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SCALING OF K-SHELL EMISSION FROM Z-PINCHES: Z TO ZR

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Outline

- Challenges for producing K-shell x-rays

- Results from K-shell experiments at *Z*
    - Mass and radius variations
    - Various materials

- Scaling to ZR
    - Scaling theories
    - Load design
    - Predicted outputs

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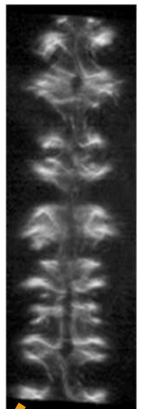
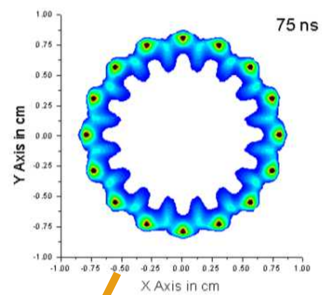
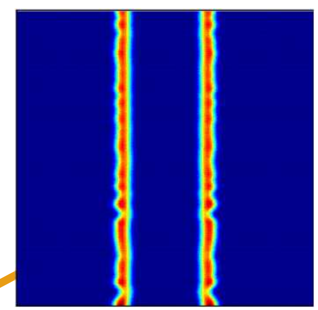
There are four fundamental phases of a Z-pinch

Wire initiation changes with material; timescales and current penetration important

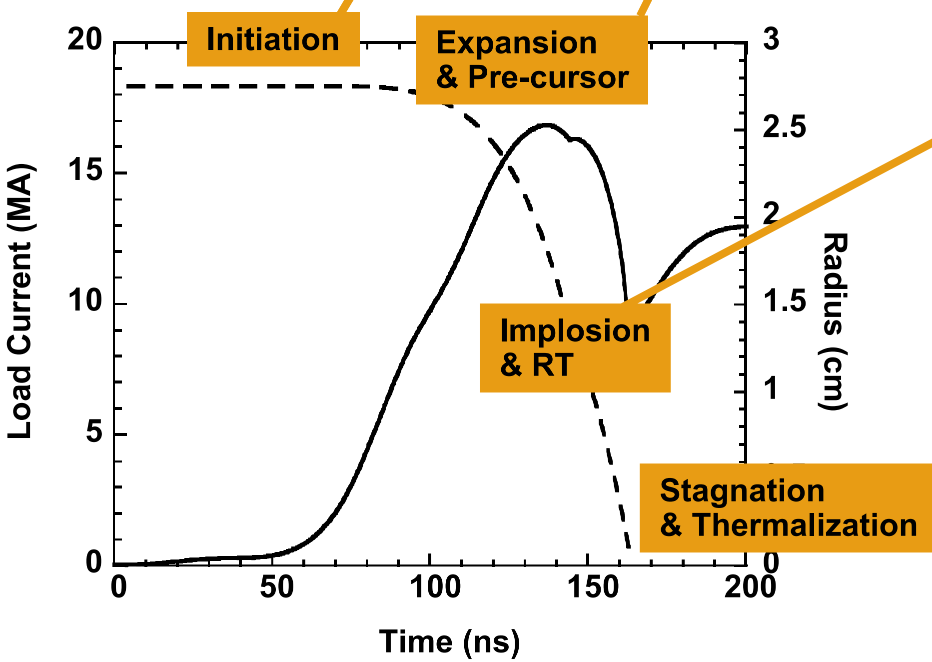


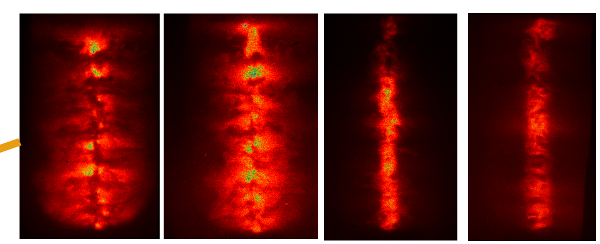


Expansion of the wires determines how shell-like an array becomes; precursor plasmas on axis can form



RT growth is a major factor





Heating and opacity impacted by velocities and masses of the arrays

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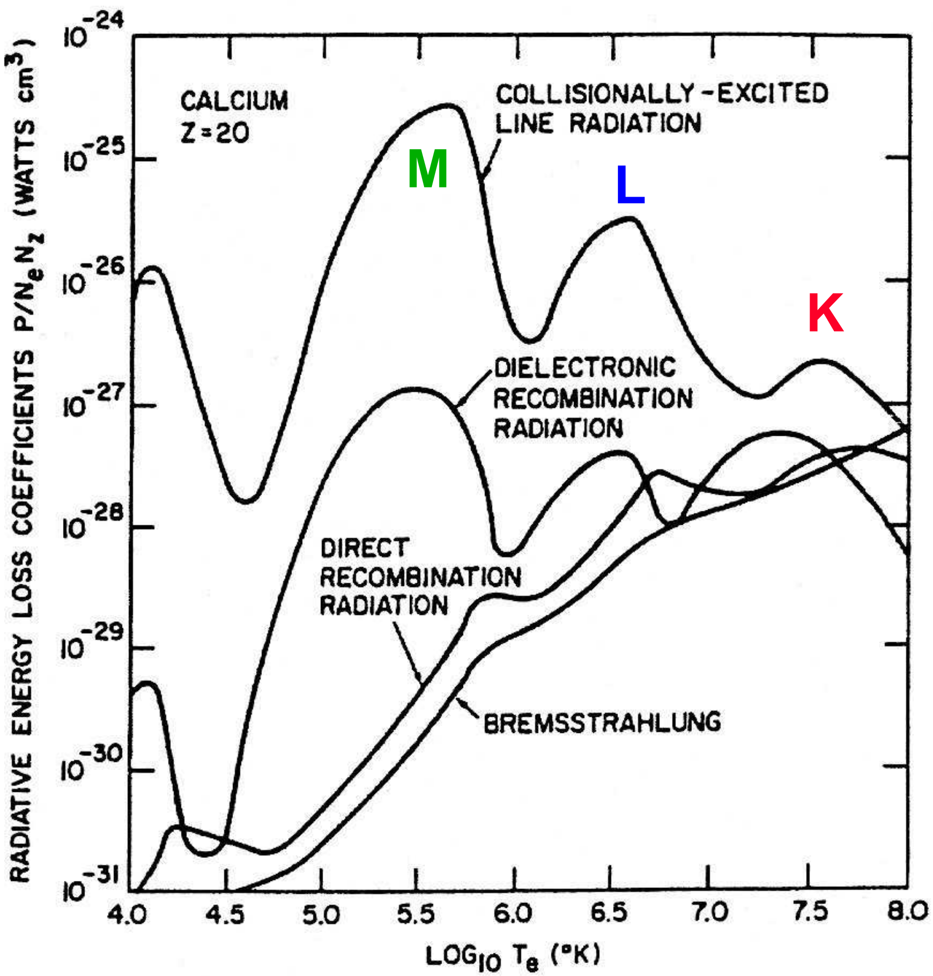
Achieving K-shell emission requires rapid ionization through stages that are copious emitters



K-shell line radiation competes with:

- Bremsstrahlung
- recombination
- lower energy line emission

Competition, especially due to lower energy line emission, increases with Z

- limits plasma temperature

Opacity effects and electron-ion coupling complicate the pinch

A.L. Velikovich, et. al., Phys. Plasmas 8, 4509 (2001)

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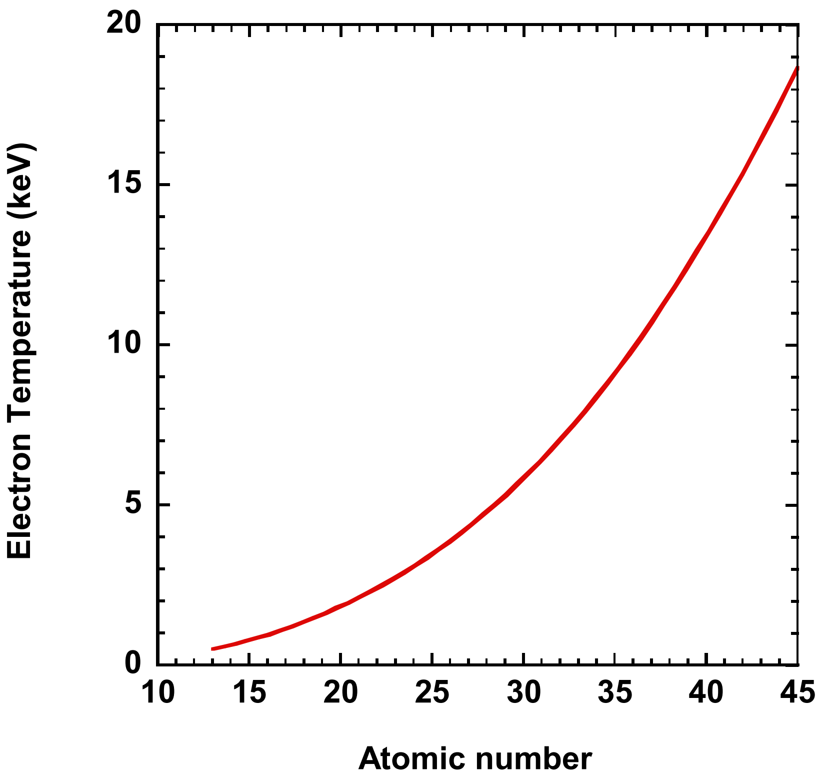
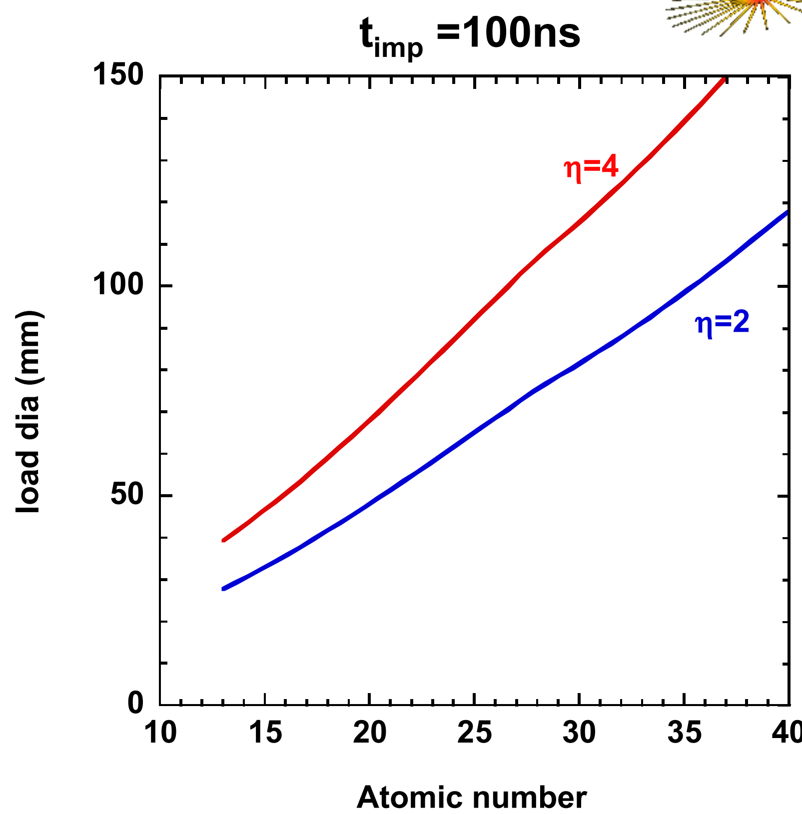
The production of high photon energy K-shell x-rays requires high temperatures





