SAND2008-2752P

Radiation Effects Sciences Z-Pinch Source Development on the Refurbished Z Machine in FY08

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Many collaborators contribute to RES-related z-pinch studies

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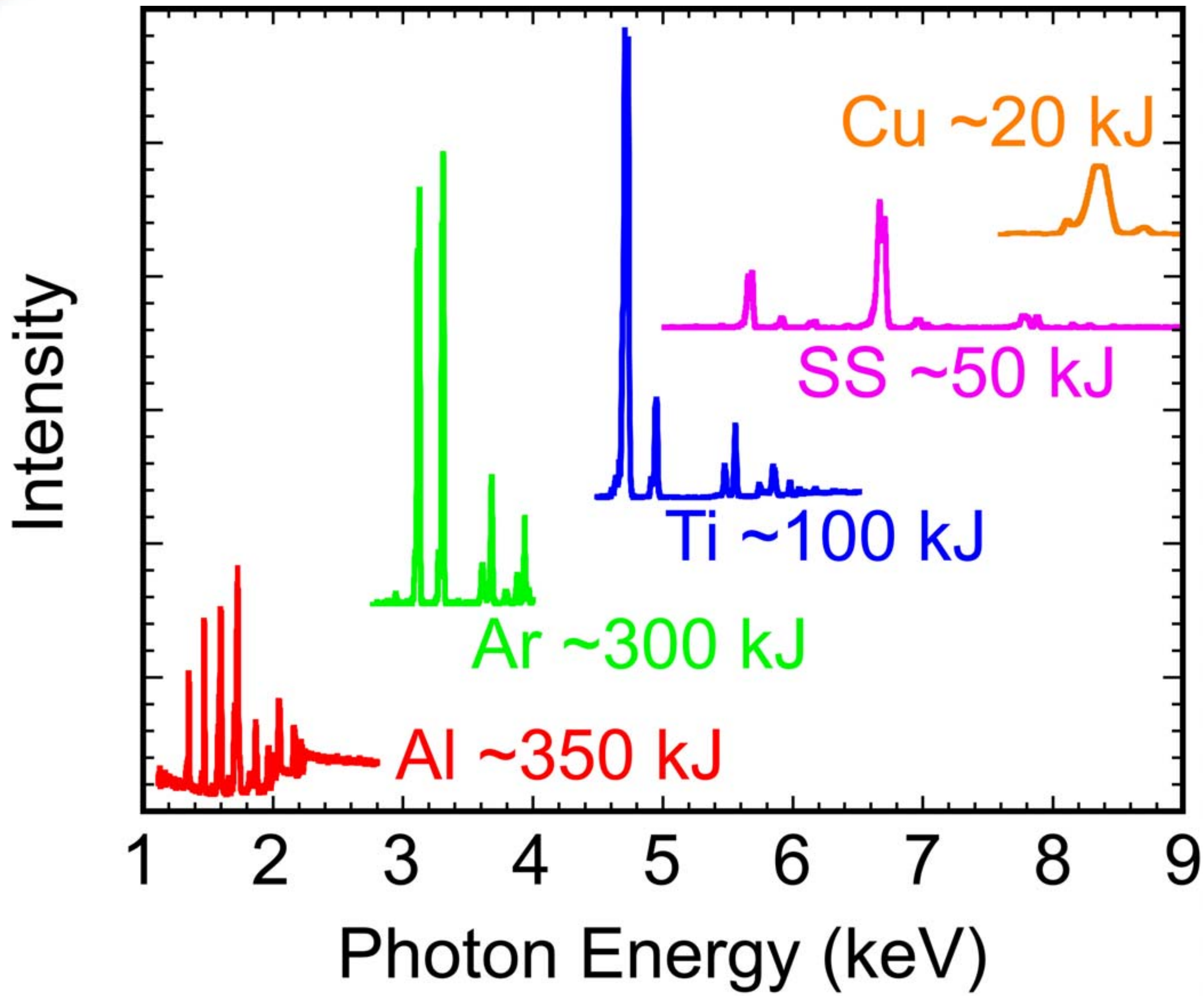
Outline

- Five-year plan for RES on Z
- K-shell scaling physics, comparison with Z data
- Predictions for yields on ZR, FY08 shot planning
- Electrode instability mitigation
- Diagnostic requirements in FY08 and beyond
- Z-pinch physics studies

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

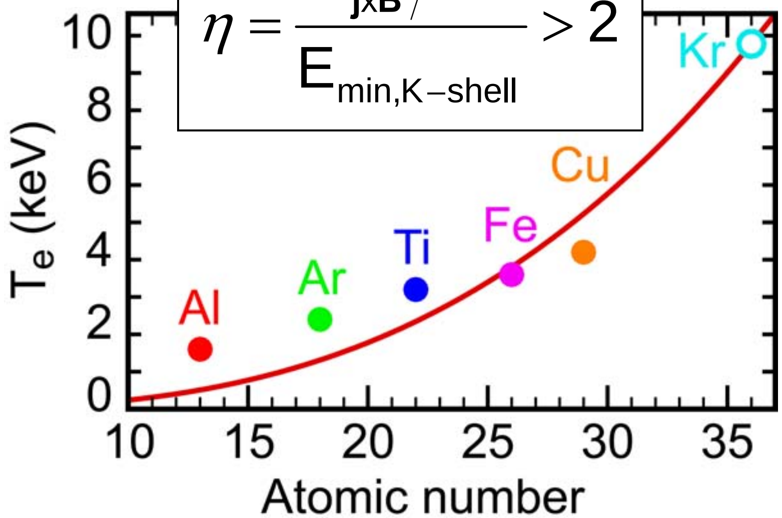
- Source development goals
  - High x-ray fluence is critical for driving radiation physics effects
  - Warmer x-rays are desired for greater material penetration
  - The Radiation Sciences Center (1300) requires Z sources at 4 photon energies by FY11
  - The Pulsed Power Center (1600) will develop sources and x-ray diagnostics

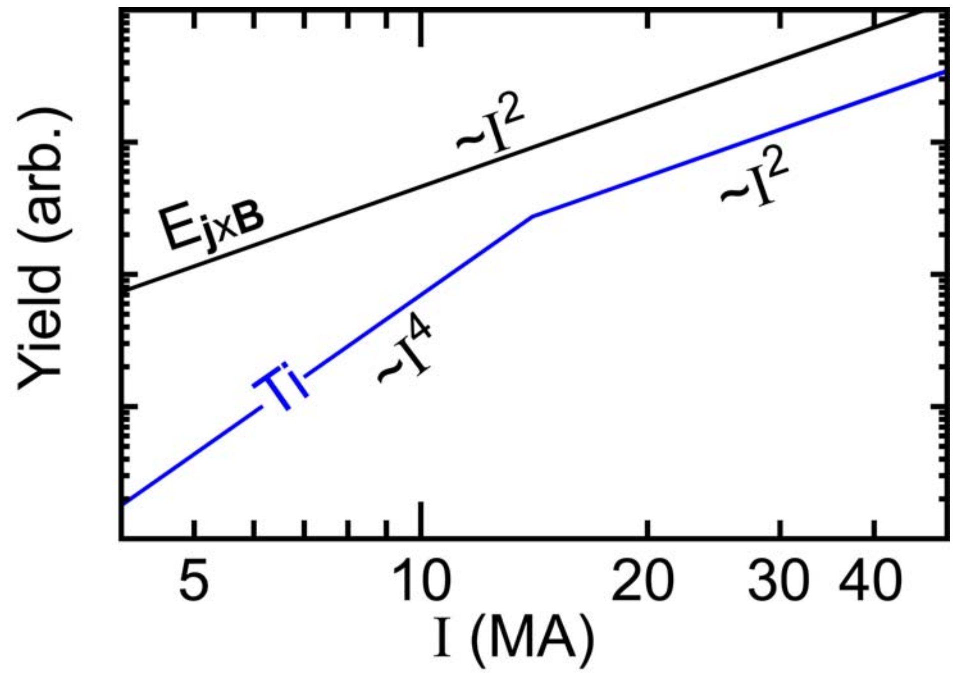
Wire array and gas puff z-pinch K-shell x-ray sources have been studied at Z

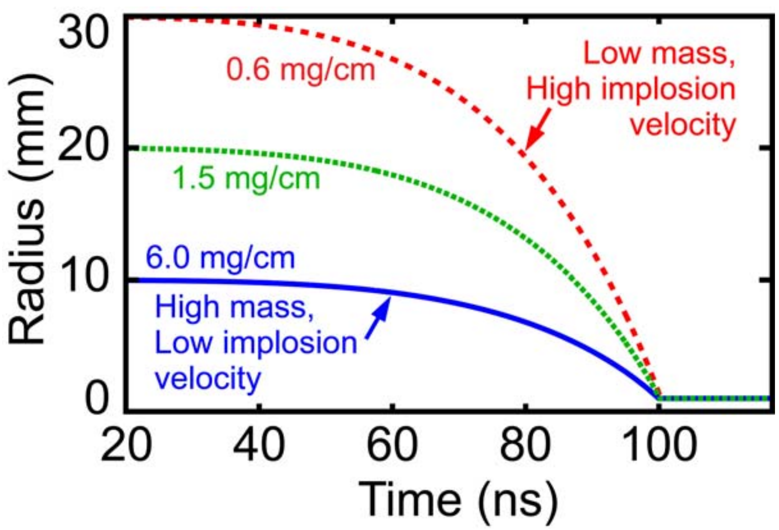


High temperature and density are required for K-shell x-ray excitation

$$\eta = \frac{E_{jx\mathbf{B}}/\mathrm{ion}}{E_{\mathrm{min,K-shell}}} > 2$$







$$F = \mathbf{j} \times \mathbf{B} = ma$$

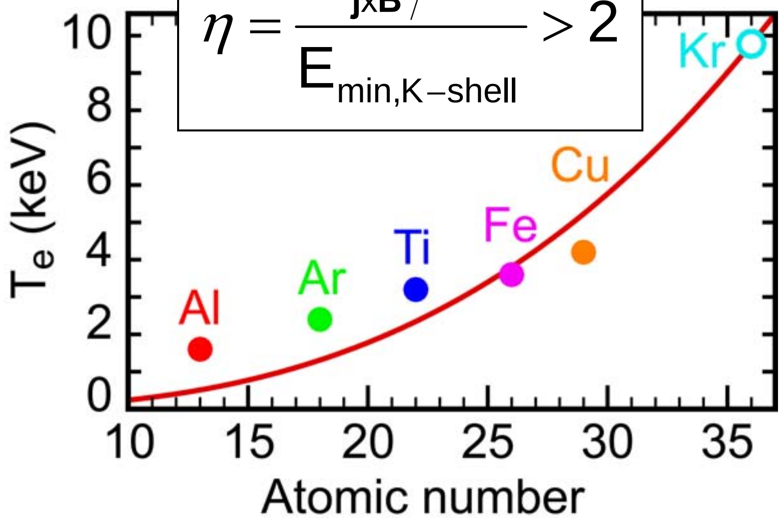
$$I^2 \sim m$$

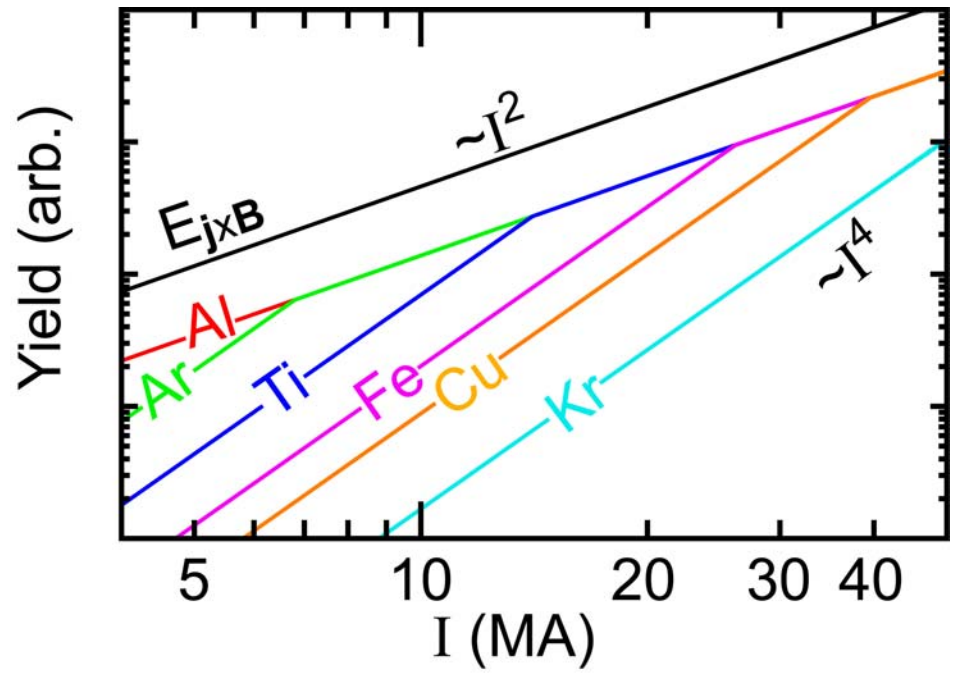
$$\varepsilon \sim n^2 \sim m^2 \sim I^4$$

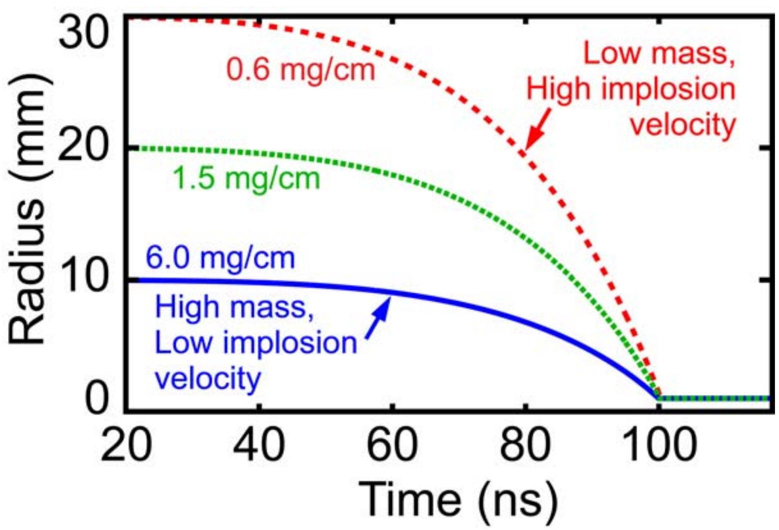
$$Y_K = \varepsilon V \Delta t \sim I^4$$

High temperature and density are required for K-shell x-ray excitation

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







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

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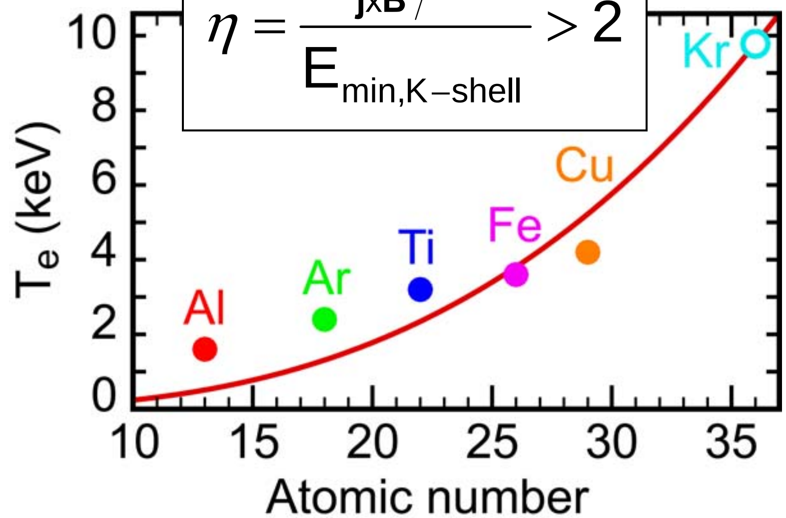
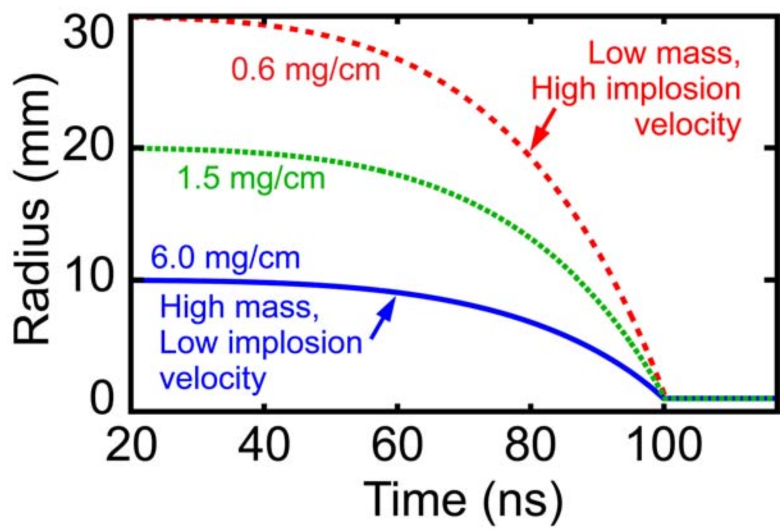
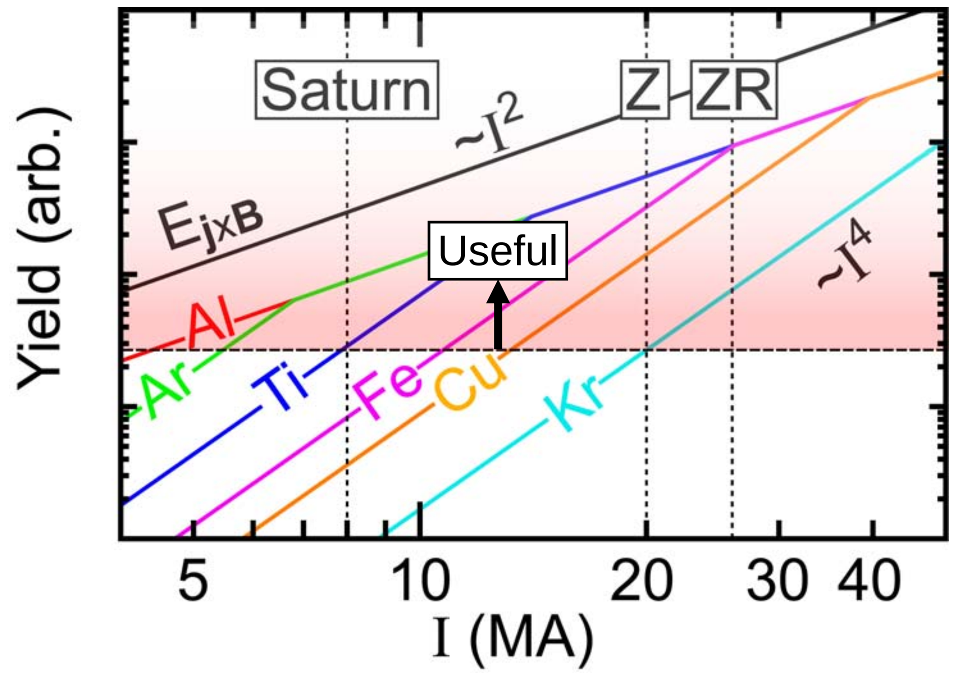
High temperature and density are required for K-shell x-ray excitation

