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International Conference on Dense Z-Pinches
Biarritz, June 9, 2011

Large diameter wire array z-pinches on the Z generator

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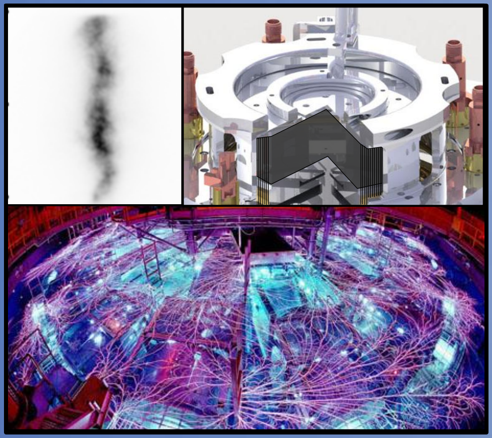

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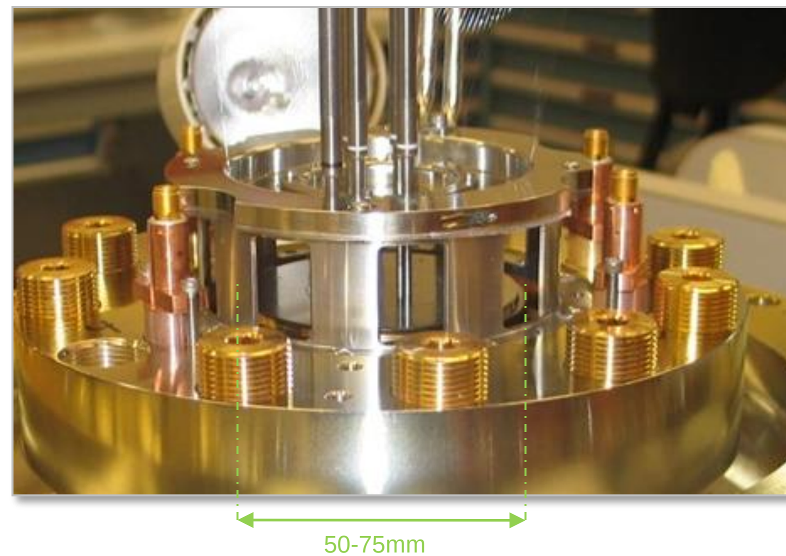
Summary

- **Large diameter wire array z-pinches reach interesting plasma conditions**
  - **Te ~ few keV**
  - **Ni ~ few 10^{20} cm^3**

- **Strong K-shell emission is observed**
  - **For SS (> 5keV) ~35TW, >80kJ**
  - **For Al (>1keV) ~35TW, 430kJ**



- **3D MHD simulations are providing significant insight into these arrays**
  - **Matching significant fraction of data**
  - **Nearing a predictive capability**

- **Radiation can drive basic science experiments**

Experiments use large diameter wire array z-pinches to produce intense few keV emission

Large diameters & fast rising current

↓

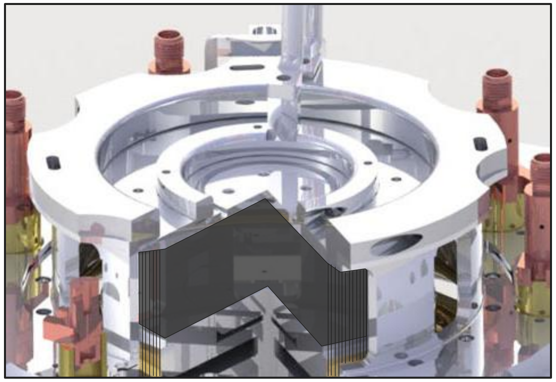
High implosion velocities

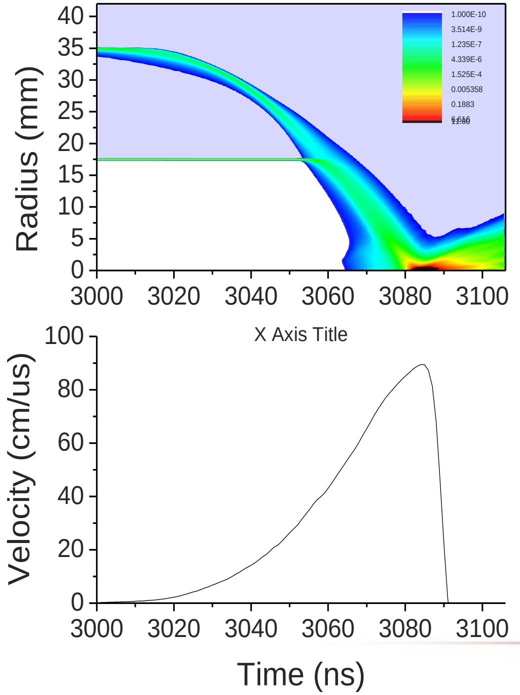
↓

High electron temperatures when they stagnate

↓

Ionization to the K-shell and hence emission



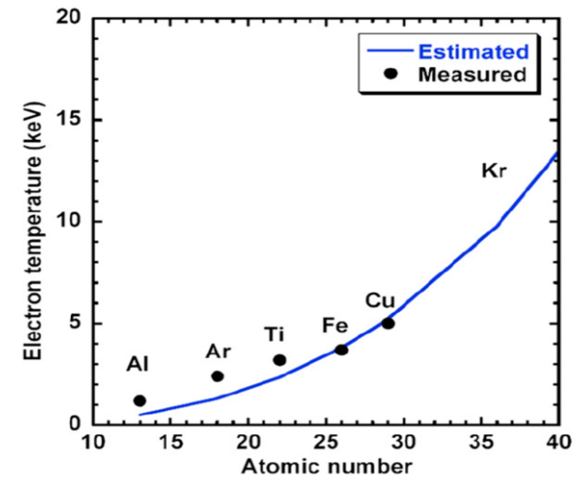


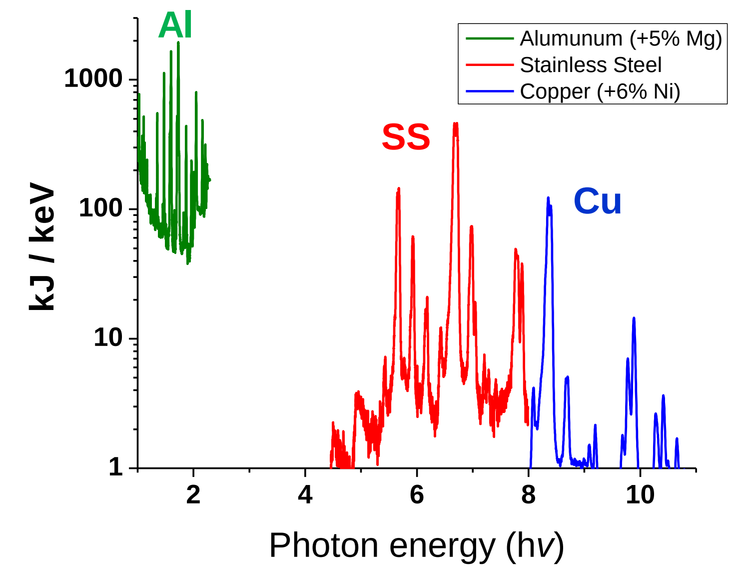
For increasing atomic number, temperature and hence velocity required for efficient K-shell radiation increases

- **Increasing Z leads to**
  - Increase in K-shell photon energy
  - Increase in electron temperature required to radiate efficiently
  - Higher velocity required to heat

- **For Al**
  - Heα at 1.6keV
  - ~1keV required to radiated efficiently
  - ~50cm/us required to heat to 2x ionization energy (η~2)

- **For Fe**
  - Heα at 6.7keV
  - ~4keV required to radiated efficiently
  - ~100cm/us required to heat to 2x ionization energy (η~2)

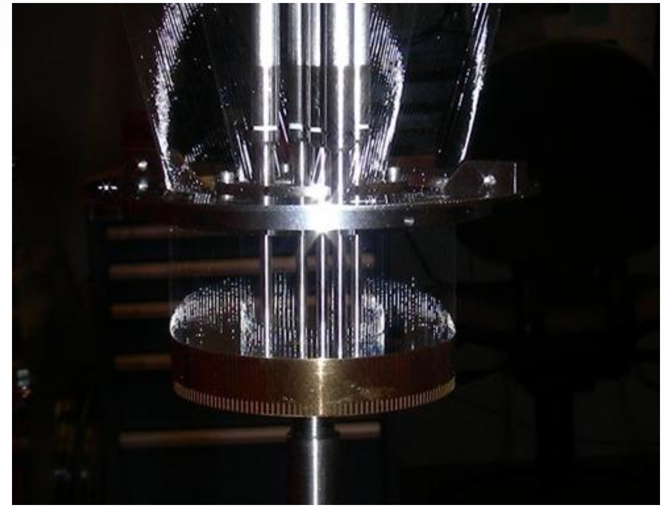




Coverdale *et al.*, HEDP 6, 143 (2010)

