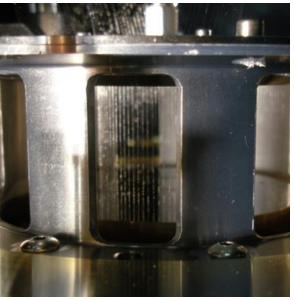
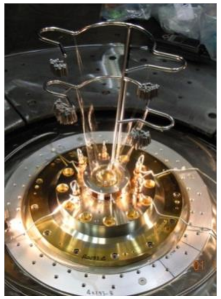
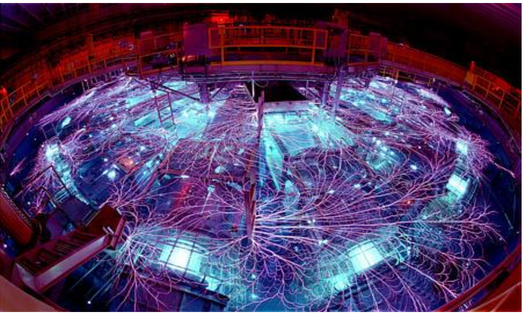
SAND2016-4351C

Radiation and Fusion Experiments on Sandia's Z Facility







David J. Ampleford

Radiation and Fusion Experiments

Sandia National Laboratories

presented by

William A. Stygar

Manager, Advanced Accelerator Physics

Sandia National Laboratories

International Conference on Matter and Radiation at Extremes

Chengdu, China

May 8-12, 2016

Sandia National Laboratories

Exceptional service in the national interest

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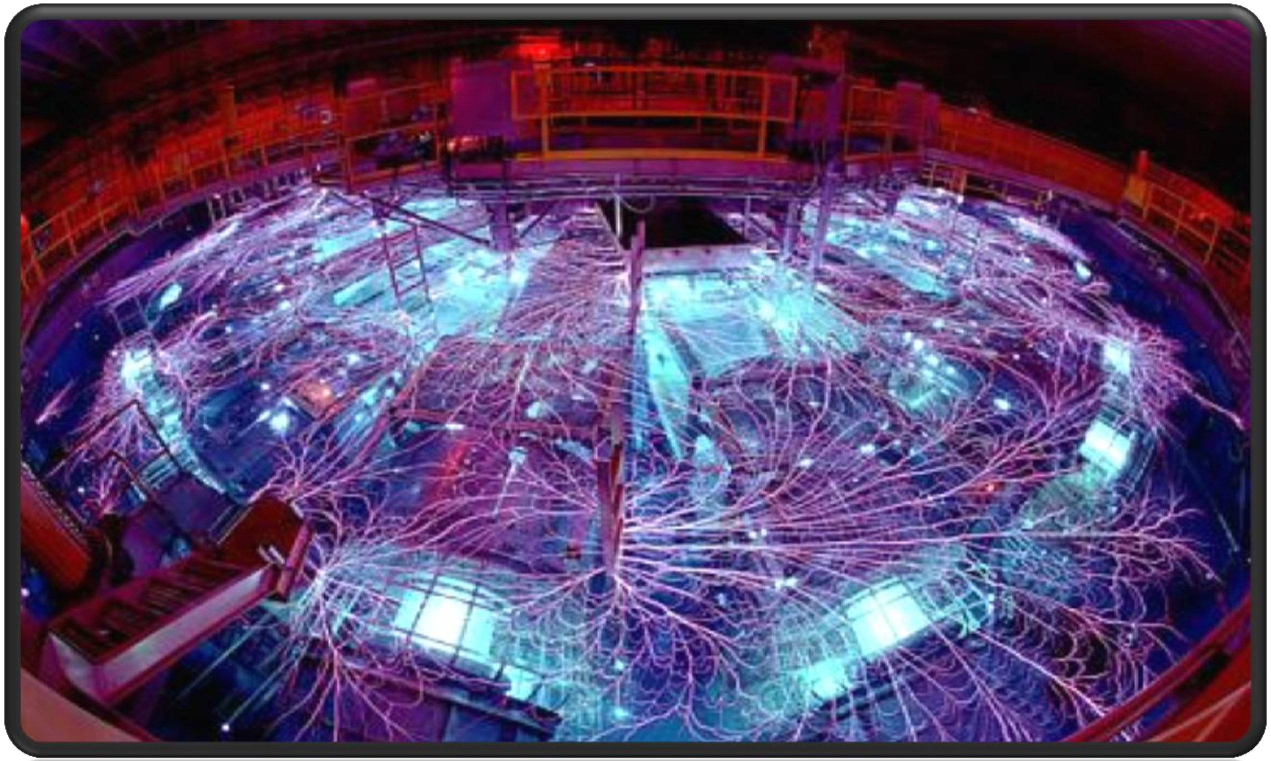
Supported in part by Sandia National Laboratories LDRD program, Project 165733