- As the radius increases, there is more jxB coupled energy available for a given mass load
  - designing loads that can take advantage of this energy and convert it to the K-shell is challenging

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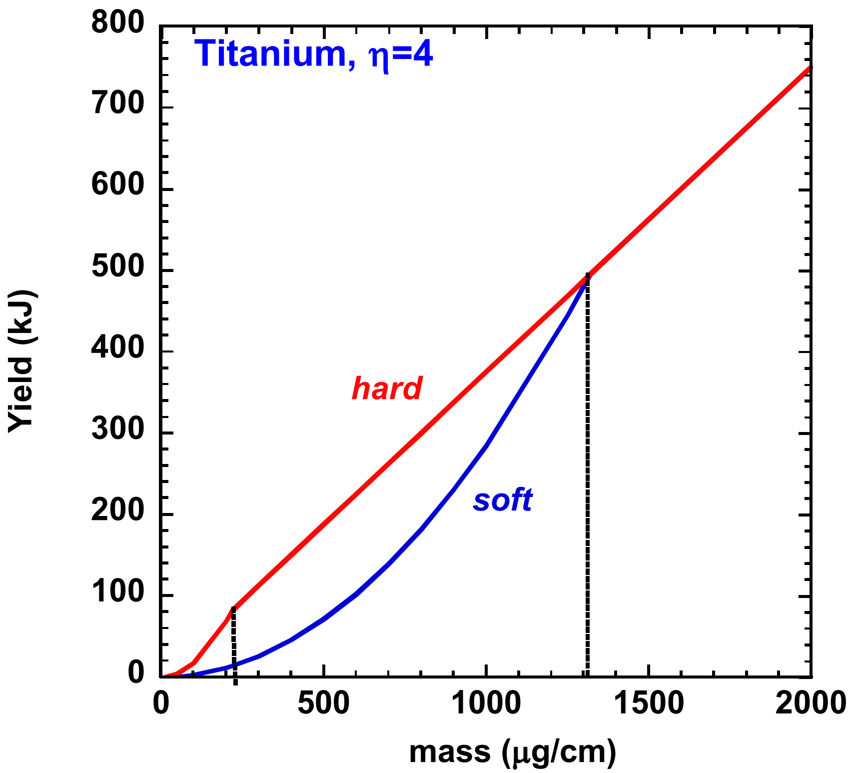
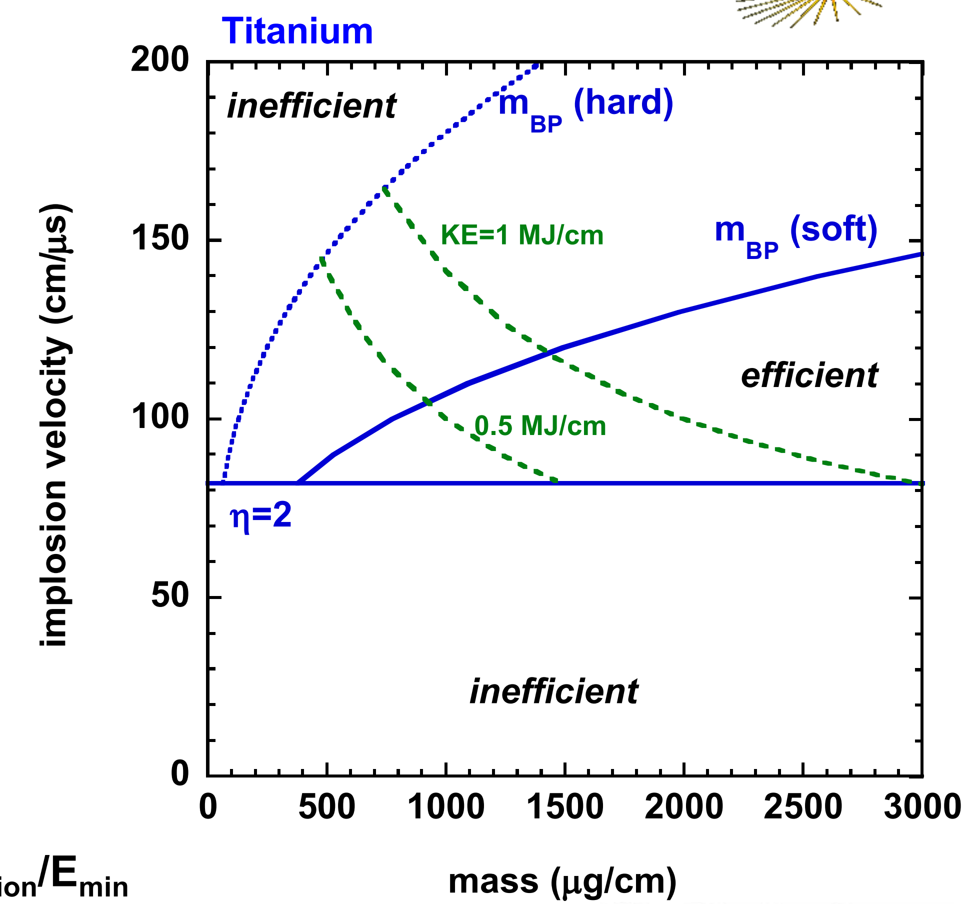
Scaling theories predict optimum regimes for K-shell production and trends in radiated yield





$Y_{h\nu} = am^2 \quad m < m_{BP}$

$= bm \quad m > m_{BP}$

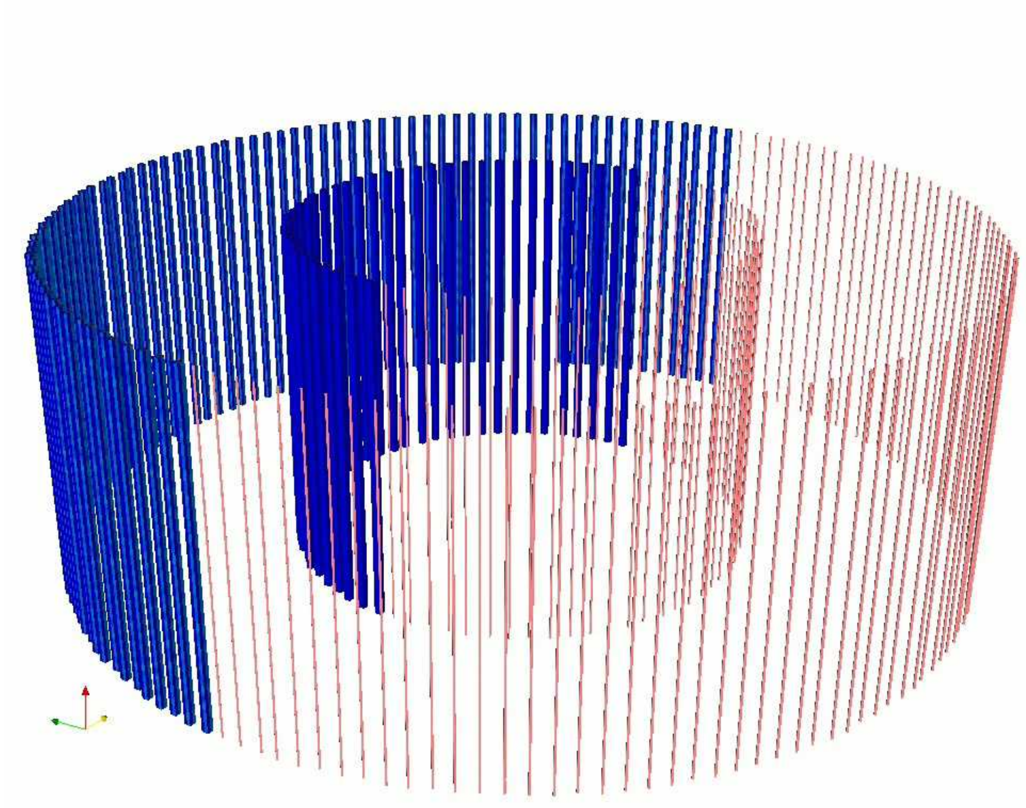
$\eta = KE_{ion}/E_{min}$

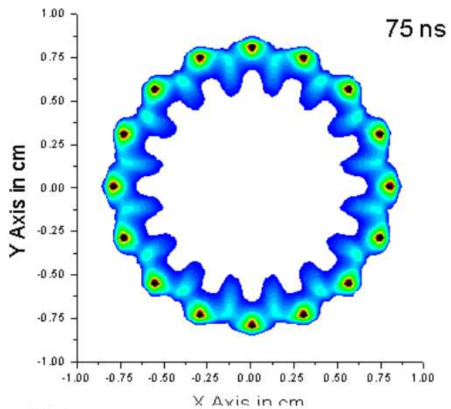
$KE_{ion} = \frac{1}{2} mv^2$

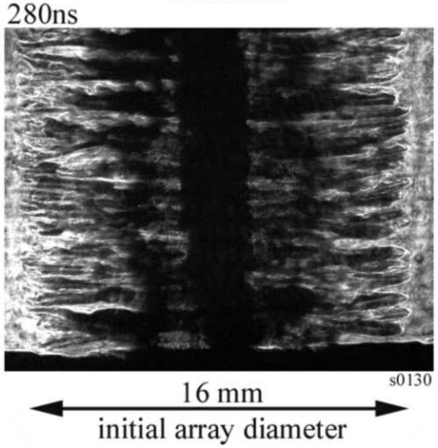
$\eta=4$, v_{imp} = 116 cm/μs

K.G. Whitney et. Al., Phys. Rev. E 50, 2166 (1994)
J.W. Thornhill et. Al., Phys. Plasmas 1, 321 (1994)