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

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







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

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

	FY08	FY09	FY10	FY11	FY12
Z Shots	20	30	40	30	30
Campaigns	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

▲ Decision on gas puff development

▲ 4 sources available

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K-shell yield model is based on energy coupling scaling matched to empirical data

$$Y_K = f\ S\ E_{\mathbf{j}\times\mathbf{B}}$$

- K. G. Whitney *et al.*, J. Appl. Phys. **67**, 1725 (1990).
- J. W. Thornhill *et al.*, Phys Plasmas **1**, 321 (1994).

$$S = \min\left(1, m/m_{BP}(Z,\eta)\right)$$

$$f = 0.3$$

$$\eta = \frac{E_{\mathbf{j}\times\mathbf{B}} / \left(ml/Am_p\right)}{E_{min}(Z)}$$

Ar gas puff z-pinches

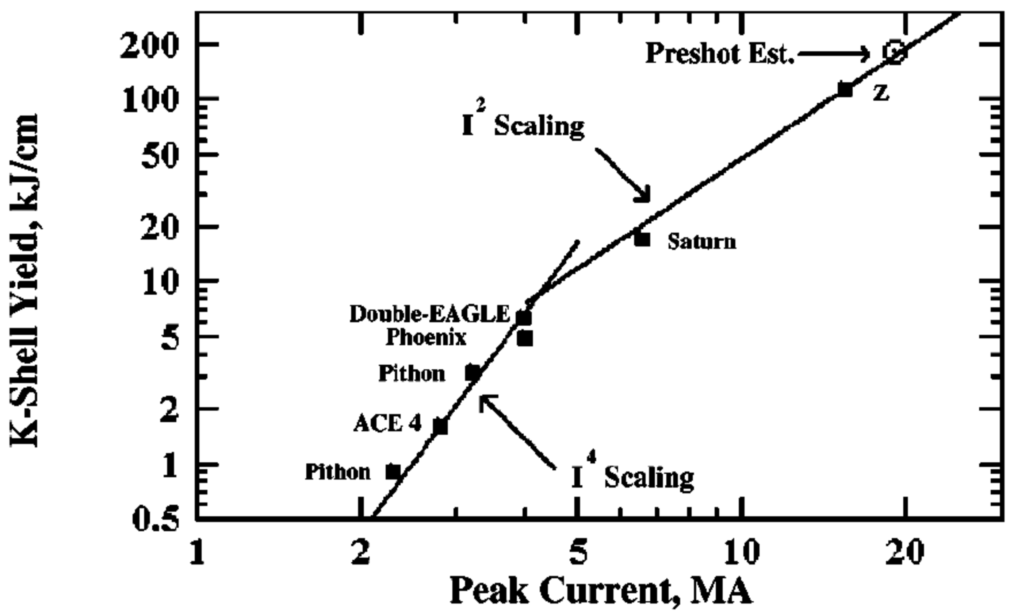

FIG. 3. Empirical scaling of argon *K*-shell yield (kJ/cm) versus peak current for nominal 100 ns implosions.

- H. Sze *et al.*, Phys. Plasmas **8**, 3135 (2001).

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Inefficient I^4 regime transitioning to efficient I^2 scaling dates back to gas puff data from 1980's

$$Y_K = f\, S\, E_{\mathbf{j}\times\mathbf{B}}$$

$$S = \min\left(1, m/m_{BP}(Z,\eta)\right)$$

$$f = 0.3$$

$$\eta = \frac{E_{\mathbf{j}\times\mathbf{B}} / \left(ml/Am_p\right)}{E_{min}(Z)}$$

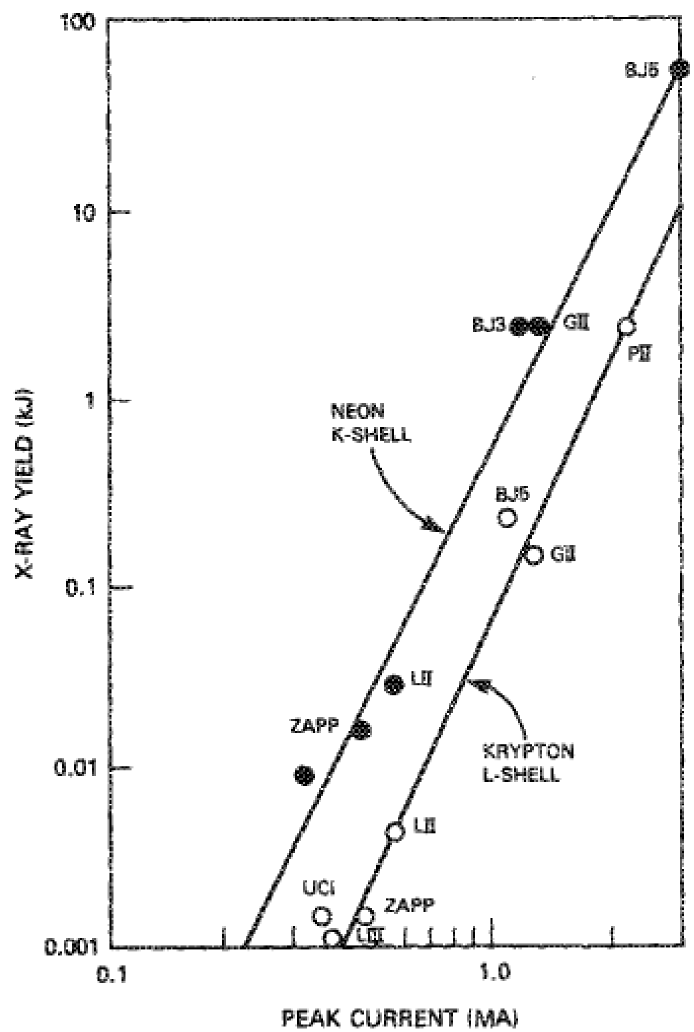

FIG. 5. Optimized radiation yield in neon K lines and krypton L radiation vs peak current I on various pulse power machines (Table I). The yield is proportional to I^4 for both types of radiation (after Pearlman, 1985a).

- N. R. Pereira and J. Davis, J. Appl. Phys. **64**, R1 (1988).

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K-shell scaling model recently updated and benchmarked to Z gas puff and wire array data

$$Y_K = f\ S\ E_{\mathbf{j}\times\mathbf{B}}$$

$$S = \min\left(1, m/m_{BP}(Z,\eta)\right)$$

$$f = \min\left(0.3,\ c(Z,\text{load})\, Z^{1.2} E_{\mathbf{j}\times\mathbf{B}}^{3/2} / m^{5/2}\right)$$

$$\eta = \frac{E_{\mathbf{j}\times\mathbf{B}} / \left(ml/Am_p\right)}{E_{min}(Z)}$$

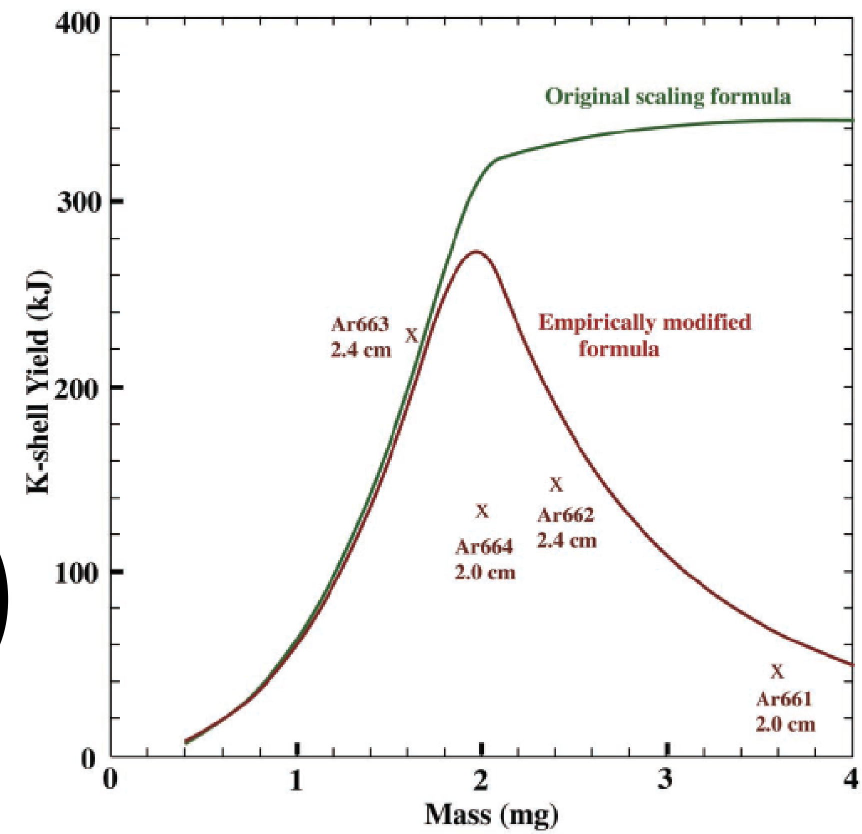

Fig. 2. Scaling predictions and measured yields for 4-cm diameter, 2-cm length, 1-2-3-4 nozzle configuration with equal masses in each annulus [13], experiments on the Z machine. Experimental shot numbers and pinch lengths are specified. Experimental results are normalized to 2 cm. For example, Ar662 produced 179 kJ and its mass was 2.88 mg. In the modified model, the K-shell conversion efficiency falls off at $m > m_{\mathrm{BP}}$.

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

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K-shell yield model benchmarked to single wire array data from Z experiments

- 1D RMHD with detailed atomic physics also applied to assess scaling in Z regime

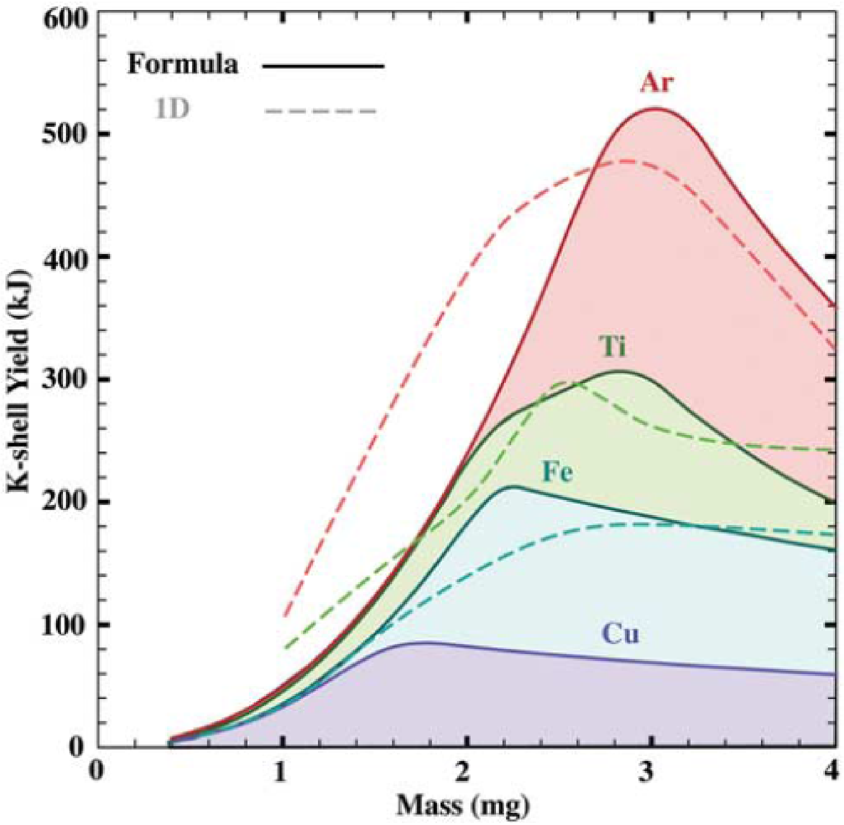


Fig. 11. Empirical formula and 1-D phenomenological predictions for K-shell yields on ZR. Fe and Cu predictions are for 55-mm-diameter single wire arrays, Ti predictions are for 45-mm-diameter single wire arrays, and argon predictions are for 8-cm-diameter 1-2-3-4 double-shell gas-puff nozzle configurations with equal masses in each annulus. There is no 1-D result for Cu.

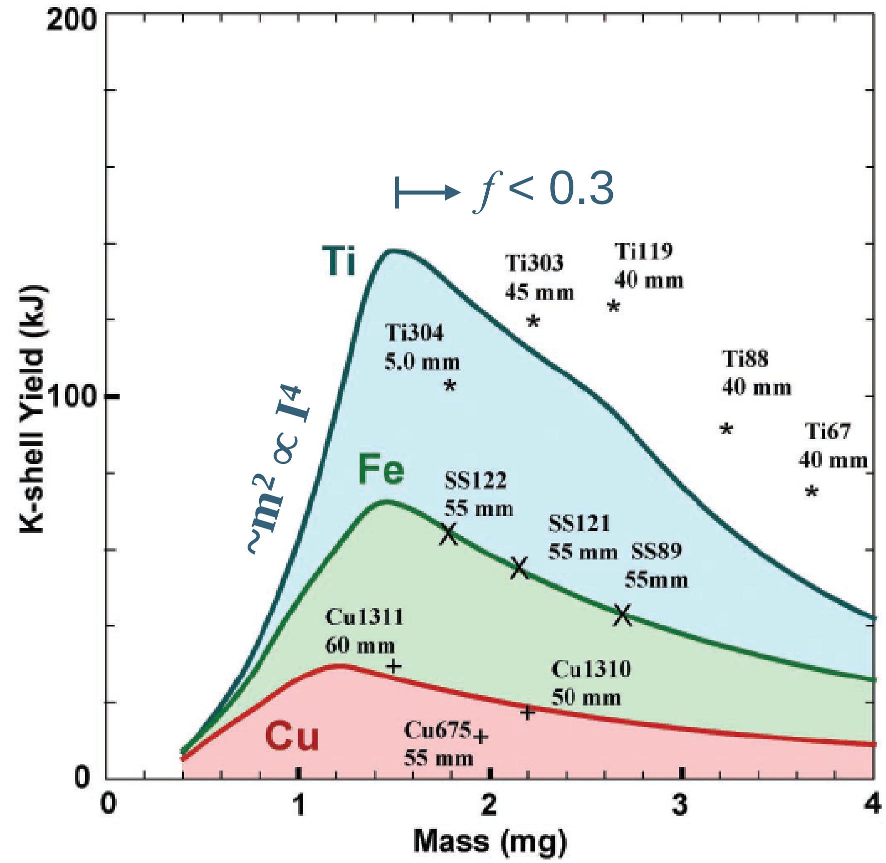
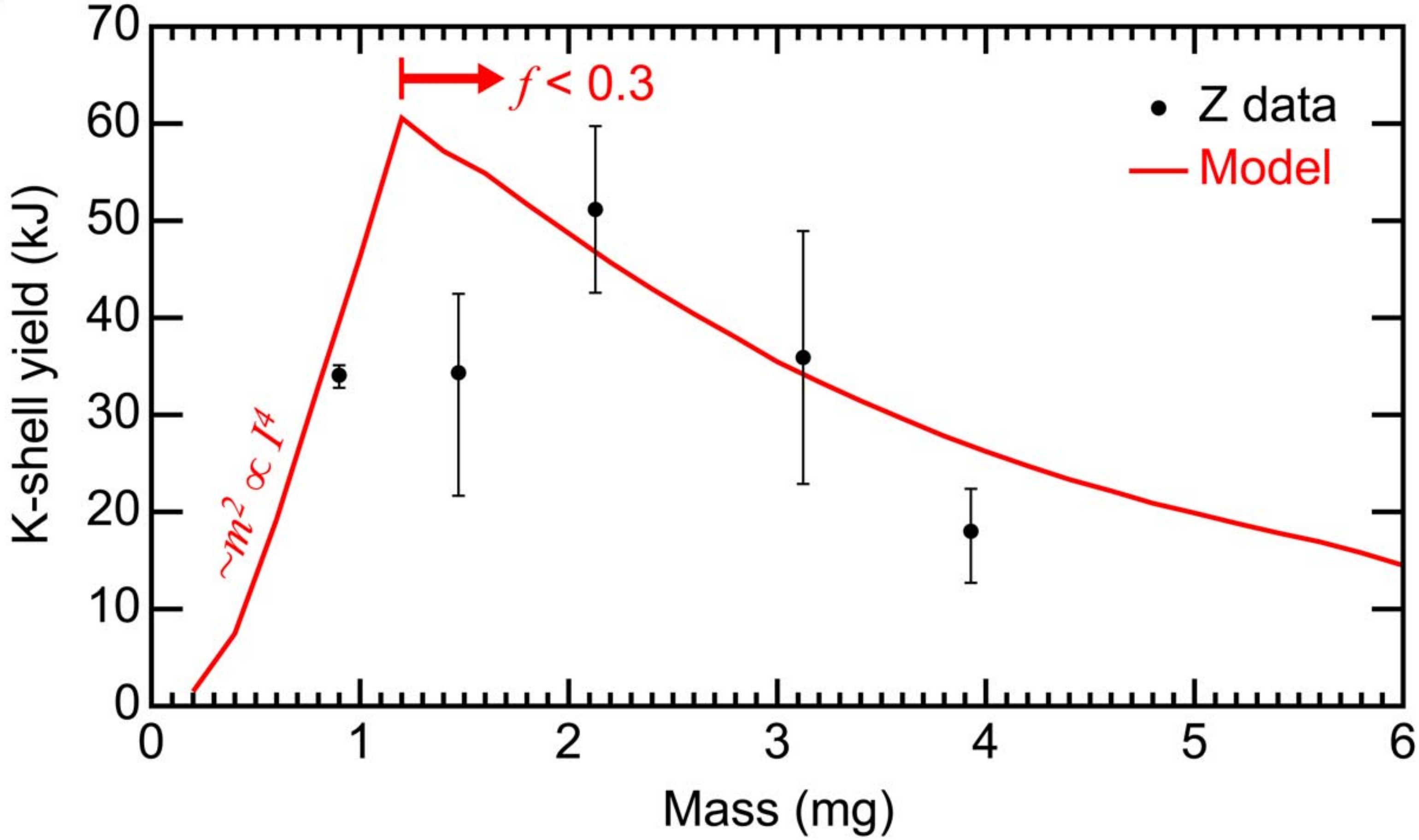