Experiments on Z involve a large group of collaborators

- Sandia National Laboratories
  - M.R. Gomez, C.A. Jennings, S.B. Hansen, M.E. Cuneo, G.A. Rochau, D.C. Lamppa, E.C. Harding, T. J. Awe, S. A. Slutz, A. B. Sefkow, R. D. McBride, K. J. Peterson, J. L. Porter, D. B. Sinars, K. D. Hahn, E. C. Harding, P. F. Knapp, P. F. Schmit, B. Jones, A.J. Harvey-Thompson, C.A. Coverdale, M. Jobe, A.R. Laspe, T.M. Flanagan, N.W. Moore, T. Webb, M. Geissel, D. C. Rovang, G. A. Chandler, M. E. Cuneo, M. C. Herrmann, M. R. Martin, C. L. Ruiz, M. E. Savage, I. C. Smith, and R. A. Vesey
  - Many, many people who enable experiments on Z
    - Diagnostics, pulsed power development, system integration, machine turnaround, Load design, fabrication, assembly and installation
- Numerous Collaborators
  - Naval Research Laboratory
  - Lawrence Livermore National Laboratory
  - Weizmann Institute
  - Imperial College
  - Alameda Applied Science

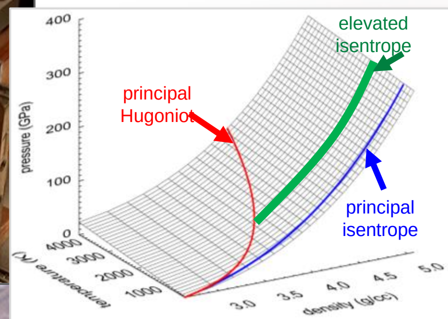
The Z generator is a pulsed power generator capable of delivering up to 25 MA in ~100 ns



Z produces extreme conditions in numerous ways

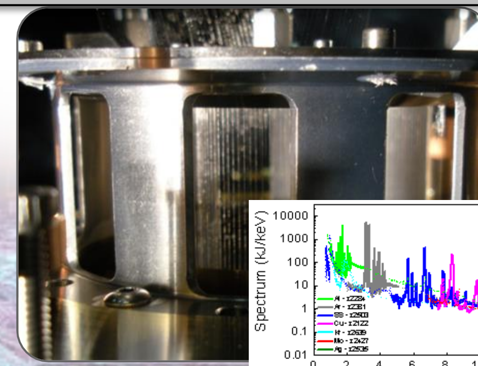
Dynamic Materials

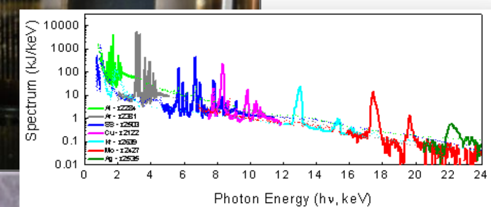
Compress materials to 10^7 Atm.



K-shell x-ray sources

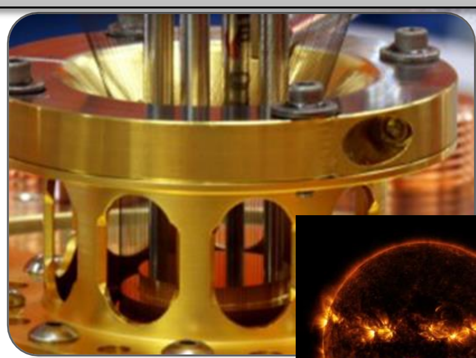
100's of kJ of multi-keV photons





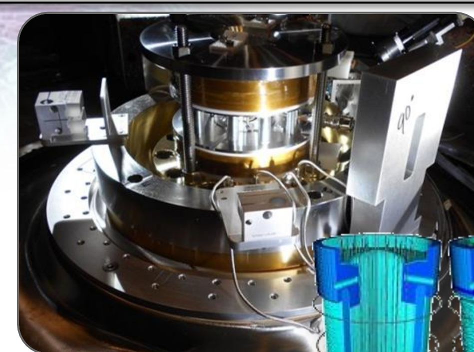
Stellar Opacities

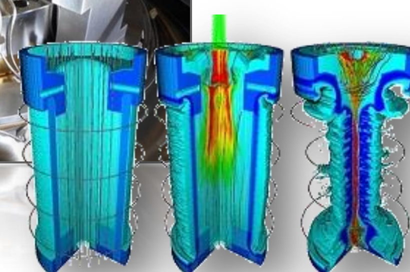
Temperature/density of convection zone



MagLIF Fusion Plasmas

Fusion yields >10^{12} neutrons





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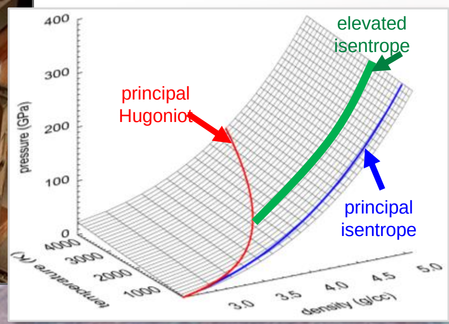

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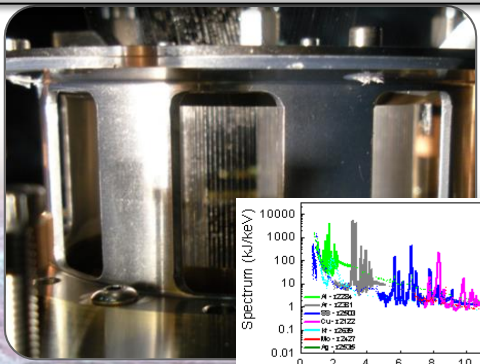