Instabilities and asymmetries impact the radiated output by reducing heating rates and lowering densities







Imperial College

55mm nested array
Gorgon, J. Chittenden

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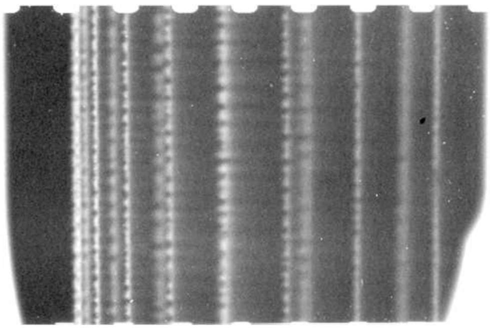
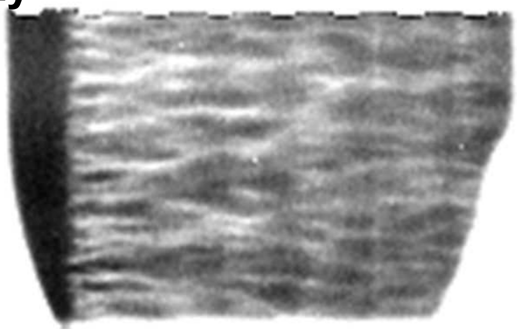
The early stages of a Cu wire array indicate significant initial structure and 2D behavior

60mm nested Cu wire array



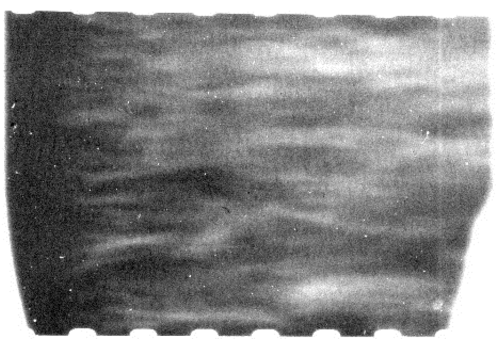
Z1284 t~ -61.4 ns

Initial radius and initial wire locations are visible



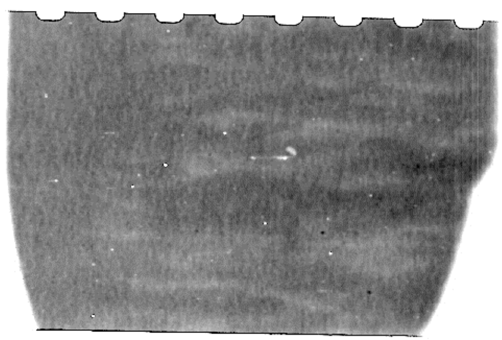
Z1270 t~ - 54ns

Wires are ablating and mass is starting to move



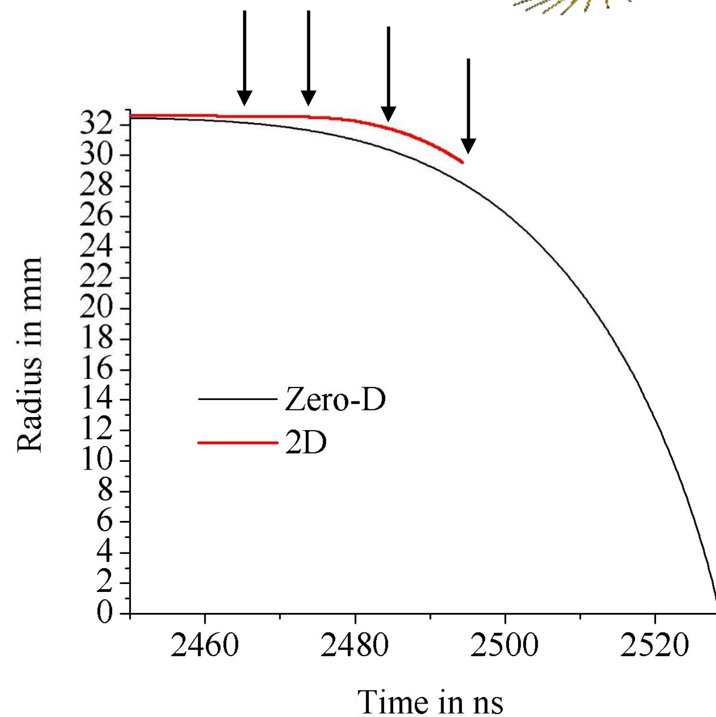
Z1268 t~ - 44ns

Mass is moving, but still extends to near the initial radius



Z1269 t~ - 34ns

The array is imploding



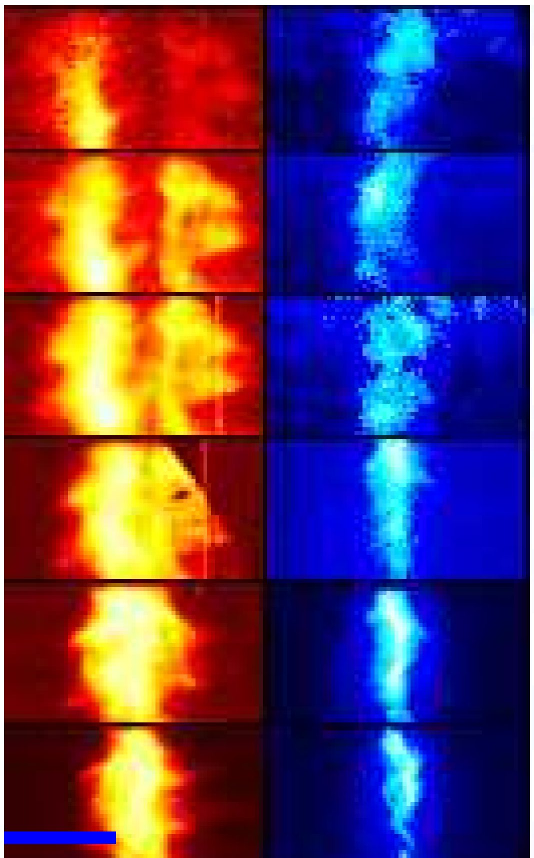
1.865 keV backlighter

B. Jones, D. Sinars, J. Chittenden

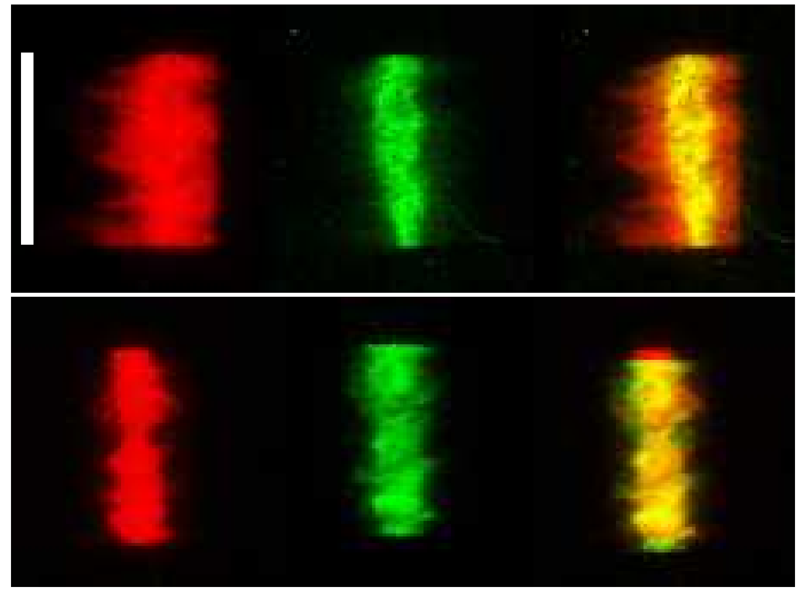
Advanced diagnostics are providing information near stagnation

- Multi-layer mirror imaging camera

Z1596
SS



Z1520, Al



- Instability
- K-shell x-rays more localized than 277 eV
- Observed structure varies with atomic number

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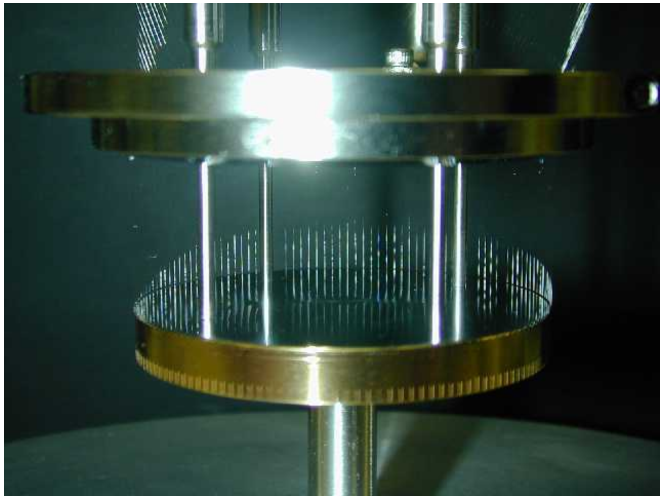
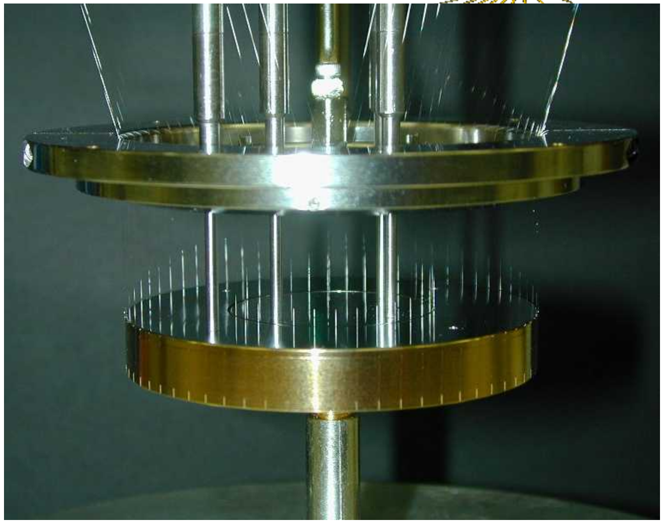
Single and nested array configurations have been fielded at Z for a variety of K-shell sources