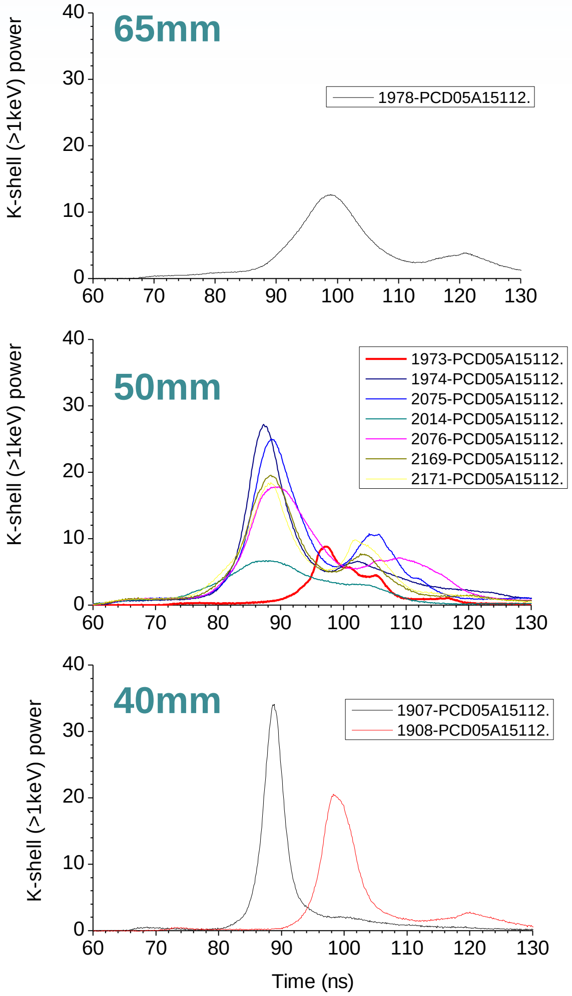
Al wire arrays at 40, 50, 65mm have been fielded on Z since the refurbishment

- **All wire arrays discussed here are nested wire arrays**
  - **2:1 Inner:Outer mass ratio**
  - **2:1 inner:outer diameter ratio**
- **Al wire arrays use Al 5056**
  - **Alloy with 5% Mg**
  - **Stronger than pure Al**
  - **Useful as spectroscopic analysis**

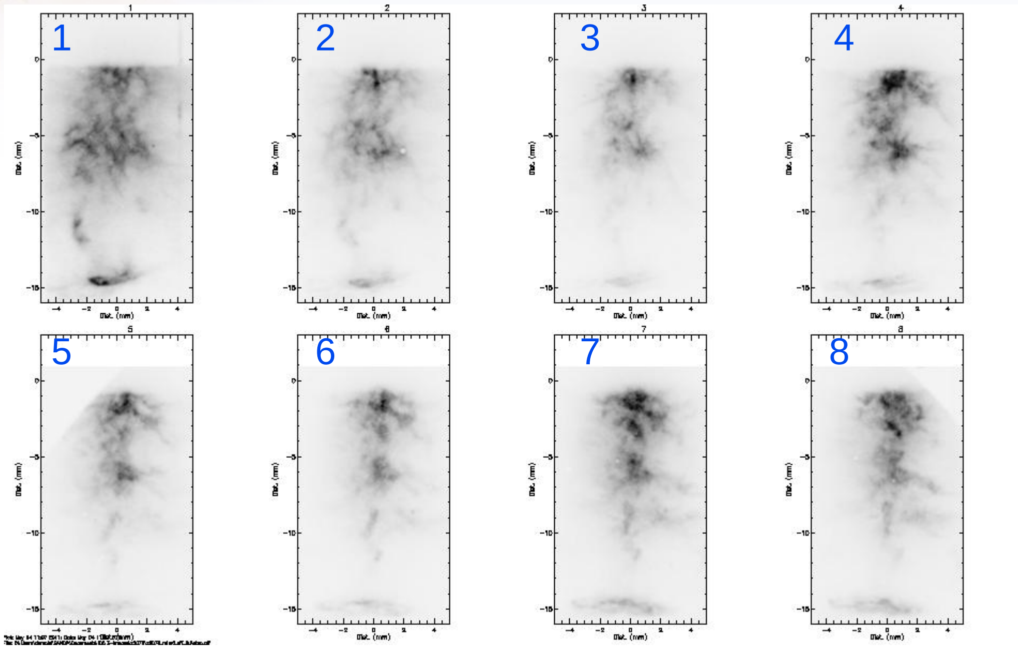


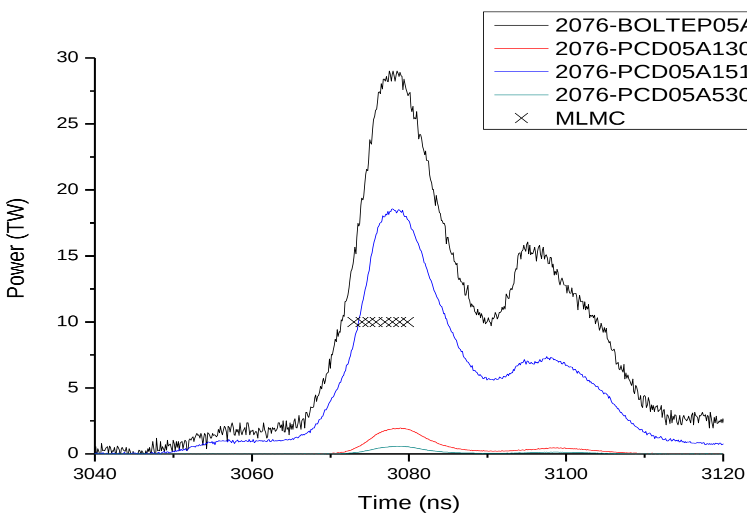
Al mass and diameter variations show significant variation of pulse shape and energy for different diameters and masses

- **Pulse shape varies considerably with different setups**
- **Significant fraction of energy comes from second hump**
- **As diameter is increased rise becomes slower and FWHM grows**
- **Optimal K-shell setup is different for yield and power**
  - **Max K-shell power at 40mm**
  - **Max K-shell yield at 50mm**



Z2076 shows significant structure in MLM images

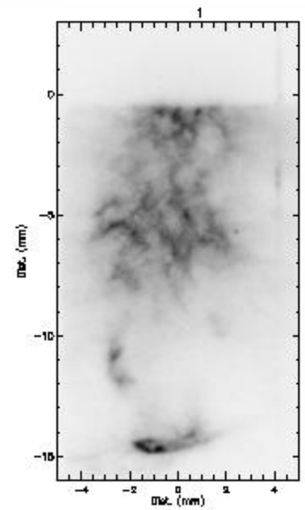




- Implosion of 'optimal' Al wire arrays is not clean
- Significant structure is observed
- Bright spots are present
- Non-uniformity has effect of reducing overall opacity of system

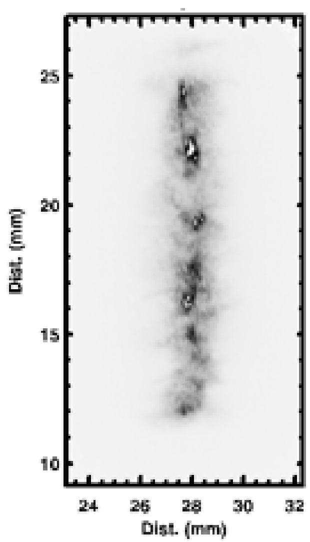
More symmetrical implosion leads higher opacity and lower >1keV yield

- **Z2076: 50mm 95ns Implosion**

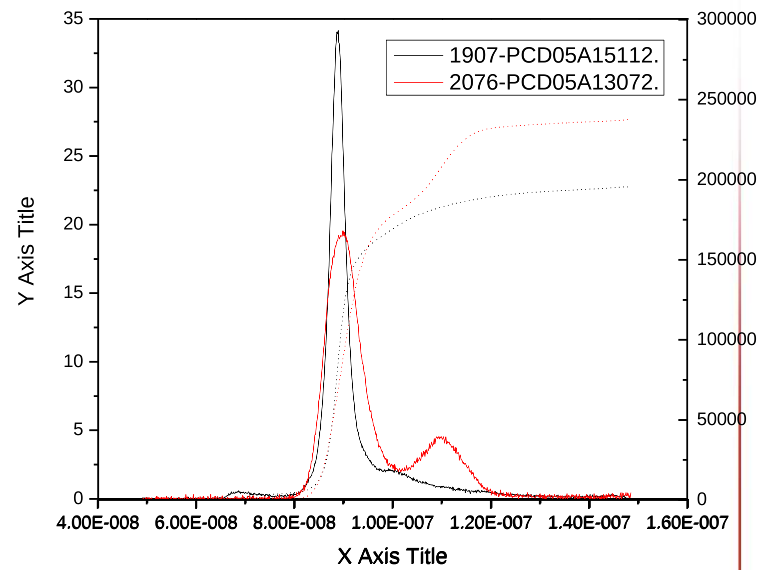


- **High degree of non-uniformity at stagnation**
- **Low opacity**
- **Larger radiated yield >1keV**