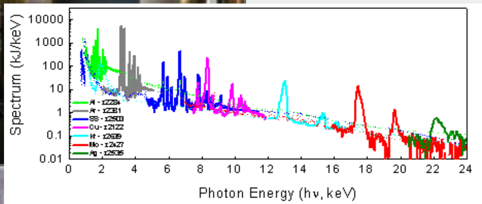

Stellar Opacities

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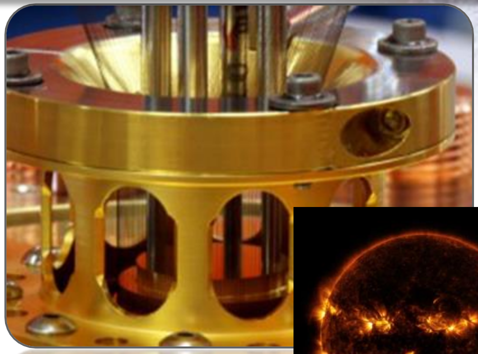
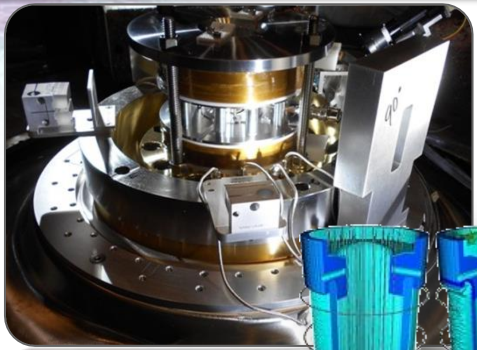
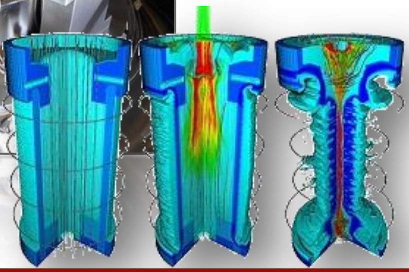


MagLIF Fusion Plasmas

Fusion yields $>10^{12}$ neutrons



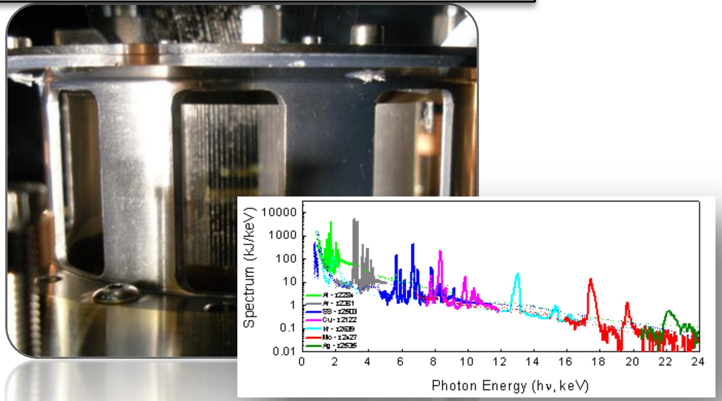


Summary: MagLIF and wire arrays very different, very similar

- Significant overlap and contrast between multi-keV x-ray source experiments and MagLIF
  - Diagnostics similar
  - Same simulation tools used on each
  - Both challenging on the generator
- K-shell sources and MagLIF have made significant progress in last 4 years
  - K-shell sources
    - Previously only source for <10 keV,
    - Now 13 keV Kr gas puffs and 17-59 keV non-thermal sources
  - MagLIF
    - Initial experiments very promising
    - Physics and optimization experiments continuing

K-shell x-ray sources

100's of kJ of multi-keV photons



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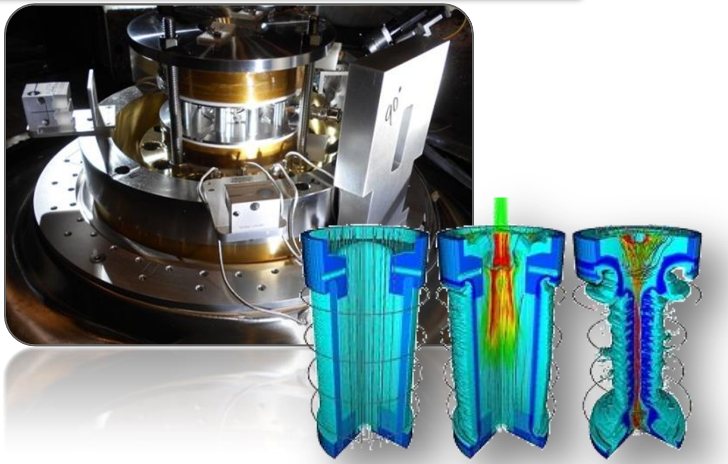
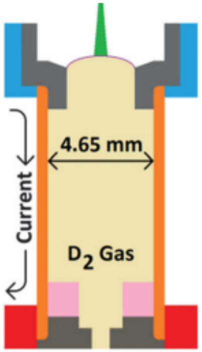
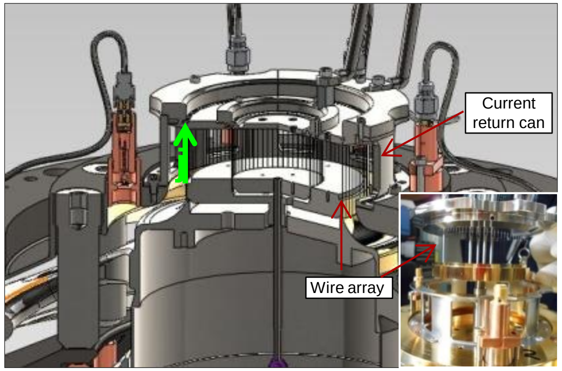
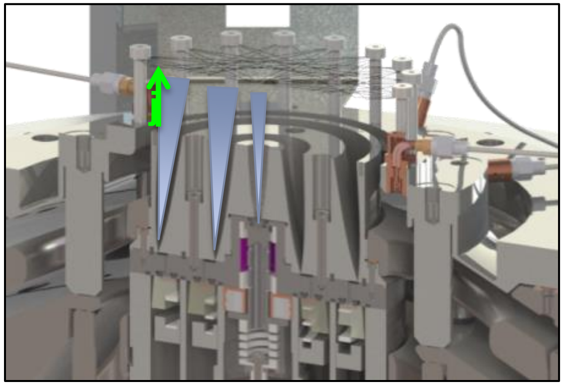