55 mm dia.,
Single array

- Single arrays
- Nested arrays
  - 2:1 mass, radius ratio
  - 40mm to 80mm outer diameter



70 mm outer dia.,
nested array

Low wire number nested arrays appear to operate effectively
- 70mm on 35mm, 64 on 32 wires (IWG = 3.44 mm)

Wire number effects impact output
- Optimal wire number *(M. Mazarakis, private communication; C.A. Coverdale et. al., Phys. Rev. Lett. 88, 065001 (2002))*
- Field asymmetries *(J. Chittenden, private communication)*

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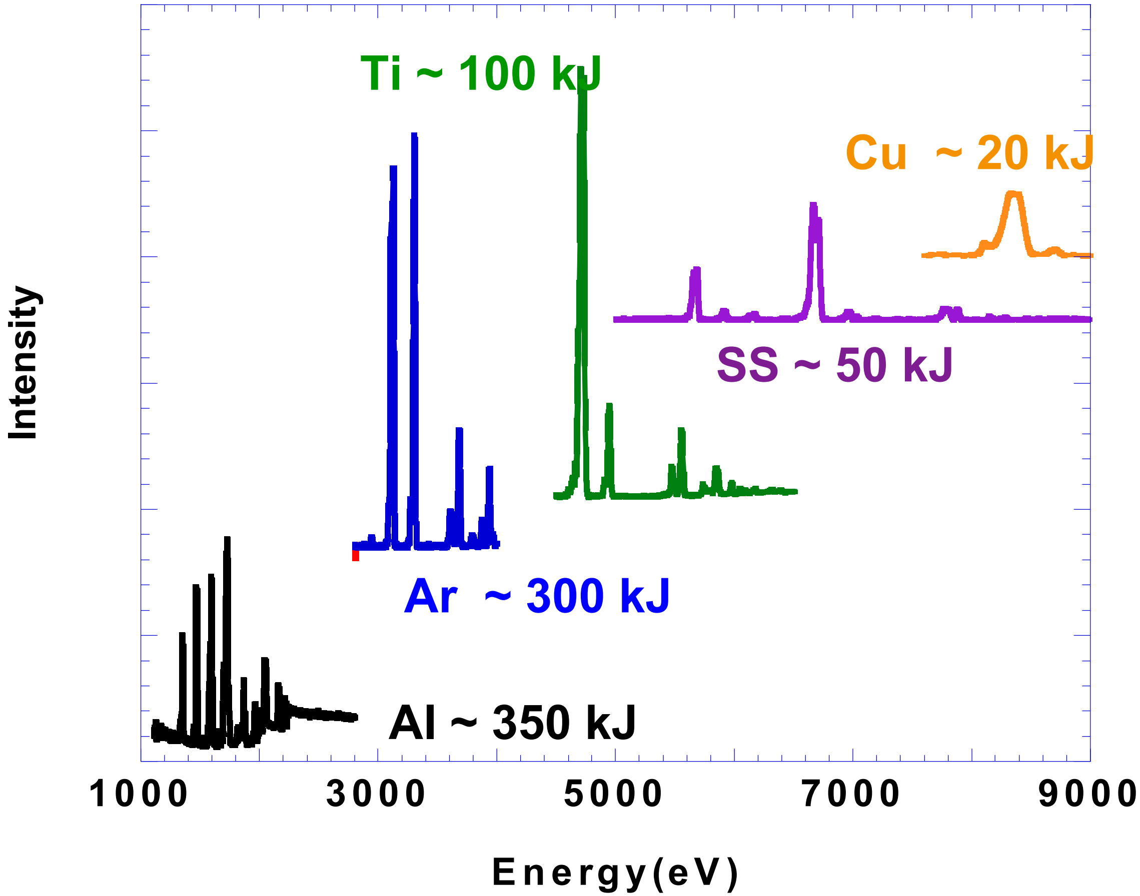
A variety of K-shell sources have been studied at Z

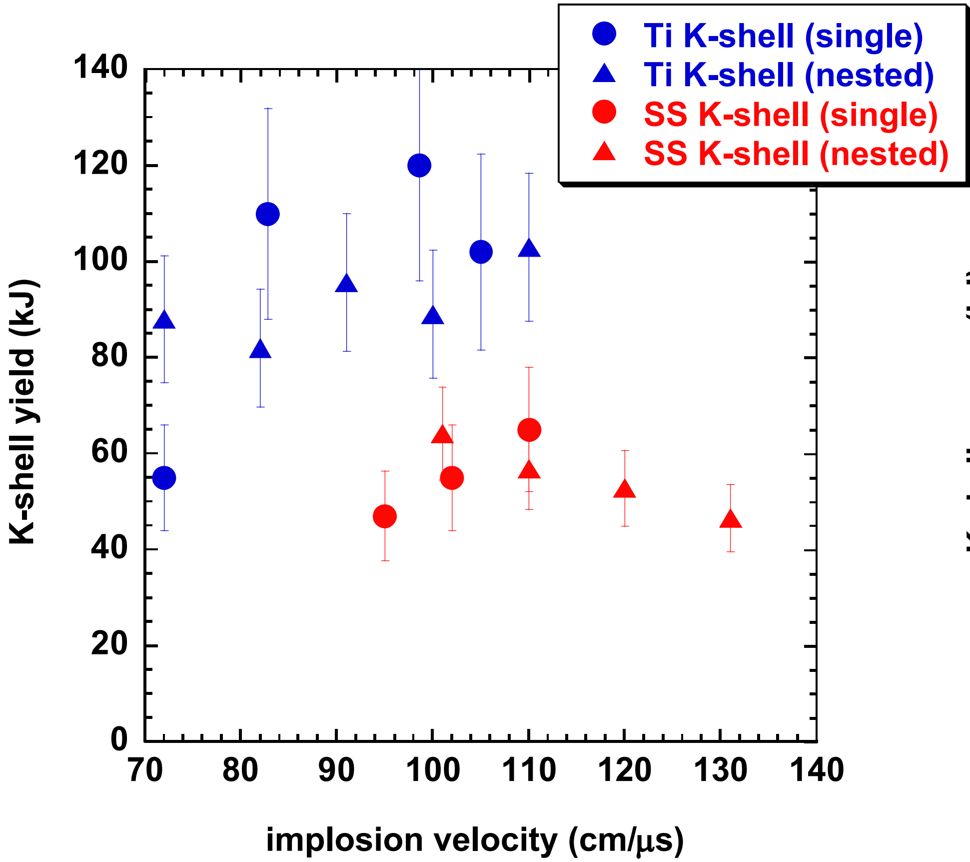


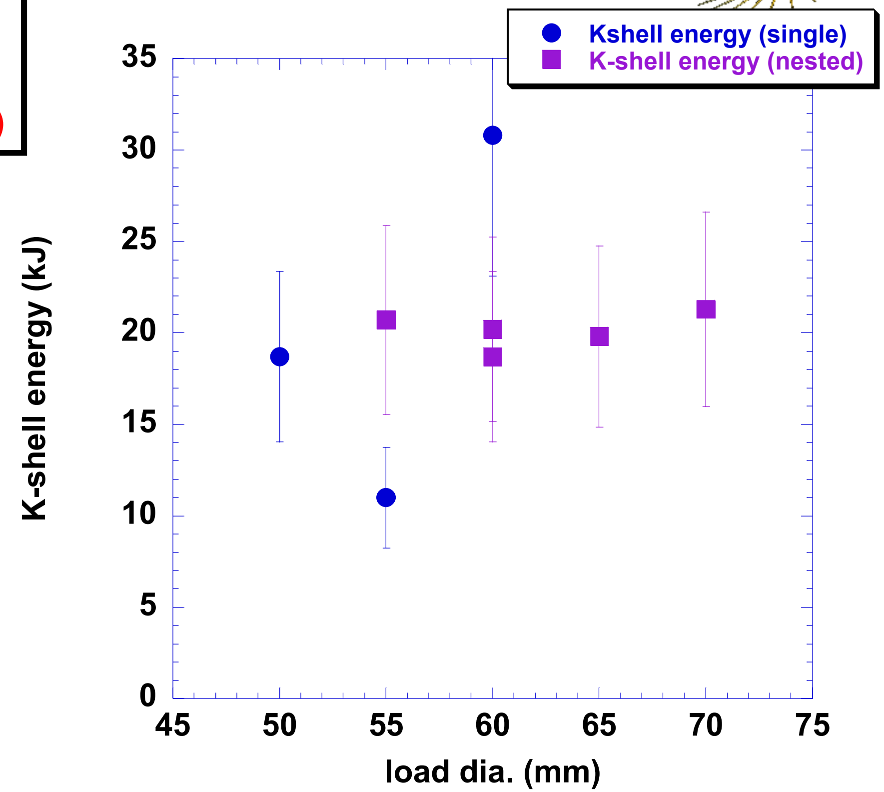
- These are peak outputs

- Al: 40mm on 20mm nested
- Ar: 1234 nozzle
  (See session 5C for other gas puff work, as well as 3C3)
- 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)

The radiated output varies with changing load configurations





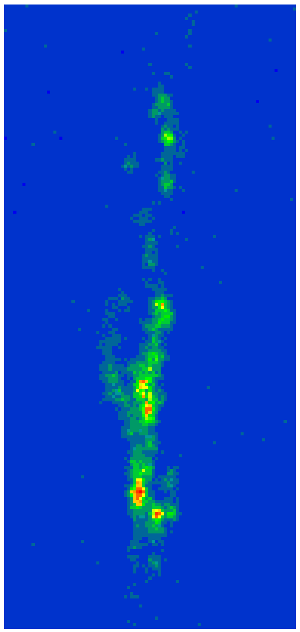
Titanium & SS, single vs. nested
- Nominally "efficient" for Ti,
- Marginally "efficient" for SS