Fig. 3. Empirical formula scaling benchmarks and measured yields for 2-cm length single-wire-array experiments on the Z machine. Experimental shot numbers and load diameters are specified. Copper and iron (stainless steel) benchmarks are modeled as 55-mm-diameter array; titanium benchmarks are modeled as 45-mm-diameter arrays.

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

K-shell yield model is reasonably applied to nested stainless steel wire array data on Z



- Waisman 0D code is used to estimate E_{jxB} and thus η in the NRL scaling model
  - Inductive current switch between arrays; 25% momentum transfer
  - No ablation model included
  - 1 mm final radius, motivated by pinhole imaging

In the Z-accessible regime, K-shell scaling for Fe reduces to a simple expression

$$Y_K = f\ S\ E_{\mathbf{j}\times\mathbf{B}}$$

$$S = \min\left(1, m/m_{BP}(Z,\eta)\right) \longrightarrow m/m_{BP}(Z,\eta=4)$$

$$f = \min\left(0.3,\ c(Z,\text{load})\,Z^{1.2}E_{\mathbf{j}\times\mathbf{B}}^{3/2}/m^{5/2}\right) \longrightarrow c(Z,\text{load})\,Z^{1.2}E_{\mathbf{j}\times\mathbf{B}}^{3/2}/m^{5/2}$$

$$\eta = \frac{E_{\mathbf{j}\times\mathbf{B}}/\left(ml/Am_p\right)}{E_{min}(Z)}$$

$$\boxed{Y_K = c(Z,\text{load})\,F(Z)\,\eta^{5/2}ml}$$

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

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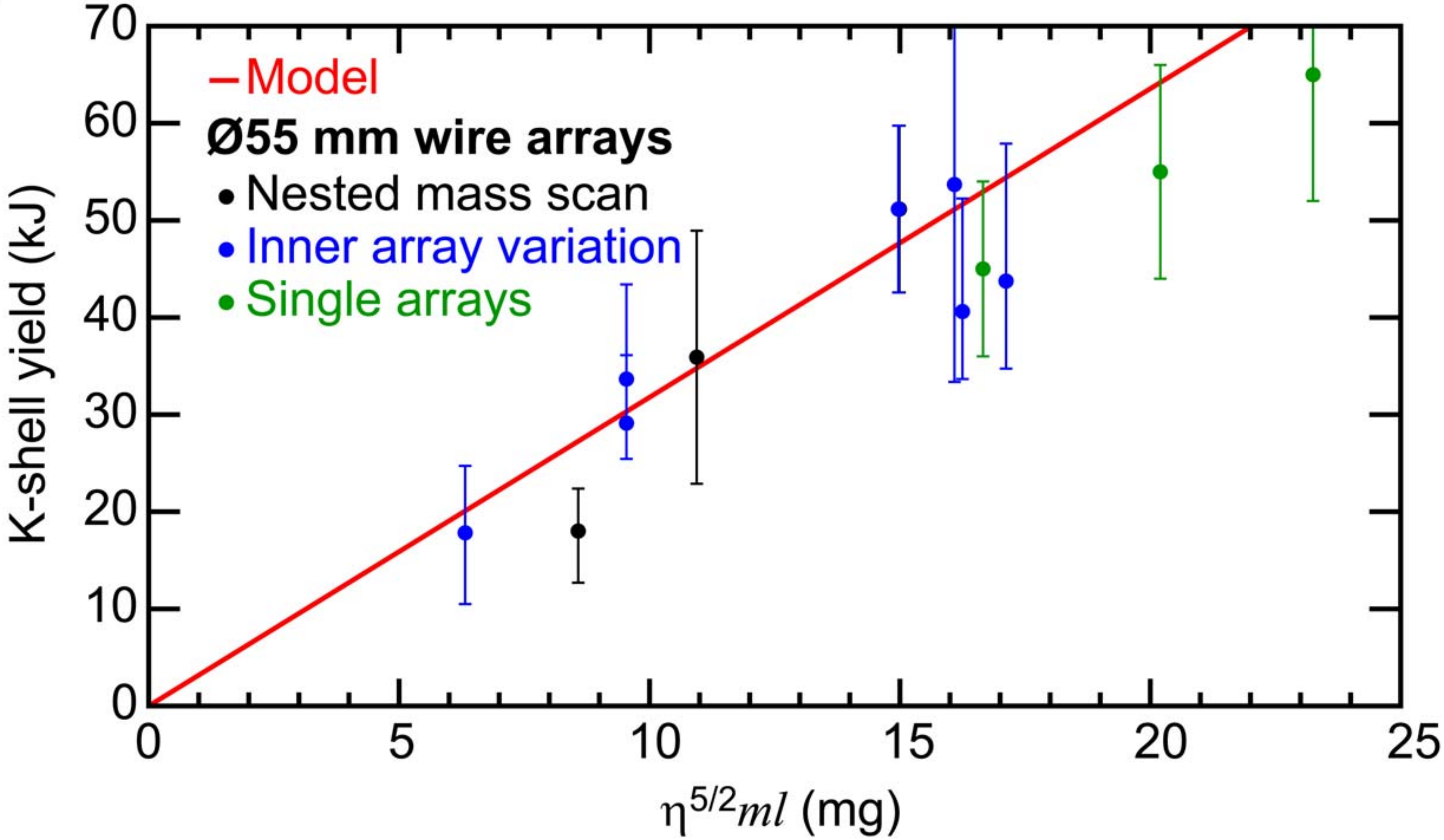
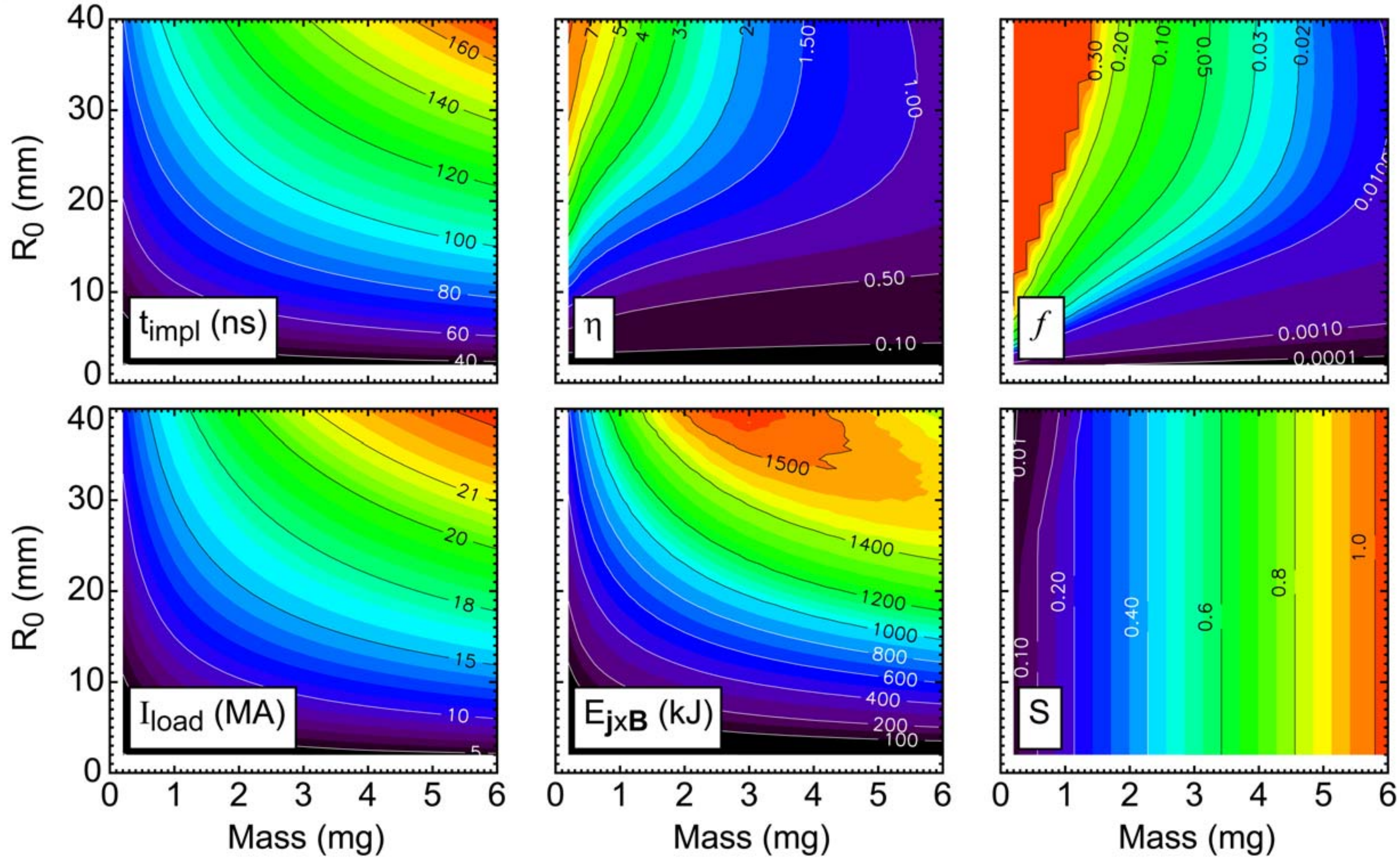
K-shell yield model benchmarked to nested stainless steel wire array data on Z



- 0D implosion model is used to estimate E_{jxB} and thus η in the NRL scaling model
  - Inductive current switch between arrays; 25% momentum transfer
  - No ablation model included
  - 1 mm final radius, motivated by pinhole imaging

K-shell yield model coupled with 0D implosion simulation guides shot design on the new Z



- **Waisman 0D model is used to estimate E_{jxB} and thus η in the NRL scaling model**
- **Lemke V_{OC} waveform rescaled for 82 kV Marx charge**

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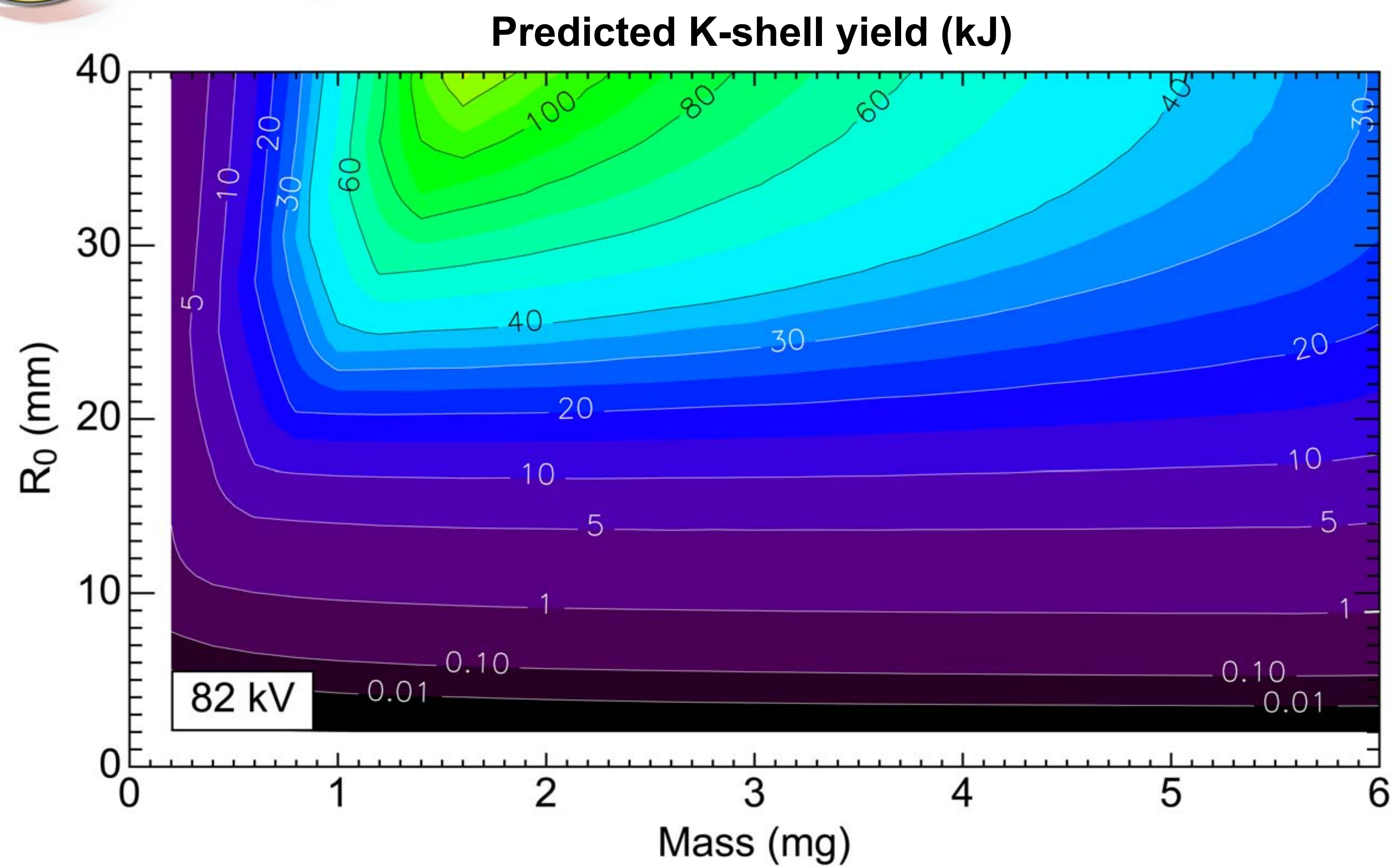
K-shell yield predicted with scaling model and 0D simulation over m,R_0 parameter space



- **Waisman 0D model is used to estimate E_{jxB} and thus η in the NRL scaling model**
- **Lemke V_{OC} waveform rescaled for 82 kV Marx charge**