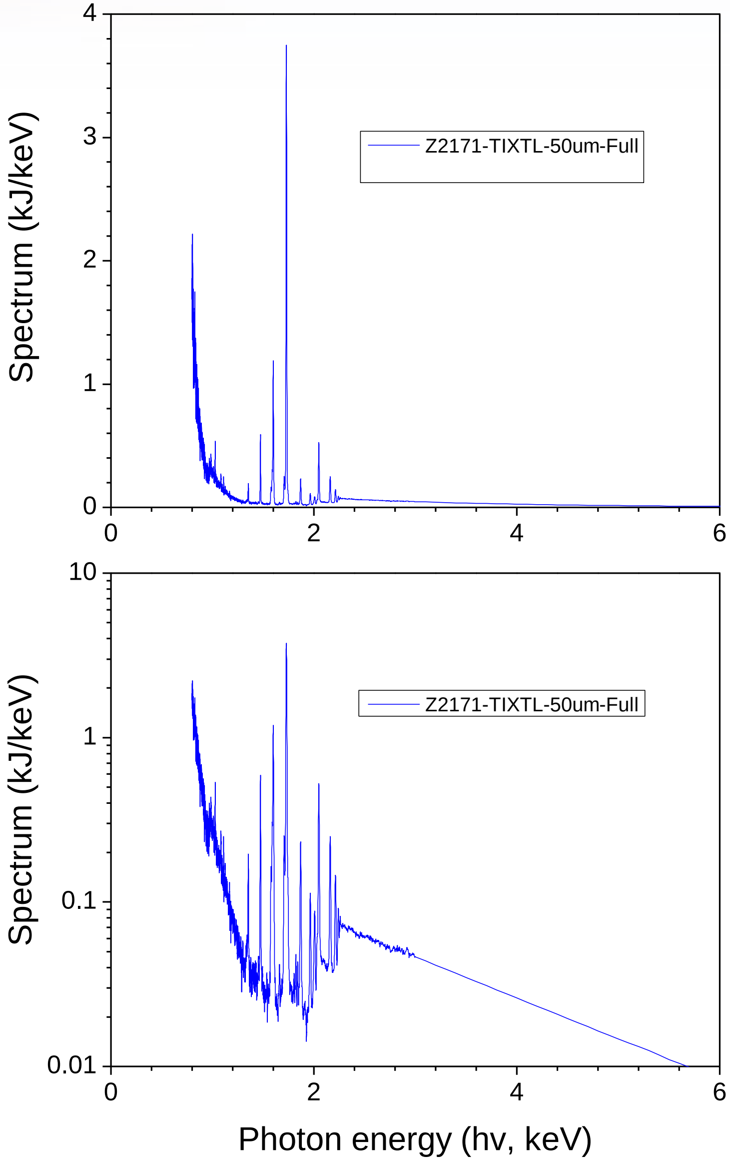
- **Z1907: 40mm 95 ns implosion**



- **Uniform column produced**
- **Higher opacity**
- **Lower yield >1keV**



Considerable Free-bound radiation is produces by Al wire arrays



- **Continuum is fitted and extrapolated assuming** $P(\nu) \propto e^{-\left(\frac{h\nu}{kT}\right)}$
- **Find temperature of emitting regions ~1.6 keV**
- **Energy in free-bound emission ~135kJ above K edge**
- **Variety of filter cuts are consistent with this extrapolated spectrum**

Diagnostic	*Filter Description*	*Z2171 Yield behind filters (kJ)* Recorded	From Spect.
PCD	38µm Be	190	190
PCD	8µmBe +CH	313	312
PCD	250µm Kapton	19	18
PCD	750µm Kapton	6	4

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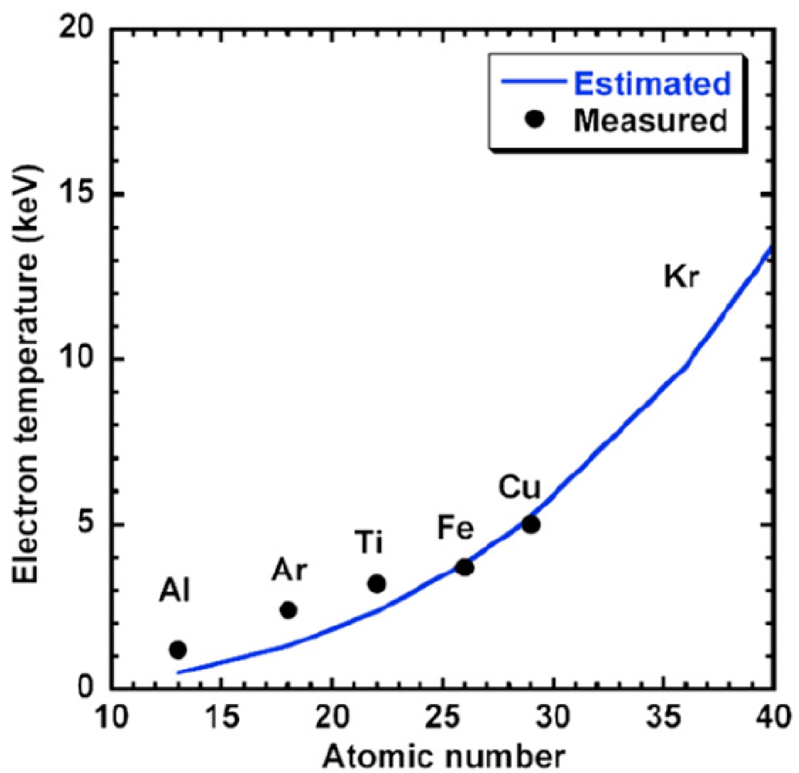
Plasma conditions required to radiate higher atomic number materials are harder to reach

- **Higher atomic number of Fe/Cu/Kr means much harder to reach K-shell**
  - **Use larger diameter loads**

- **Larger diameter loads are essential to reach sufficient electron temperatures to radiate efficiently**

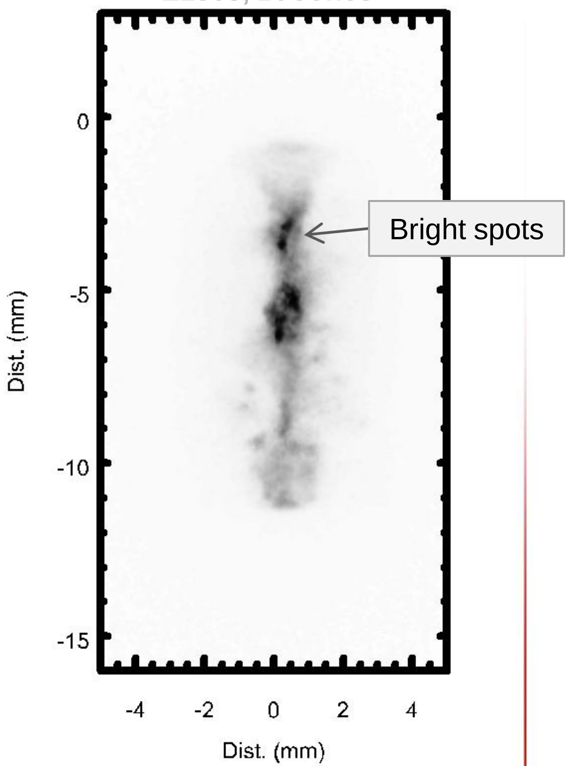


Behavior of higher-Z arrays influenced by competing constraints

- **In many cases high temperatures and high densities are contradictory aims**
- **Large diameters needed are not good for symmetry**
  - **Large implosion distances lead to instability growth**
  - **Low wire numbers and large interwire gaps are bad for symmetry**
  - **Bright spot can easily dominate the radiating column**
- **Large implosion velocities equate to a high rate of change of inductance, stressing the machine**
- **Efficiency is aided by**
  - **Good driver to Kinetic Energy conversion through magnetic coupling**
  - **Efficient transfer of kinetic energy to K-shell line radiation**

Cu pinch at peak x-ray power

Z1863, B. Jones



See J.P. Apruzese analysis

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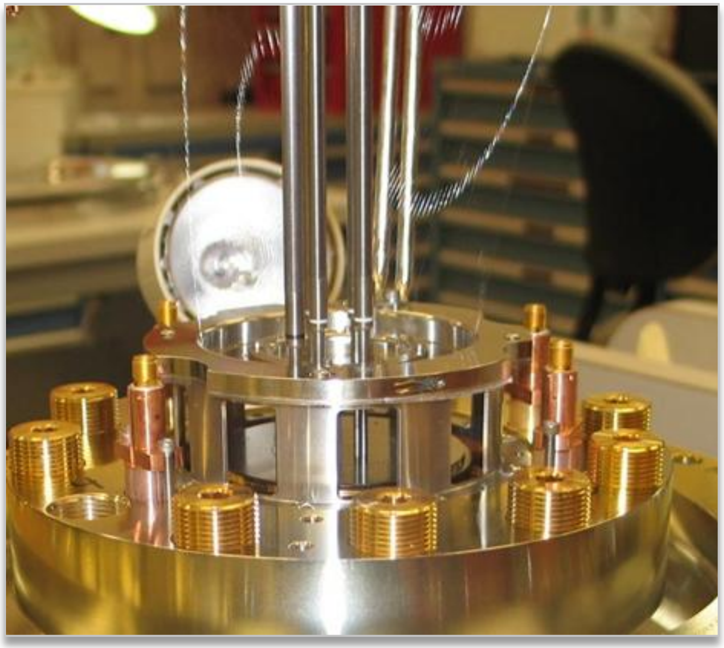
Variety of masses/diameters used to optimize

- All shots discussed use
  - Nested wire arrays
  - Stainless steel wires
  - 2:1 mass and diameter ratio

- Variations are performed in
  - Array Diameters:
    65mm, 70mm, 75mm
  - Masses
    1.01mg to 5mg
  - Implosion time
    90ns to 130ns



Subset of shots discussed:

Shot Number	Outer Diameter	Total Mass	Implosion Time
Z1857/1860*	65mm	2.5mg	103ns
Z2011	70mm	1.23mg	90ns
Z1995 / Z2079 / …	70mm	1.38mg	92ns
Z1996	70mm	2.25mg	102ns
Z2021	75mm	1.26mg	92ns

