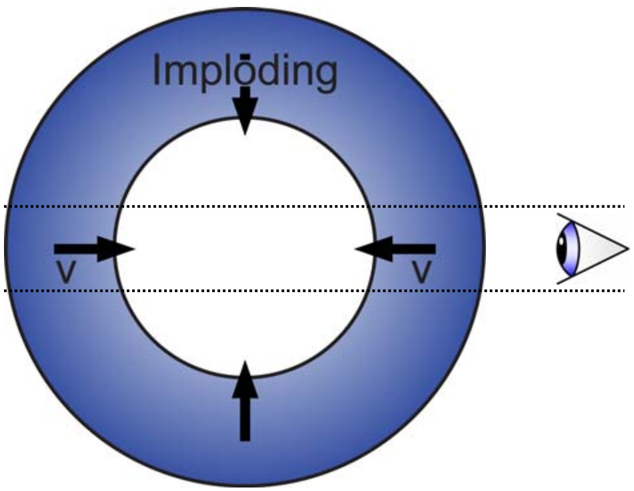


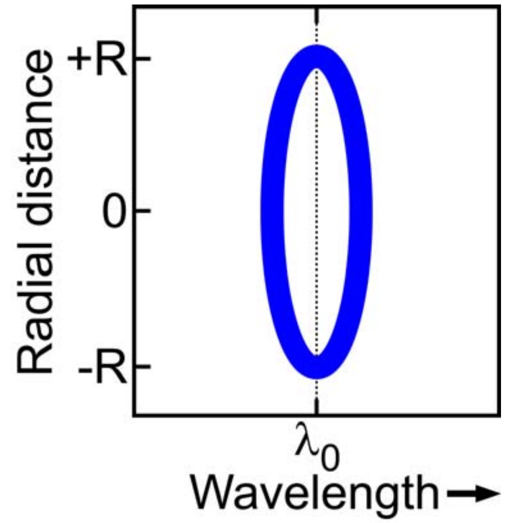


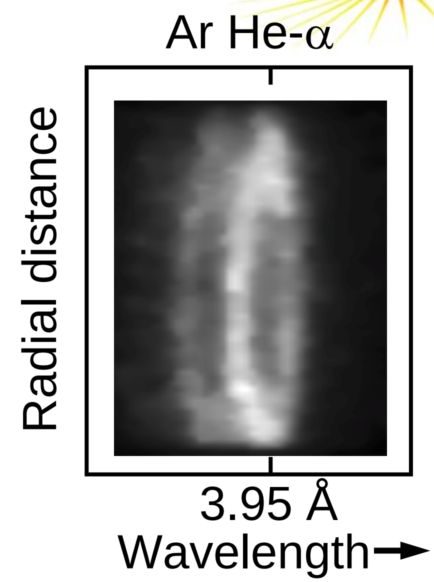
$$P = n_e T_e + n_i T_i$$
$$= n_i m_i v^2 + B^2/8\pi$$

- Accretion implies a density limit—implications for K-shell scaling theory

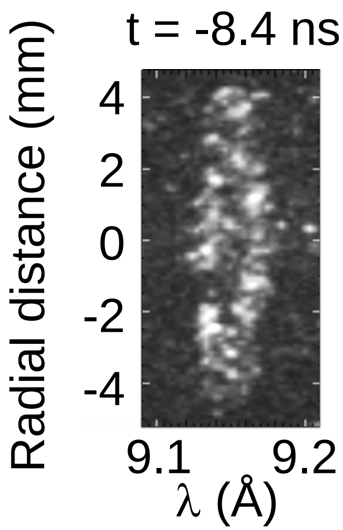
Doppler splitting can be used to measure implosion velocity



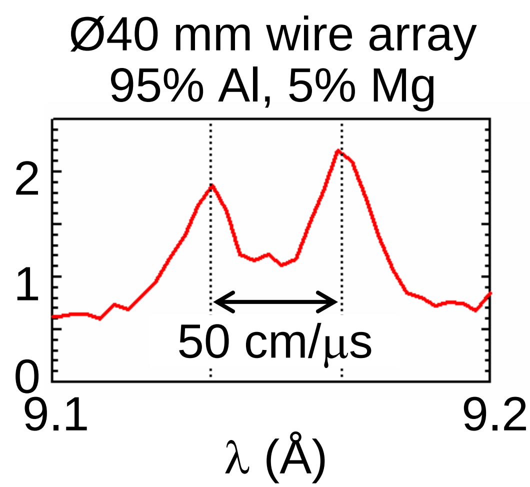




Ar-doped D_2 gas puff



Mg He-α



- Measurement of v_{impl} is essential for understanding z-pinch energy coupling

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FY08 shot plan addresses physics, emphasizing SS source

Shot series	Experiment	Load
1	Ti K-shell yield current scaling	Ti single wire arrays
	Cathode instability mitigation	60mm SS, 2:1 nested arrays
	Triple nested arrays	60mm SS
2	SS diameter scan	Double or triple nested
	SS reproducibility	Favorite configuration
	Cu initial study	Scaled from initial SS data

- First shot series will emphasize load physics improvements
- Diagnostic development will advance with shots

Summary

- The refurbished Z machine offers unique capabilities to meet Sandia nuclear survivability research requirements
  - Higher usable photon energies than other pulsed power generators
  - Higher fluences than other x-ray simulators
- The Pulsed Power RES program focuses primarily on meeting the needs of customers (e.g. Radiation Sciences Center)
  - Four sources will be developed, qualified, and utilized for radiation effects physics experiments by FY11
  - We will improve source performance and extend to higher photon energies beyond FY11
  - Diagnostic development will reduce error bars on K-shell power/yield measurements and provide advanced, calibrated spectroscopy
- The RES program will pursue understanding of basic z-pinch physics in order to optimize K-shell sources, but also to benefit HEDP science in Sandia's Pulsed Power Center