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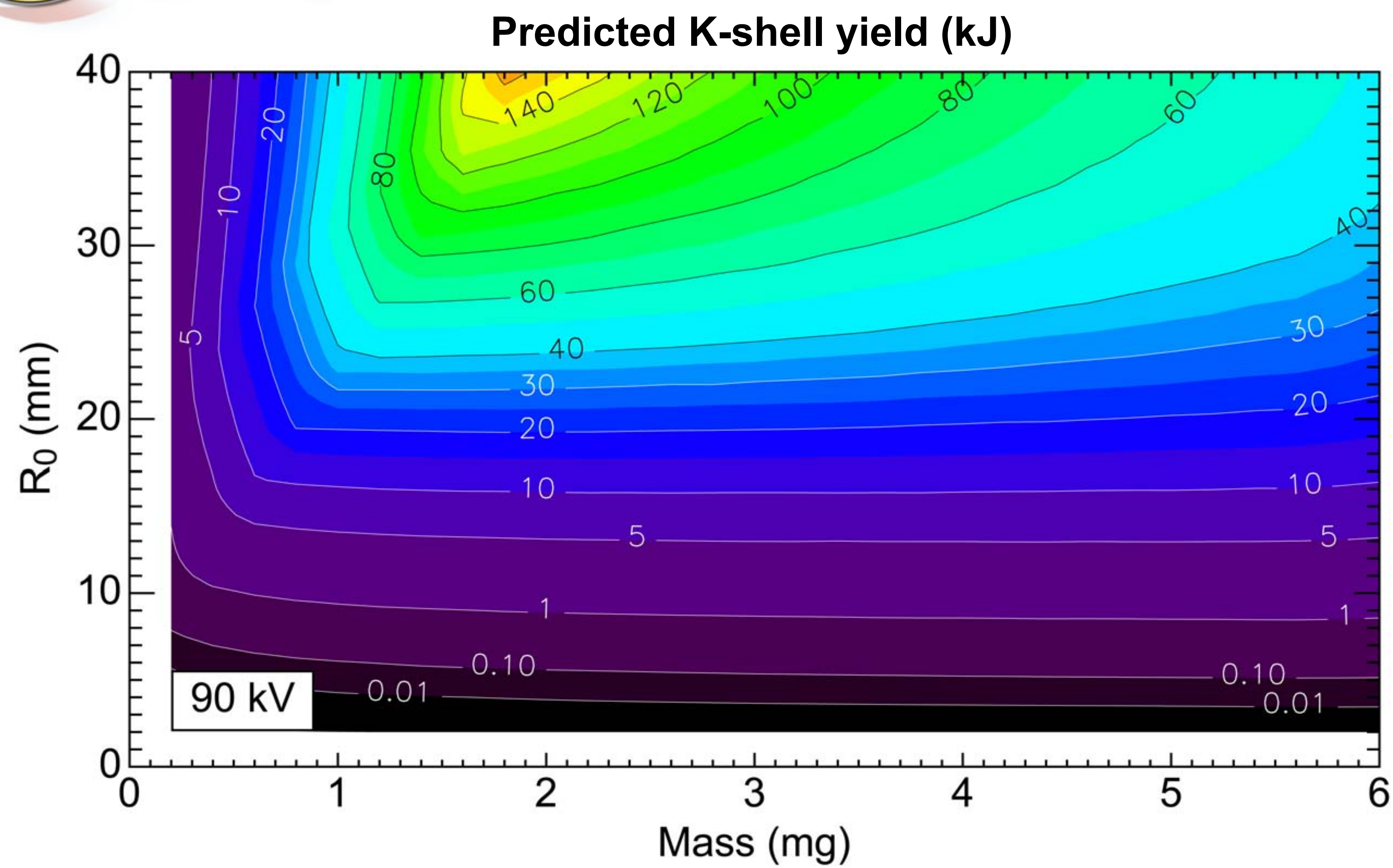
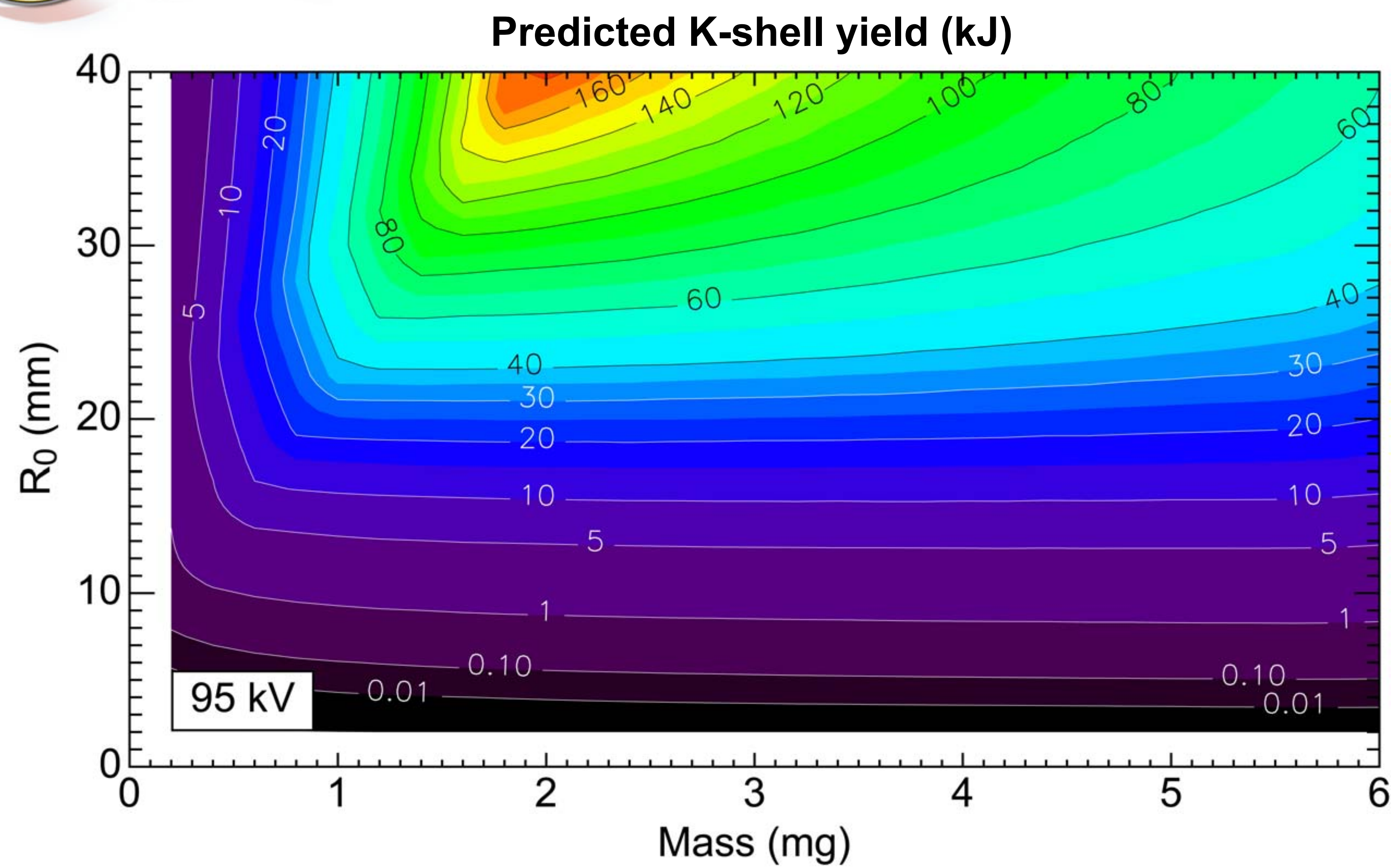
K-shell yield predicted with scaling model and 0D simulation over m,R_0 parameter space



- **Waisman 0D model is used to estimate E_{jxB} and thus η in the NRL scaling model**
- **Lemke V_{OC} waveform rescaled for 90 kV Marx charge**

K-shell yield predicted with scaling model and 0D simulation over m,R_0 parameter space



- Waisman 0D model is used to estimate E_{jxB} and thus η in the NRL scaling model
- Lemke V_{OC} waveform rescaled for 95 kV Marx charge

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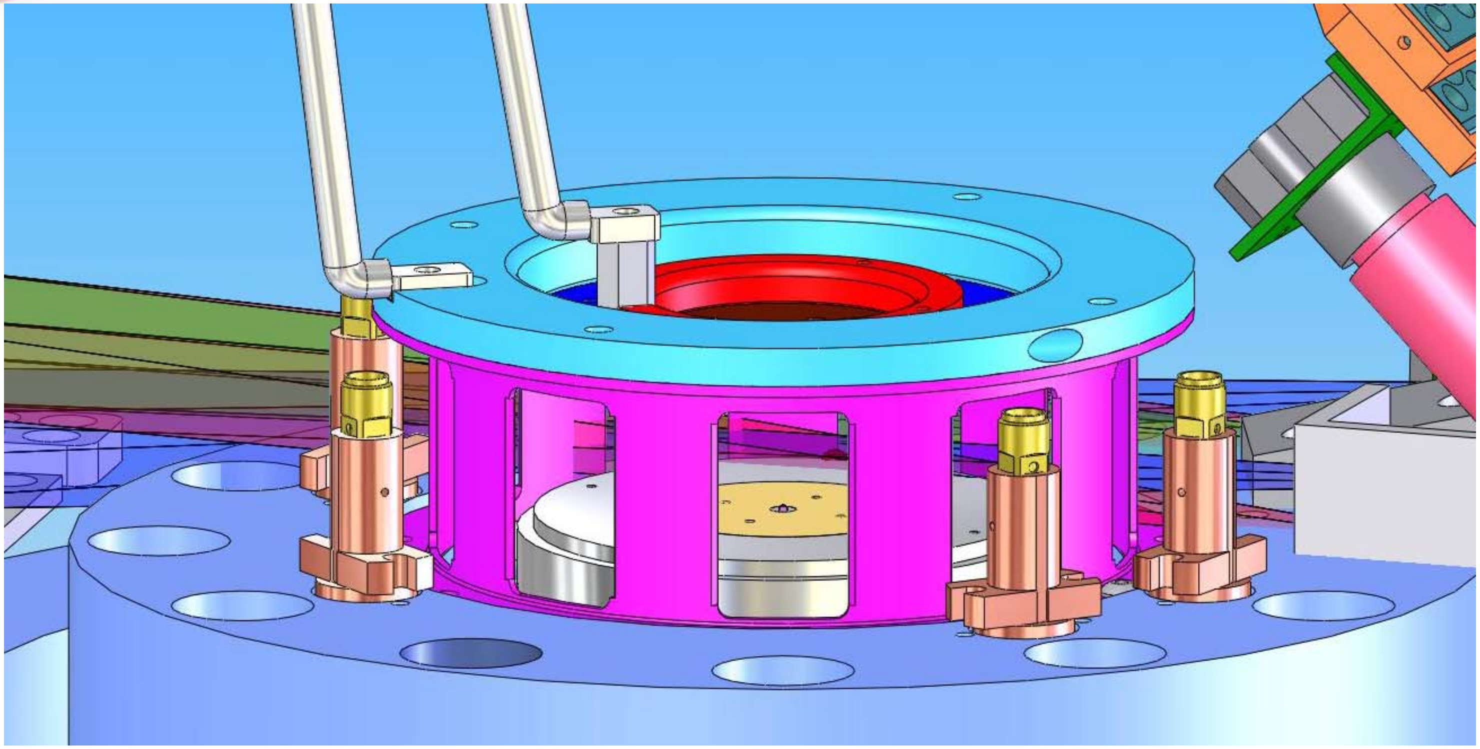
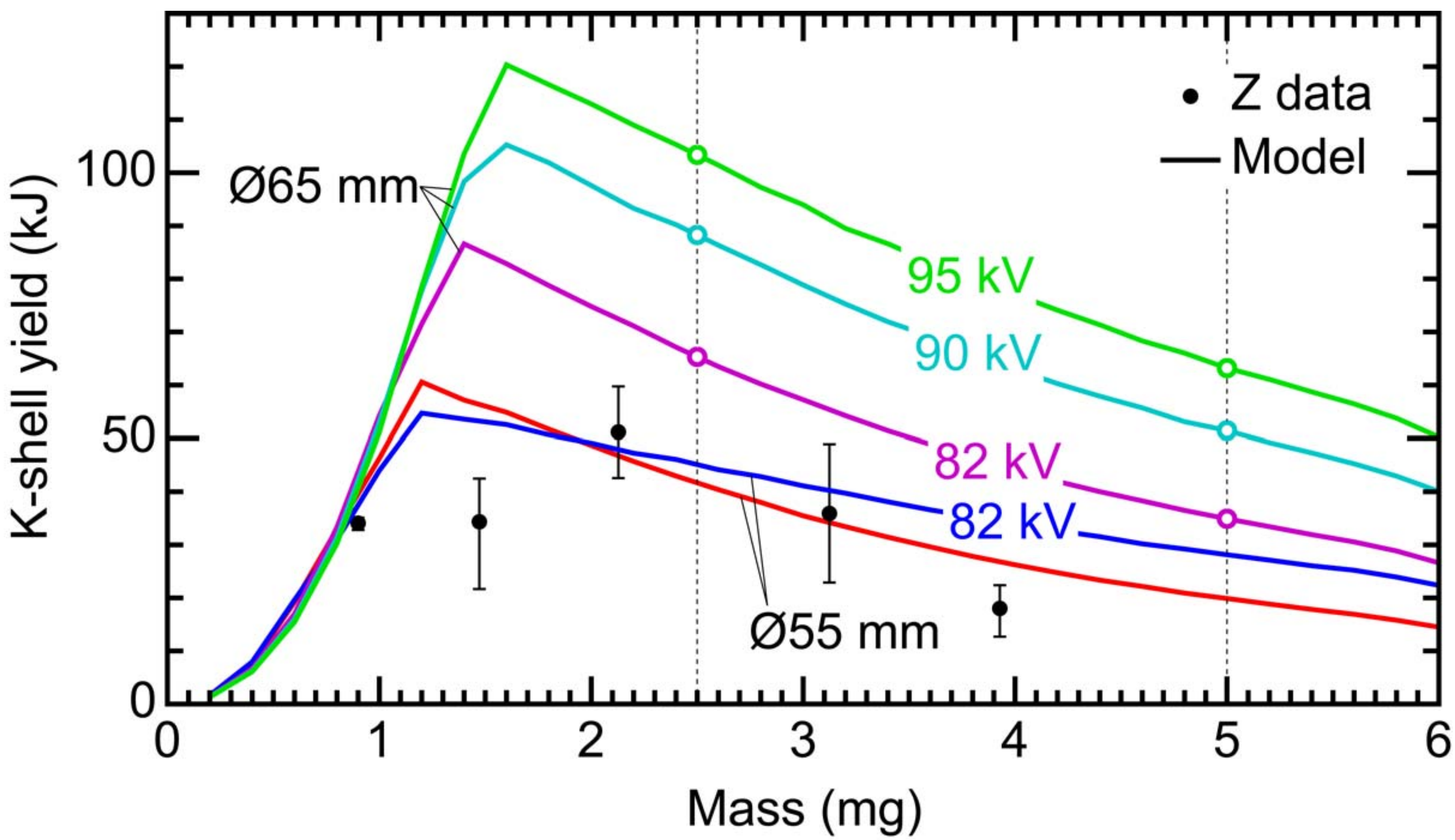
Hardware design in progress: convolutes and load B-dot limit maximum pinch diameter



- **Maximum load diameter is 65 mm with load B-dots and present convolute**
  - **80 mm is possible without load B-dots (C. A. Coverdale)**
  - **B-dots are essential for characterizing Z_{flow} losses**
  - **Still working on opening gap between B-dot and return current can**
- **9.75 mm AK gap, 7 mm convolute feed: more conservative than previous shots**
- **9-slot geometry, 16 mm wide rectangular slots extending full height of can**
- **Load raised 4 mm for ZBL diagnostic access**

K-shell predictions indicate robust load design with potential yield increase over prior Z shots



- 2.5 mg chosen to be near K-shell yield optimum but avoid drop at low mass
- 5 mg load will test model in $\eta^{5/2}ml$ scaling regime, and have higher wire number
- Increasing Marx charge will enhance yield for fixed load design

FY08 RES shot plan

- June 2008: 6 shots
  - All nested stainless steel wire arrays with 2:1 mass and radius ratio
  - 20 mm tall, 9.75 mm AK gap, 8.15 μm diameter SS304 wire

Number of shots	Outer array dia. (mm)	Outer wire number	Inter-wire gap (mm)	Total mass (mg)	0D calculation			
					Marx charge (kV)	Implosion time (ns)	Peak current (MA)	Predicted K-shell yield (kJ)
2	65	200	1.0	2.5	82	119	19.4	65
					90	113	20.6	88
					95	111	21.2	103
2	65	400	0.5	5.0	82	142	21.7	35
					90	135	23.1	51
					95	131	24.0	63
2	65	200	1.0	2.5	As above for 2.5 mg Cathode modification			

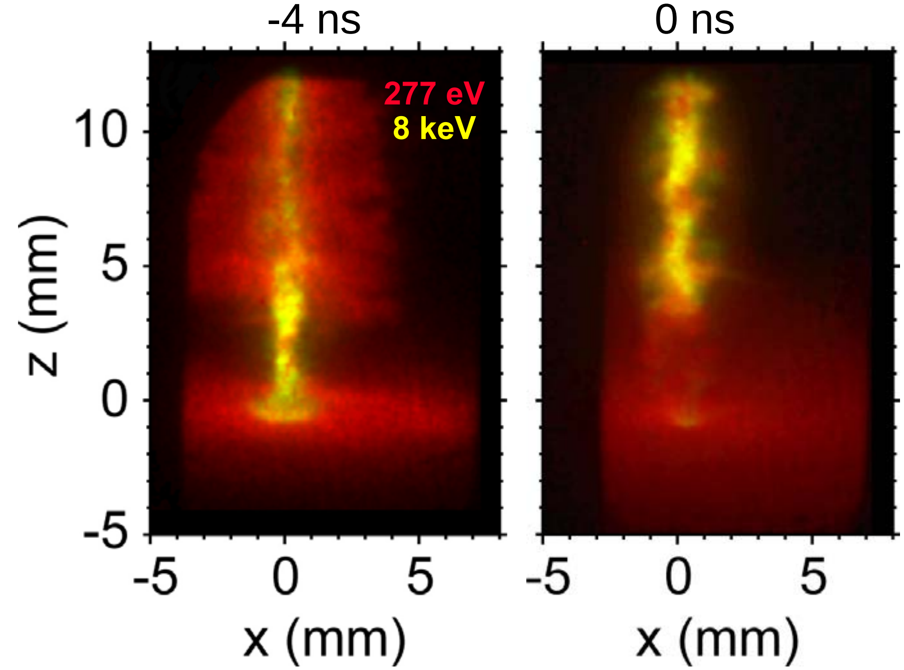
- September 2008: 10 shots
  - Copper nested wire arrays (6 shots)
  - Larger diameter nested stainless steel (requires larger convolute)
  - Triple nested wire arrays