* Z1857-1861, Z2077-2082 were performed jointly with B. Jones

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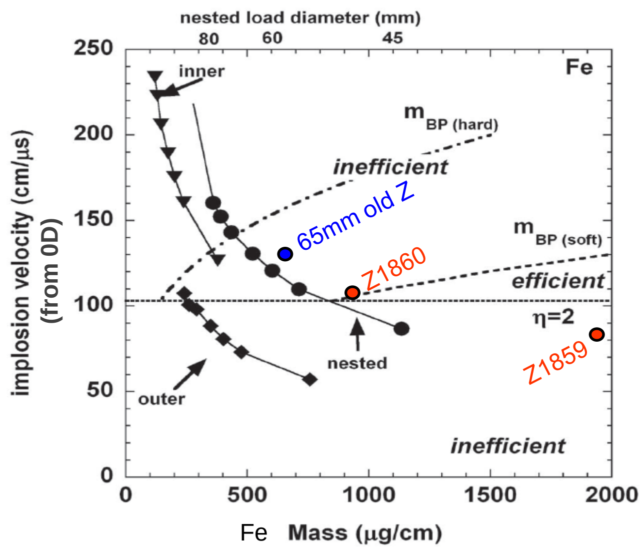
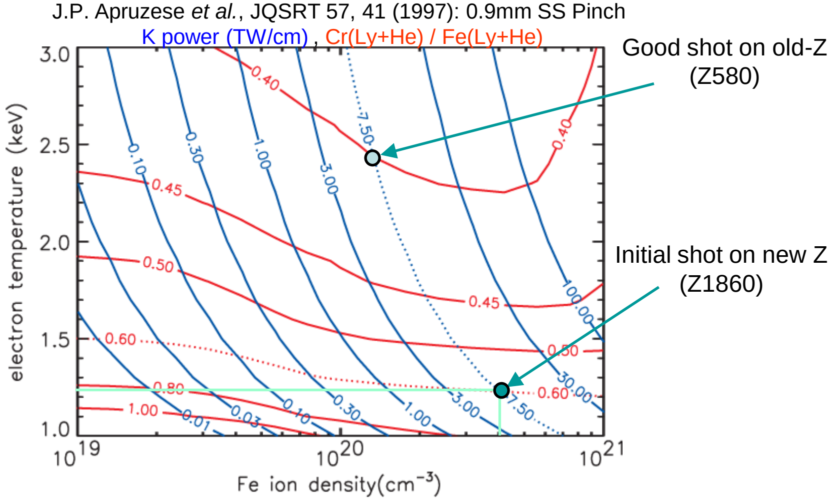
Initial 65mm diameter nested arrays on refurbished Z showed low electron temperature at stagnation



- **Initial SS shots on ZR used 65mm diameter**
  - B-dots: Higher coupled energy than pre-refurbishment Z
  - Spectroscopy: T_e lower than optimum on old Z

J.P. Apruzese *et al.*, JQSRT 57, 41 (1997): 0.9mm SS Pinch



- **Need higher KE/ion therefore higher velocity**
  - Larger diameter and earlier implosion time arrays explored with SS

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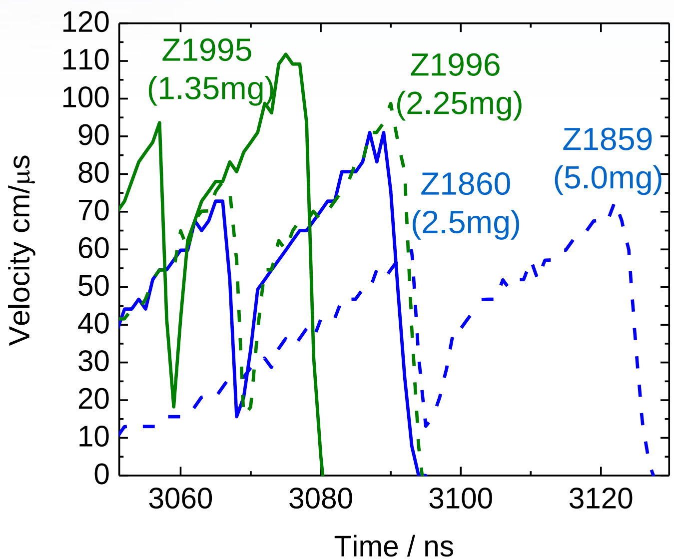
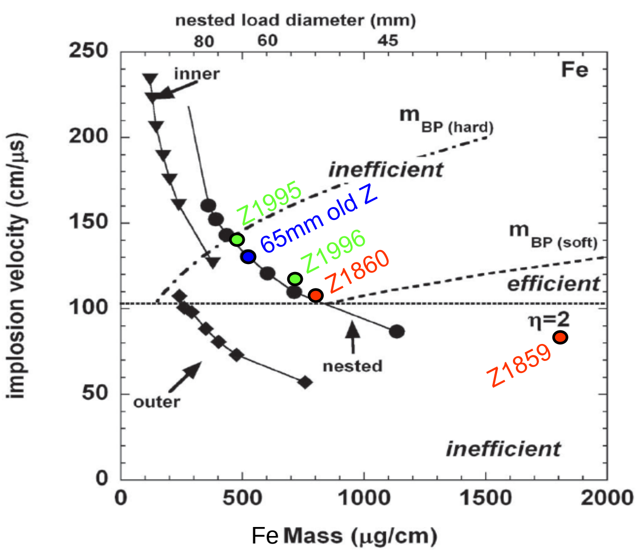
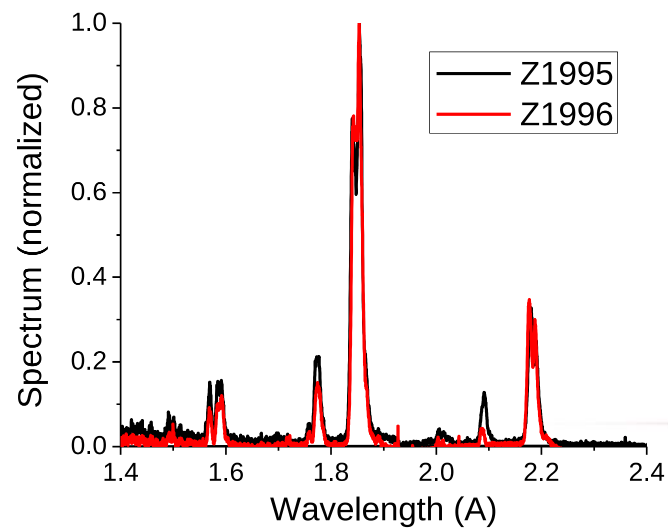
Larger array diameter and lower masses will lead to higher implosions velocities



- **Gorgon MHD simulations used to determine peak center of mass velocity**
- **Higher velocities are achievable by**
  - **Using larger array diameters**
  - **Using earlier implosion times**
- **Both also lead to lower masses**





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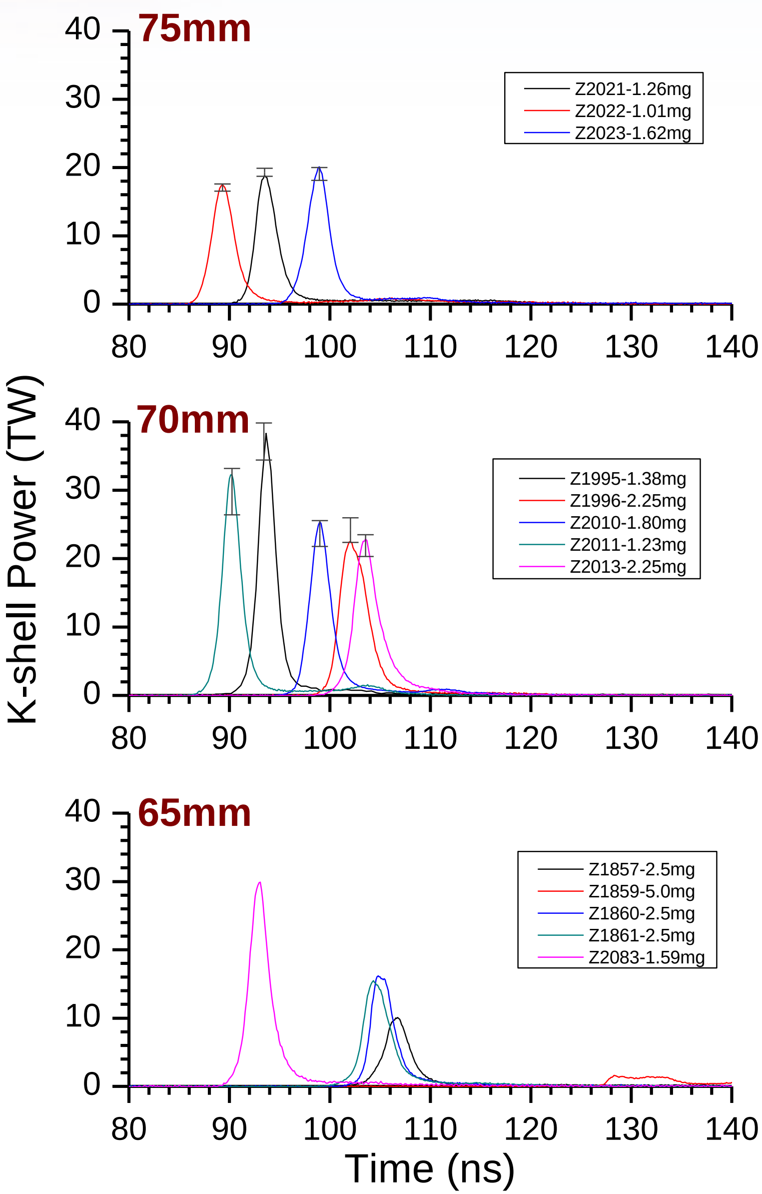
Diameter scan at various implosion times indicates that 70mm is optimal mass



- **Arrays massed such that similar implosion times at each diameter**
- **Over various diameters and masses 70mm is optimal diameter**

