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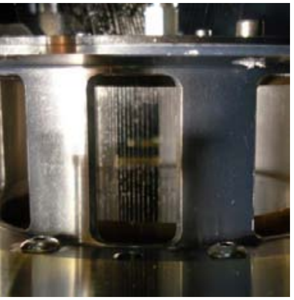
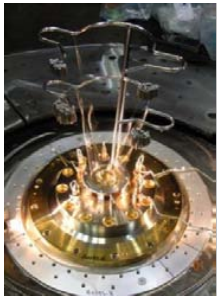
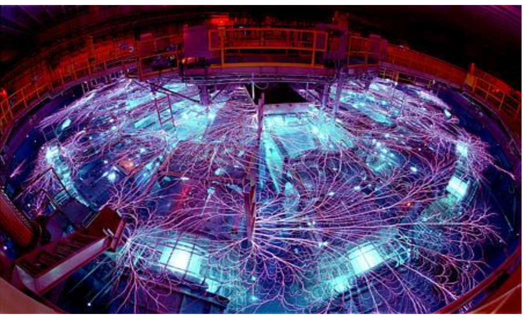

Sandia National Laboratories

Exceptional service in the national interest

Contrasting physics in sources of 1-20keV emission on the Z facility

D.J. Ampleford

Radiation and Fusion Experiments

Sandia National Laboratories

APSDPP

Denver CO

November 2013

(Also to be presented at Non-LTE workshop Nov 6th)

U.S. DEPARTMENT OF ENERGY · NNSA National Nuclear Security Administration · Laboratory Directed Research & Development

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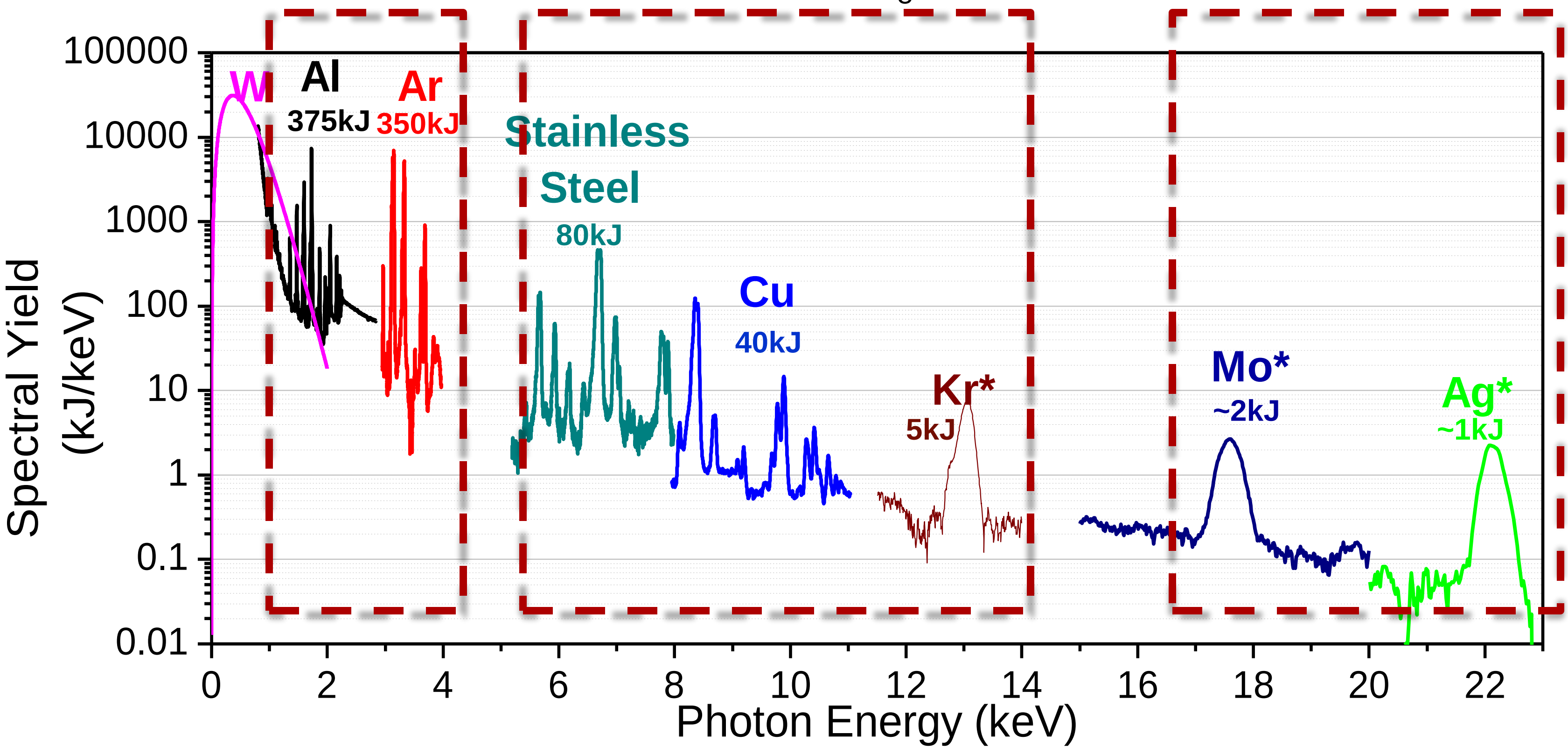
Experiments on Z involve a large group of collaborators

- Sandia National Laboratories
  - C.A. Jennings, S.B. Hansen, B. Jones, A.J. Harvey-Thompson, M.E. Cuneo, G.A. Rochau, D.C. Lamppa, C.A. Coverdale, M. Jobe, A.R. Laspe, T.M. Flanagan, N.W. Moore, T. Webb
  - Many, many people who enable experiments on Z
    - Diagnostics, pulsed power development, system integration, machine turnaround, Load design, fabrication, assembly and installation
- Naval Research Laboratory
  - J.W. Thornhill, J.L. Giuliani, Y.K. Chong, J.P. Apruzese, A.L. Velikovich, A. Dasgupta, N. Ouart
- Weismann Institute
  - Y. Maron, B. Bernshtam, Y. Zarnitsky, V.I. Fisher, A. Starobnates
- Imperial College
  - J.P. Chittenden, N. Niasse, B. Appelbe
- Alameda Applied Science
  - M. Krishnan, P.L. Coleman, K. Wilson Elliott, R.E. Madden

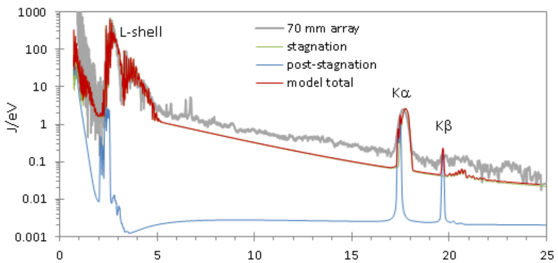
Summary: Imploding Z pinches on the Z generator create extremely bright plasmas, however efficiency and mechanisms for emission are different, providing a rich dataset to study emission from dense plasmas

Opacity affects emission	**Temperature is critical**	**Inner shell ionization**
Tune to give large surface area	Implosion velocity determines T_e	Novel ideas to enhance hot e^-

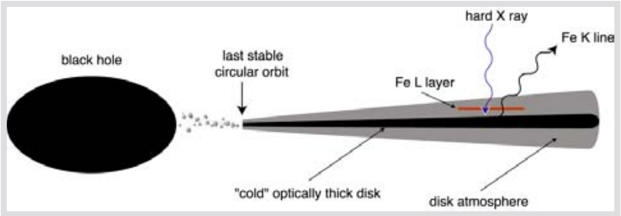


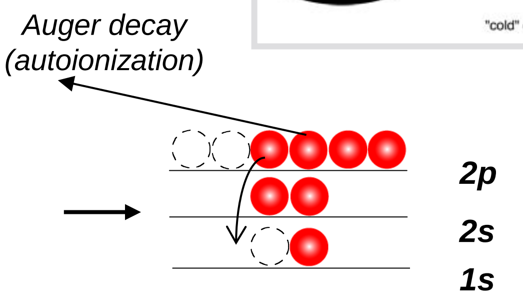
Large diameter implosions and K-shell x-ray sources can be useful for a number of applications