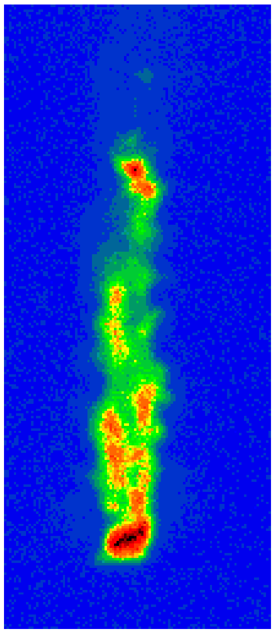
Copper, single vs. nested
- Nominally "inefficient"

Single arrays show less uniformity than nested arrays

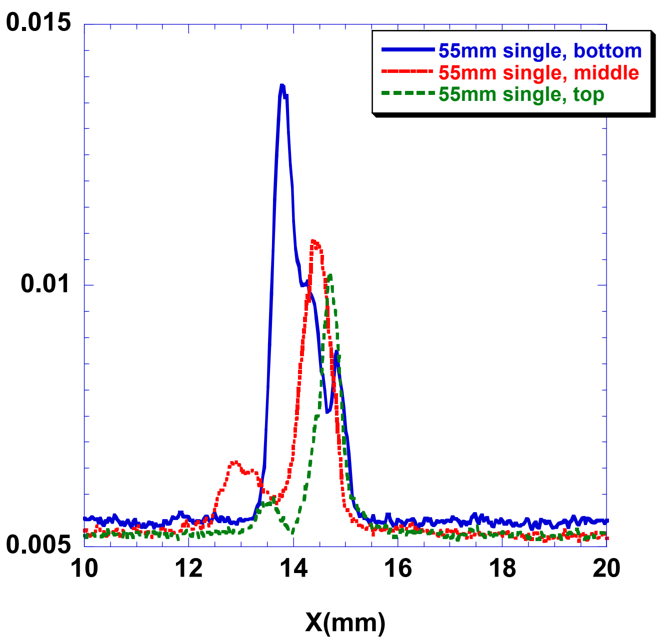
Stainless Steel K-shell images near peak radiation

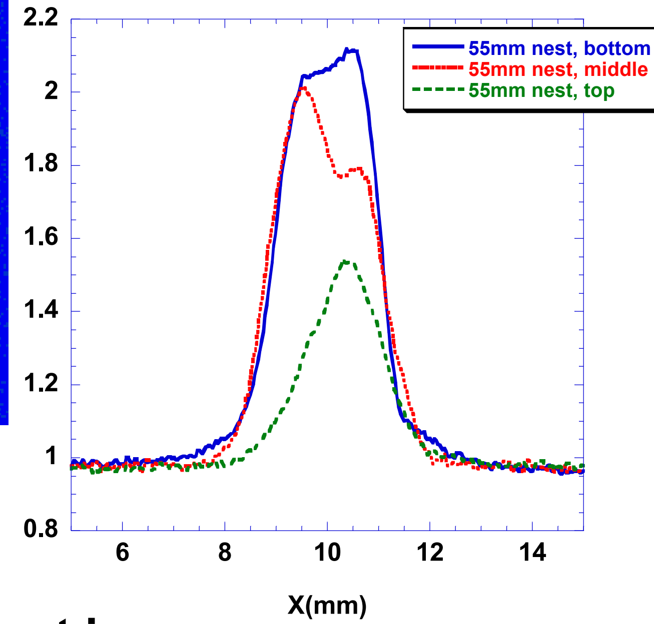
55mm single





55mm nested





- **Intense regions present in both configurations**
- **Softer x-ray images show less structure, wider pinch**

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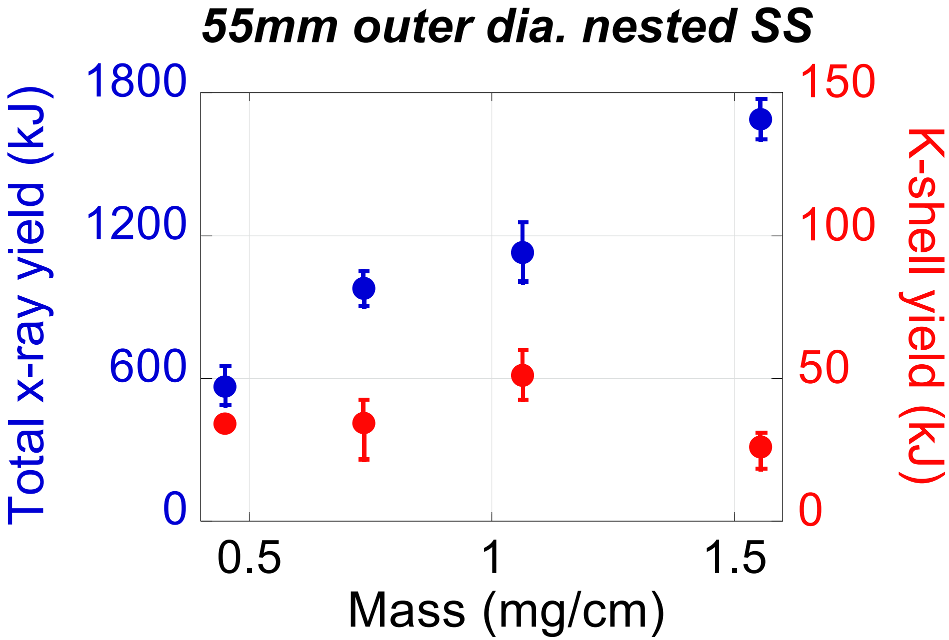
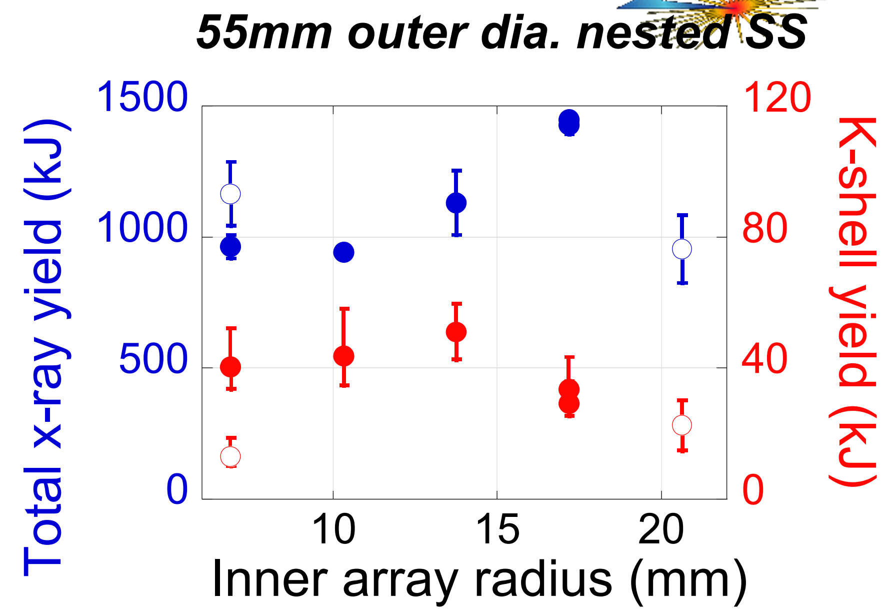
Experiments have also studied variations of the mass and nested configuration





- Peak K-shell at implosion time ~ 100 ns
- More electrical energy is coupled to load region for higher mass, longer implosion time load
- High ion temperatures observed after peak x-rays (> 100 keV) *M.G. Haines et. al., Phys. Rev. Lett. 96, 075003 (2006)*

- Varies transparency of the inner array
- Designed to have simultaneous implosion of inner and outer arrays

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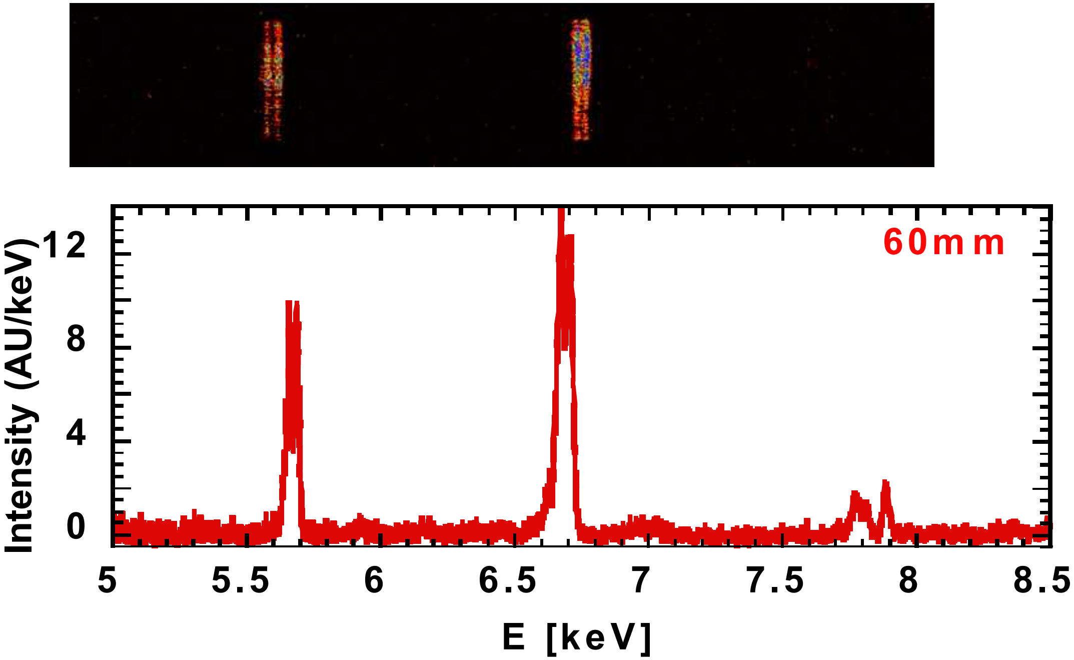
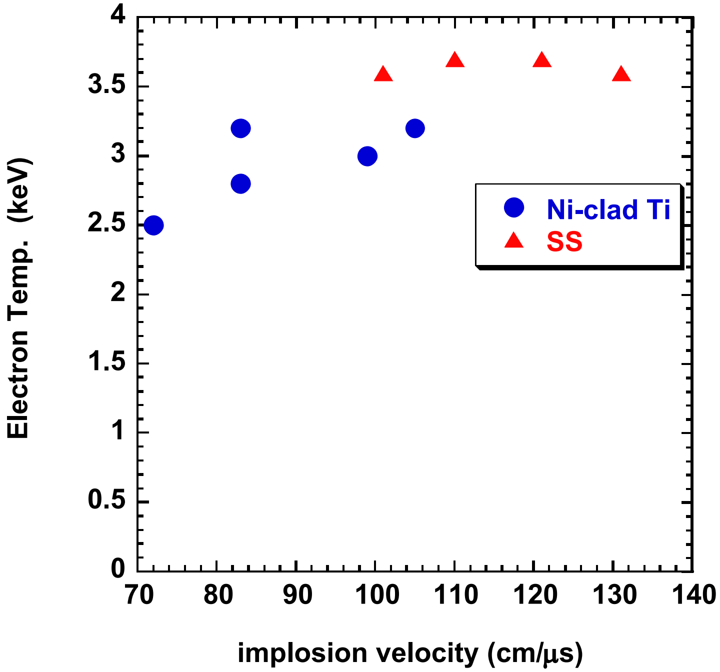
B. Jones, ICOPS04