Experiments use liners, wire array and gas puff z pinches imploded on the Z generator



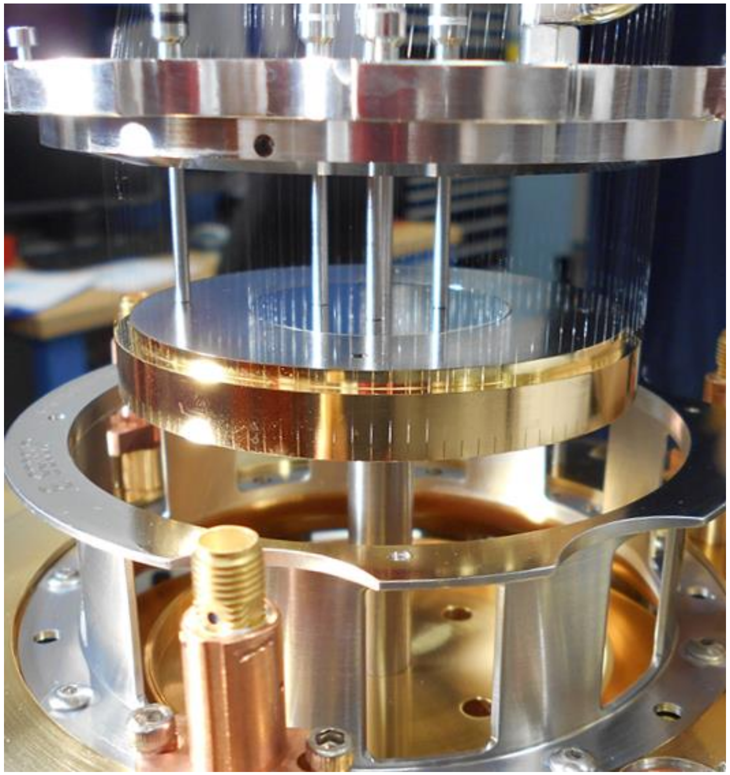




- **MagLIF**
  - Solid Be **liner**, Deuterium gas fill
  - ~100 mg/cm, 5.6mm initial diameter
  - Coating can be used to minimize instability seed
- **Wire arrays**
  - ~100 wires
  - ~1 mg/cm, 70mm initial diameter
  - Nested wire arrays for stability
  - Al, Stainless Steel, Cu, Mo, Ag
- **Gas puffs**
  - Azimuthally symmetric gas shells
  - ~1 mg/cm
  - Shape density profiles for stability
  - Ar, Kr, D2
- Initial diameters, masses and mass distribution define stagnation temperature, uniformity

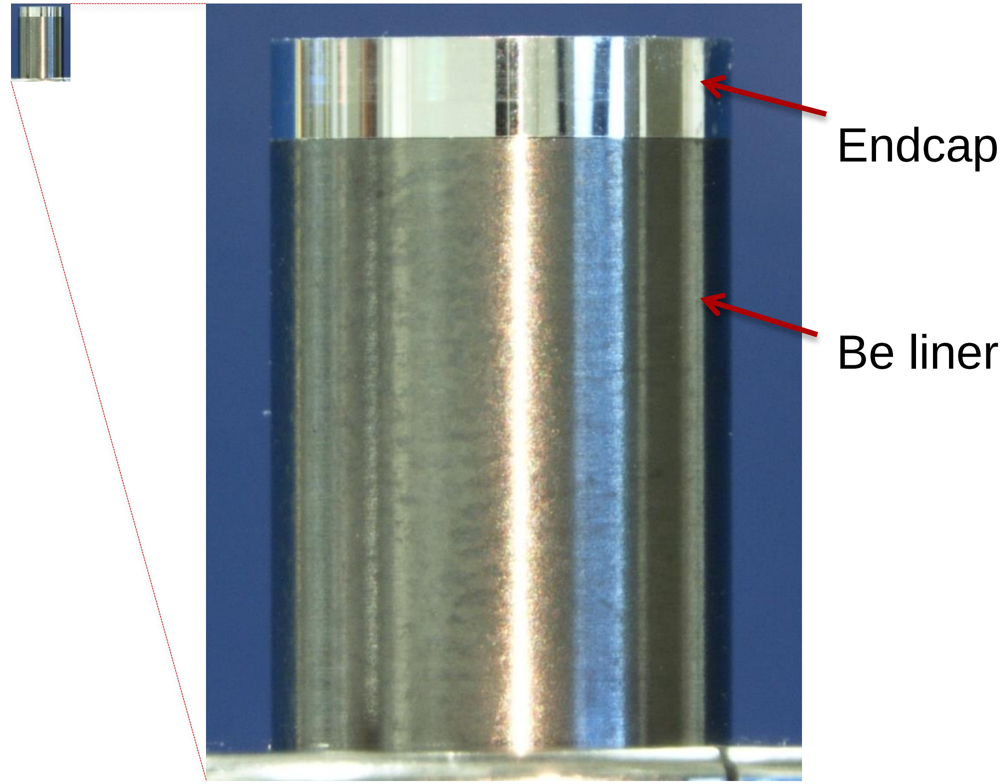
Scales and structure of different experiments vary significantly