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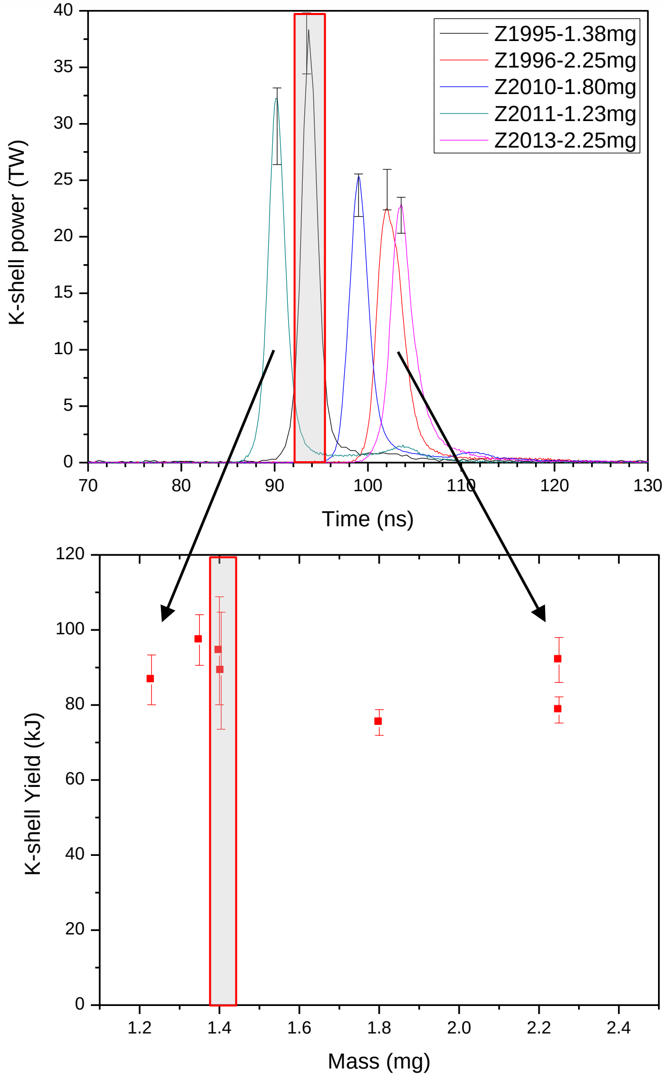
SS mass scan at 70mm has demonstrated ~1.38mg is optimum mass, imploding at ~95ns



- Optimal K-shell power achieved with
  - 95ns implosion time
  - 1.4mg total array mass
- K-shell yield reasonably independent of implosion time

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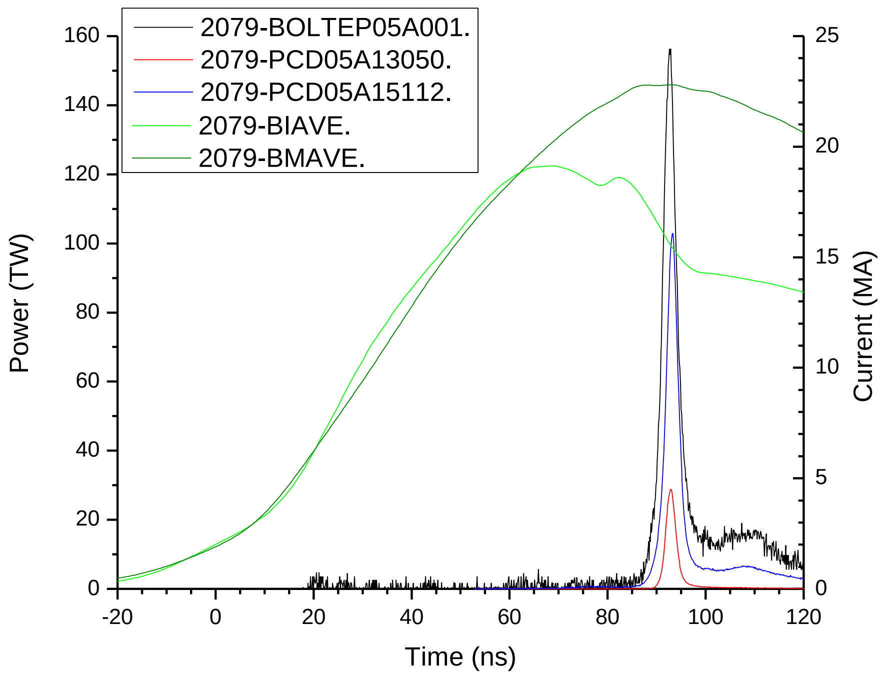
Despite radiating ~85kJ, optimal arrays have significant current loss due to voltage needed to drive implosion

- **Implosions velocities ~110cm/us produces large dL/dt**
- **Effect of interaction pulse observed on delivered current**
- **dL/dt voltage significantly impacts ability of generator to deliver current**
- **Convolute loss drops the current able to drive the load**



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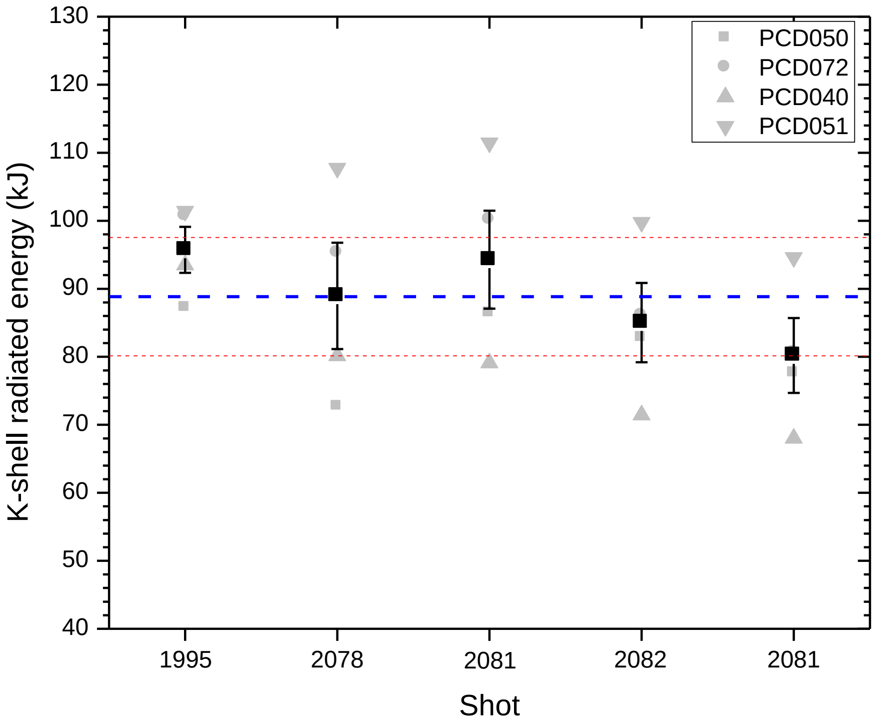
Reproducibility of Z1995 looks reasonable



- Good shot chosen to investigate reproducibility
- On all shots Standard Error in measured PCD yields <10%
- Z2077 had significantly lower yield
  - All others ≥80kJ
  - Number of diagnostic issues on Z2077 led to inconsistent diagnostics from other shots
- Neglecting Z2077
  - Mean = 88kJ
  - St. Dev = 6kJ
- Recent shots have not maintained this reproducibility
  - More work needed to understand

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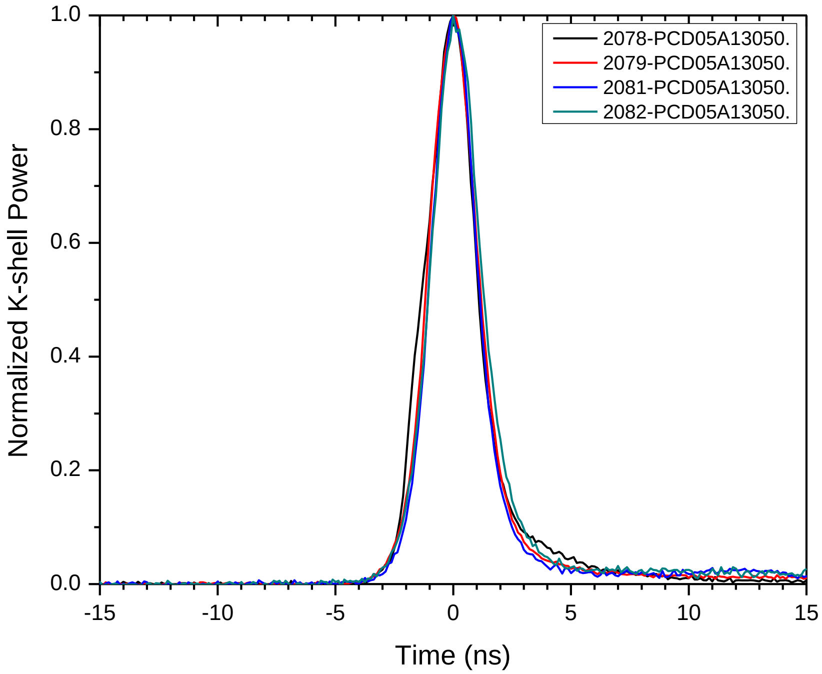
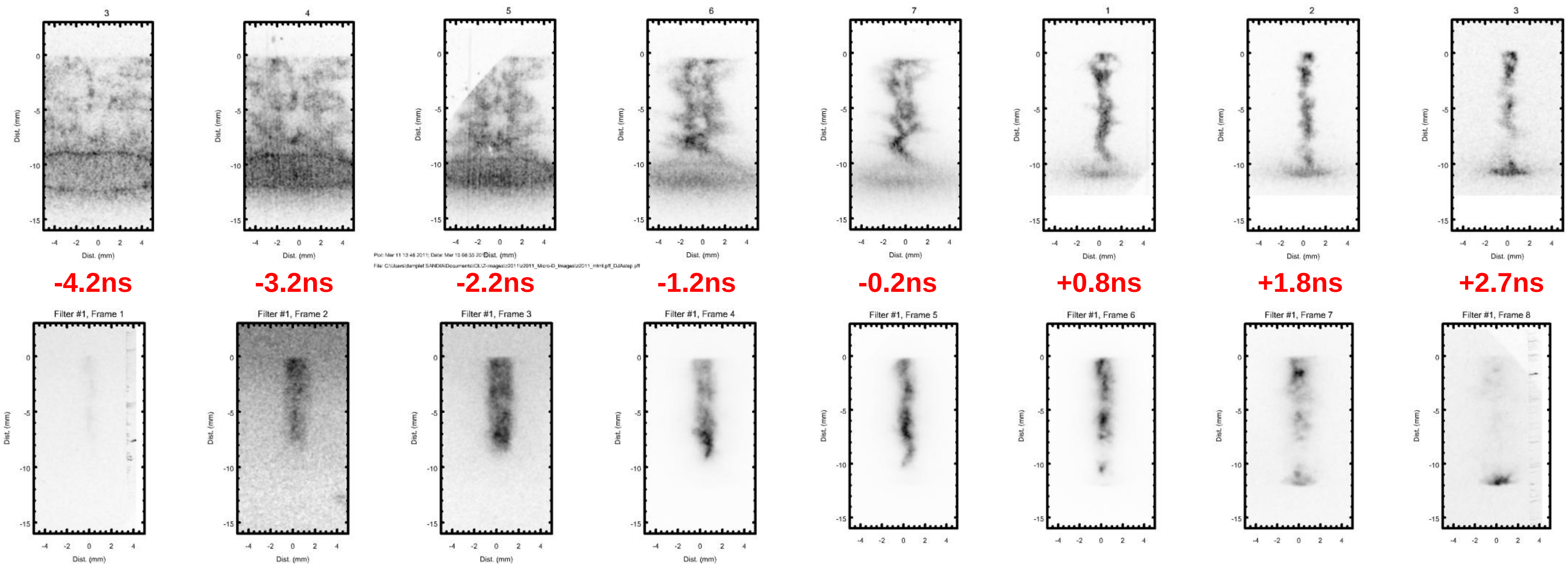
Pulse shape for 1.4mg 70mm load is highly reproducible