Testing atomic models

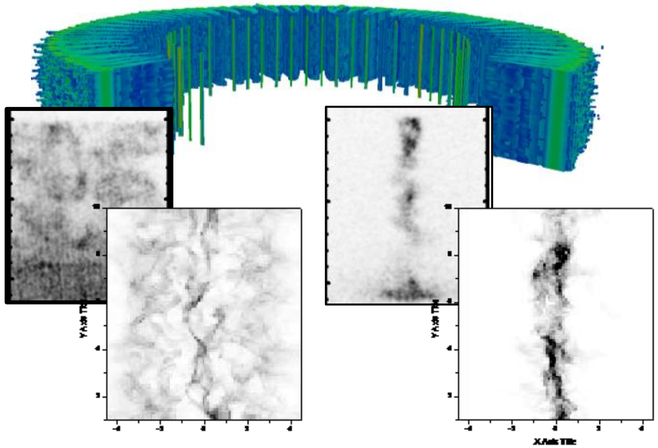


X-ray source for inner-shell photoionization

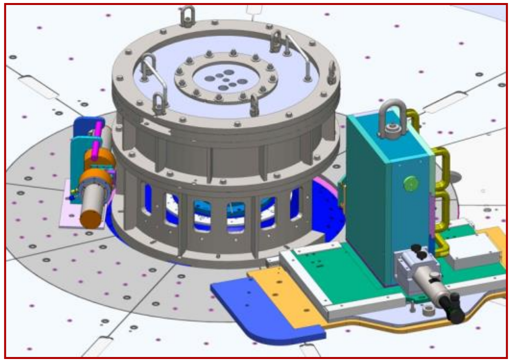




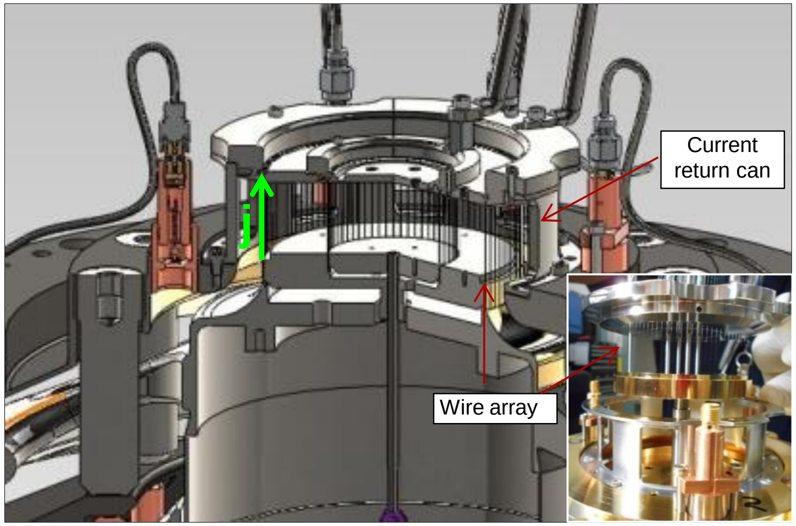
Complex 3D problems for MHD simulations

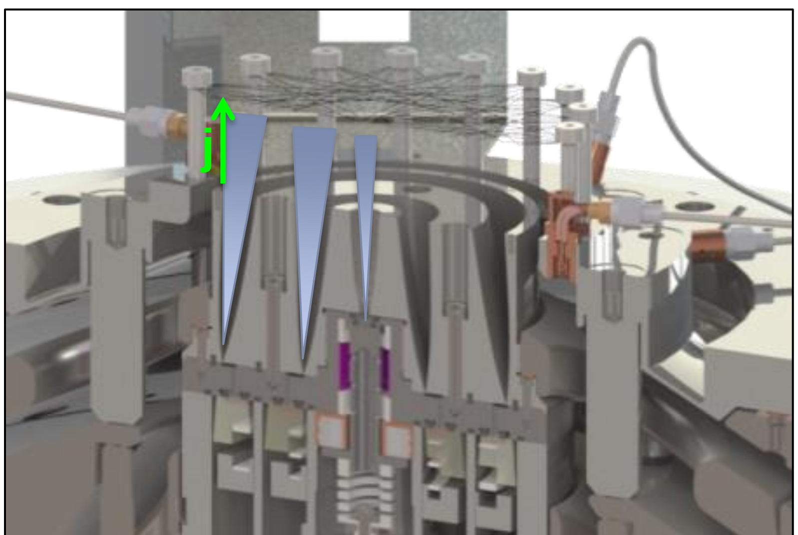


X-ray source for scattering experiments



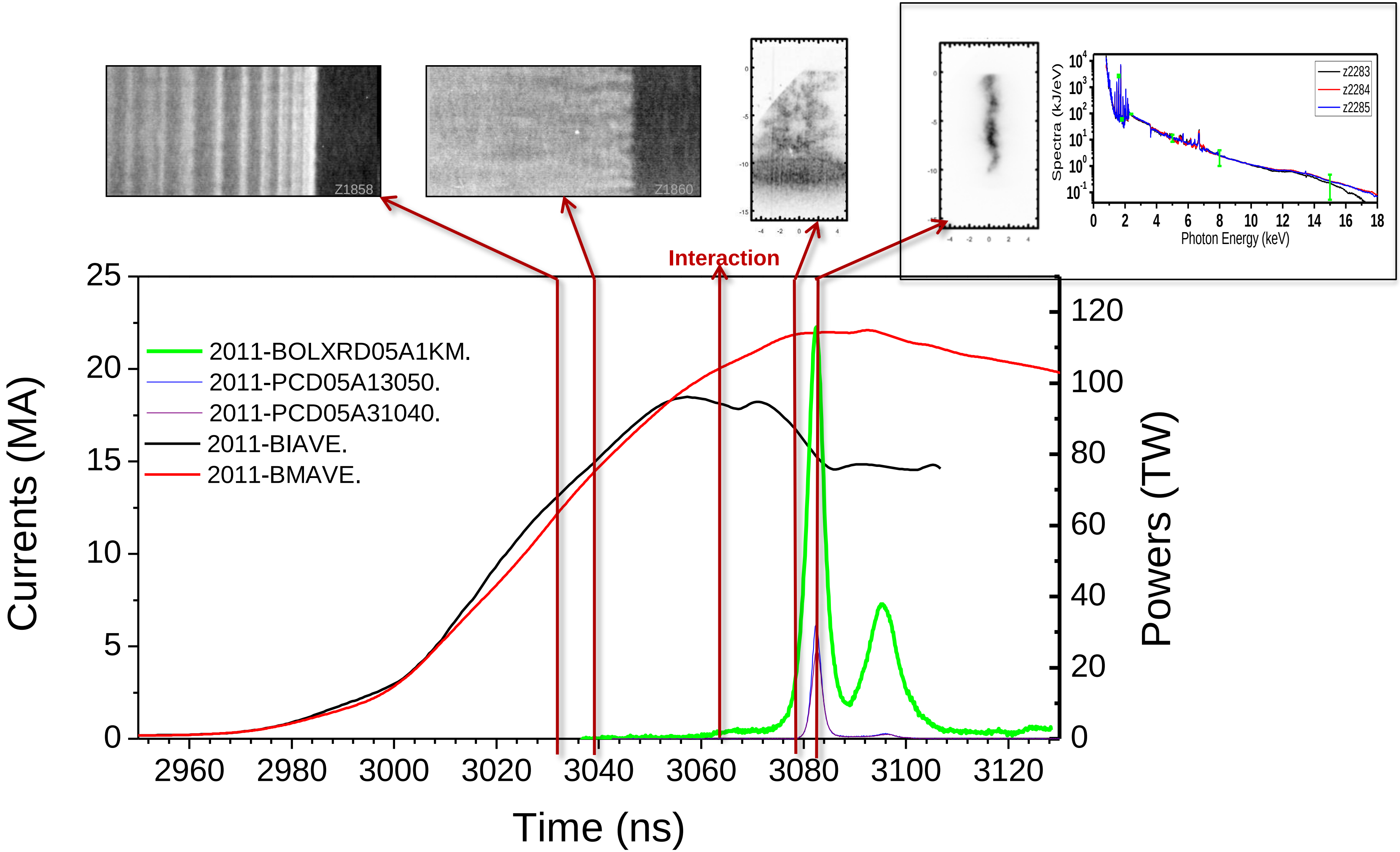
Experiments use wire array and gas puff z pinches imploded on the Z generator





- Wire arrays use
  - ~100 wires
  - ~.5 mg/cm
  - Nested wire arrays for stability
  - Al, Stainless Steel, Cu, Mo, Ag
- Gas puff use
  - Azimuthally symmetric gas shells
  - ~1 mg/cm
  - Shell-like and ramped profiles
  - Ar, Kr
- For both, initial diameter, mass and mass distribution define stagnation temperature, uniformity

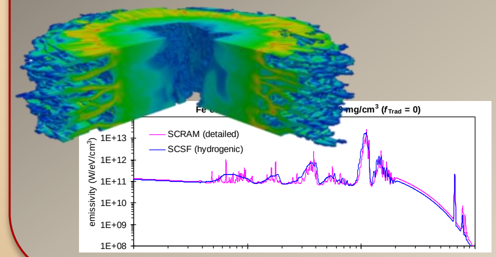
Z pinches undergo a multi-stage implosion, to produce a dense hot plasma on the axis of symmetry



High velocity implosions on Z provide a rich test-bed for MHD and atomic physics codes

Pre-shot design

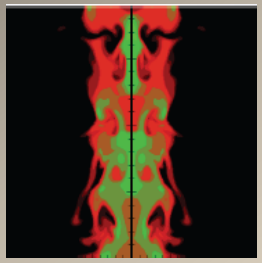
3D Gorgon MHD coupled to tabulated non-LTE emissivities



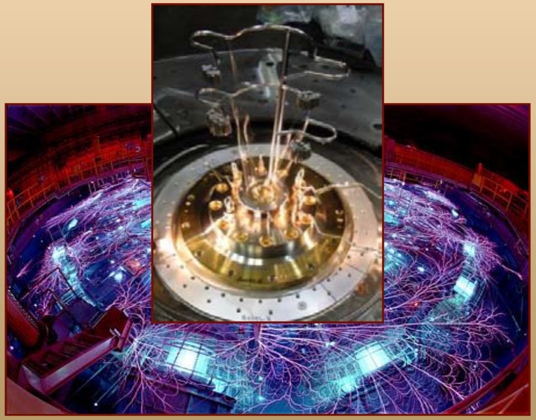
Energy balance arguments

$$v \sim \sqrt{\frac{2\eta E_{min}}{m}} \sim \sqrt{\frac{2.024\,\eta\, Z^{3.662}}{A}}$$

2D rad-MHD
Mach2 with DDTCRE



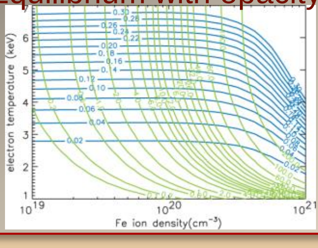
Experiment



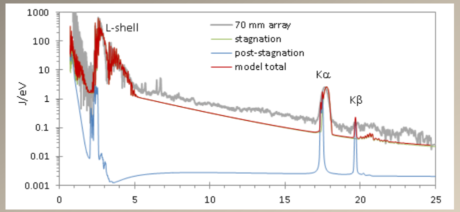
Feedback into design models

Analysis

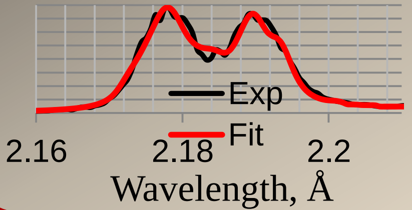
Static Collisional Radiative Equilibrium with opacity



Hybrid structure Collision Radiative model (SCRAM)

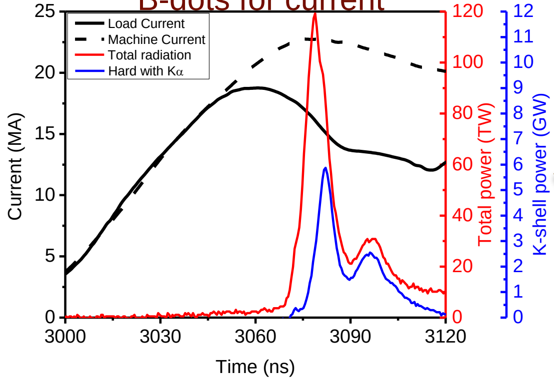


Collisional Radiative modeling of specific features

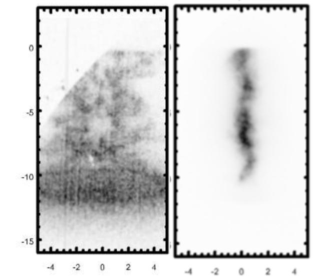


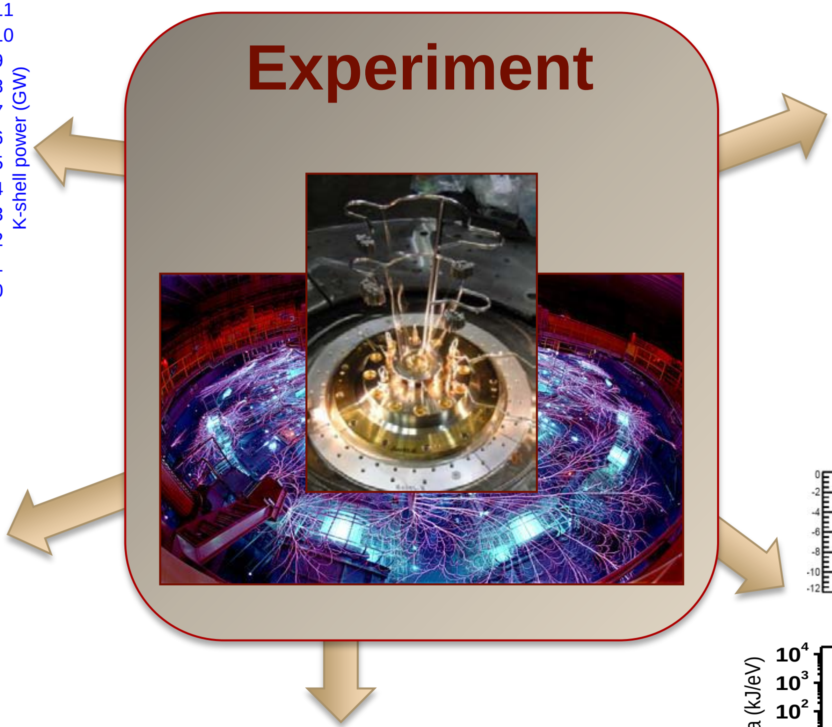
High velocity implosions on Z provide a rich dataset of spectral, imaging and current diagnostics

PCDs for K-shell power
XRD/TEP/Bolo for total emission
B-dots for current

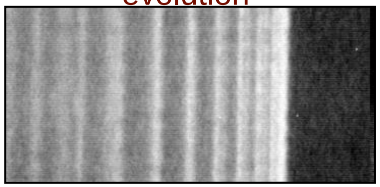


Time-resolved imaging of soft and K-shell emission

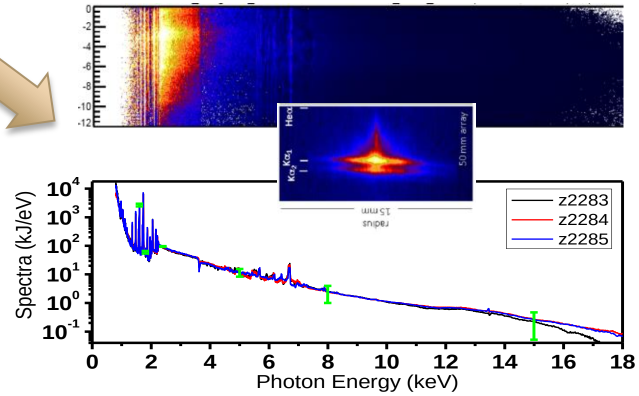




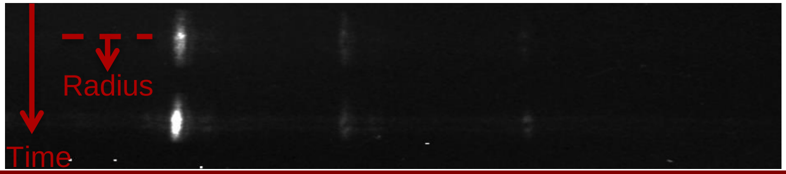
Radiography of early-time evolution



Broadband (0.8-24keV) time-integrated 1D-spatially-resolved self-emission spectra



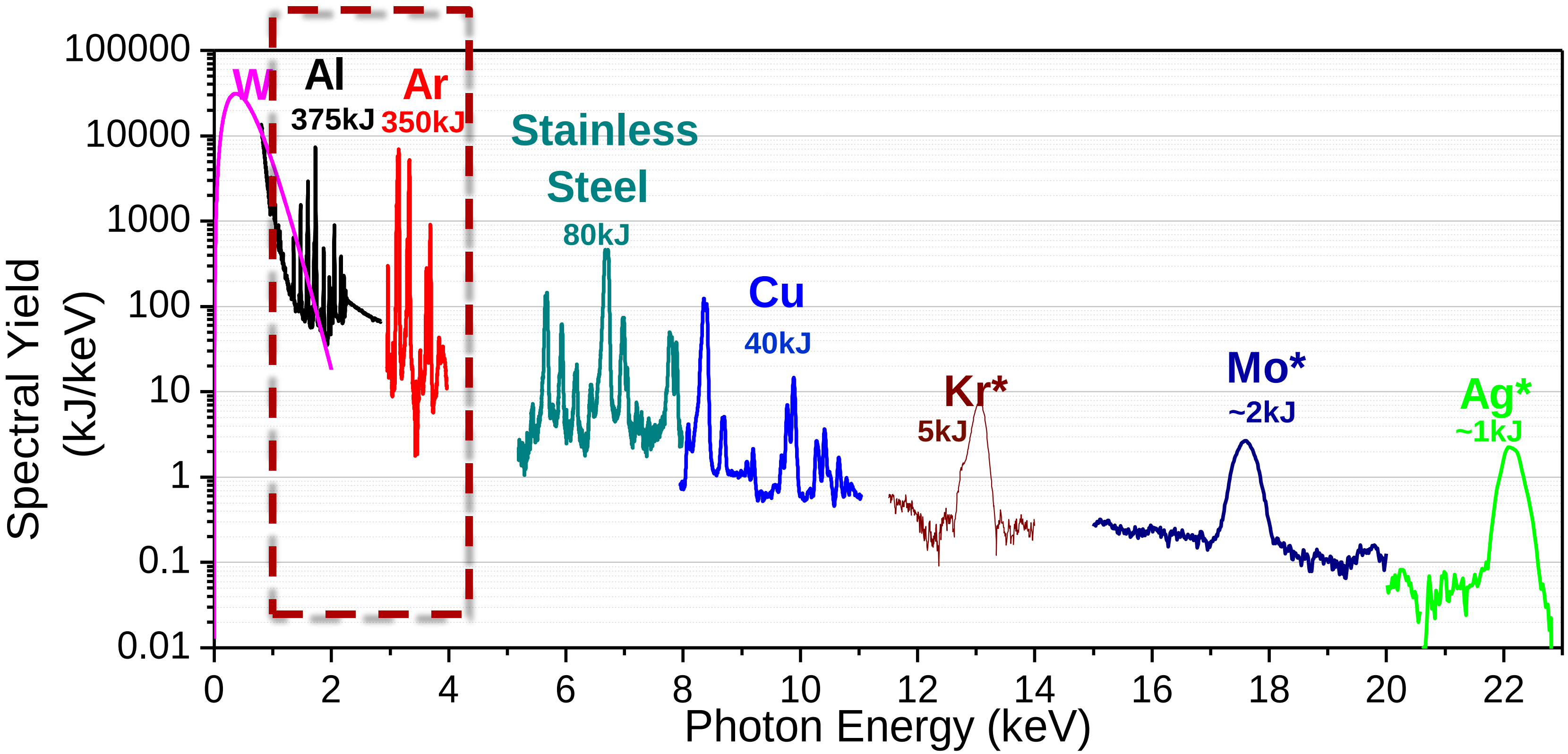
Time-resolved 1D-spatially-resolved spectra