70 mm wire array



5.6 mm liner

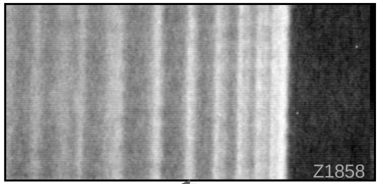
10 x magnification

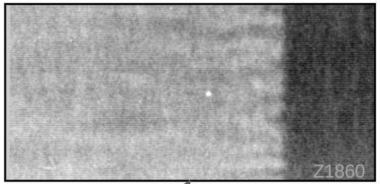


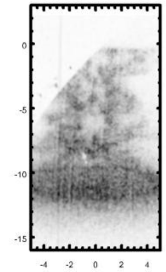
- Diameters: few cm or few mm
- Azimuthally discrete wires or continuous liner
- µm scale wires vs. 100s of µm thick liner

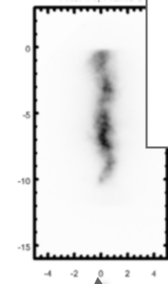
Magnetically driven implosions undergo a multi-stage implosion, make hot plasma on the axis of symmetry

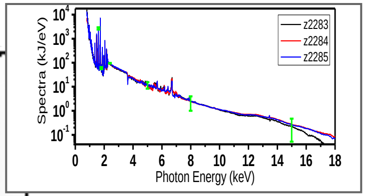
Wire arrays











Wire ablation

Dwell time

Initial location

Initial motion

Correlated instabilities

Final implosion

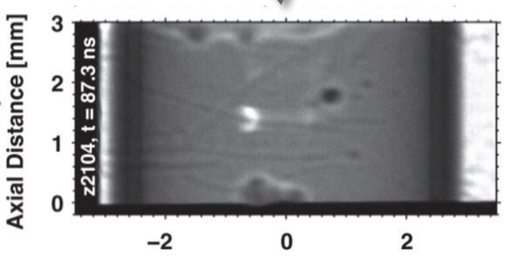
Large scale instabilities

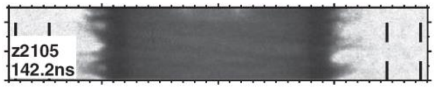
Stagnation

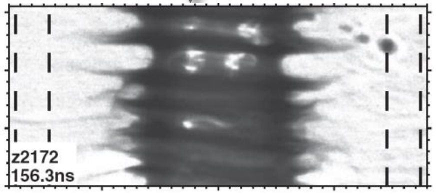
Structured column

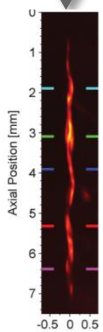
MagLIF

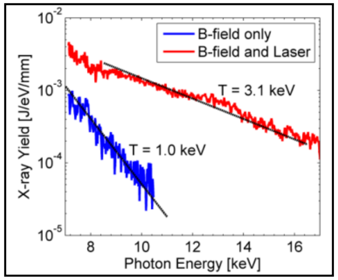
Shock propagation











D.J. Ampleford. B. Jones *et al.*, Phys Plasmas **21** 056708 (2014); R.D. McBride *et al.*, PRL **109**, 135004 (2012)l M.R. Gomez *et al.*, PRL **113**, 155003 (2014)

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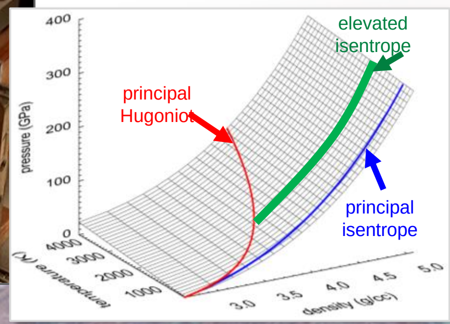