- **Very good reproducibility of K-shell radiation pulse shape**
- **FWHM is 2.42 ± 0.15ns**
- **Rise time is 1.90ns ± 0.14ns**
- **Heavier masses have longer rise and FWHM**



Pinhole camera imaging at different photon energies provides insight into dynamics of implosion

277eV



>5keV

- Pinhole cameras on MLM instrument show time history of emitting regions
  - One camera filtered to look at SS K-shell
  - Two cameras look at bulk emission (277eV)
- 277eV shows imploding 'hollow shell' approaching axis
- Some hollowness seen on K-shell before peak x-rays

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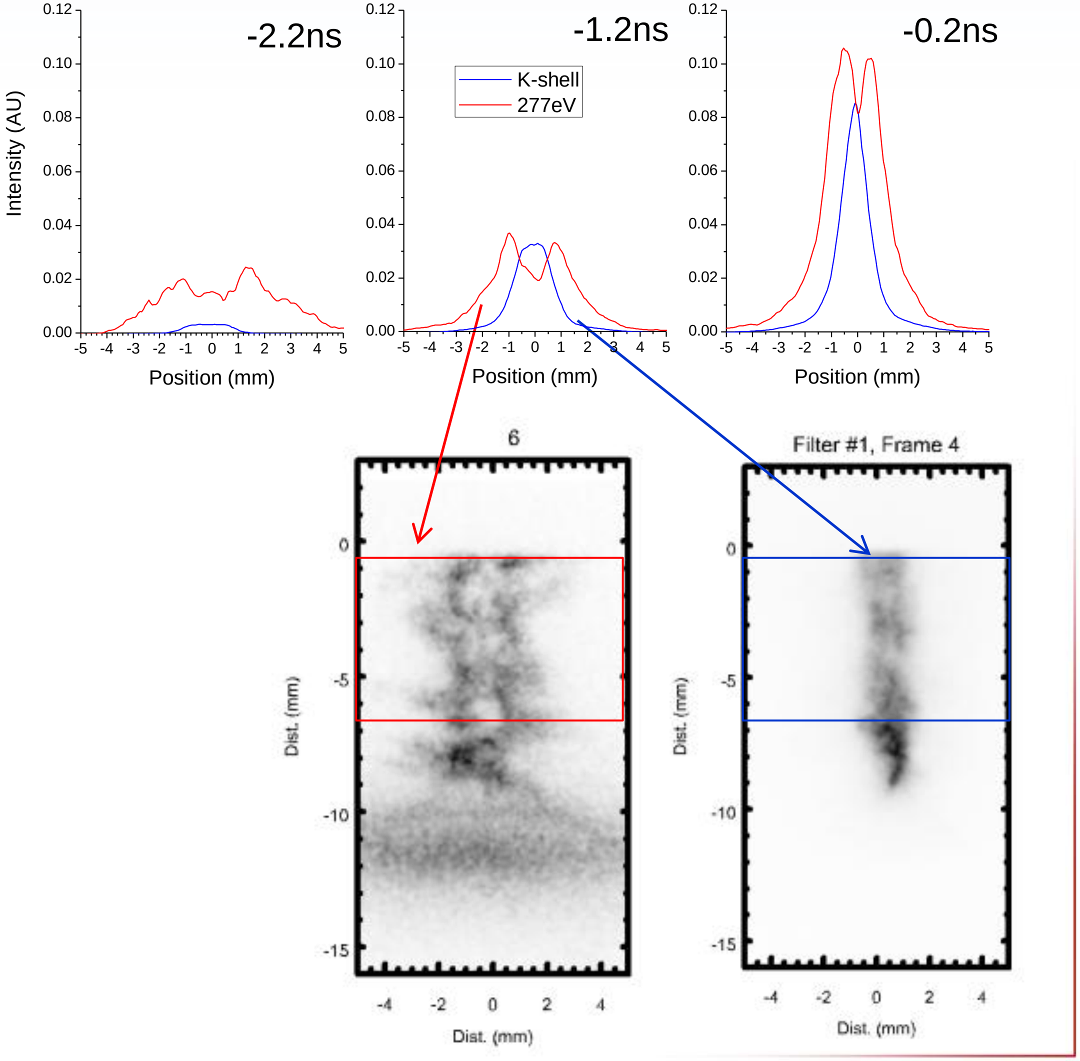
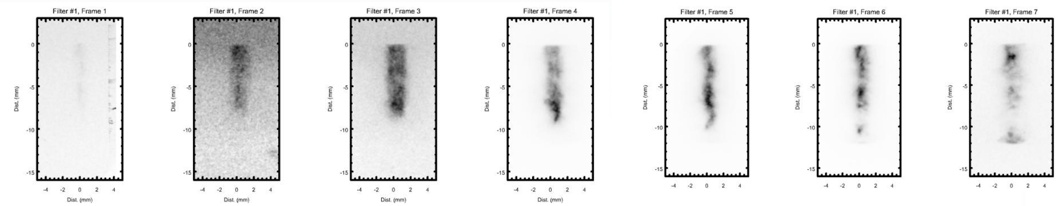
K-shell emitting region is compressed through the x-ray rise

- K-shell emission is always more confined to the axis
- Data is consistent with hot spike on inner edge of colder annulus
- Locally K-shell image is also somewhat hollow, however axial averaging does not show

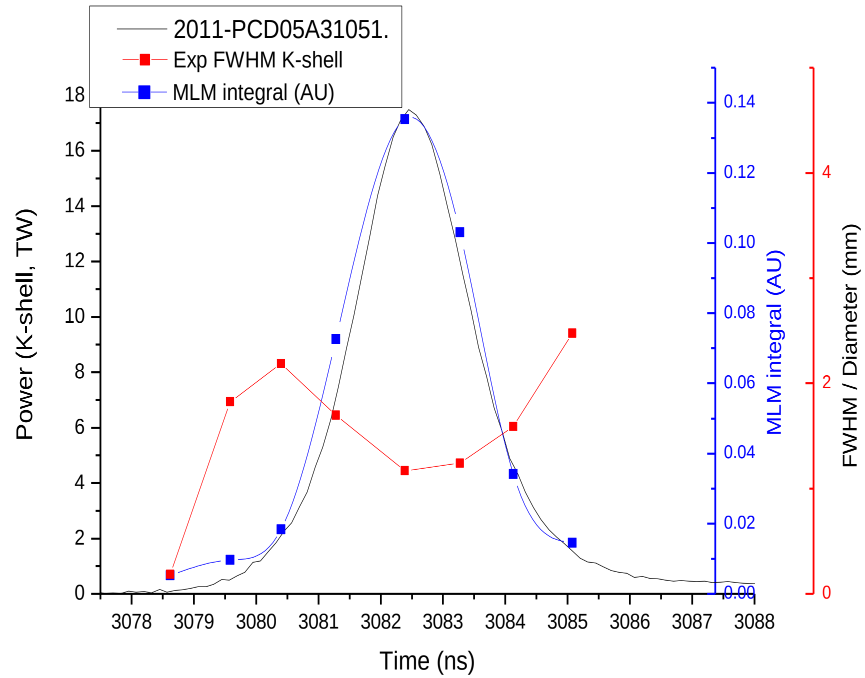


FWHM of K-shell emitting region is consistent with compression of the column during x-ray rise

- **Integral of K-shell filtered pinhole camera strongly follows K-shell x-ray pulse**



- **Rise of x-ray pulse coincides with decrease in FWHM of K-shell region**
- **Reason for earlier rapid expansion unclear**
  - **Very low emitted power at that time**
- **From images, expansion post-peak is representative of column break-up**
  - **Instability growth**
  - **Angular momentum**
  - **Hot spot formation**