Summary: Imploding Z pinches on the Z generator create extremely bright plasmas, however efficiency and mechanisms for emission are different, providing a rich dataset to study emission from dense plasmas

Opacity affects emission

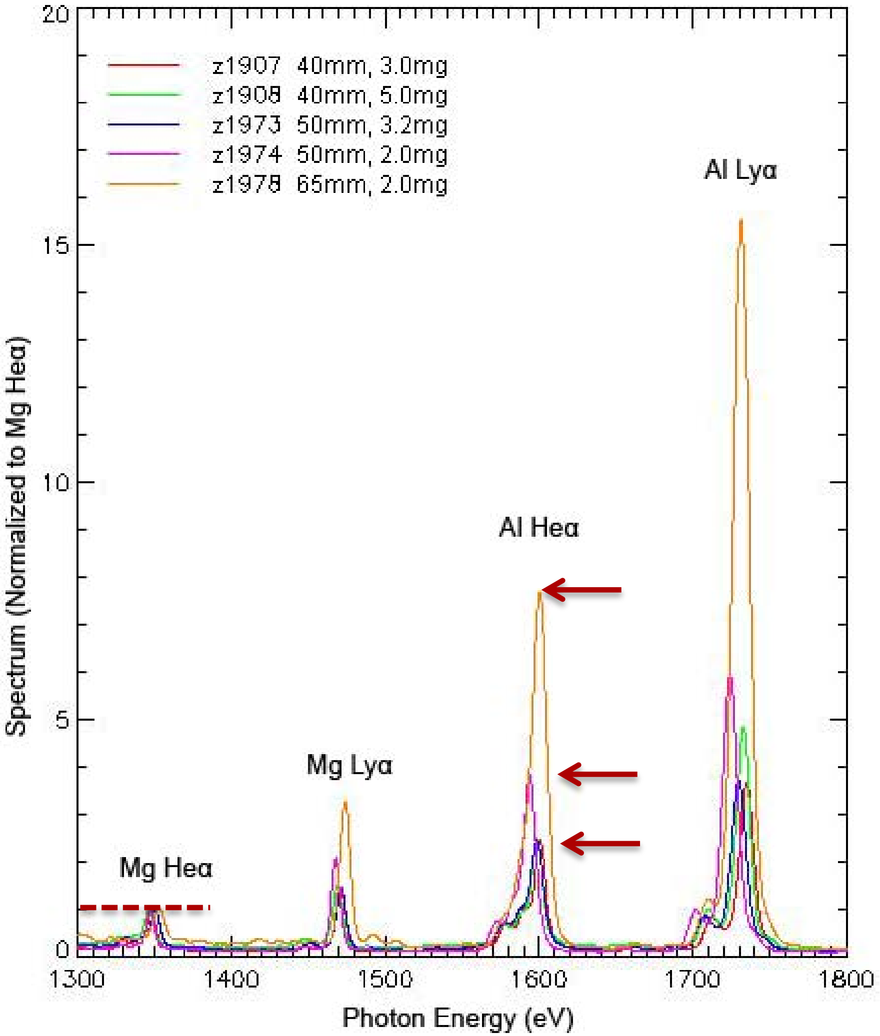
Tune to give large surface area



Using 5% Mg alloy in Al experiments shows that opacity varies between different shots

- Al experiments use variety of initial masses/diameters
  - Produce varying pinch uniformity, and density
- Presence of 5% Mg provides lower opacity tracer
- All experiments show Al lines that are <20x the Mg lines
  - Opacity effects Al emission on all shots
- Relative effect of opacity varies between shots

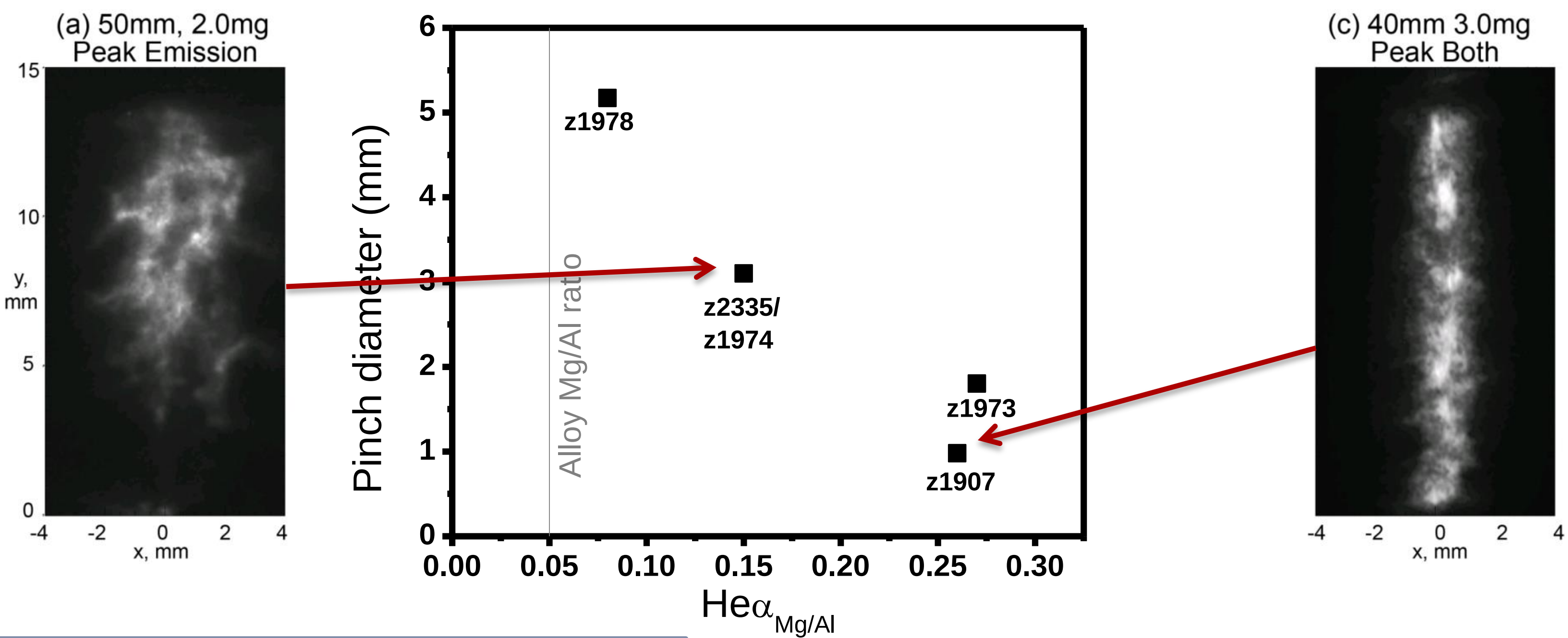
Spectra, normalized to Mg Heα



J.P. Apruzese *et al.* Phys. Plasmas (****)
D.J. Ampleford, S.B. Hansen *et al.*, accepted for publication in Physics of Plasmas

Lowest opacity shots correspond to large initial diameters and largest stagnated pinches, and highest radiated yields

- More diffuse pinches show lower opacity in Mg lines
  - Pinch dynamics (e.g. larger initial diameter) can lead to increased diameter and structure at peak emission
  - Opacity is lower
  - Better at maintaining high temperature



For effect of opacity on Ar see Apruzese et al., JO5.11

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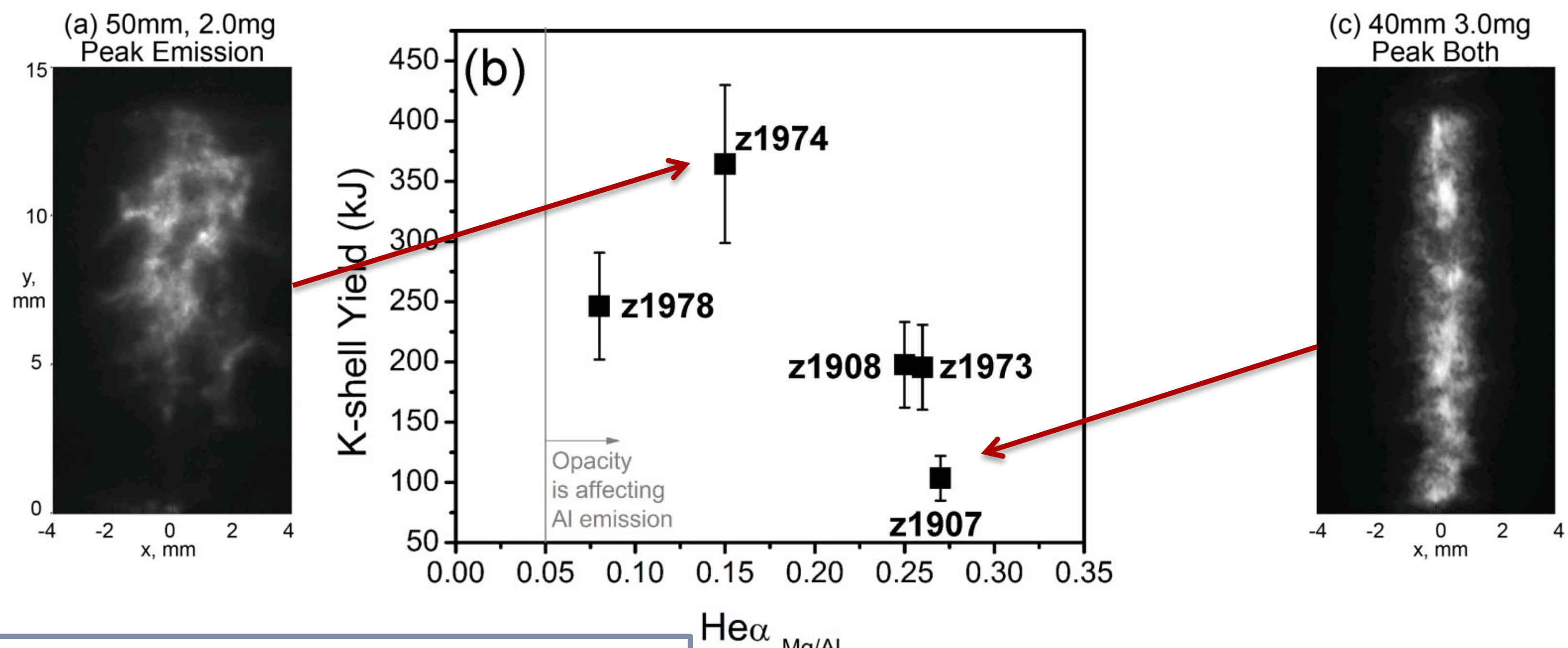
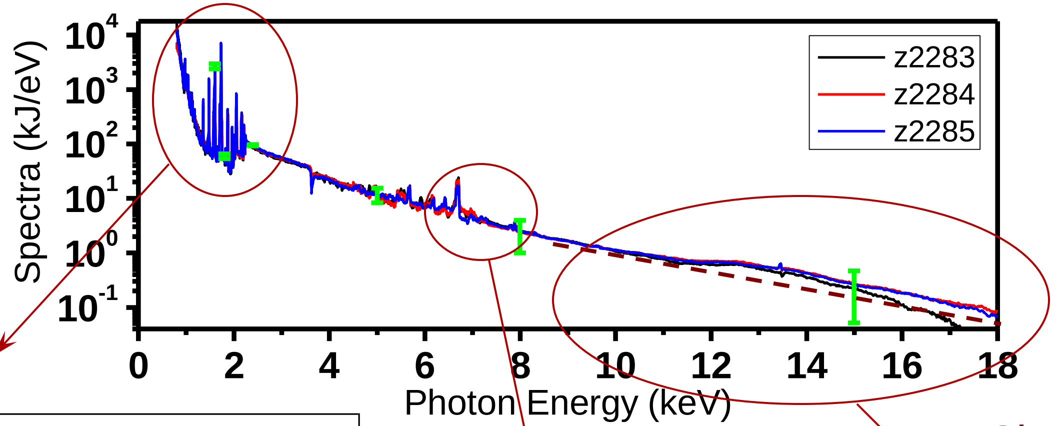
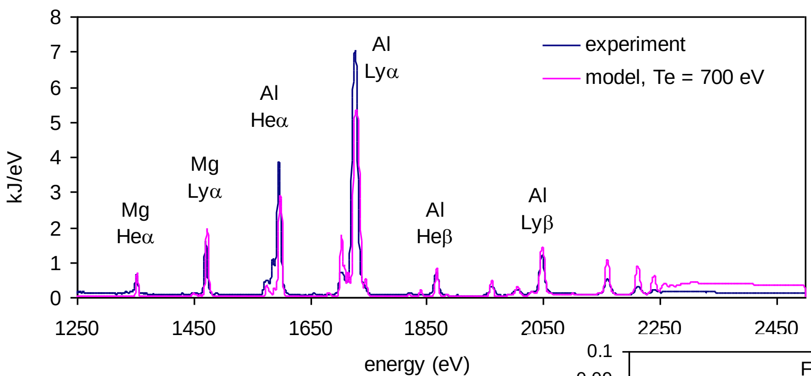


For effect of opacity on Ar see Apruzese et al., JO5.11

Different plasma conditions can be inferred from analysis of different spectral regions, indicating significant gradients