End effects have been observed on many different drivers with different array configurations

- **On Z, MLM (multi-layer-mirror) diagnostic demonstrates early implosion near base of array**
  - **Lower photon energy (red) indicates non-uniform implosion (most of array still imploding when cathode has stagnated**
  - **Higher photon energy (yellow) shows emission from cathode first, and then rest of axis**

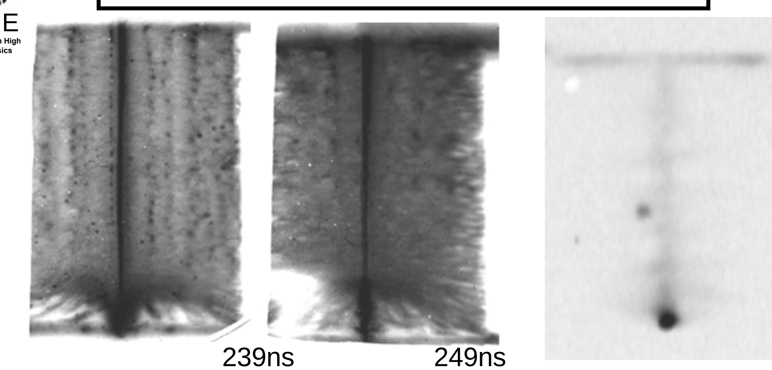
- **Data on MAGPIE shows effect initiated near cathode contact point**
  - **Bubble implodes, and propagates axially**
  - **Time integrated emission shows non-uniformity**

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

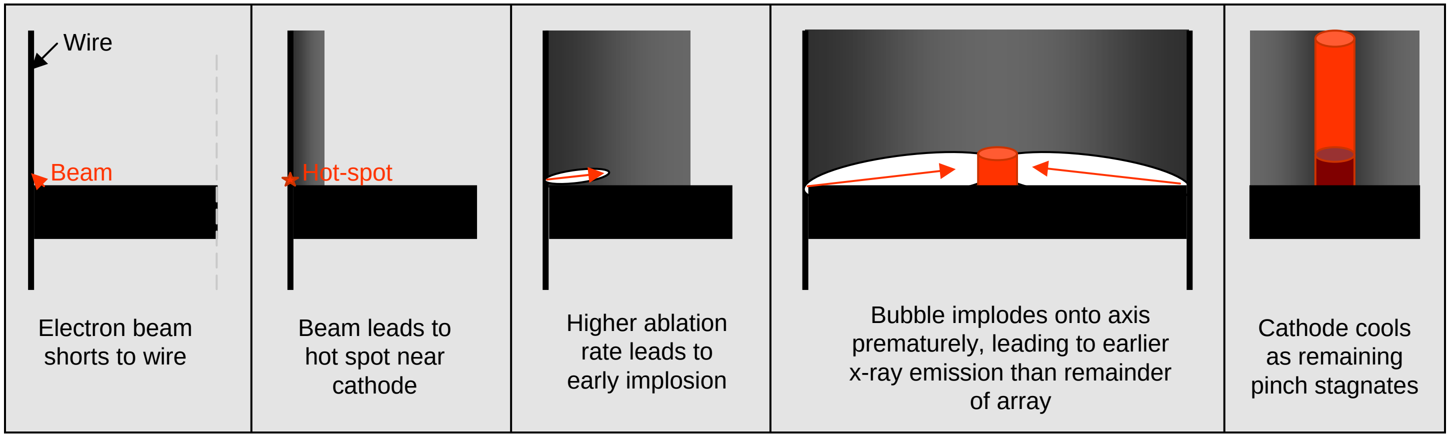


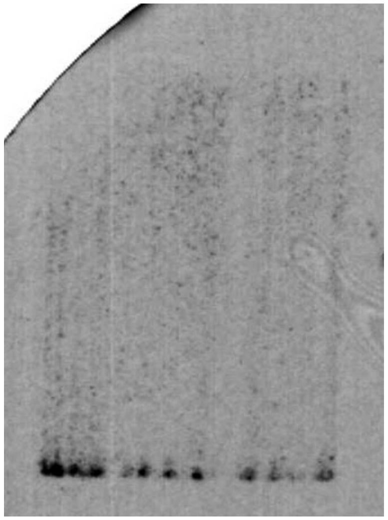
MAGPIE
Centre of Excellence in High Energy Plasma Physics

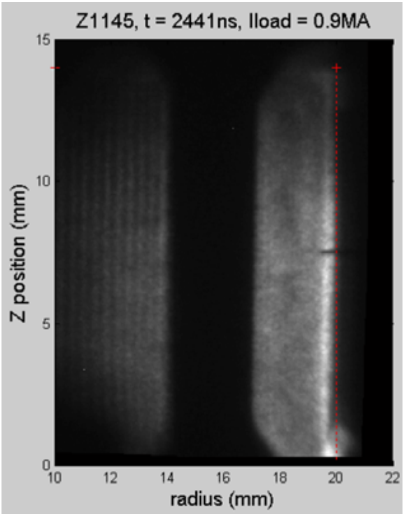
XUV and soft x-ray imaging on MAGPIE
S.N. Bland et al. Rev Sci Inst 75, 3941 (2004)



Early cathode implosion could be initiated by a hot-spot at the wire-cathode contact point

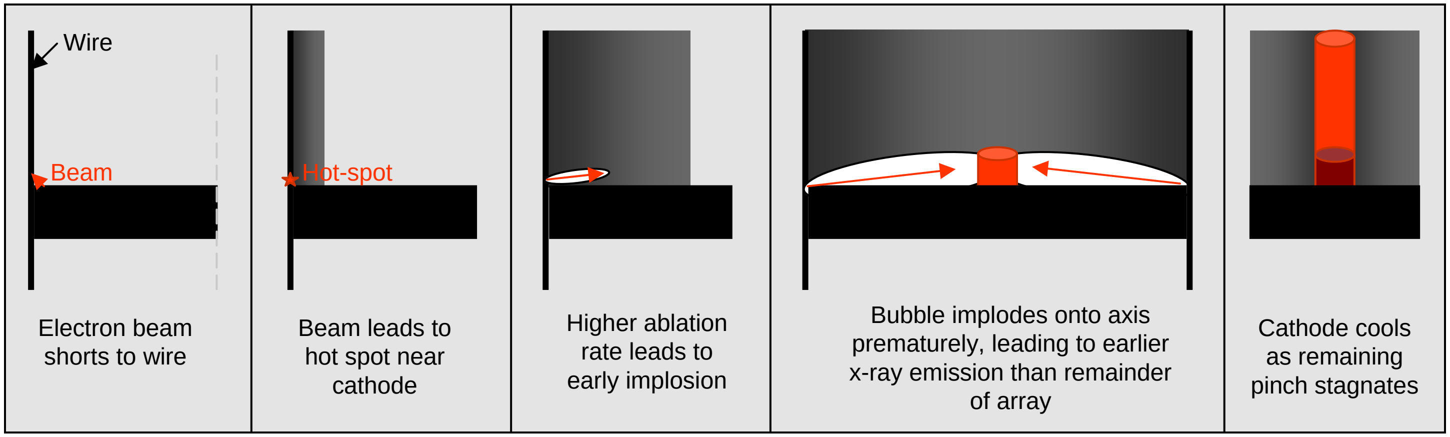




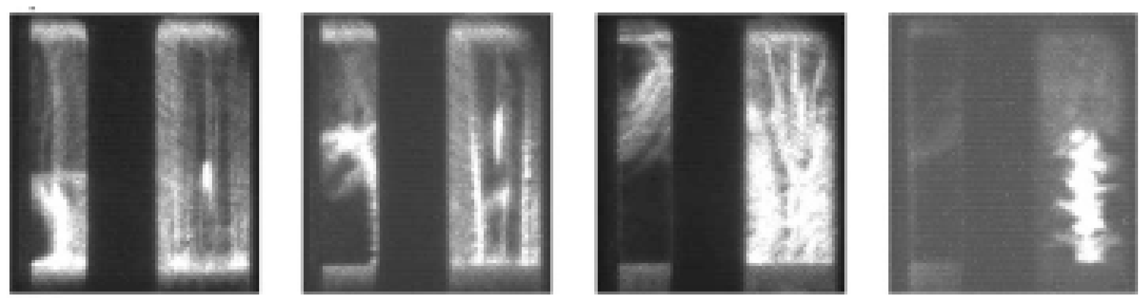


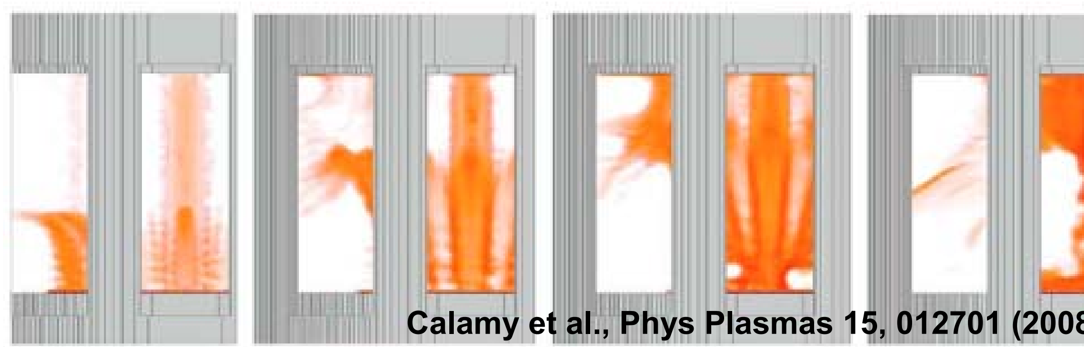
Data from both MAGPIE and Z demonstrate a hot spot at the wire-cathode contact point

Early cathode implosion could be initiated by a hot-spot at the wire-cathode contact point



- **Bubble propagates to the axis and grows axially**
- **MHD simulations (Chittenden et al.) can match dynamics well by initiating wire with a hot-spot**
- **Proposed as mechanism for top-bottom asymmetry observed by T. Sanford *et al.***

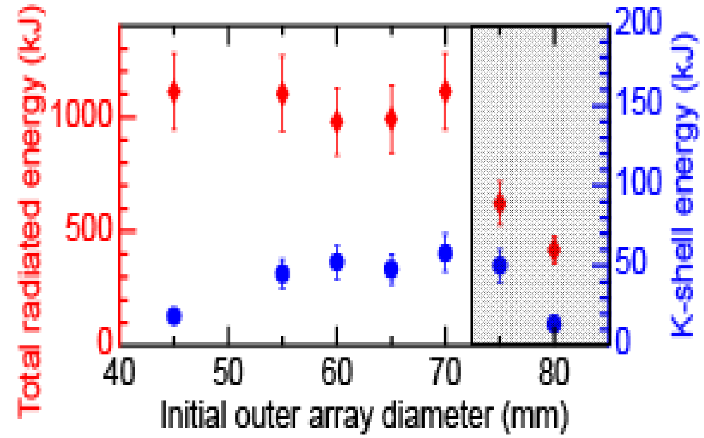


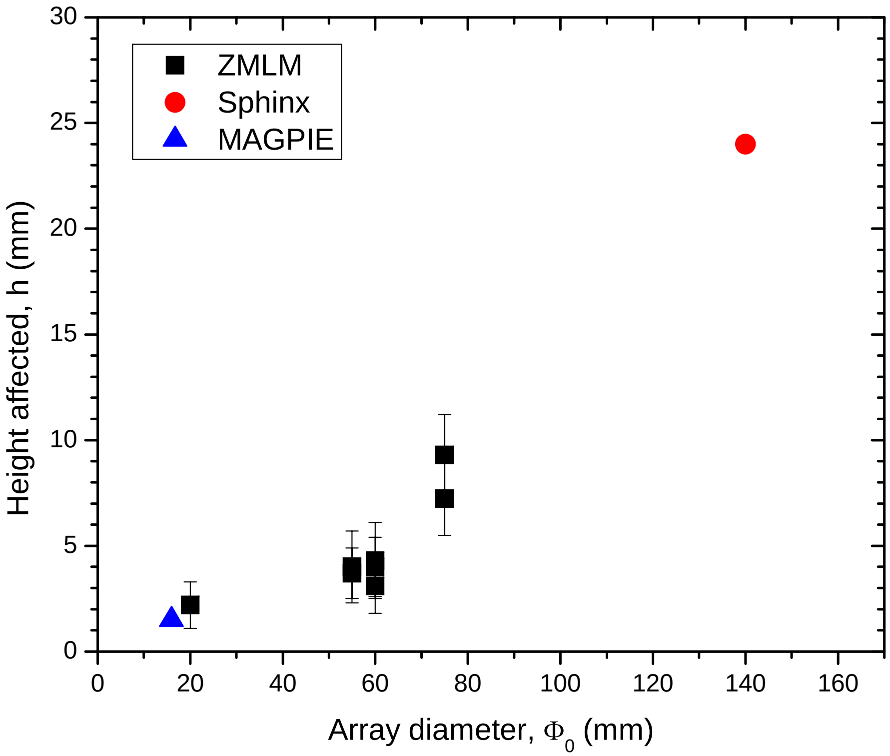


Calamy et al., Phys Plasmas 15, 012701 (2008)

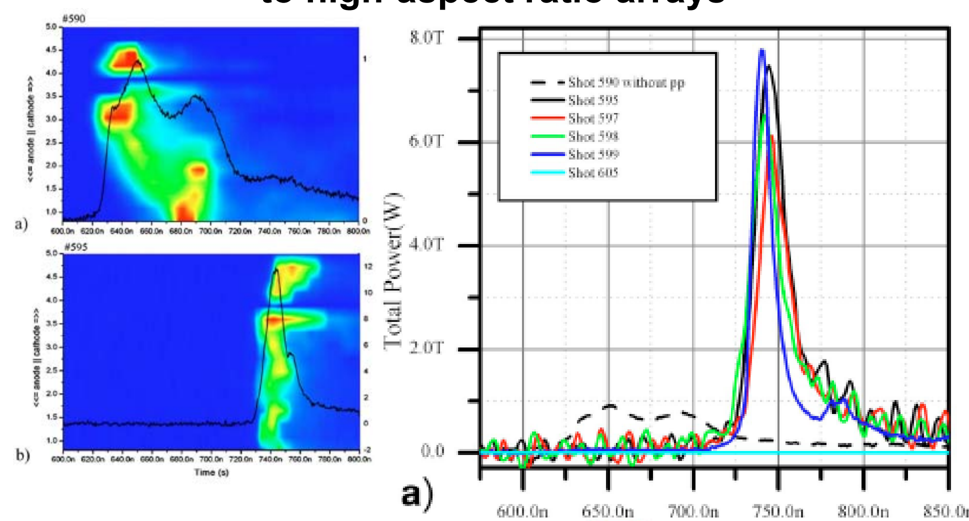
Axial non-uniformity becomes critical for high-aspect-ratio arrays, such as used for RES

- End effects increase with increasing array diameter
- RES uses these large diameter arrays
- With new Z, will try to access even larger diameters





Gramat data shows huge difference to high-aspect ratio arrays



Calamy et al., Phys Plasmas 15, 012701 (2008)

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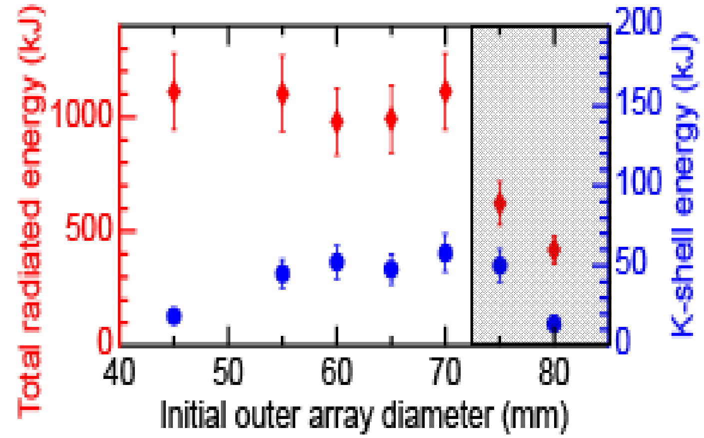