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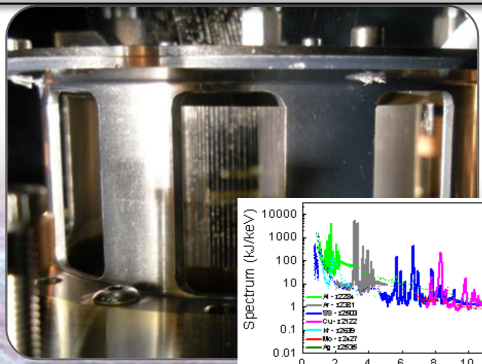
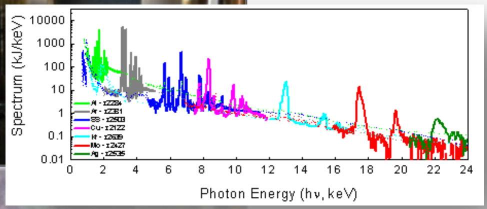
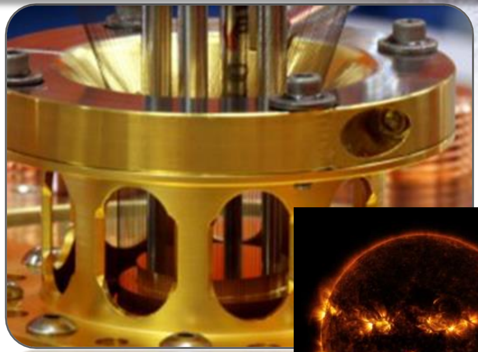




Stellar Opacities

Temperature/density of convection zone



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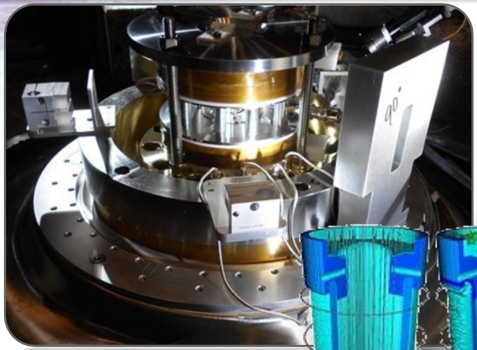
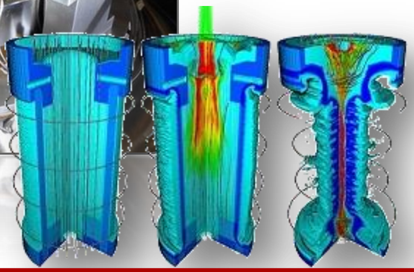
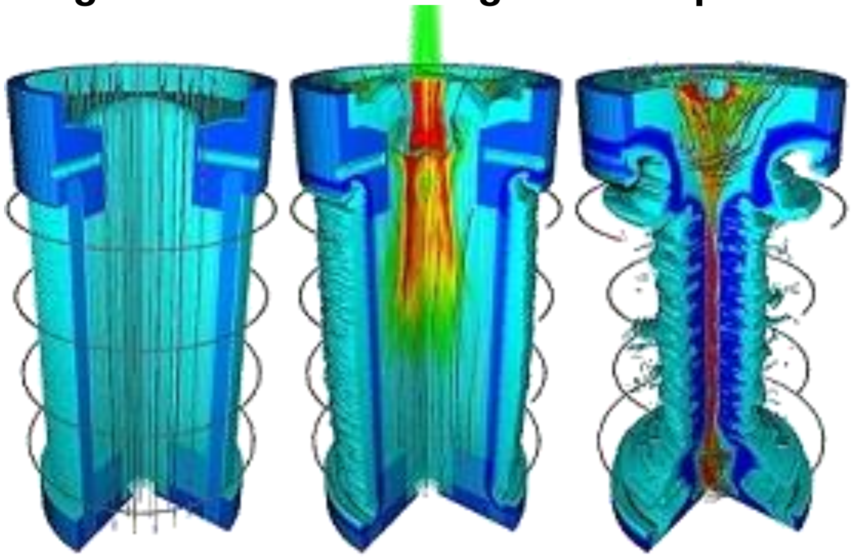