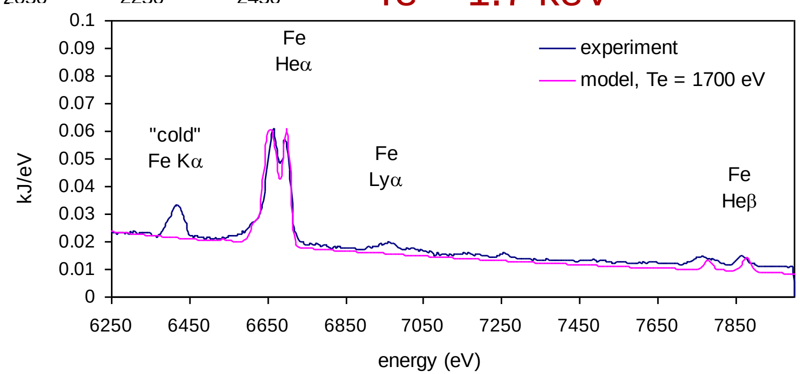


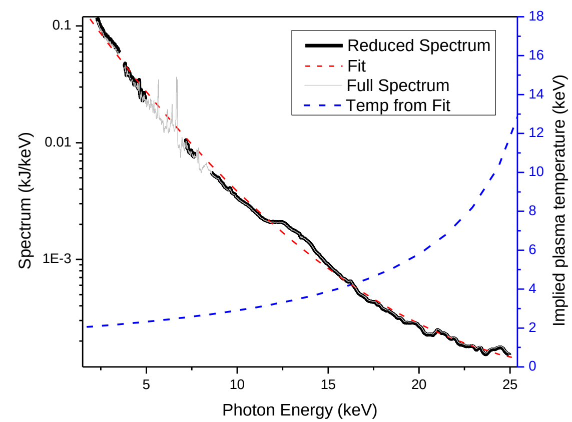
Line ratios of Mg impurities: Te ~ 0.7keV



Slope of free-bound continuum: Tc varies from 2 – 12 keV depending on region

Line ratios of Fe impurities: Te ~ 1.7 keV





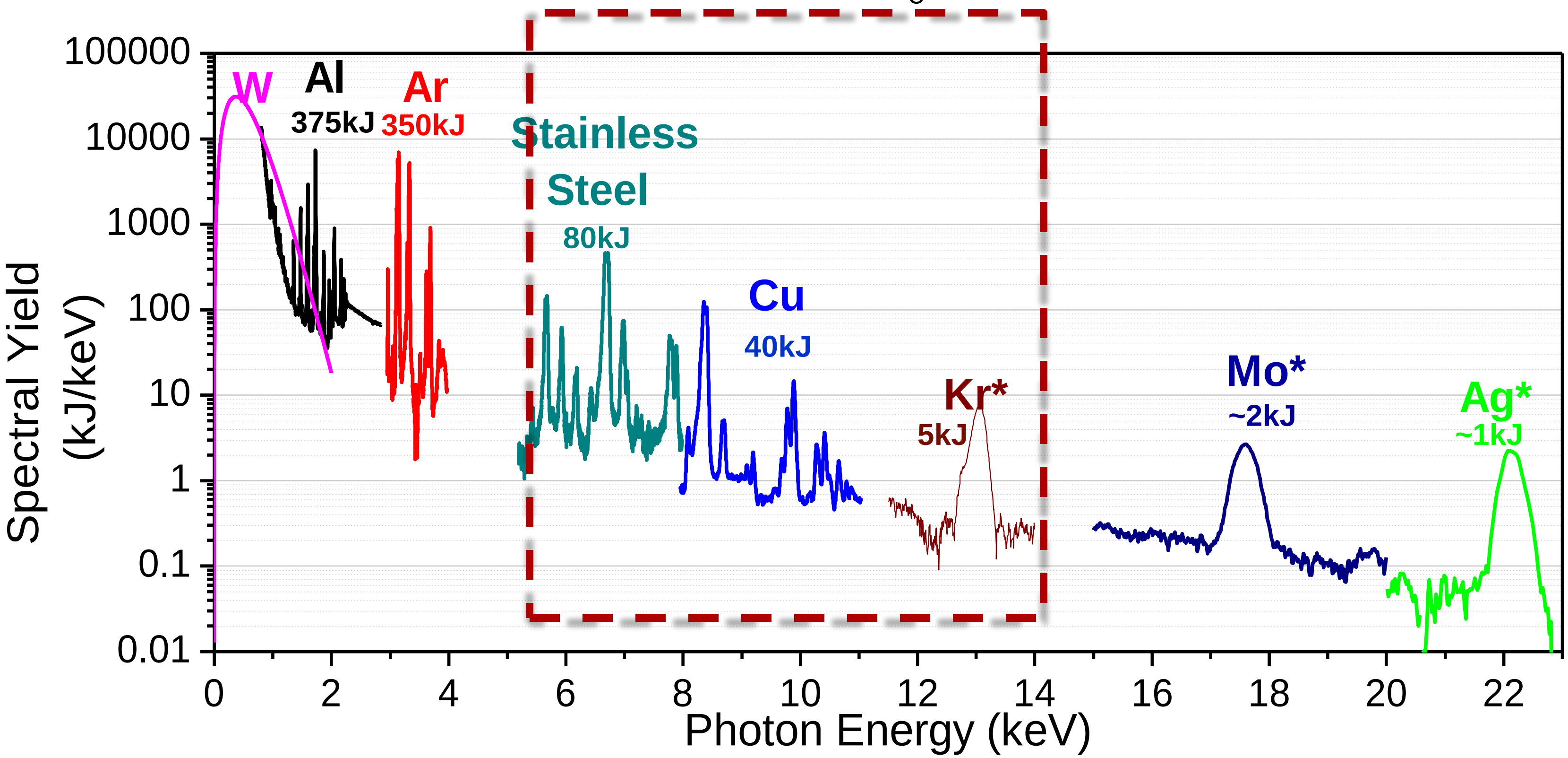
Models for both spectral ranges use $n_{ion} \sim 3\times10^{20}$/cc, $\varphi \sim 1.5$ mm, $\Delta t \sim 30$ns

Not a uniform column: Cannot describe with single temperature, or even set of temperatures

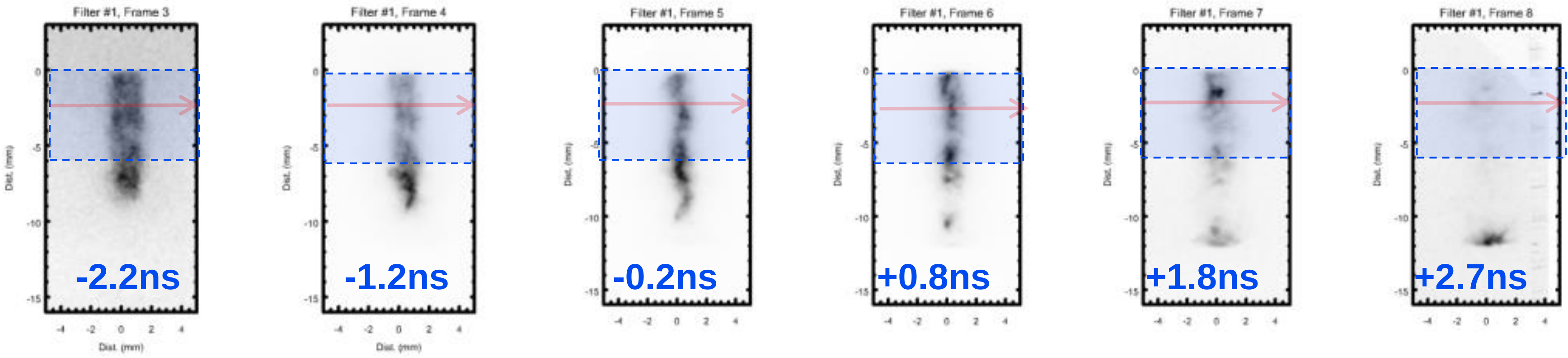
Summary: Imploding Z pinches on the Z generator create extremely bright plasmas, however efficiency and mechanisms for emission are different, providing a rich dataset to study emission from dense plasmas

Temperature is critical

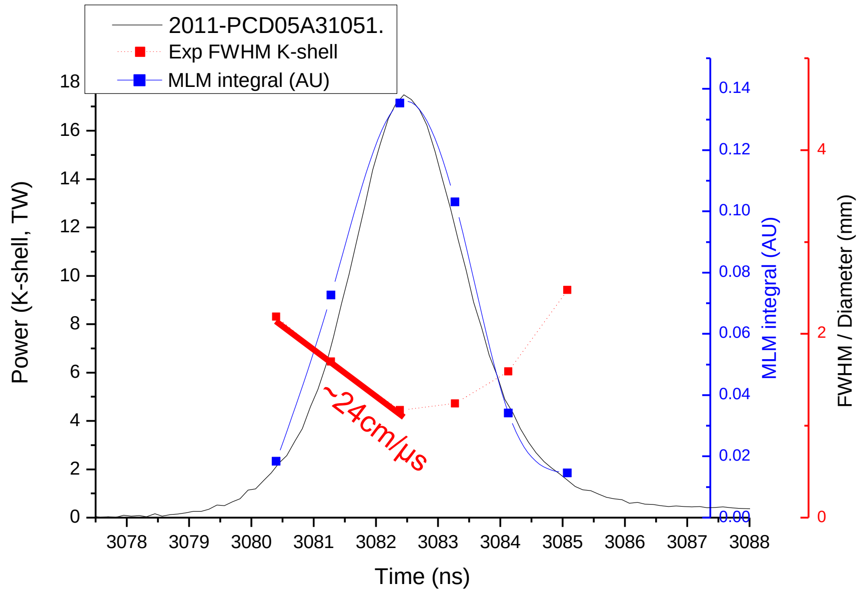
Implosion velocity determines T_e



For stainless steel, peak K-shell emission occurs at peak compression and peak temperature



- Main rise of x-ray pulse coincides with decrease in FWHM of K-shell region
- Earlier in time indication of increase in diameter, but may be from precursor plasma

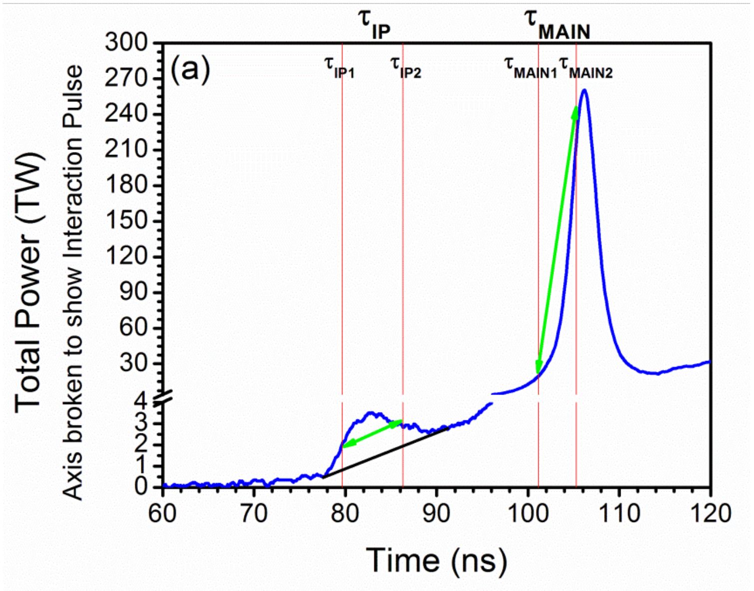


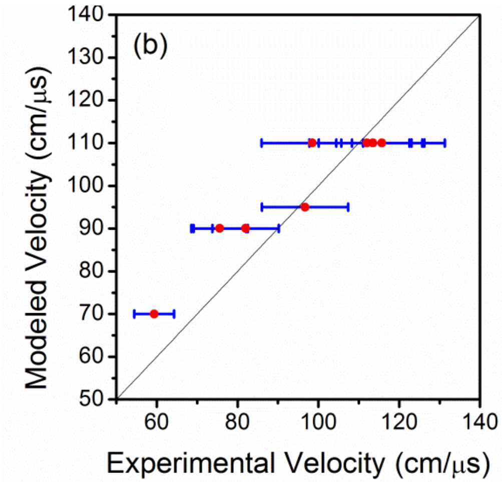
The nested interaction pulse and main x-ray pulse provides simple implosion velocity measurement

- Distinct x-ray pulses are emitted during a wire array implosion
  - Interaction pulse emitted as outer passes inner immediately before inner moves (τ_{IP})
  - Main x-ray pulse rises as implosion reaches the array axis (τ_{MAIN})
  - Each occurs within ~0.5mm of nominal location
- Use these two to provide velocity estimate (based on array diameter ϕ)

$$v_{imp} = \frac{\Delta r}{\Delta \tau} = \frac{\left(\frac{\emptyset array}{4} - 1mm\right)}{(\tau_{Main} - \tau_{IP})}$$

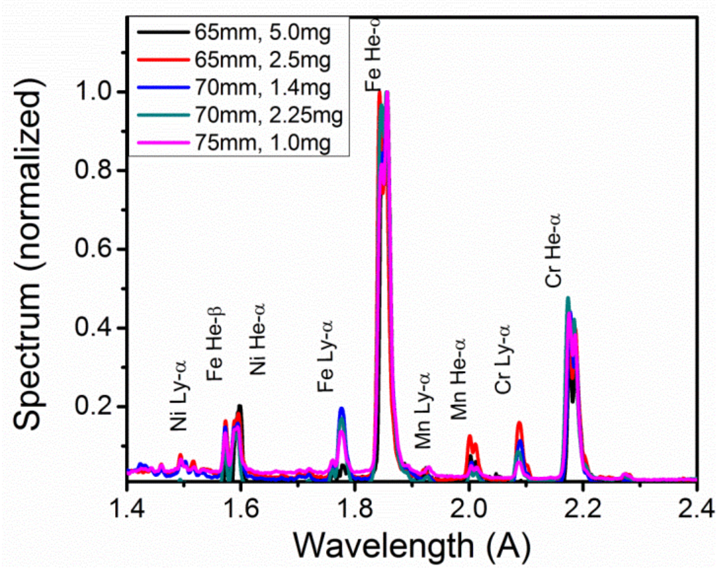
- Can compare to simulations for reality check
  - Trend very similar to that with simulated implosion velocities
  - Post processed simulated radiation pulse agrees with simulated velocity