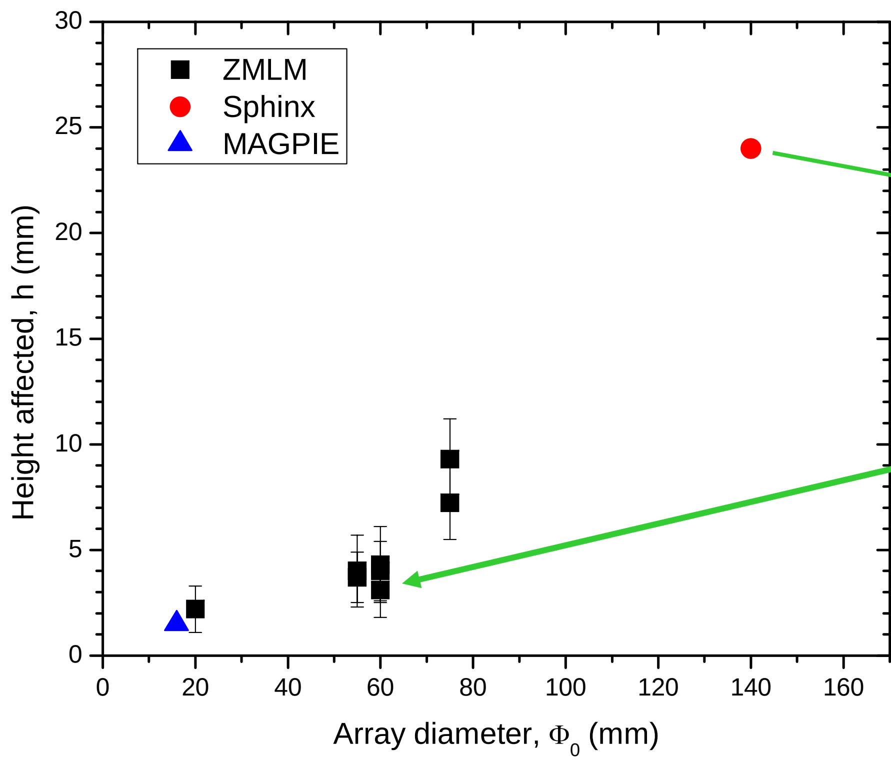

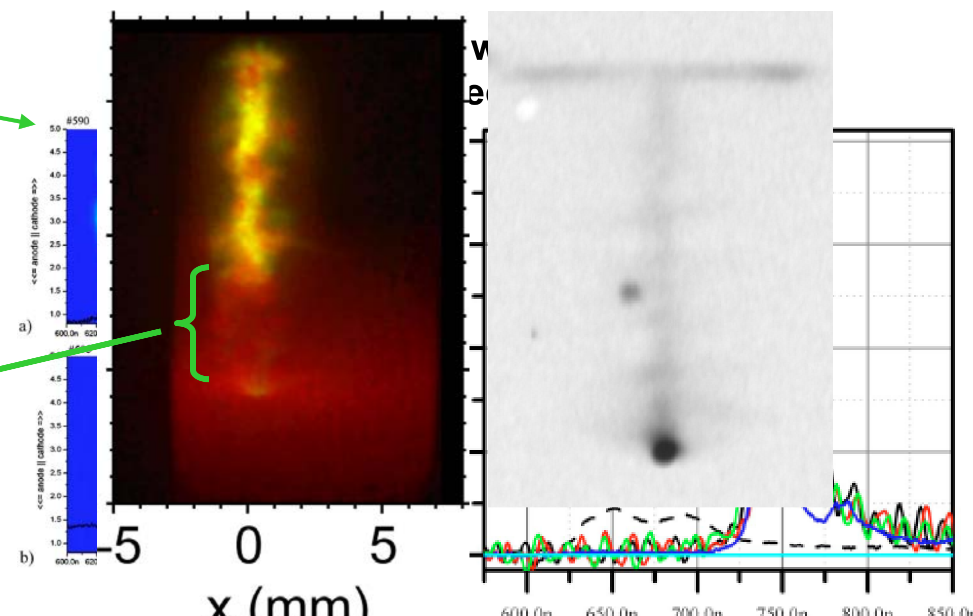

Calamy et al., Phys Plasmas 15, 012701 (2008)

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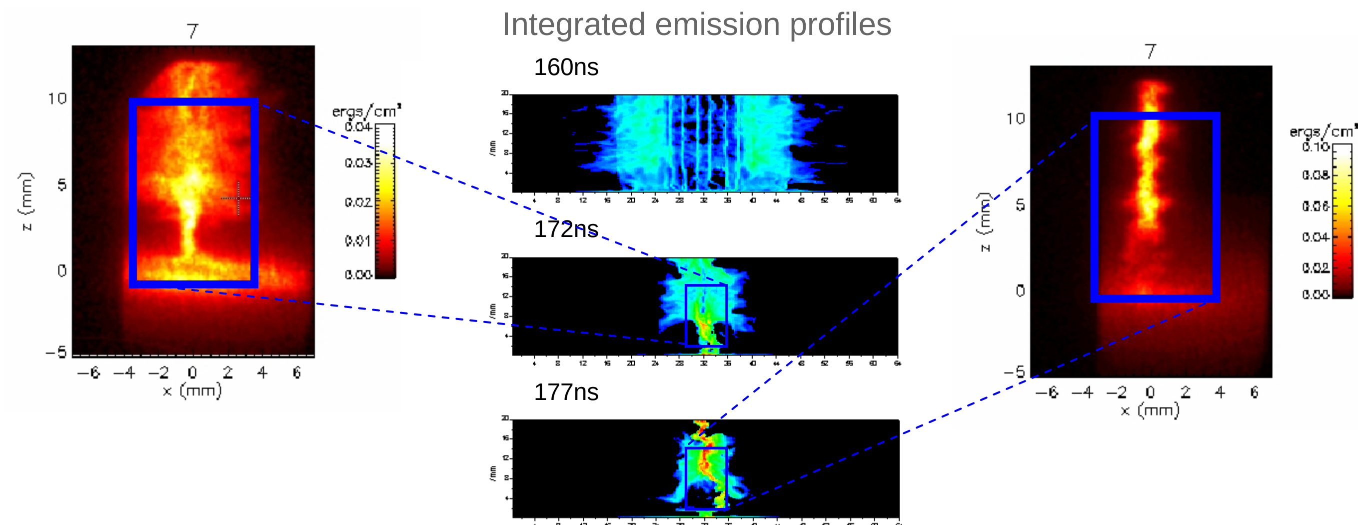
MHD simulations can match ‘bubble’ and indicate possible solution is place a *step* on the cathode surface

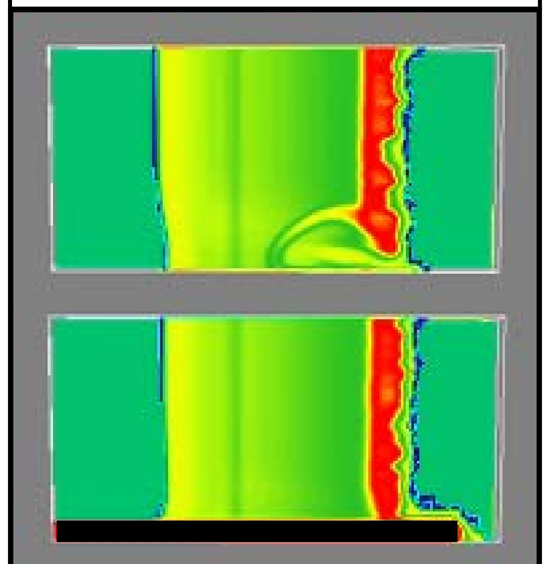
Simulations of Z Shot 1617
- **60mm on 30mm array diameters**
- **80 on 40 copper wires**

- **Simulations with Gorgon are able to recreate effect of bubble**
- **Seeded with a 0.5eV hot spot in the core near the cathode contact point**



- **Simulations indicate that a step effectively eliminates the propagation of the bubble to the array axis.**

Cathode step (black) blocks end-effect

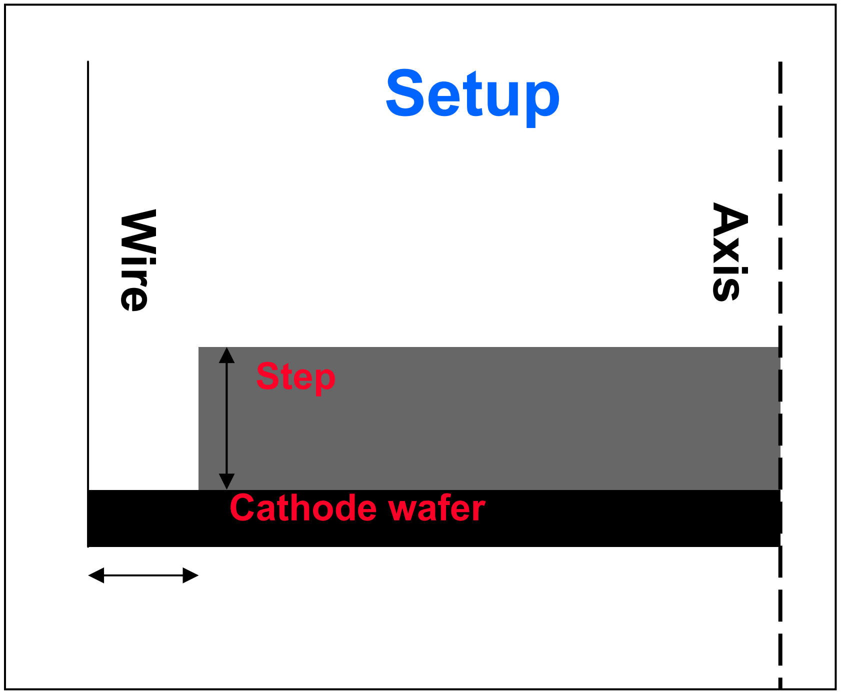


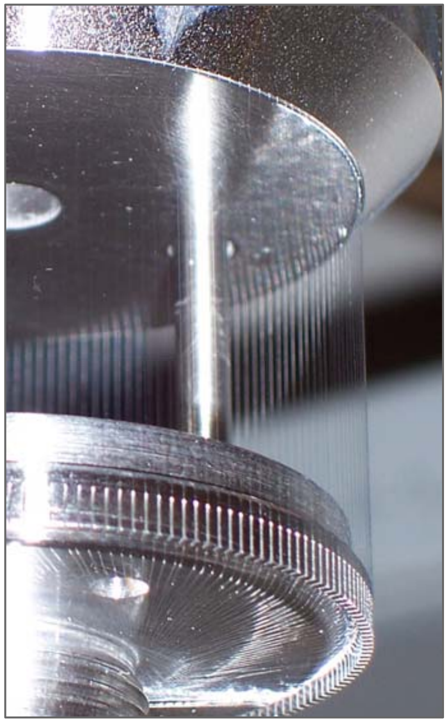
3D MHD models courtesy of Chris Jennings

Experiments on Saturn tested this configuration

180x12.7μm Al 5056 on 40mm diameter, 20mm tall

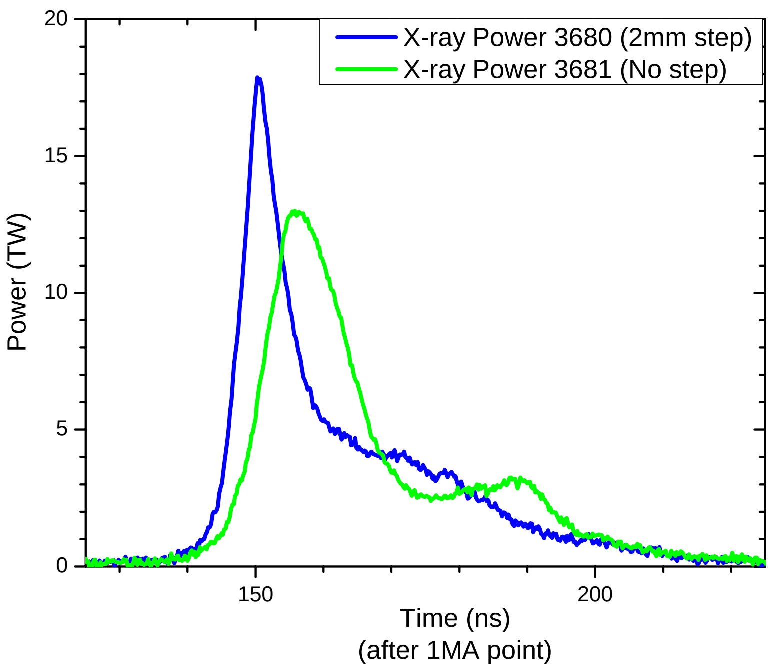
- 8 shots on Saturn trying difference step diameters and heights
- 4 reference shots with no step taken for comparison

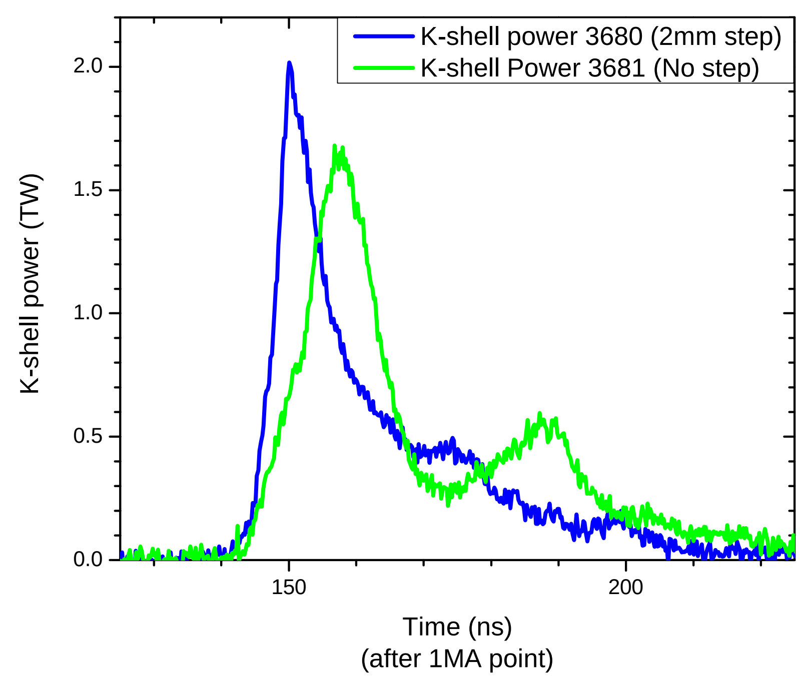


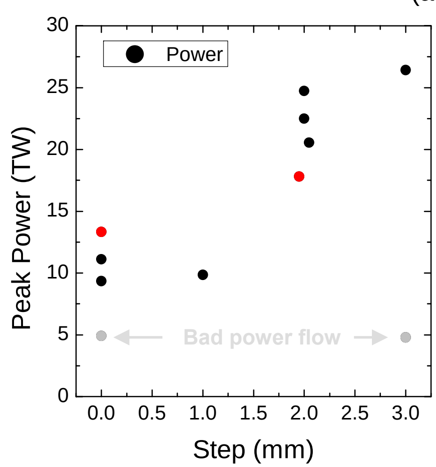


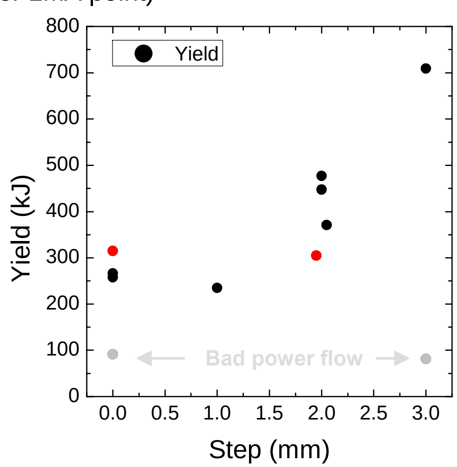
Saturn data indicates Increased in full spectrum and K-shell powers

180x12.7µm Al 5056 on 40mm diameter, 20mm tall









Questions:
Why are x-rays earlier?
Is the step doing what we think?

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2 shots on Z planning to examine effects further

- Using step 2mm tall and 2mm in from the wire
  - Setup that worked well on Saturn
- Nested array, 2mg outer at 65mm diameter
- Will have 2 identical step shots, with
  - Use 2 no-step shots from mass scan as a reference
- Field of view will be significantly better than on Saturn
- Hopefully ZBL will image end effects

Diagnostic requirements focus on evaluating source for RES, but also aim to bring a physical understanding

Priority 1
Priority 2
Developmental

K-shell energy

- Integrated PCD (need re-calibrating)
- Au bolometers (need significantly better signal to noise)
- In chamber P.D.I. (S.C.Jones, 1344)
- In chamber bolometers

Need to work towards ~10% accuracy in power/yield measurements

K-shell pulse shape

- PCD (need re-calibrating)
- Ga-As PCD
- K-shell version of TEP???