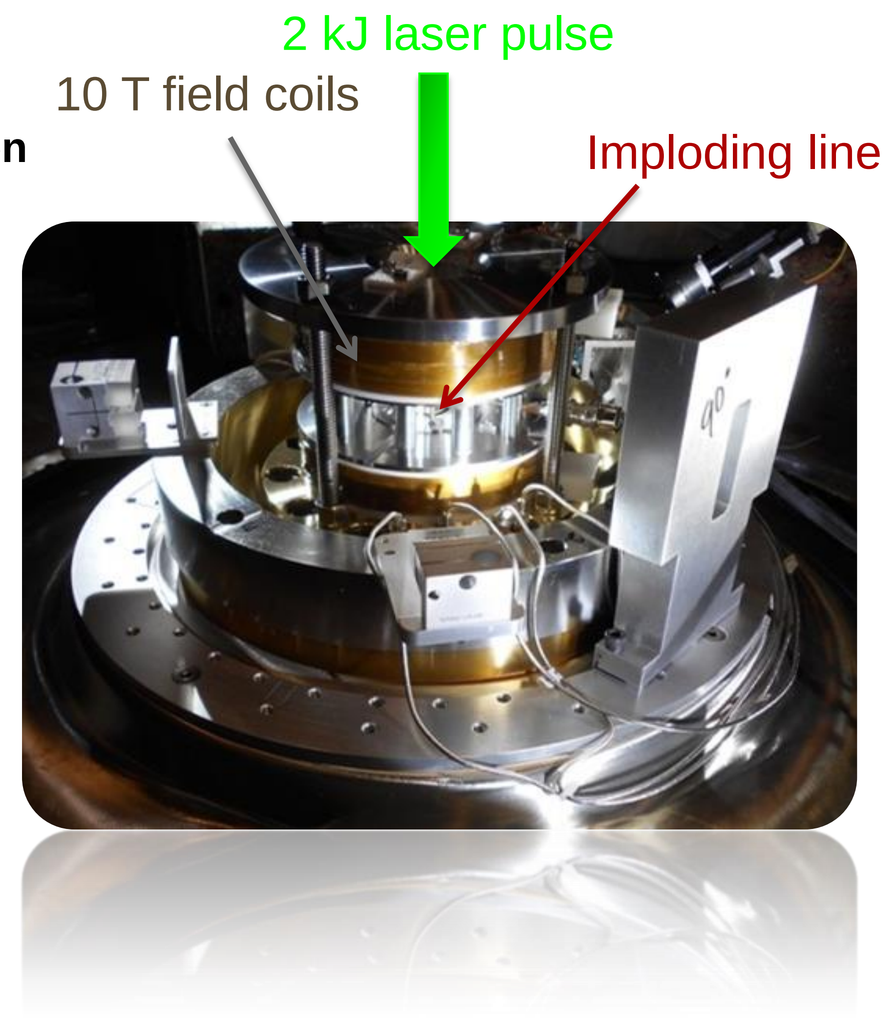


MAGnetized Liner Inertial Fusion consists of imploding a pre-magnetized, pre-heated liner with the Z electrical pulse

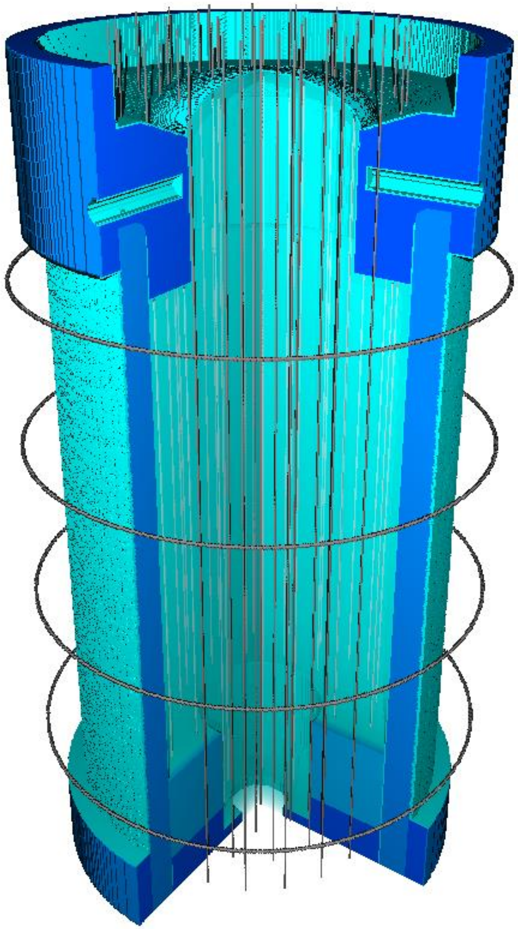
Axial Magnetization **Laser Heating** **Magnetically-driven Compression**



Results of 3D MHD simulations



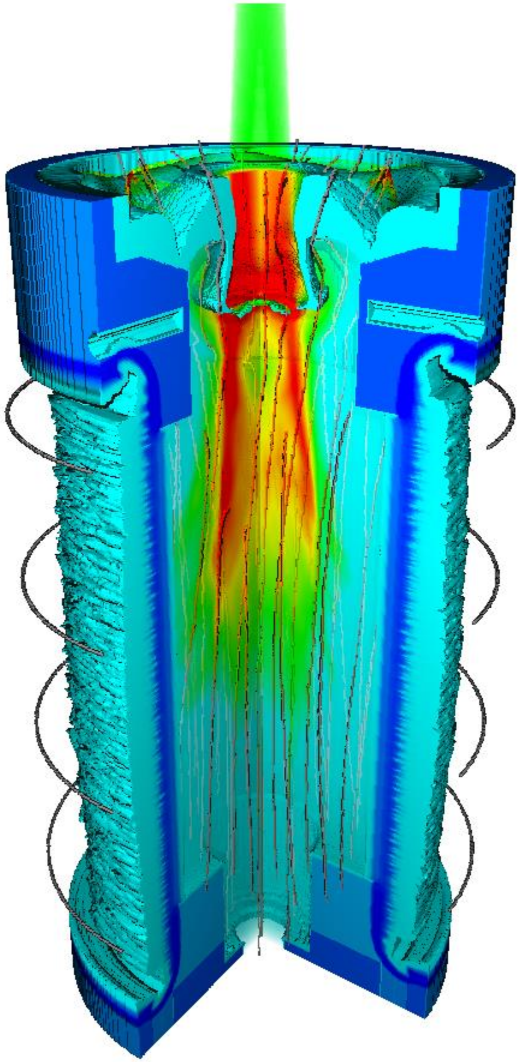
MagLIF has three stages: Stage 1 is Magnetization