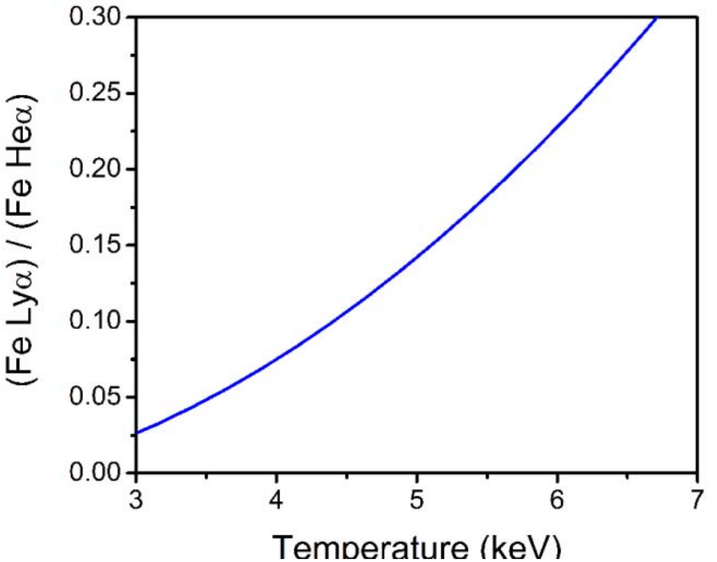




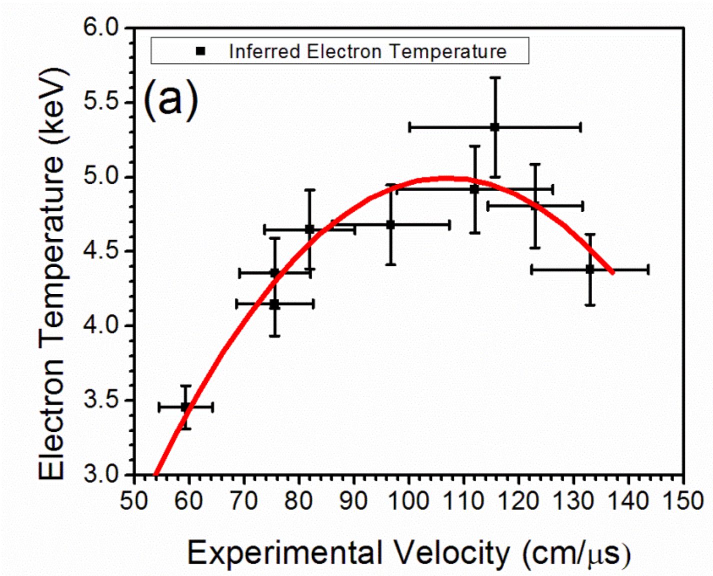
Temperatures vary considerably in different SS experiments

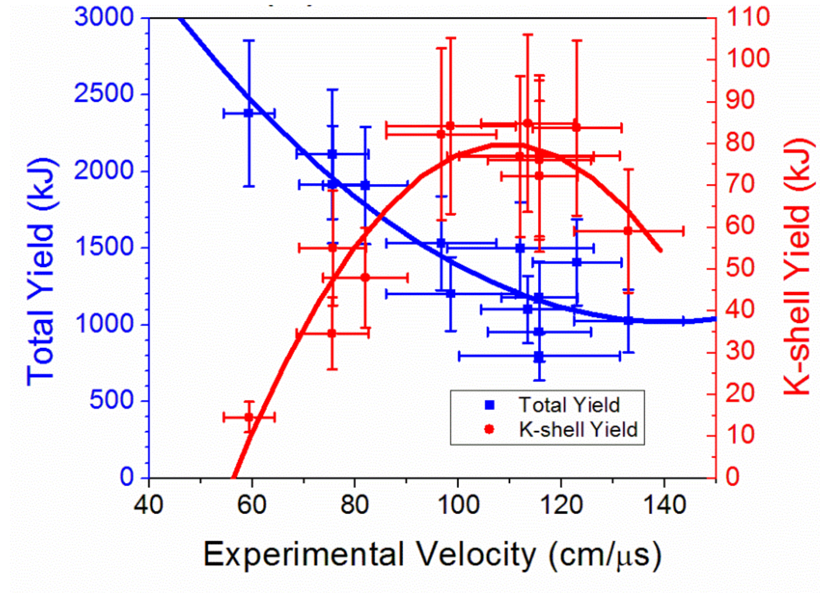
- Stainless steel implosions exhibit finite but small opacity
- Largest difference in spectra between different pinches is relative strength of Lyα to Heα
  - Indicative of strong temperature changes





Electron temperature and hence radiated K-shell yield depend strongly on implosion velocity





- Electron temperature inferred from spectra are strongly dependent on implosion velocity
- K-shell yield is highest for ~110cm/μs implosions
- Total yield is highest for later/slower implosions, where more energy is coupled
- Beyond that velocity pinch disruption from Magneto-Rayleigh-Taylor instabilities is considerable
  - Nested wire arrays provide stabilization but not sufficient for 130cm/μs implosions

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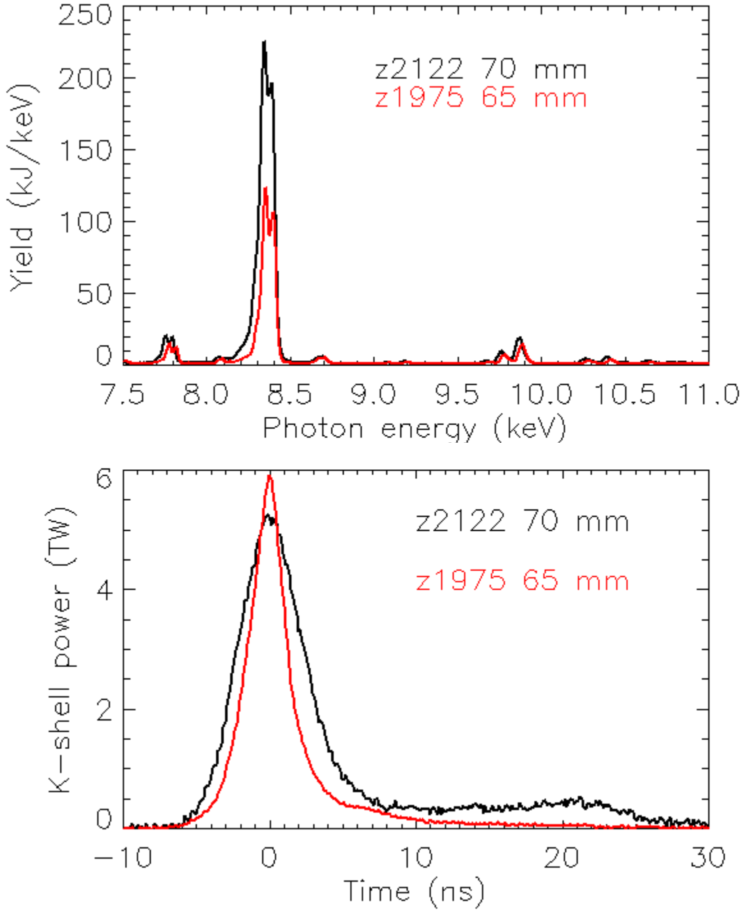
D.J. Ampleford, C.A. Jennings *et al.*, Physics of Plasmas **20**, 103116 (2013);

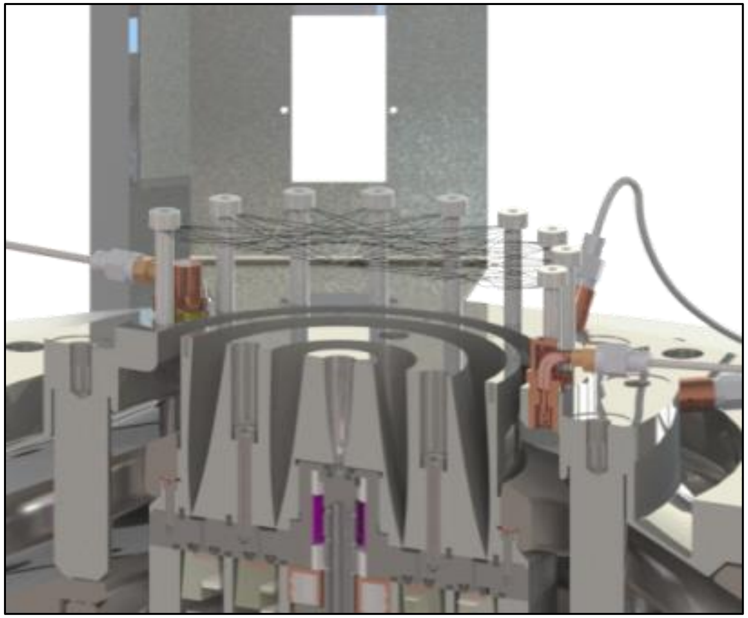
Similar to Stainless Steel, Cu needs fast (≥100cm/μs) implosion velocities

- Experiment with ~100cm/μs implosion velocity radiated 40kJ in the K shell
  - 70mm, 1.4mg array
- This setup demonstrates higher pinch temperatures and yields than other heavier/smaller arrays
- Only single shot data, but trend is consistent with SS data
- Beyond Cu, MRT has a significant effect on achieving the velocities and temperatures needed for efficient emission

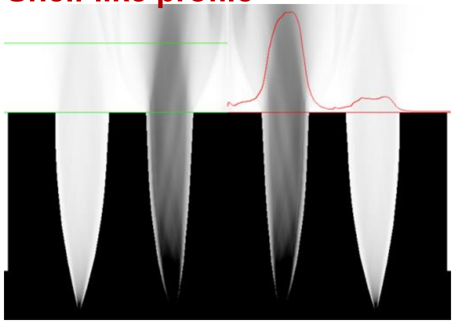


For the higher electron temperatures (i.e. implosion velocities) required for Kr need more stabilization of MRT

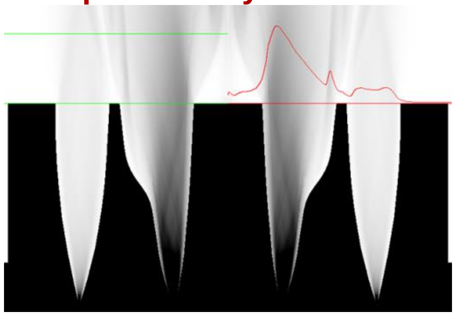
- Many tools have been developed to provide customizable gas profiles
  - Interferometer to measure profiles
  - Hydrodynamic simulations of gas flow to design nozzle contours
  - Rapid-prototyping of nozzle parts to provide benchmark interferometer data
- Combined capabilities
  - Allow control over density distribution
  - Eliminate need for cathode grid that has previously inhibited symmetry of implosion
  - Allow self-consistent initial gas profiles to be coupled to MHD



Shell-like profile



Ramped density



C.A. Jennings, talk **TO4.11**

J. Hammer *et al.* Phys. Plasmas (****); M. Krishnan *et al.*, Rev. Sci. Instrum. (2012);
P. Colemen *et al.*, Rev. Sci. Instrum. (2012); B. Jones *et al.*, IEEE TPS accepted (2013)

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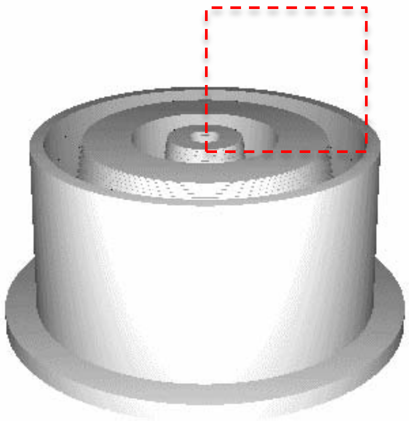
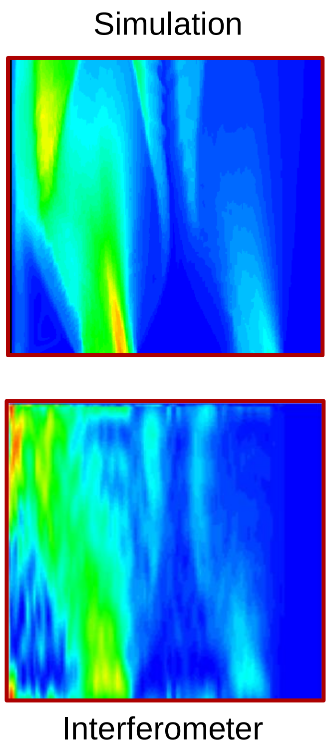
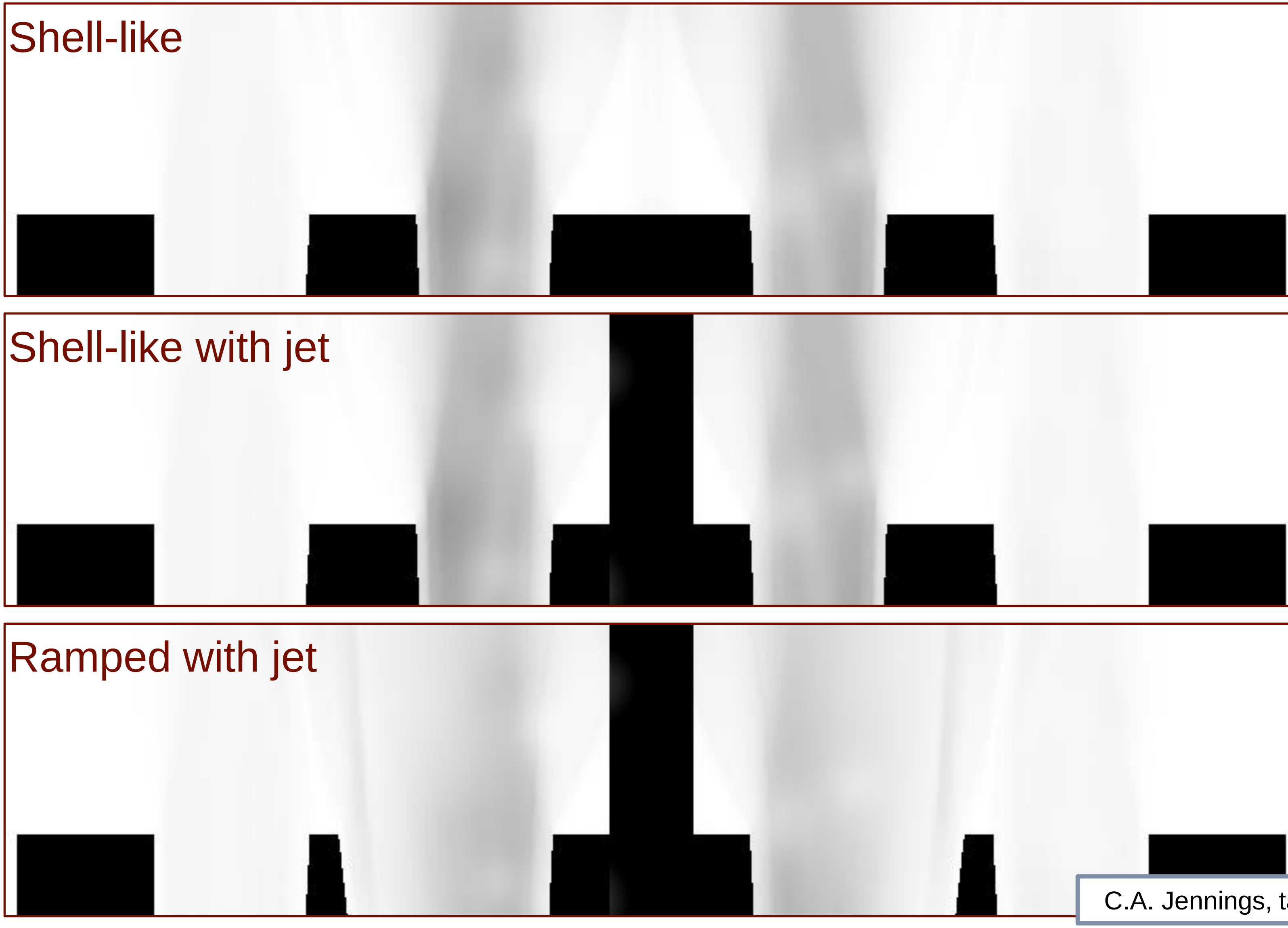