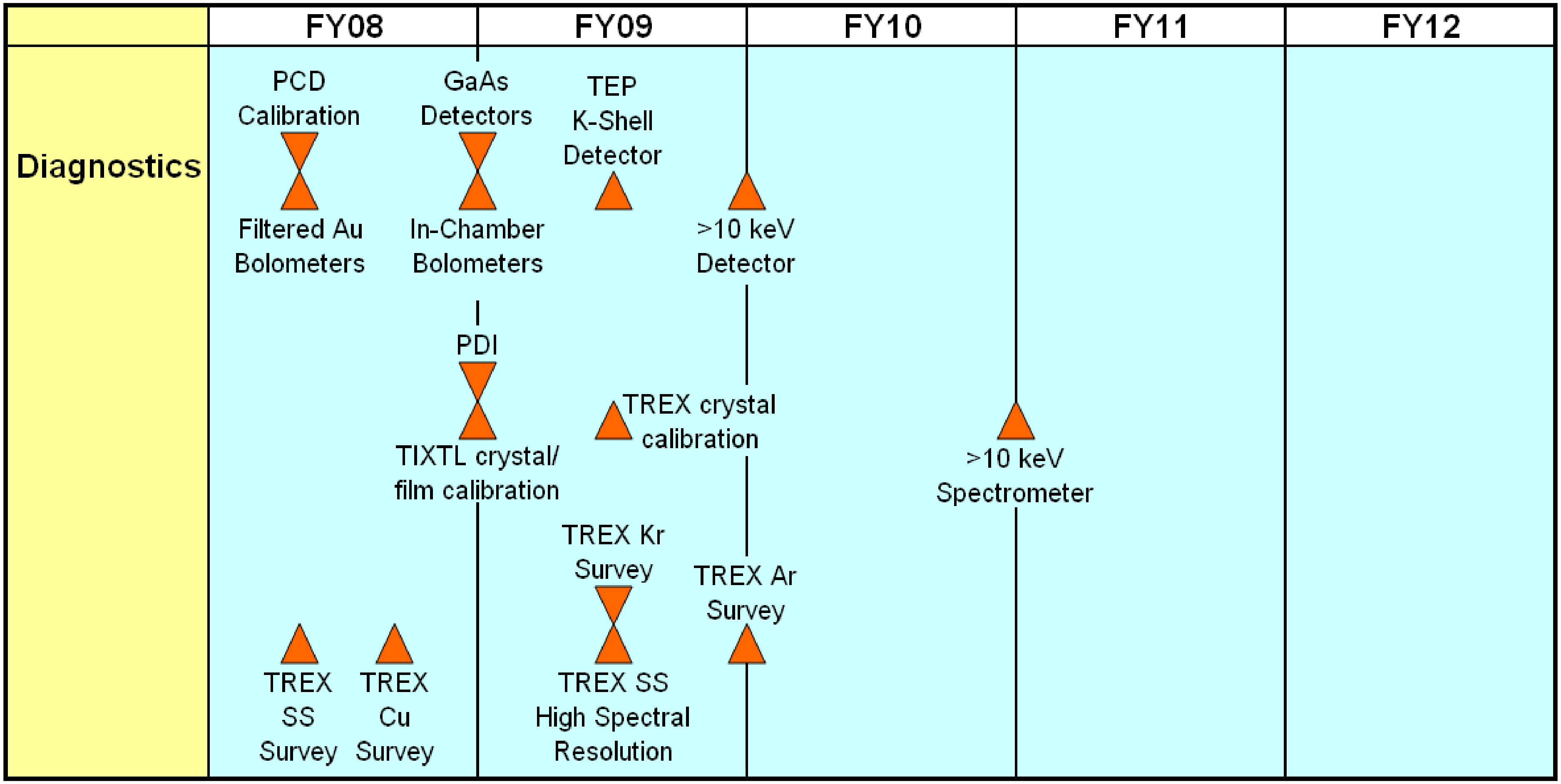
K-shell spectrum

- TIXTL (configurations, alignment, film cal, Crystal cal, analysis)
- TREX (configurations, MCP cal, radial & ?axial?, analysis)

Source-size & dynamics

- MLM central camera (SS K-shell)
- MLM mirrored cameras (277eV)
- ZBL

K-shell diagnostics will be developed in step with the 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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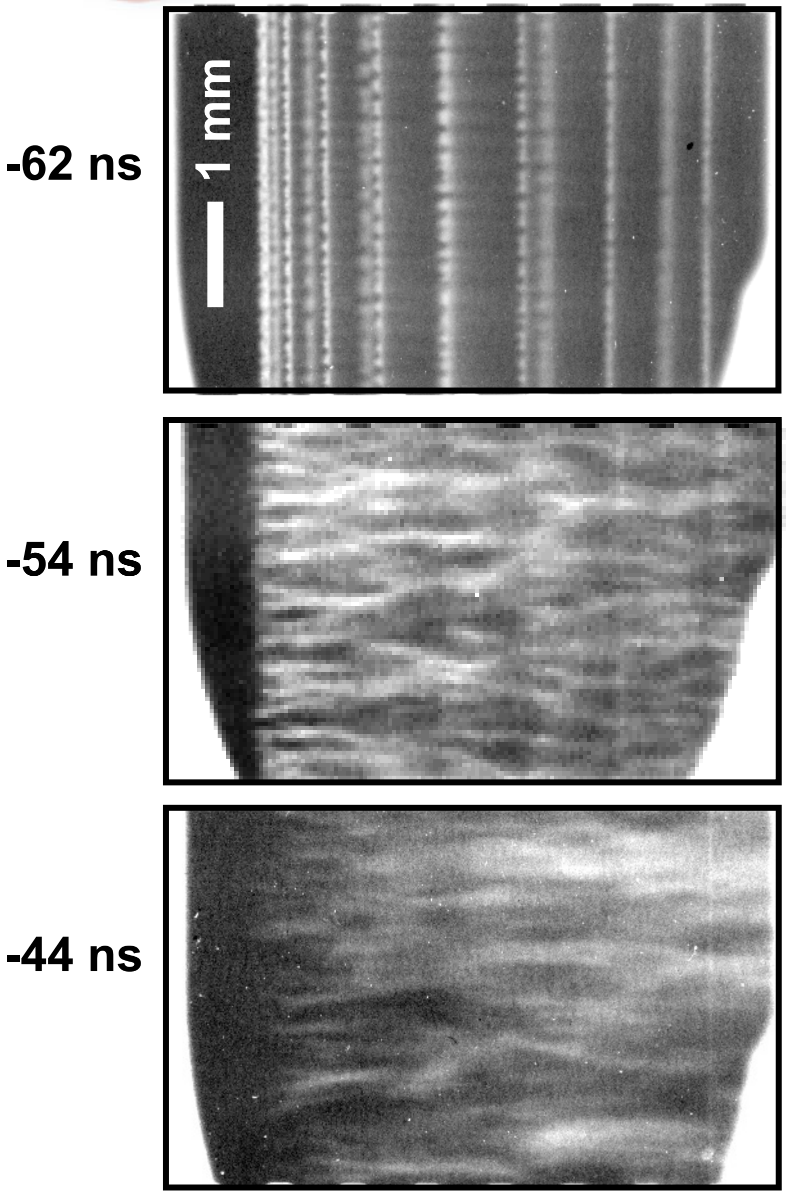
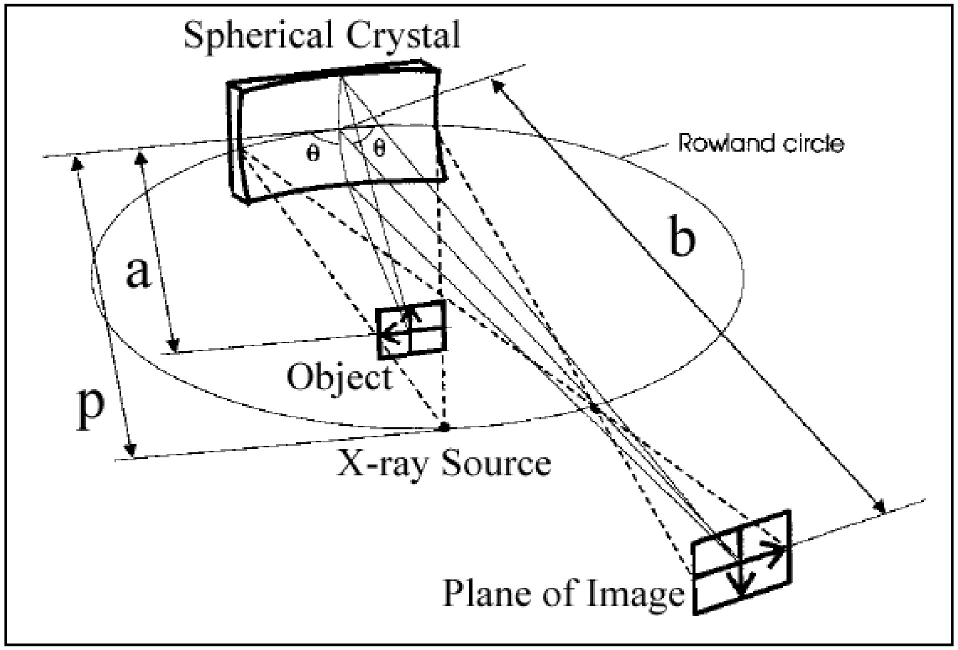
Non-uniform wire ablation seeds magnetic Rayleigh-Taylor implosion instability



1.865 keV radiography
Ø60 mm nested Cu arrays



- D. B. Sinars *et al*., PRL **93**, 145002 (2004).

- **ZBL bent crystal backlighting provides high-spatial-resolution, time-gated radiography for a variety of Z experiments**

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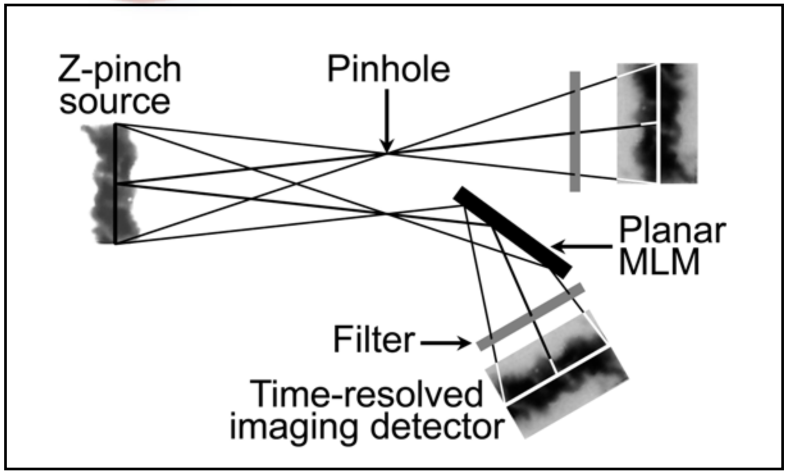
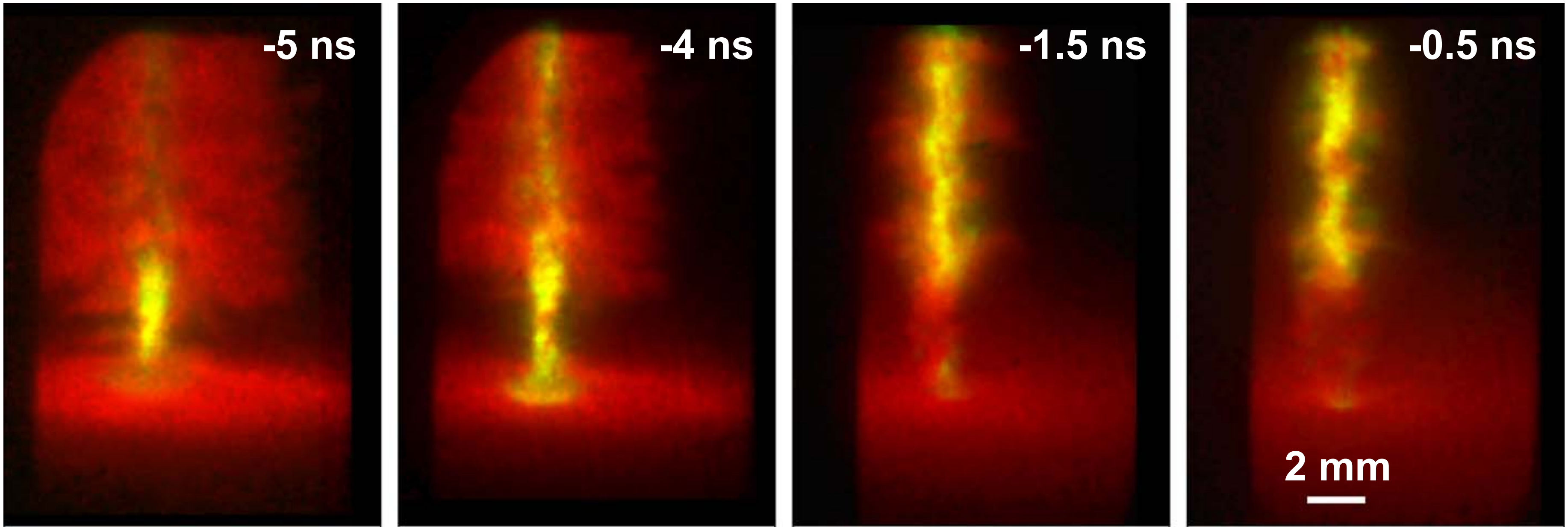
Plasma heating and K-shell excitation occur on axis as distributed mass assembles



Multi-color x-ray imaging, Ø60 mm nested Cu arrays

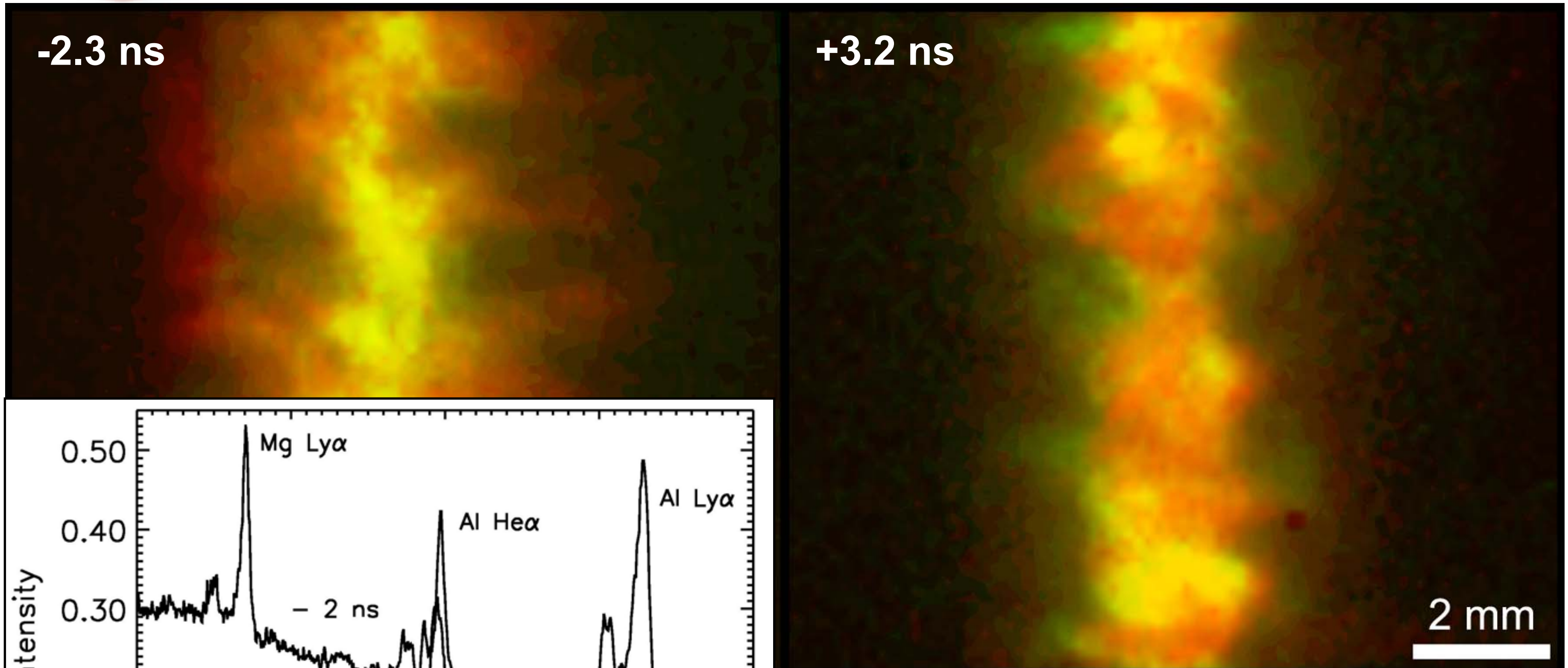
277 eV **8 keV**

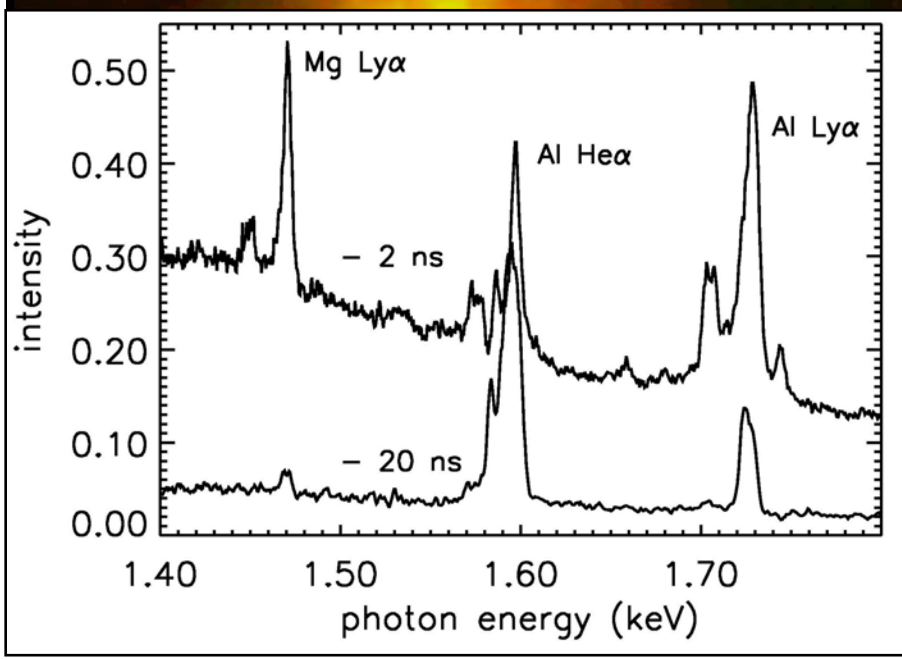
- B. Jones *et al.*, RSI **77**, 10E316 (2006).
- **Saturn and Z experiments seek to mitigate early implosion near cathode**



Opacity can limit K-shell yield—3D structure complicates radiation transport

- B. Jones *et al.,* IEEE T. Plasma Sci., to be published (2008).