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

Time integrated spectroscopy can be used in conjunction with pinch size and K-shell power to infer electron temperature and ion density

(J.P. Apruzese et. al., J. Quant. Spectrosc. Radiat. Transfer 57, 41 (1997))





P.D. LePell, 2P13
J.P. Apruzese, 3P23
N. Ouart, 3P22

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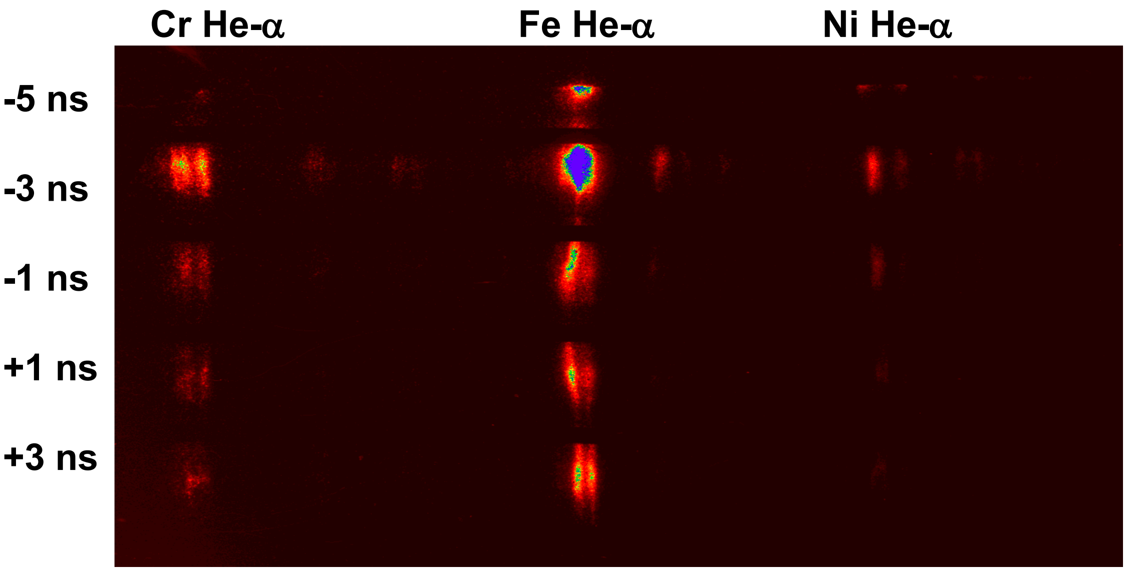
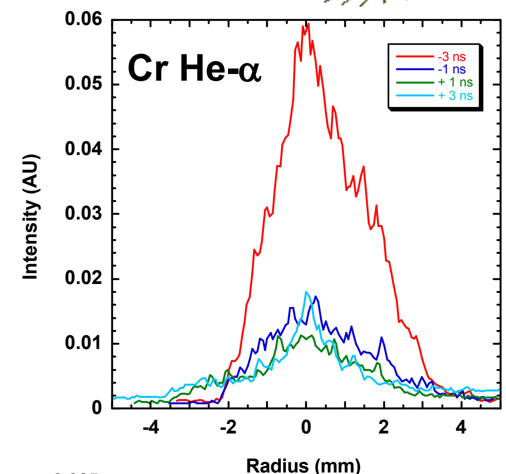
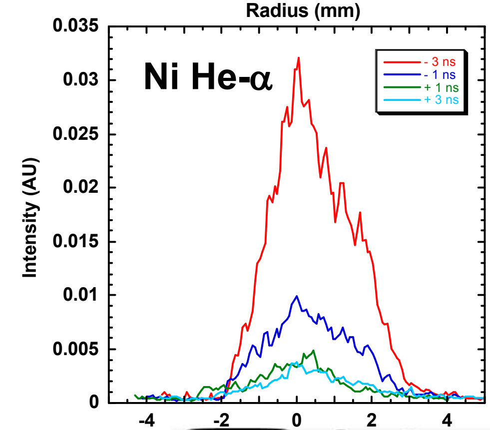
Time and space resolved spectroscopy can be used to further evaluate the stagnated plasma

Z1709 -- SS



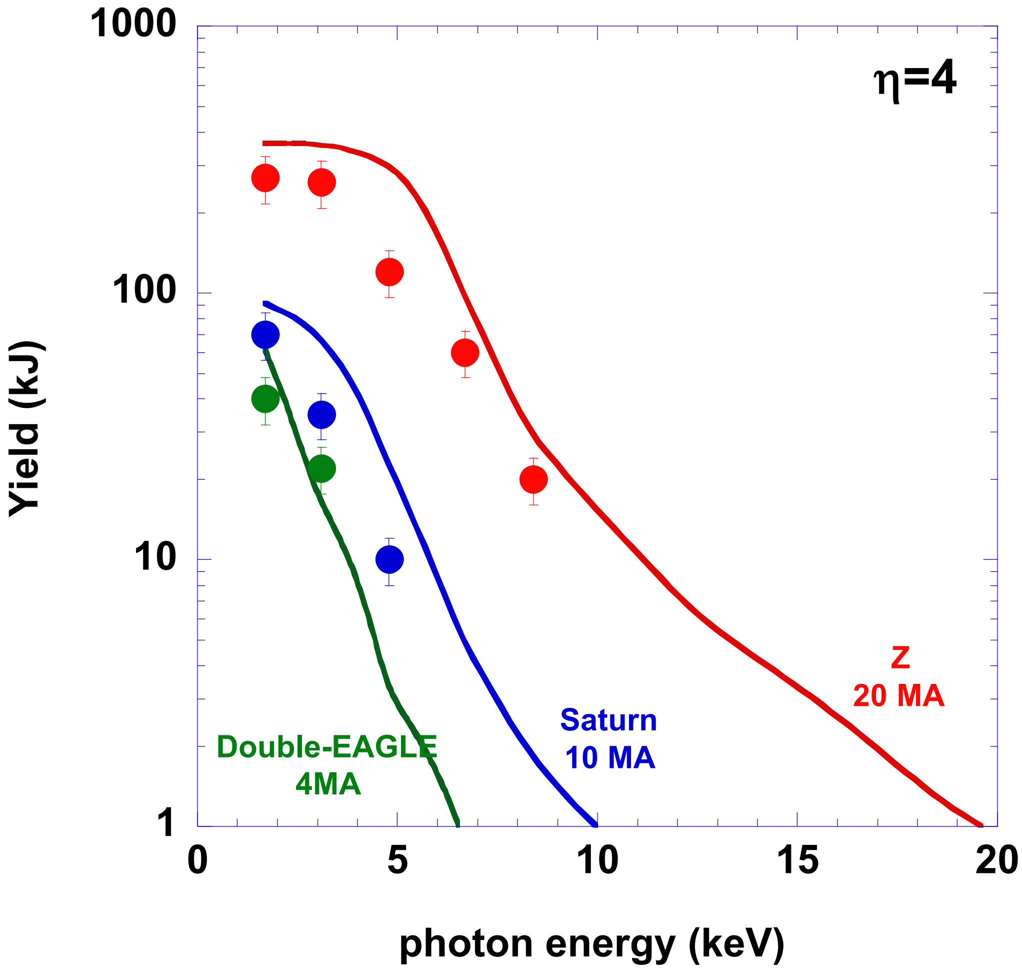




Radial Data Shows Similar Spatial Extent for Cr and Ni He-α Emissions

- **Ni He-α shrinks faster than Cr He-α**

How do *Z* experiments compare to scaling law predictions?