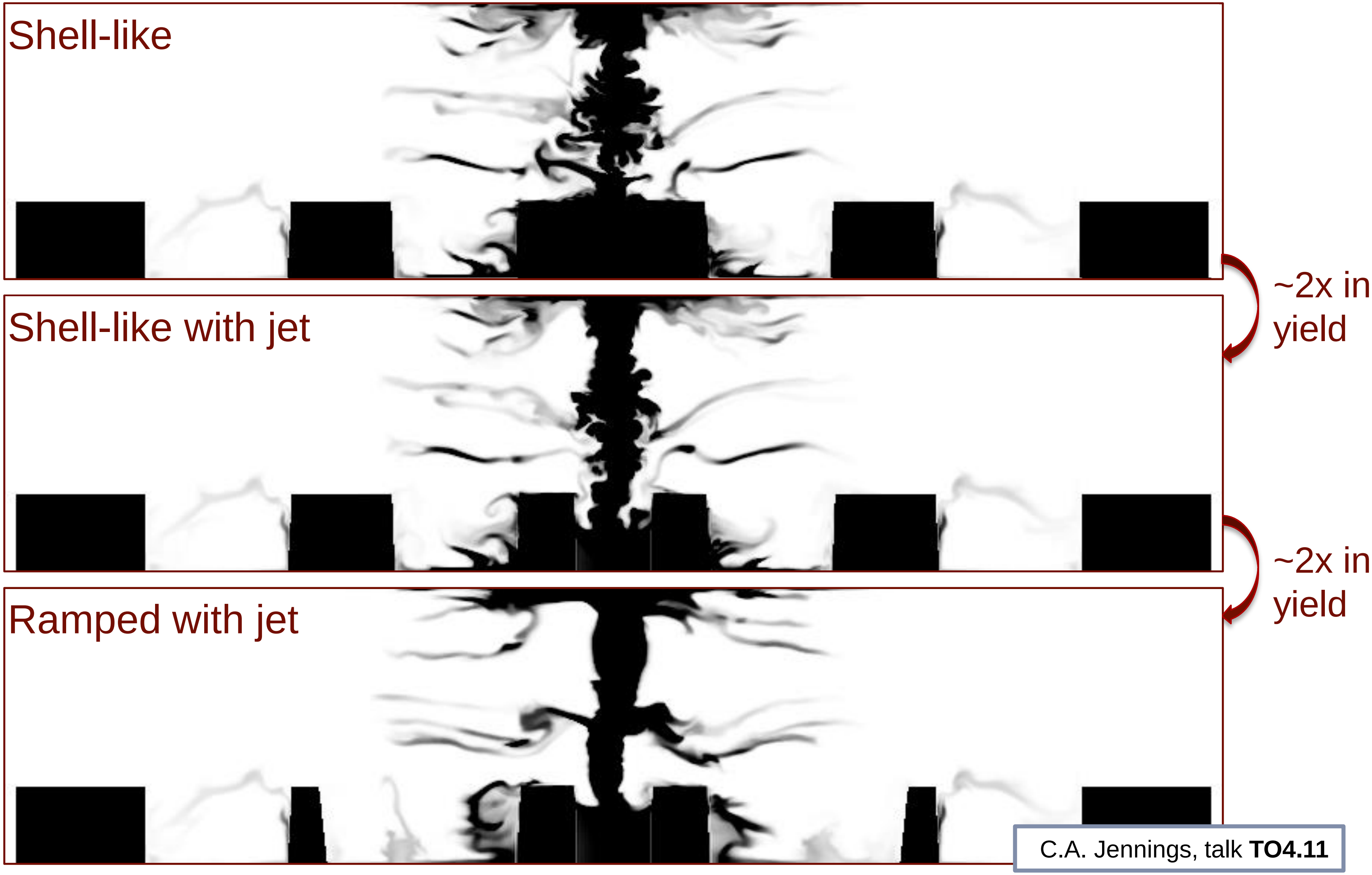
C.A. Jennings, talk **TO4.11**

MHD demonstrates expected effect of different initial gas profiles: same circuit, outer shell, varying inner profile



C.A. Jennings, talk **TO4.11**

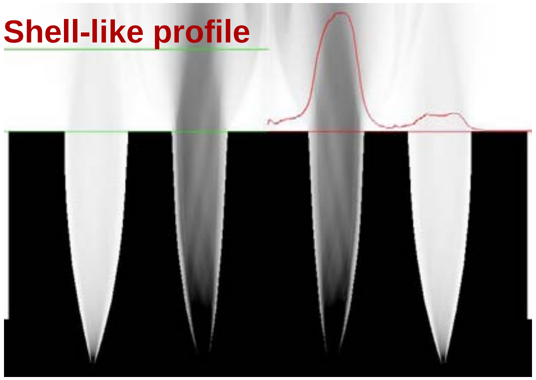
MHD demonstrates expected effect snowplow stabilization

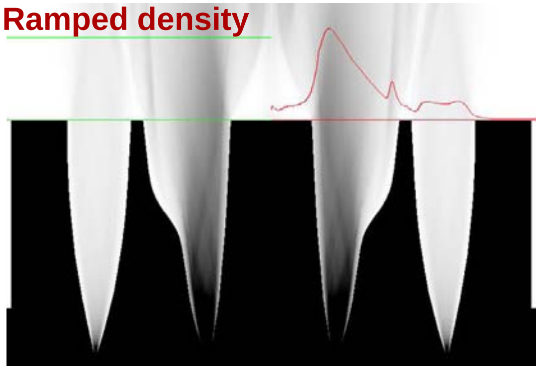


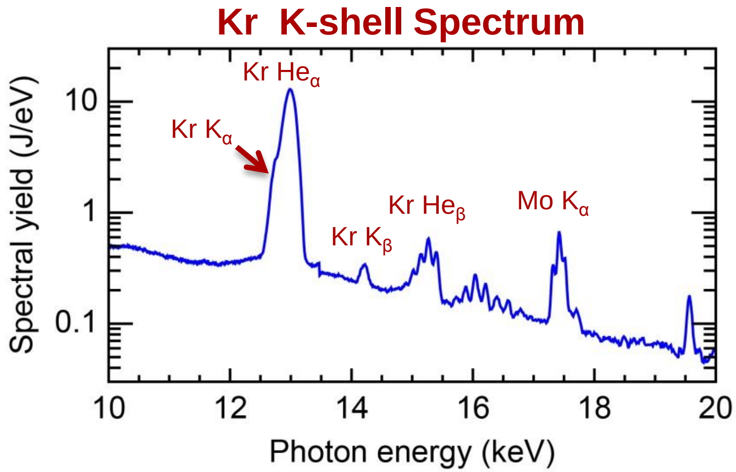
C.A. Jennings, talk **TO4.11**

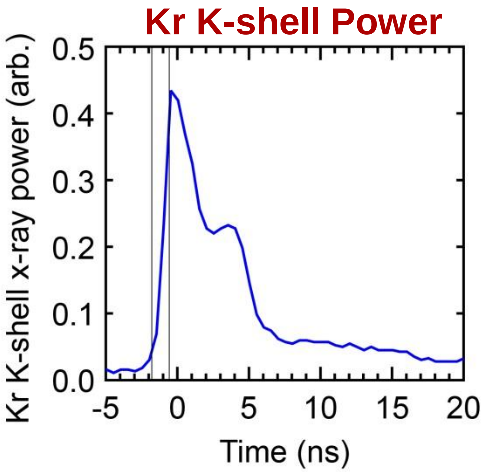
Initial 12cm Kr shots agree with simulations, demonstrating effect of stabilizing density profile on radiated yield

- Shots compared shell-like and ramped density profiles
- Ramped profile radiated ~2x higher than shell-like
  - 5±1 kJ >10kJ and 3.5 kJ in Heα line
- Central jet not used
  - In future will add, potentially increasing further
- **Improved current coupling would greatly enhance radiated yields (however voltages needed to drive these implosions are many MV)**



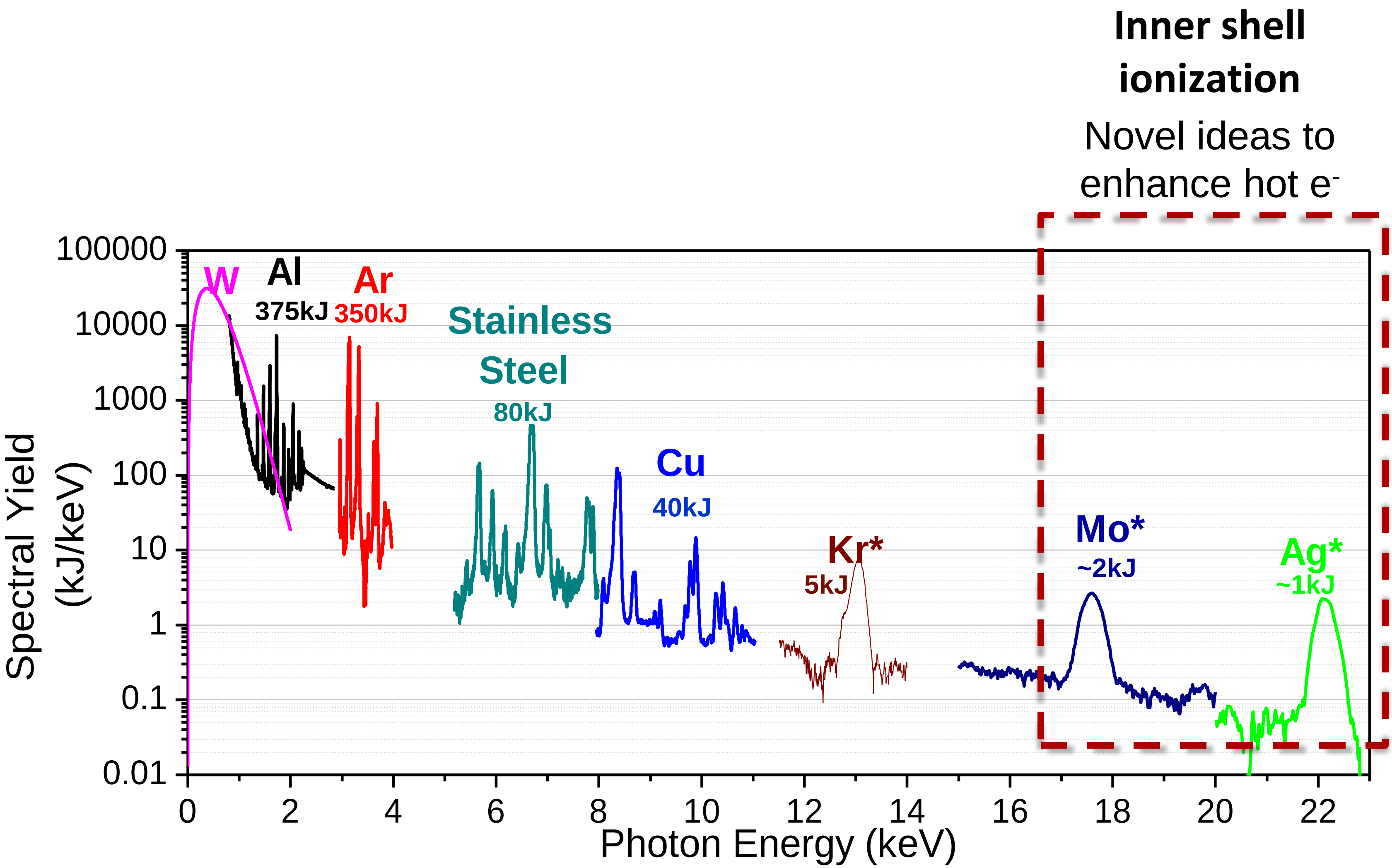






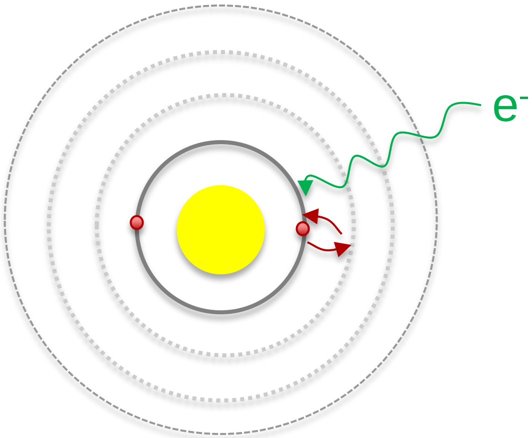
C.A. Jennings, talk **TO4.11**

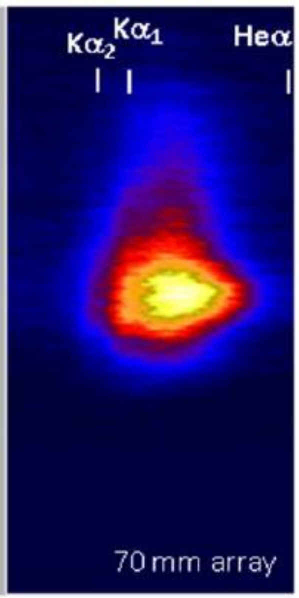
Summary: Imploding Z pinches on the Z generator create extremely bright plasmas, however efficiency and mechanisms for emission are different, providing a rich dataset to study emission from dense plasmas