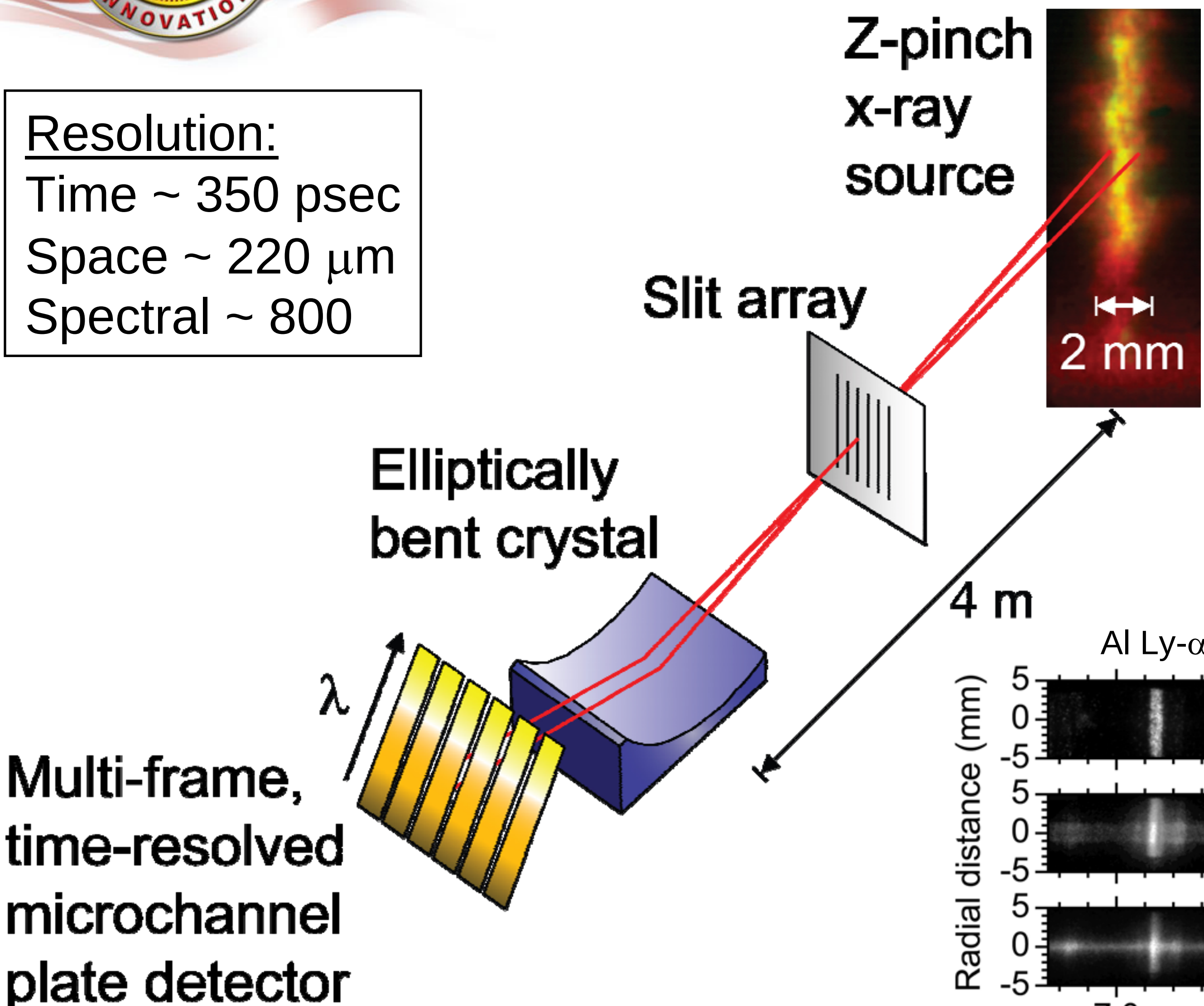


- B. Jones *et al.,* JQSRT **99**, 341 (2006).

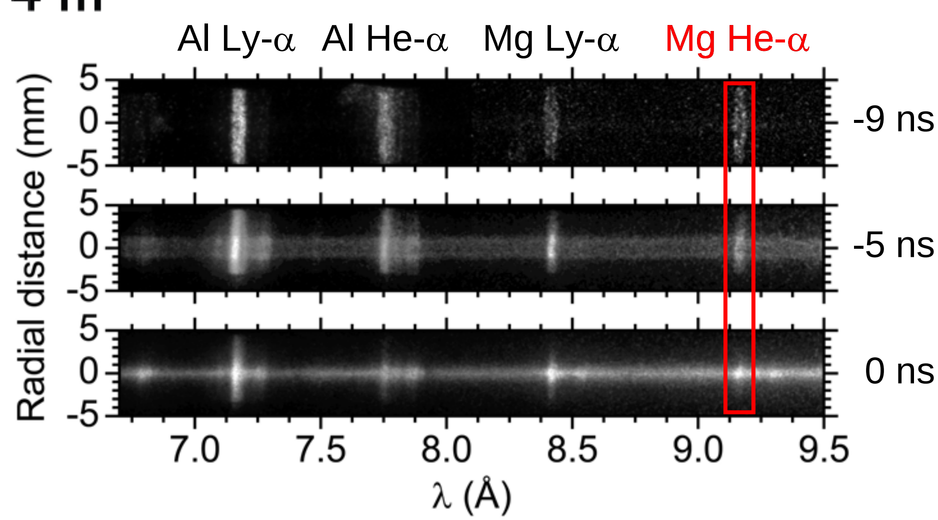
- **95% Al, 5% Mg wire array z pinch**
- **Near peak power, Al lines are limited by opacity to near Mg line intensities**
- **Opacity may have less impact at higher *Z***

Time- and space-resolved crystal spectrometers provide a powerful diagnostic capability on Z

Resolution:
Time ~ 350 psec
Space ~ 220 μm
Spectral ~ 800



- Slits provide 1D (radial) spatial resolution for multiple frames
- Elliptically bent mica crystal provides dispersion
- MCP gated detector



- J.E. Bailey *et al*., PRL **92**, 085002 (2004).

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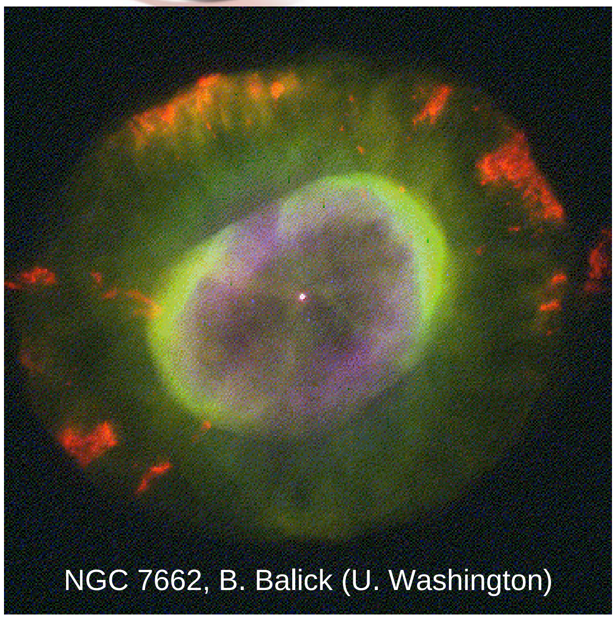
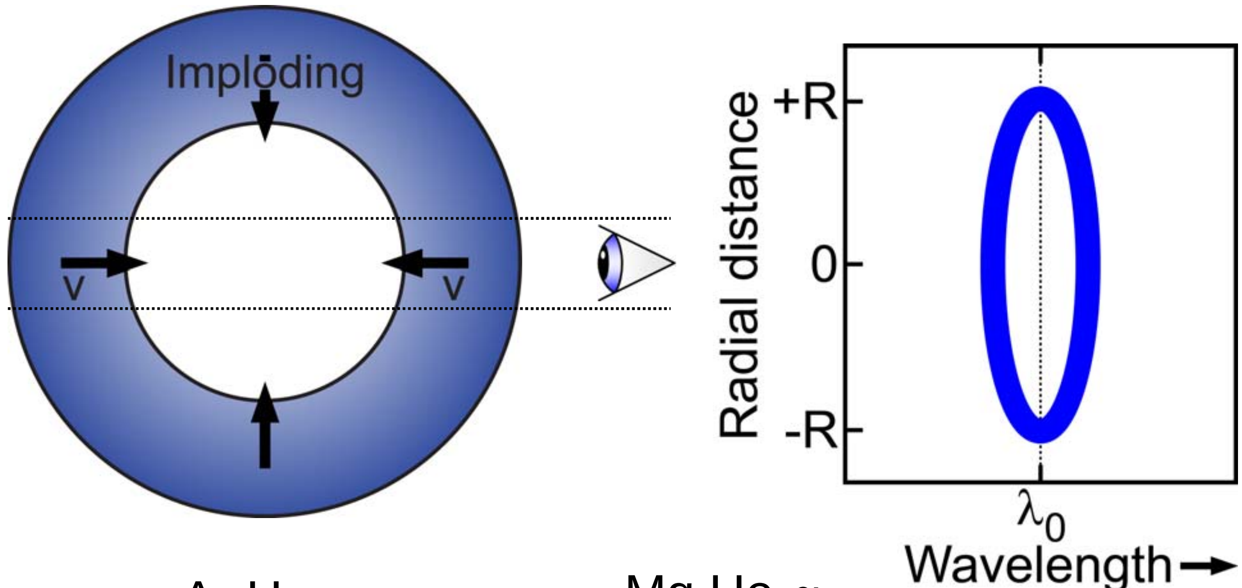
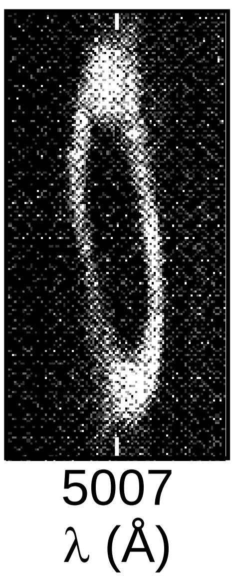
Doppler shift is observed spectroscopically in a moving plasma shell



NGC 7662, B. Balick (U. Washington)

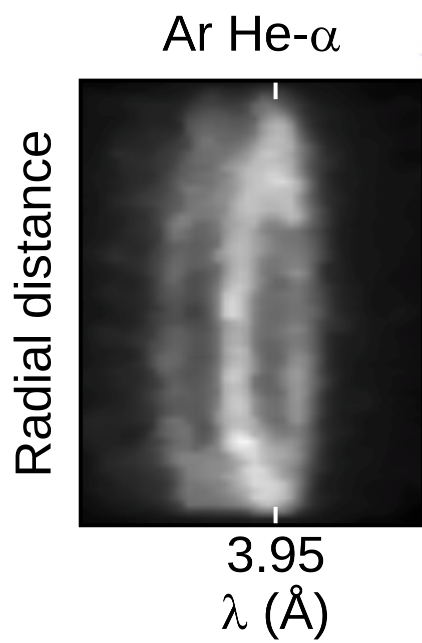


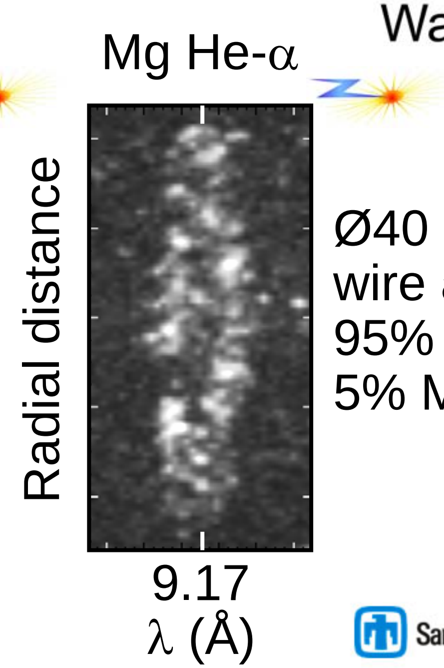


Planetary nebula
NGC 7662
Doppler splitting
in O-III line

Osterbrock (1966)

Campbell (1918)

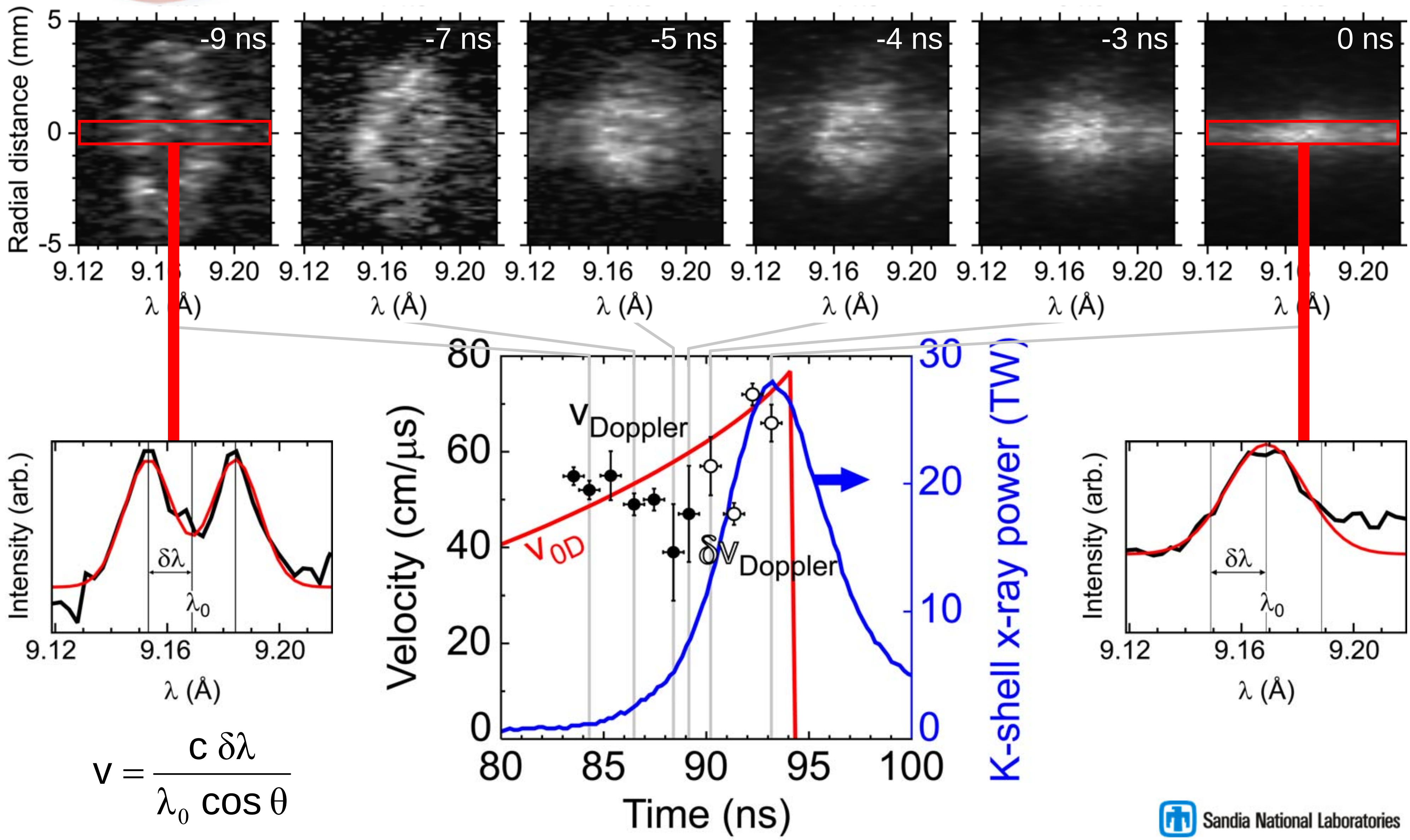




Ø40 mm
wire array
95% Al
5% Mg

Doppler splitting vanishes at the start of the main x-ray rise—thermalization of kinetic energy

Z1520, Ø40 on 20 mm nested Al 5056 wire array, 1.5 mg/cm, Mg He-α



$$v = \frac{c\,\delta\lambda}{\lambda_0 \cos\theta}$$

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Summary

- Pulsed power is an enabling technology for HEDP science
- Z serves multiple critical roles in Stockpile Stewardship
- Z-pinch RES K-shell x-ray source development on Z provides an opportunity to study HED plasma dynamics with spectroscopy and other diagnostics
- There is a lot of room for creativity in z-pinch-driven HEDP, and collaboration with universities and other laboratories is a valuable component of Sandia's program