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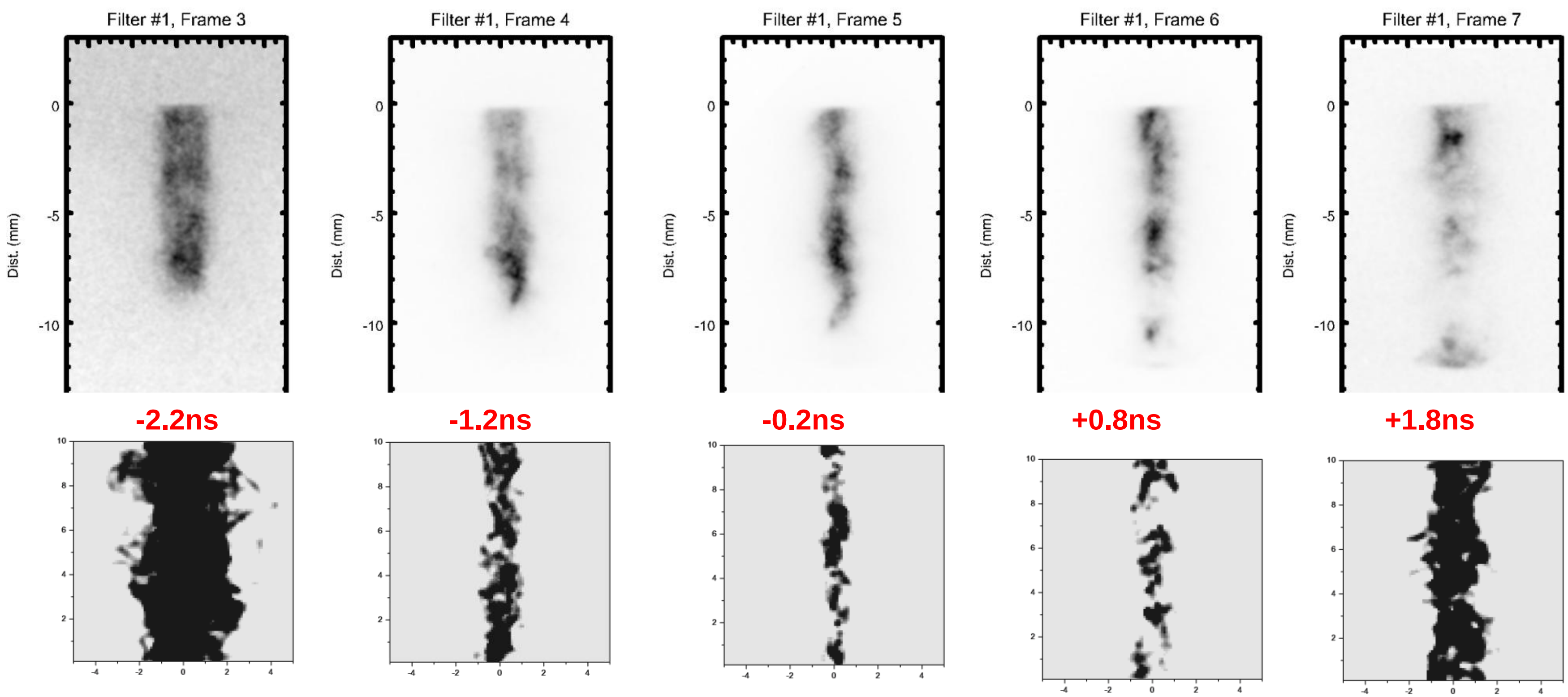
MHD simulations are able to reproduce the global structures seen in MLM images

- Gorgon simulations post-processed with tabulated emissivities for >5keV filter cut (work in progress)

- Matches well to dynamics seen in MLM images



3D MHD modeling by C.A. Jennings
(in collaboration with S.B. Hansen)

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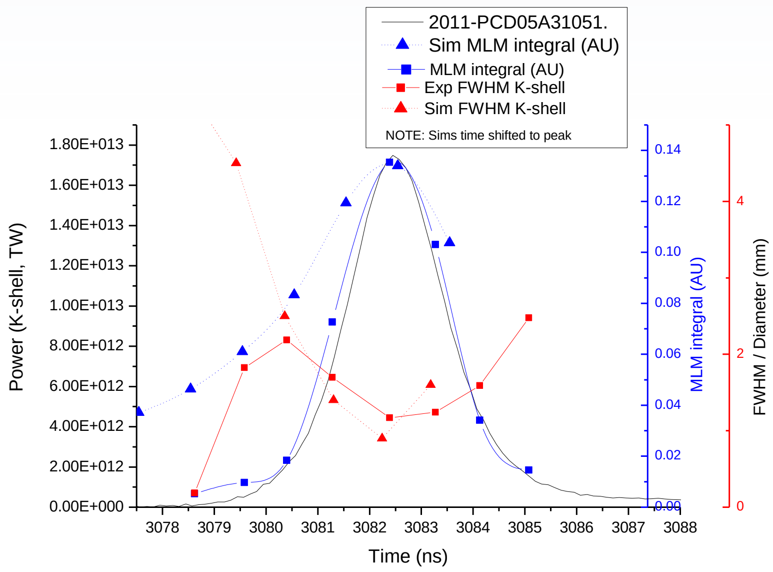
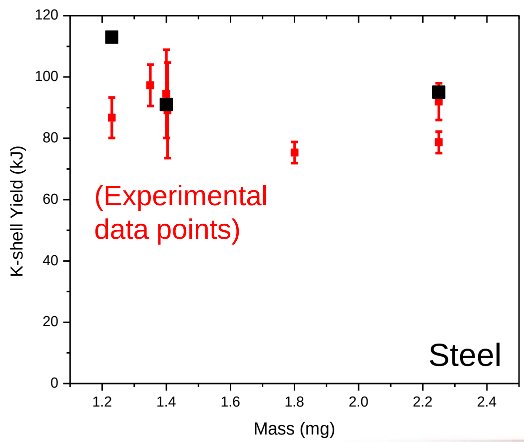
FWHM of K-shell emission provides a more quantitative comparison between simulations and experiments

- Line-out from both simulated and experimental K-shell images
- Both limited to top 6mm which many other diagnostics view
- Very good agreement on FWHM during times of K-shell emission
- Work continuing on simulations to better match pulse shape
- Modeled K-shell yields in good agreement for heavier cases

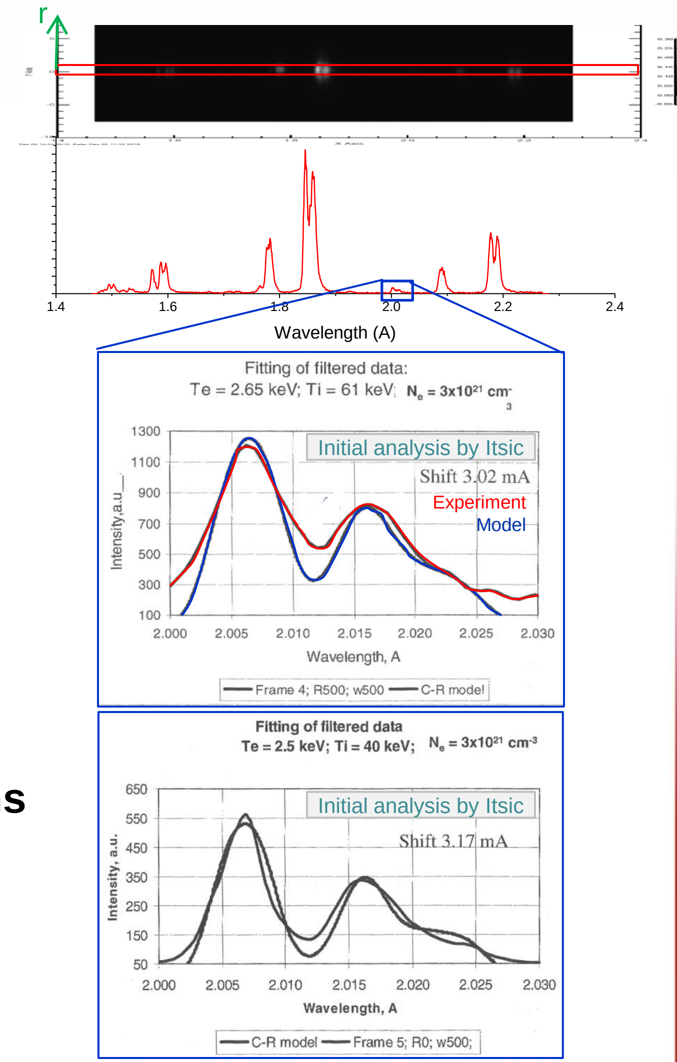




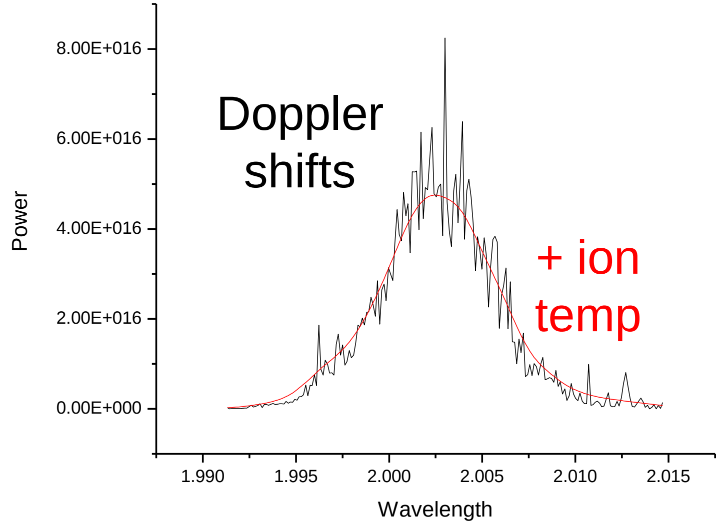
For Stainless Steel pinches, optically thin lines can be used to put limits on ion temperature

Z2011 gives narrow Mn He-α lines at stagnation

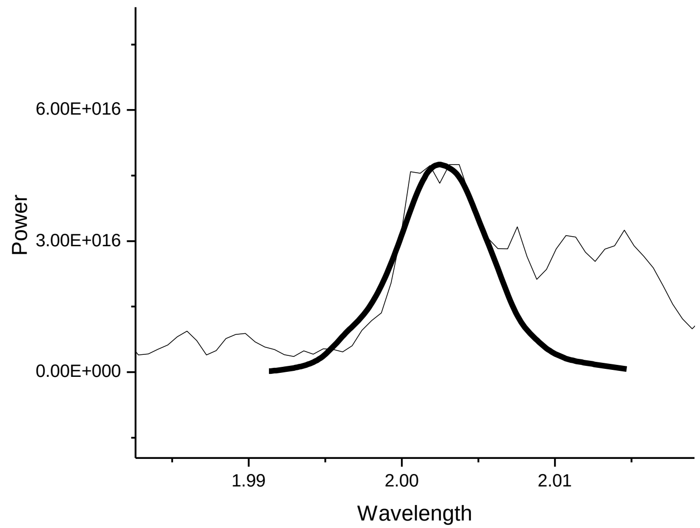
- **Space and time resolved side-on specta**
  - **End-on being pursued for similar measurements**
- **Line narrows in the ~1ns interframe time of TREX**
- **May provide a bound on ion temperature**
  - **Bound will include bulk motion**
  - **Small radius(~1mm) may help counter this**
- **Current estimate, neglecting plasma motion, ion temperature decreases from 60 keV to 40 keV over ~1ns**
- **Very early stages of analysis!**