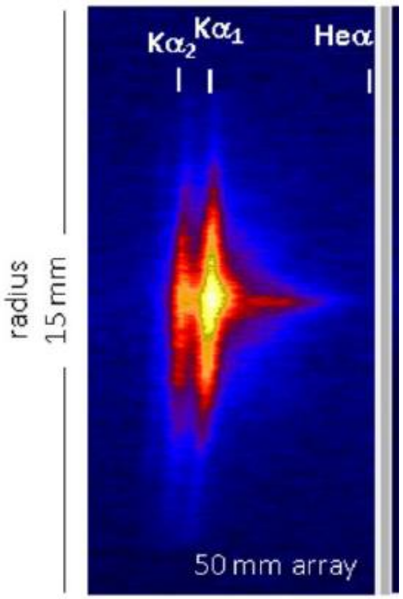


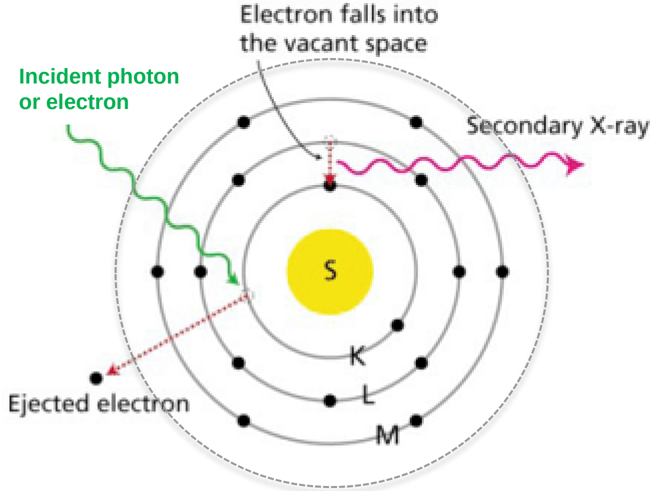
For higher photon energies inner shell ionization becomes a more effective emission mechanism

- Thermal K-shell
  - He-like and H-like lines
  - Need to ionize to the K-shell
- Non-thermal K-shell
  - Cold K-lines
  - Need hot electrons
  - Don't need to ionize bulk plasma





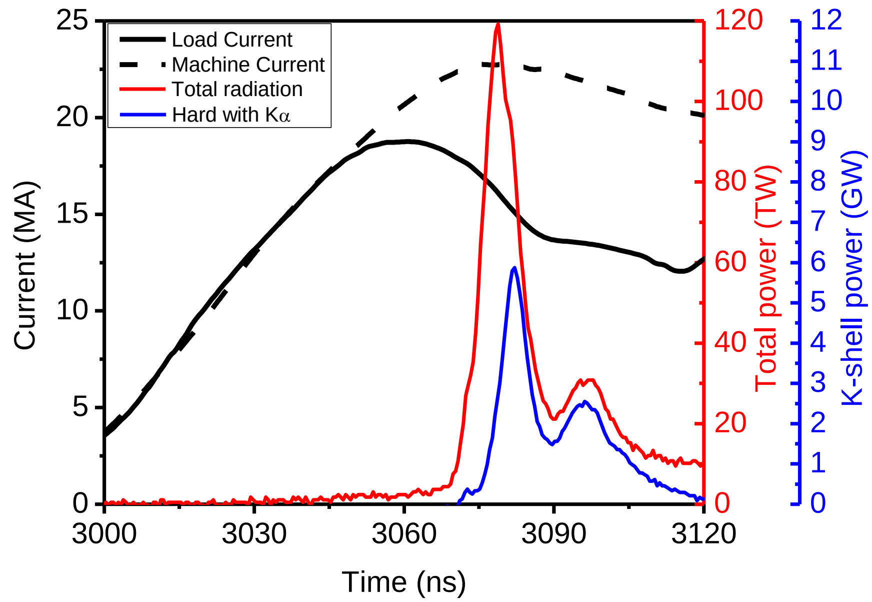


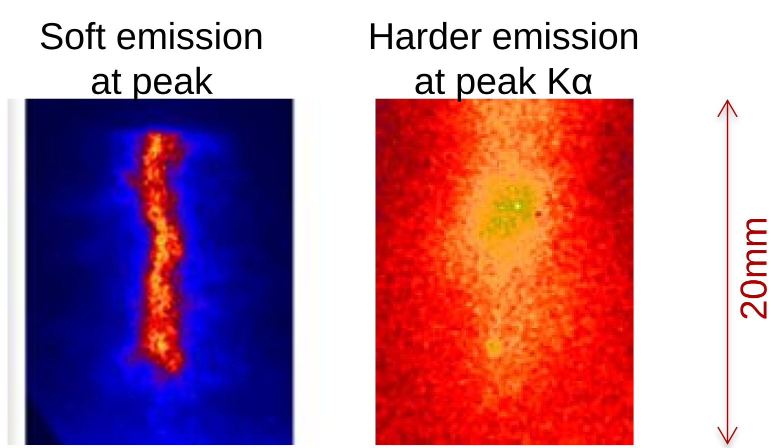


Initial experiments: P.D. LePell, S.B. Hansen *et al.*, Physics of Plasmas **12**, 032701 (2005)
Recent work: S.B. Hansen, D.J. Ampleford *et al.*, Submitted to Physics of Plasmas

Data from Mo wire arrays indicates Kα emission comes late in time, and corresponds to high energy electron beams

- PCD detectors indicate that hard (e.g. Kα) emission is late in the x-ray pulse
- Hard emission originates from broader area than soft emission
  - Consistent with pinch disruption
- Initial Faraday cup data indicates Kα generation coincides with peak of electron beams





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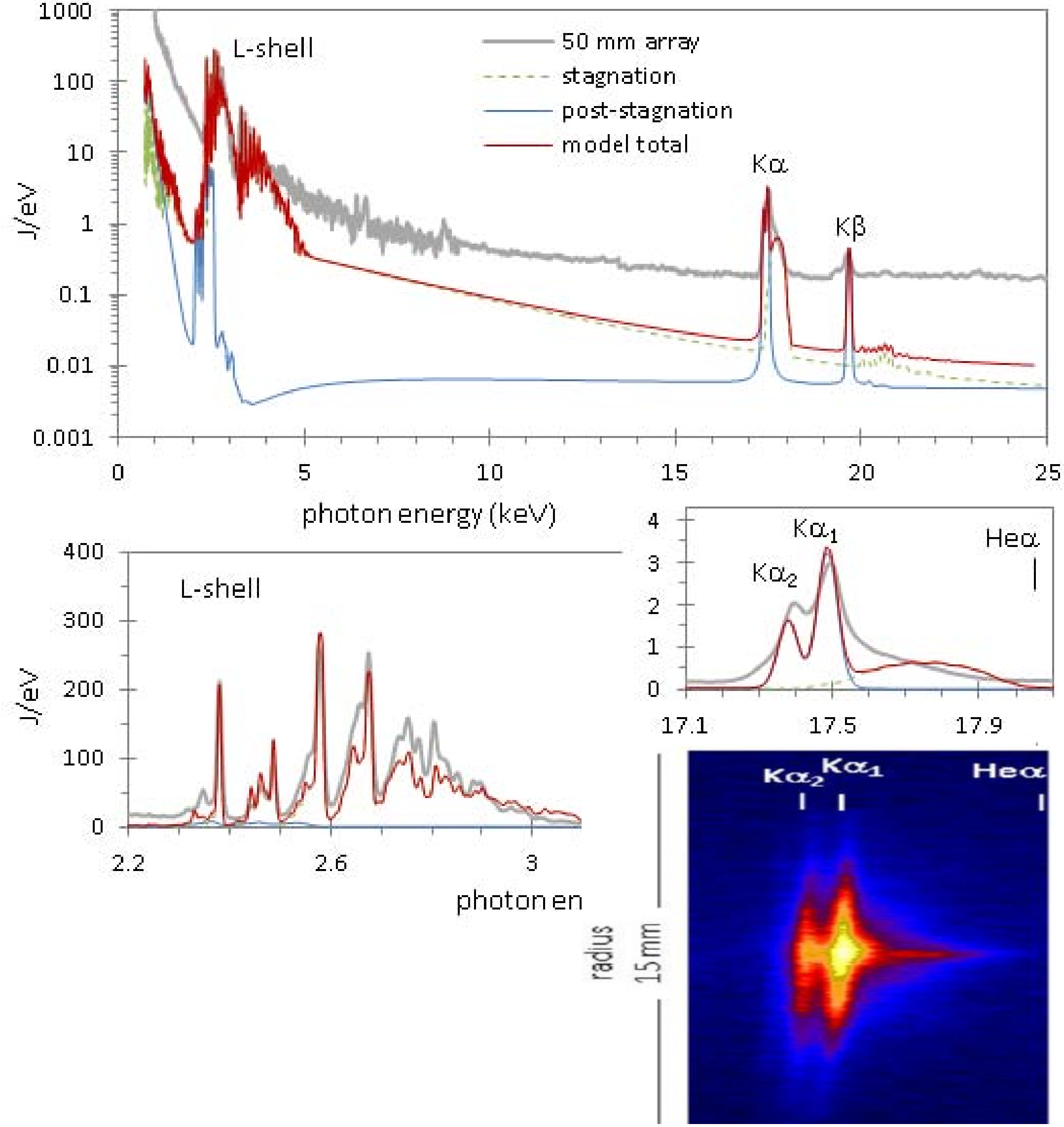
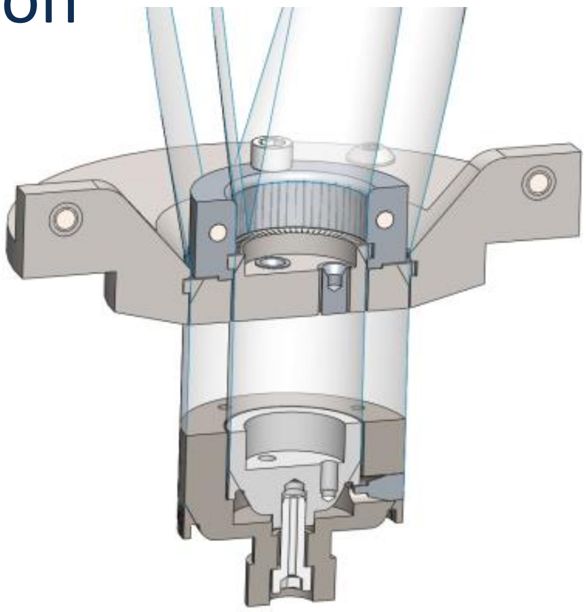
Modeling of 50mm-diameter Mo data consistent with multi-stage evolution

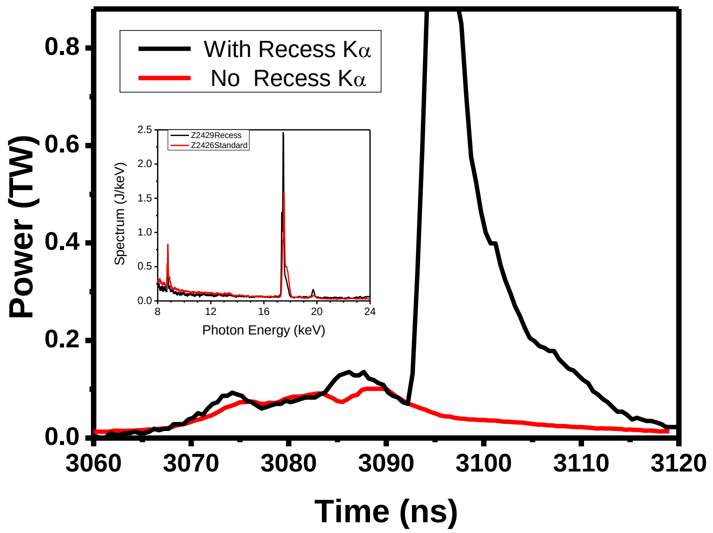
- Spectral diagnostics on Z provide broad spectral coverage (0.8-26keV)
- Comparing SCRAM simulations to broadband spectra provides insight into plasma conditions present
  - Hot core (0.8mm diameter) emitting some thermal K-shell and highly ionized L-shell
  - Surrounded by cooler, larger plasma (12mm diameter) emitting Ne-like L-shell
  - Followed by late-time 7mm cold plasma with hot electrons emitting cold Kα over 10s of ns



Experiments have been designed to enhance hot electron population and Kα generation

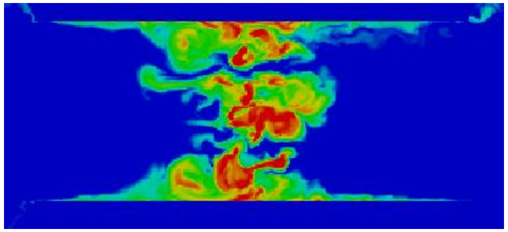
- Cutting a recess in the cathode of an imploding wire array enhances Kα
  - Doubles energy in Kα and changes pulse shape
  - Initial assumption had been that this could create a vacuum gap
- Post-processed MHD simulations indicate introduces region of low B-field
  - Unmagnetized electrons are launched
  - Data indicating plasma filled recess is better than empty recess