- Scaling concept generally predicts trends
- Excellent for design of reasonable experimental configurations

BUT theory does not include:

1. L-shell losses
2. Dependence of KE conversion efficiency in efficient regime on η
3. Modification in inefficient regime as a function of η
4. Realistic implosion dynamics

Need more detailed experiment-calculation comparisons

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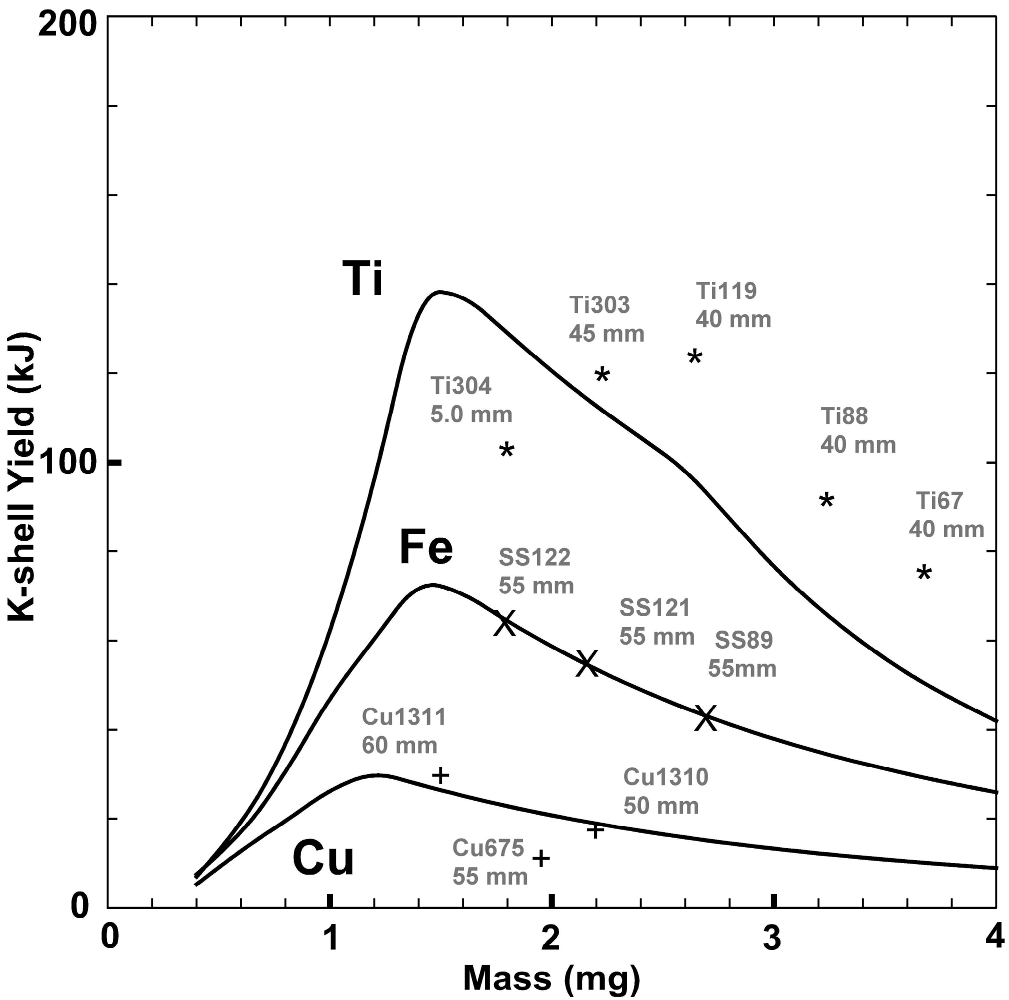
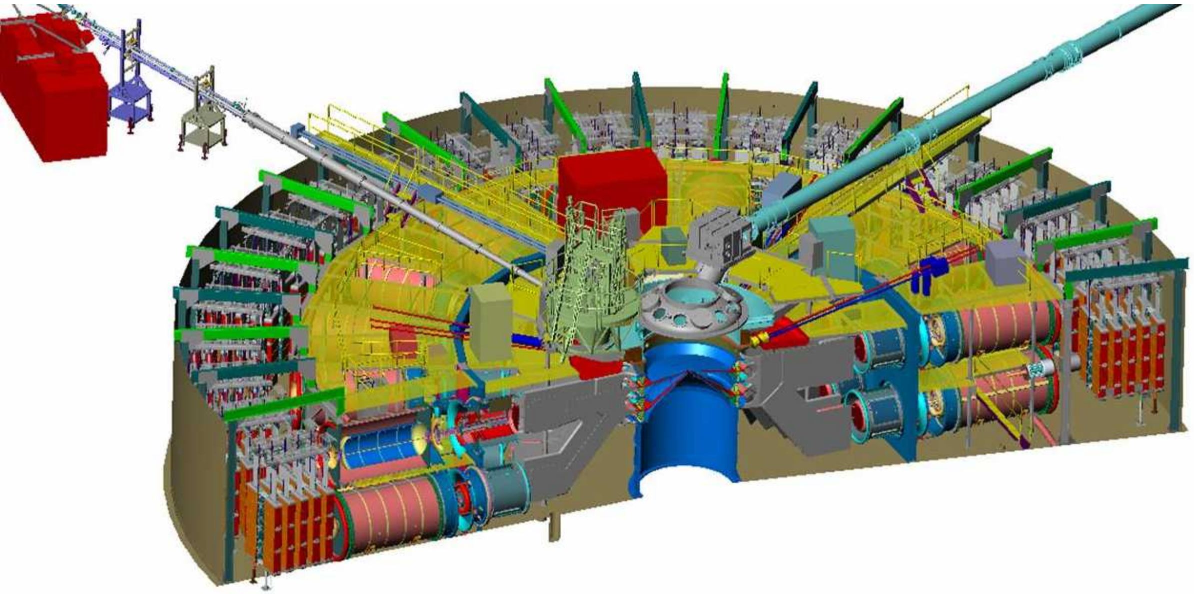
Using the data from Z experiments, NRL has modified their K-shell scaling theory



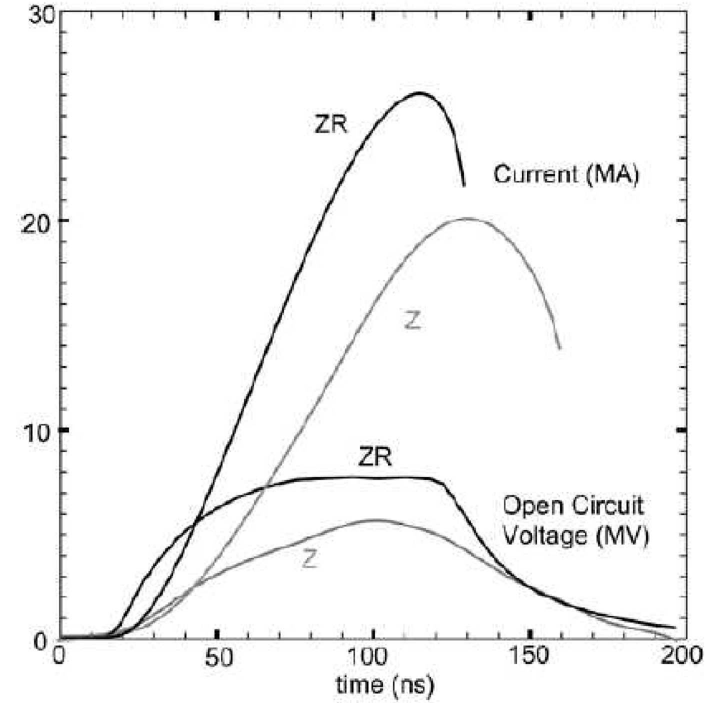
- Original scaling theory was benchmarked to Al at lower current facilities
- Phenomenological modifications have been made and then benchmarked to the Z data
- Scaling to higher currents is then possible

J.W. Thornhill et. al., submitted to Trans. Plasma Sci.

ZR will increase the current delivered to an imploding load



55mm single, 2 cm, 4 mg



ZR will deliver

- **22 MJ stored energy**
- **3 MJ to a load**
- **Approximately 25-26 MA with 100 ns implosion**

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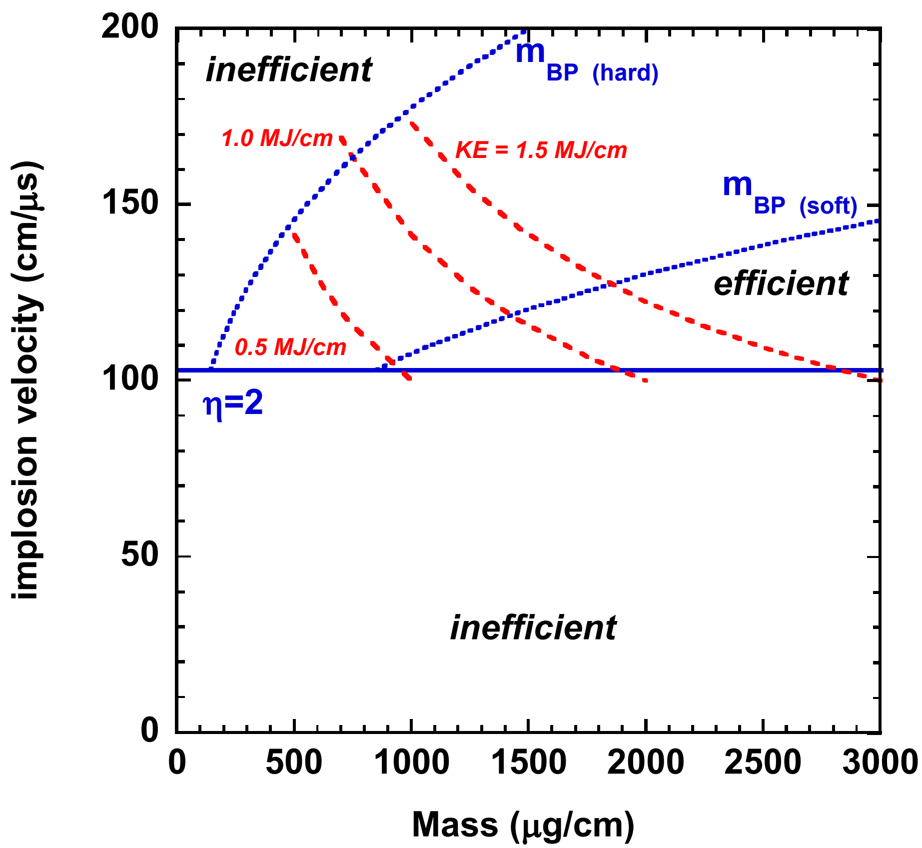
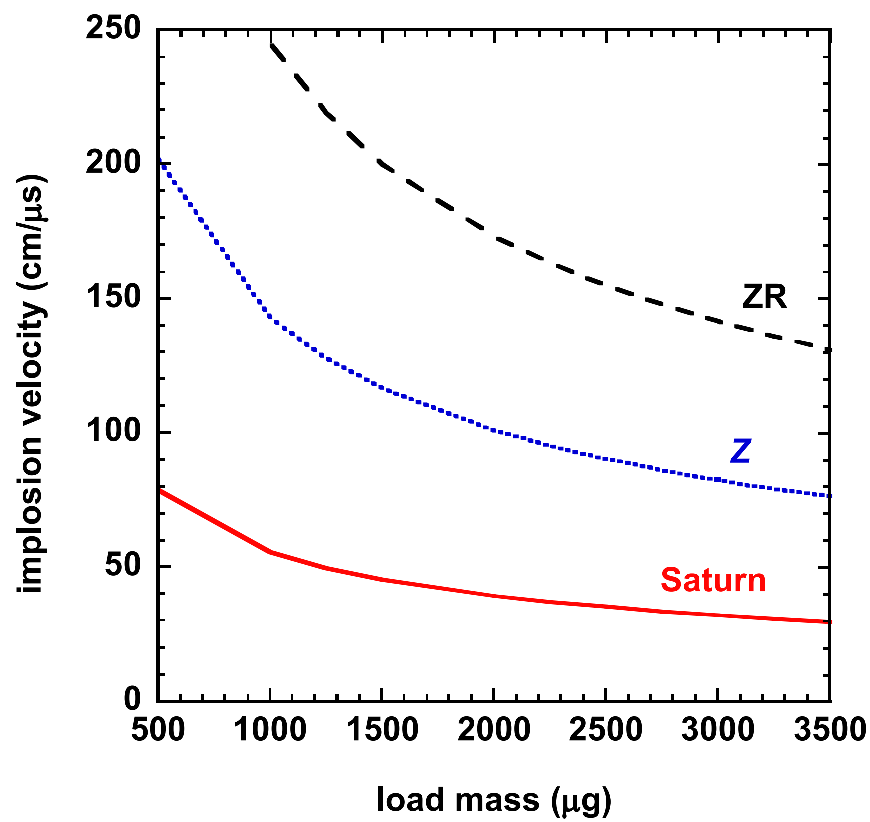
The original scaling theory would suggest that ZR will be able to produce higher Z K-shell efficiently