MHD simulations post-processed to compare with specific line widths give reasonable fit to the experiments



Reconstructing spectral line features using specific line emissivity to compare effects of ion temperature and motional broadening



Comparison to measured Mn-He-alpha for 2011

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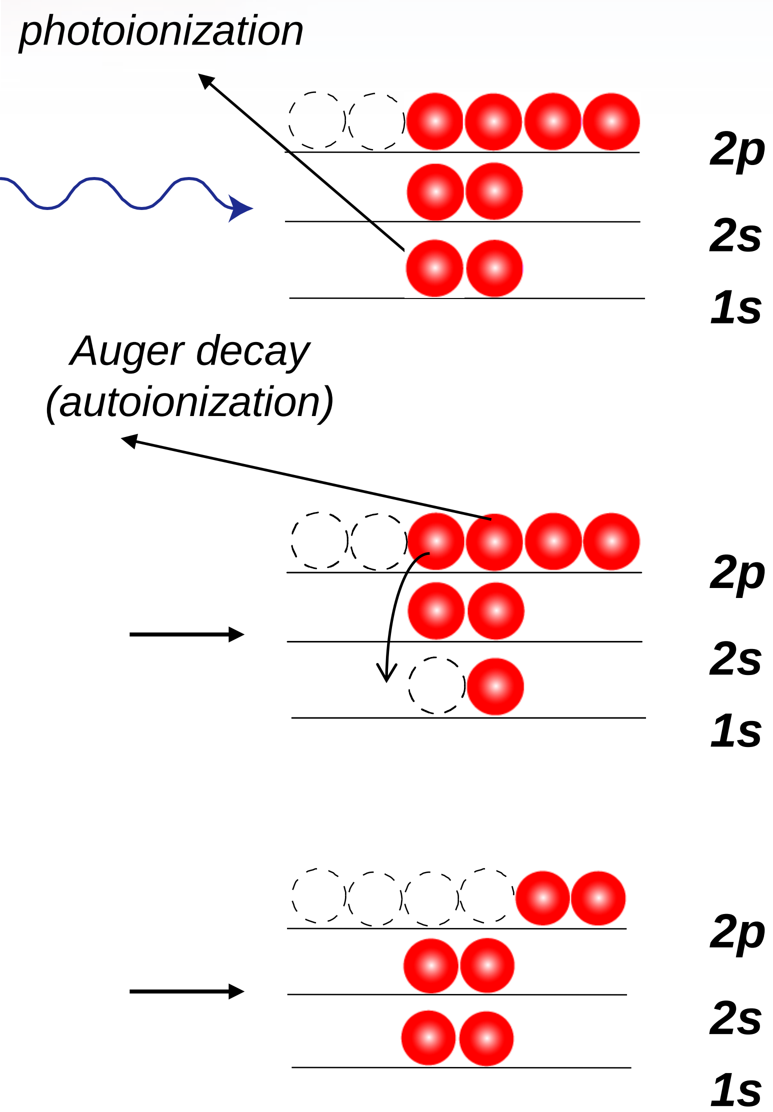
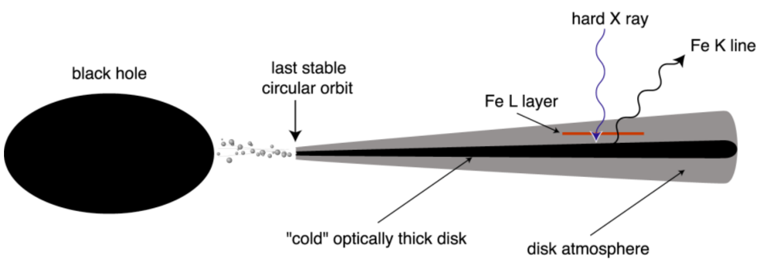
K-shell sources discussed in this presentation can be used to drive basic physics experiments



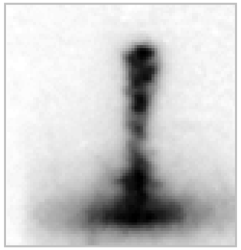
- **Resonant Auger Destruction leads to uncertainty in black hole accretion disk dynamics**
- **Autoionization competes with radiative decay following inner-shell photoionization**
- **K-shell lines can be used to excite specific transitions**



Courtesy of Duane Liedahl, LLNL

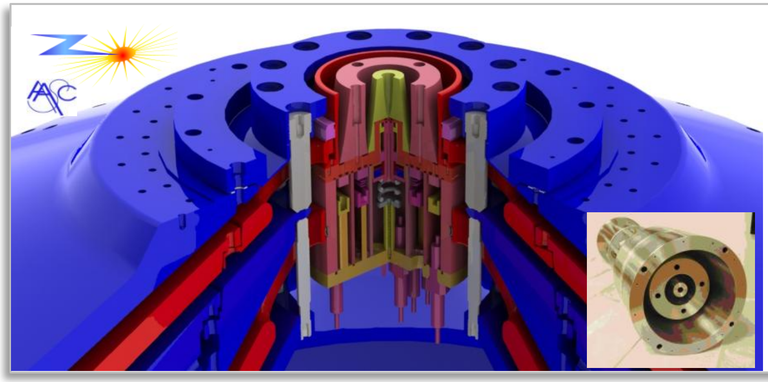
1MA generators can provide insight into specific questions that arise for large diameter arrays at 20MA

- Large diameter implosions are sometimes seriously impacted by end-effects
  - Primarily near cathode
  - First seen on MAGPIE
  - Presently on Z appears for some setups but not all
  - Insufficient shots on Z to really investigate



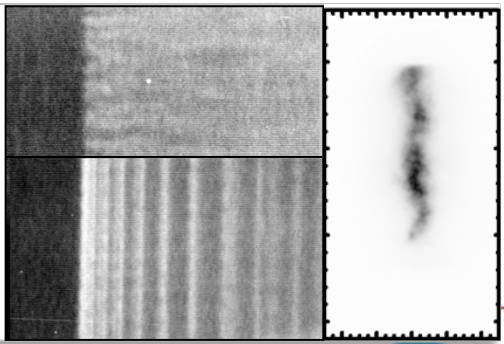
No end-effect
Z2021

With end-effect
Z2020



- Gas puffs are an upcoming capability at Z
  - Minimal data on whether pre-ionizer helps
  - What density profiles are optimal
    - Trade off between R-T and pinch temperature

- Understanding specifics of wire array physics is incredibly useful
  - Wire initiation
  - Wire ablation
  - Precursor formation
  - Stagnation dynamics
  - Requires good time and spatial resolution



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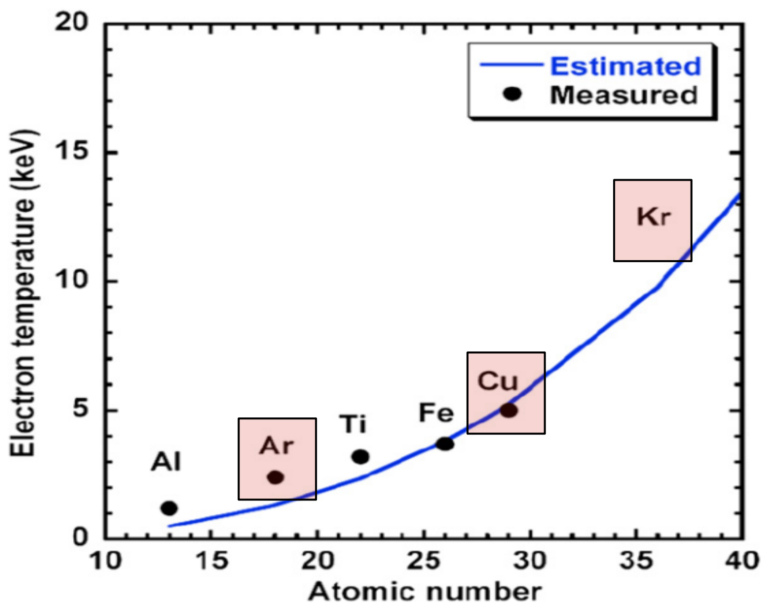
Upcoming experiments plan to expand the photon energies covered by K-shell x-ray sources on Z

- **Wire array experiments continue**
  - **Optimization of ~8.4keV Cu wire arrays continuing this year**
  - **Study of Free-Bound continuum available from both Al and SS arrays continuing**
- **Gas puffs are being reestablished on Z**
  - **Will allow ~3.1keV Argon gas puff experiments**
  - **Combination of large (~12cm) gas puff with improved delivered energy on Z will allow investigation of ~13keV Kr gas puffs**



Summary

- Higher K-shell powers and yields have been achieved with recent SS and Al arrays on Z
  - SS wire arrays have produced ~85kJ of >5keV emission
  - Al wire arrays have produced ~400kJ of >1keV emission
- 70mm wire arrays have demonstrated reasonable reproducibility despite large implosion distance for instabilities to grow
- MHD simulations are playing a major role in design and understanding of experiments
  - 3D MHD coupled to tabulated atomic physics models are recreating many features seen in the experiment
  - Significant modeling insight also from NRL using more detailed transport & in-line atomic physics
- Development of Al, Ar, SS, Cu and Kr K-shell sources are continuing
- Large diameter wire arrays create interesting plasma conditions and can be used to drive basic science experiments