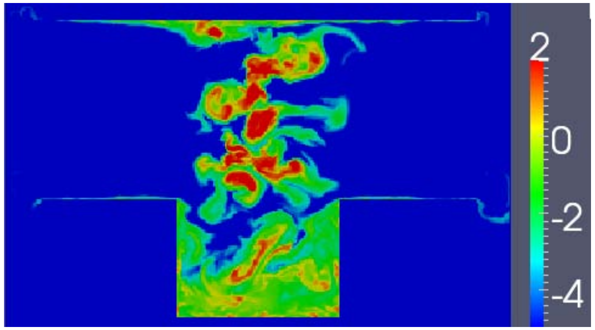


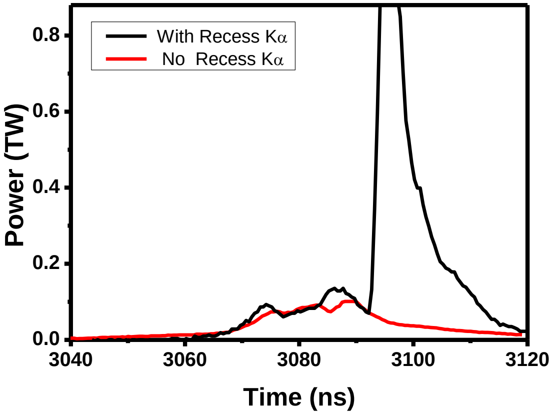


Comparison of effect of recess on 20mm and 50mm diameter Mo implosions agrees with un-magnetized e- hypothesis

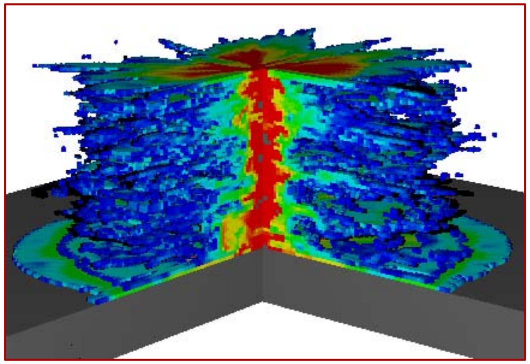
- 20mm diameter – fills recess with plasma, enhances Kα

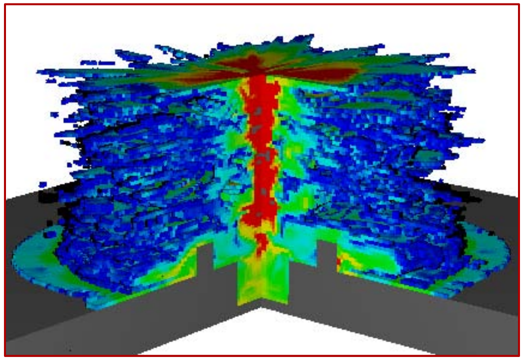


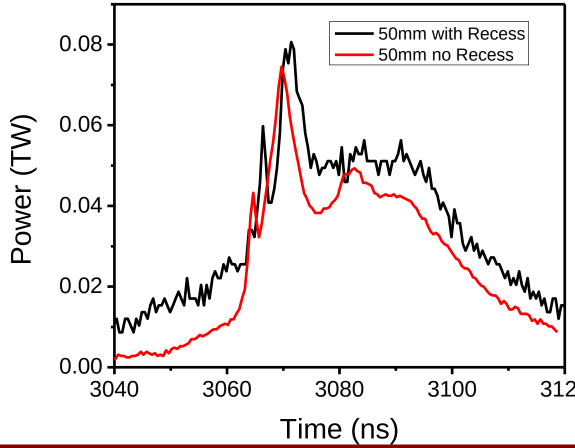




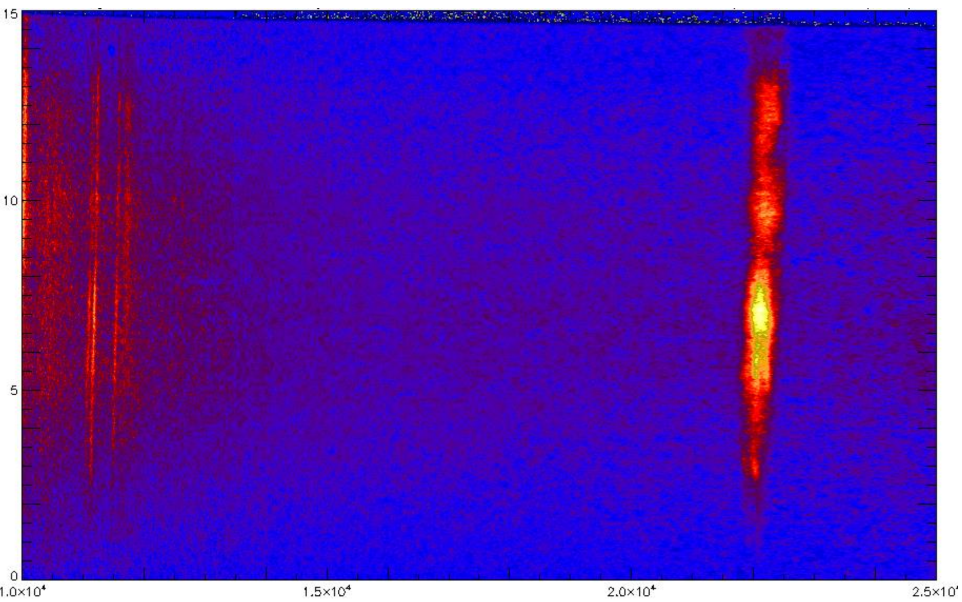
- 50mm diameter – recess less filled, no enhancement of Kα



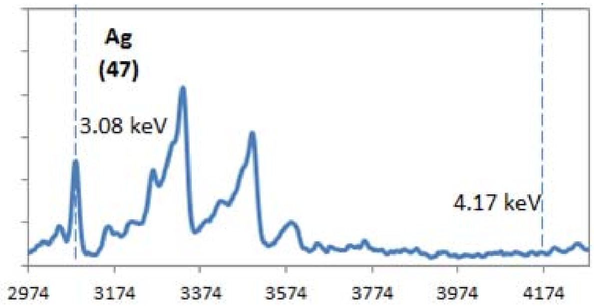


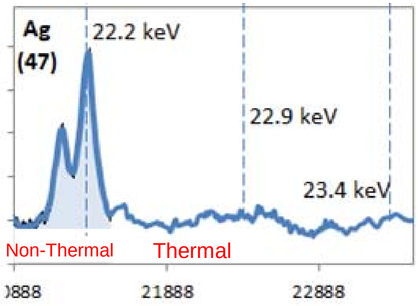


Initial experiments have demonstrated ability to emit Ag Kα



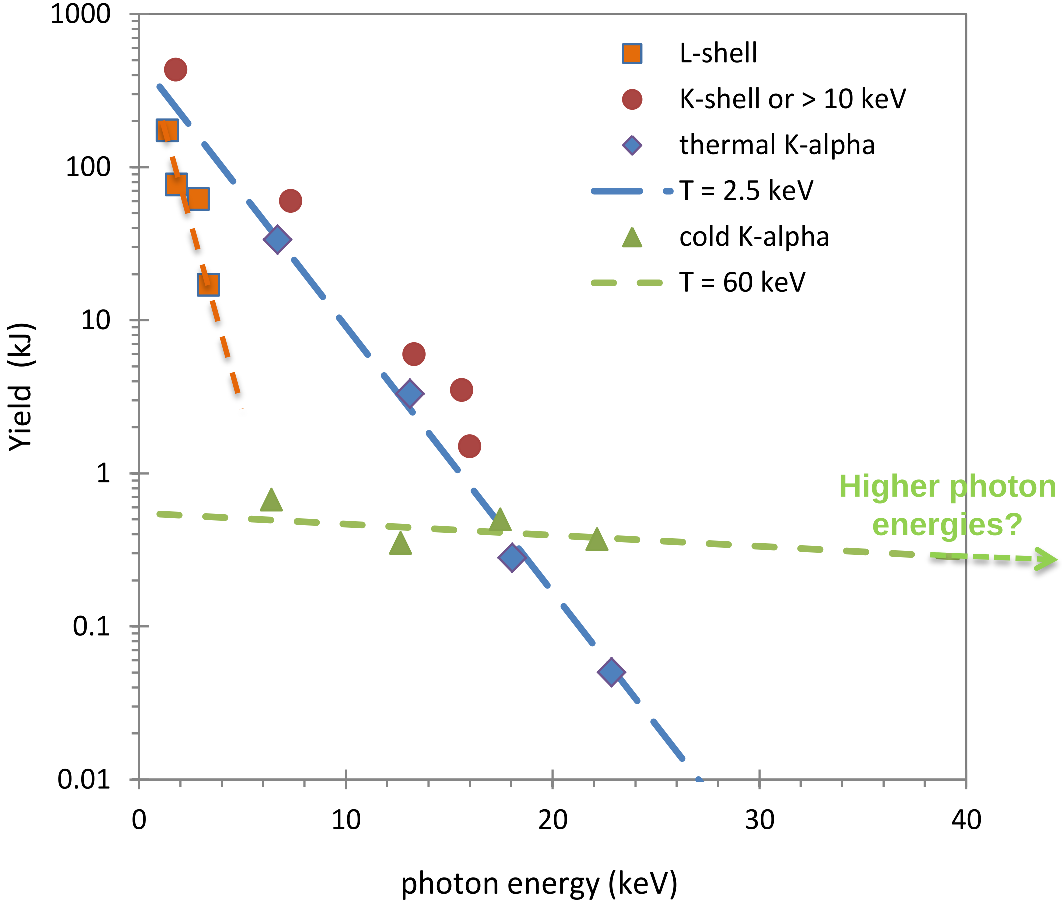
- Ag Kα emitted from most of length of pinch
- No measureable thermal K-shell emission



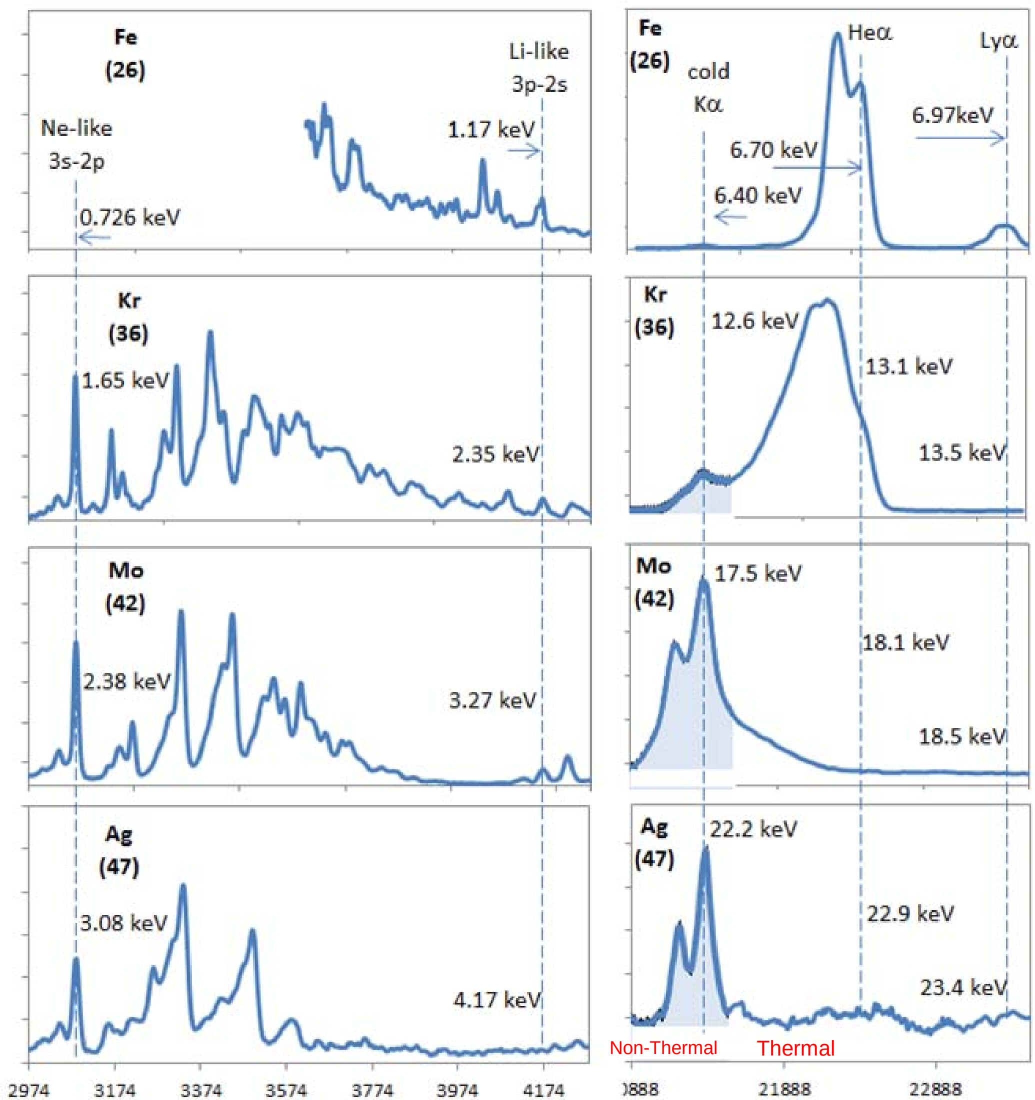


Comparison of different materials demonstrates transition from efficient thermal K-shell generation to efficient non-thermal K-shell generation

- By comparing different material implosions can see trends in emission
- L-shell drops precipitously with hv
- Thermal K-shell drops fairly quickly
- Cold Kα becomes much more efficient for >20keV emission



Comparison of spectra from different elements demonstrates transition from thermal to non-thermal emission



- Fe
  - Some Li-like L-shell
  - K-shell dominated by He-like, some H-like
- Kr
  - Li-like dropping
  - Cold Kα starts to show considerably
- Mo
  - Negligible Li-like
  - Cold Kα dominates K-shell emission
- Ag
  - No Li-like
  - No thermal K-shell, all Cold Kα

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