Iron

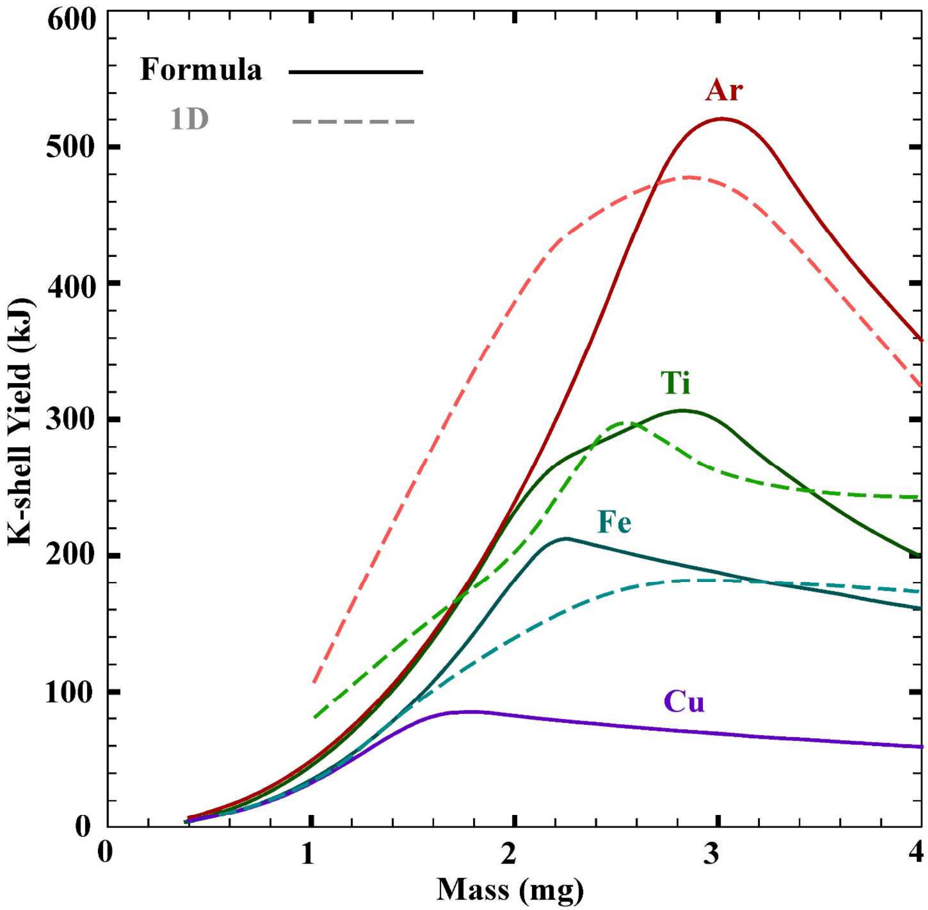




$\eta = KE_{ion}/E_{min}$

K.G. Whitney et. Al., Phys. Rev. E 50, 2166 (1994)
J.W. Thornhill et. Al., Phys. Plasmas 1, 321 (1994)

The new scaling theory can be used to estimate anticipated outputs for various K-shell sources at ZR



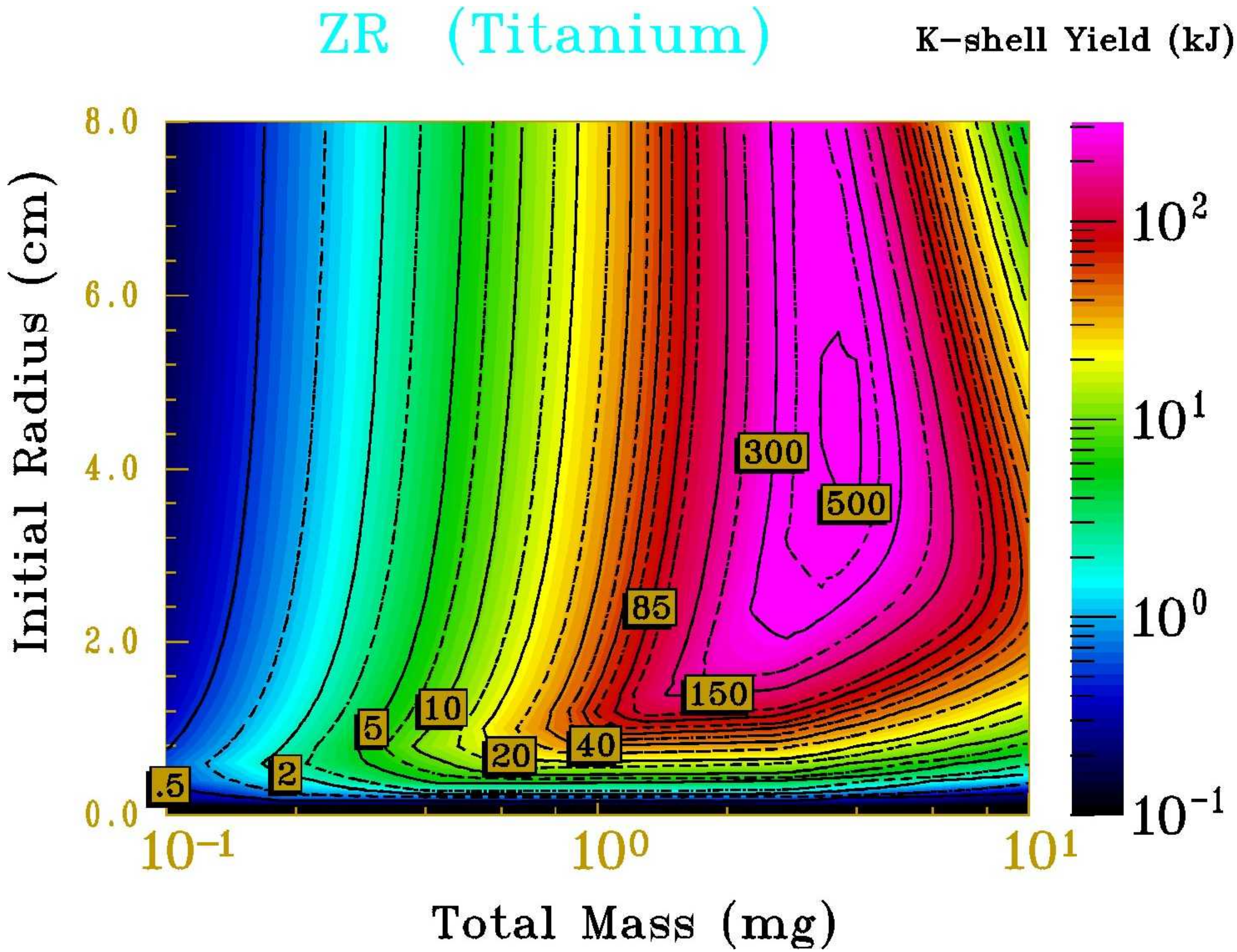
Scaling theory predictions:

- **Argon, 8cm 1234 nozzle**
- **Ti, 45mm single array**
- **Fe, 55mm single array**
- **Cu, 55mm single array**

$Y_k = min(0.3, c(Z)\beta(Z)) \times min(1.0, m/m_{BP}) \times E_{jxB}$

J.W. Thornhill et. al., submitted to Trans. Plasma Sci.

Initial load conditions can be suggested based on the new model



J.W. Thornhill et. al., submitted to Trans. Plasma Sci.

These predictions suggest significant increases in radiated output

Generator	> 1 keV (kJ)	3 keV (kJ)	5 keV (kJ)	7 keV (kJ)	8 keV (kJ)	10-13 kJ (keV)
4 MA Double-EAGLE	40	25*	2	0	0	0
8 MA Saturn	75	35	10	2	2	0
20 MA Z	450	300	100	50	20	10
26 MA ZR	900	500	300	200	70	40

Summary

- The production of K-shell radiation is challenging and requires high temperatures and densities
- Copious K-shell output has been obtained at the Z facility for a variety of sources
    - Experiments have focused on variations in mass, comparisons of single vs. nested, nested variations
    - Primary materials studied have been Al, Ti, SS, and Cu
- Using the Z data, the original NRL scaling theories have been modified
    - Phenomenological modifications to better match the data
    - Compared with 1D simulations
- Applying the new scaling theories to ZR parameters indicates significant enhancements in K-shell output
    - Current available at ZR enables higher mass, but will require larger diameters to achieve appropriate conditions

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Nested configurations would likely do…..

Do extrapolation from nested stuff on the scaling…

Circuit model for ZR can be used to estimate appropriate loads for K-shell sources

- Plot showing imp vel as fcn of mass
- Plot showing current, KE