- **Start with a thick metal liner (Be) containing gaseous fusion fuel (D2)**
- **A 10 Tesla axial magnetic field is applied slowly so the field can diffuse through conductors**

S. A. Slutz et al., Phys. Plasmas, 17 056303 (2010).

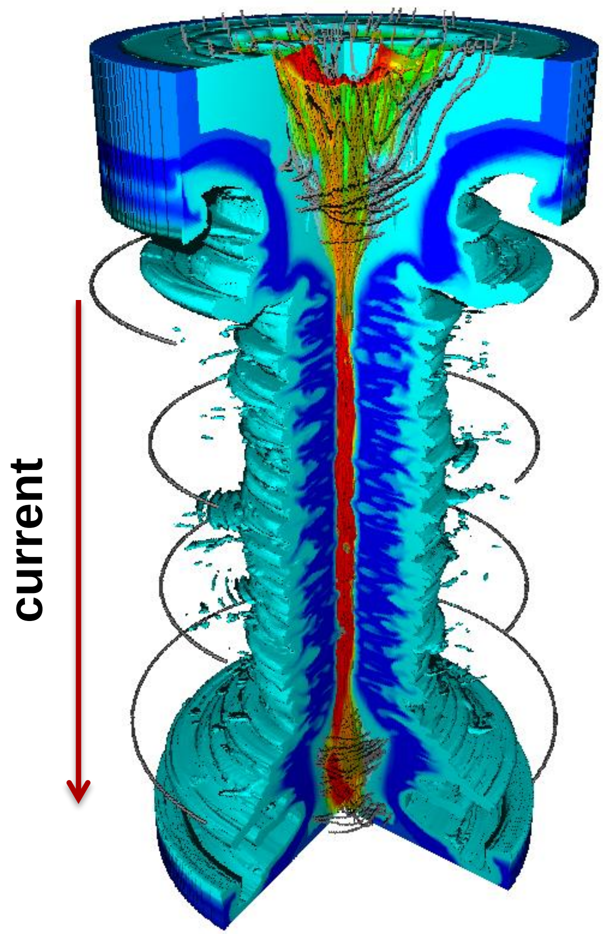
MagLIF has three stages: Stage 2 is Laser heating



- **A laser enters the target axially**
  - **2Ω light from ZBL laser**
- **The laser heats the fuel through inverse bremsstrahlung absorption**
- **The magnetic field insulates the warm gas from the cool liner**

S. A. Slutz et al., Phys. Plasmas, 17 056303 (2010).

MagLIF has three stages: Stage 3 is Compression



- **Current flowing on the outside of the target squeezes the liner which compresses the fuel and magnetic field**
  - **Typically achieve 18 MA currents**
- **The fuel heats through near adiabatic compression to fusion relevant temperatures**

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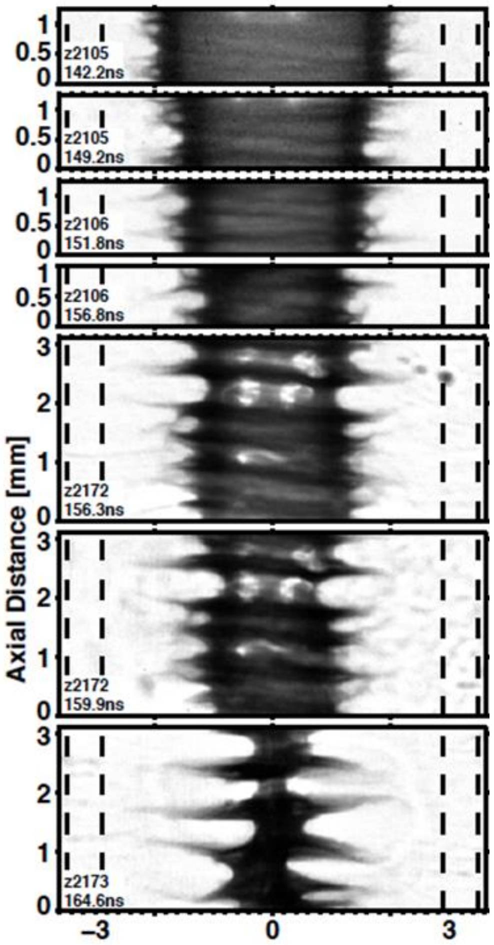
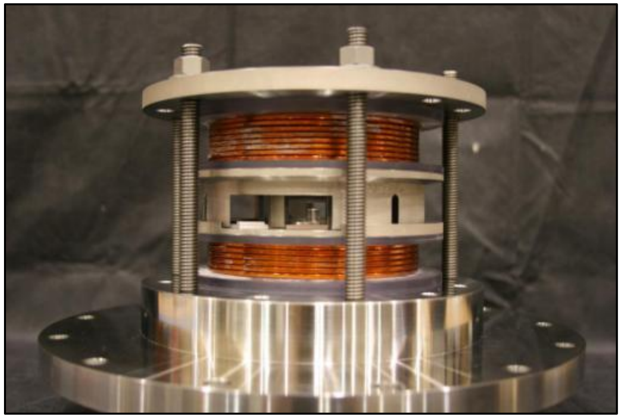
Several experimental campaigns were conducted to investigate liner robustness

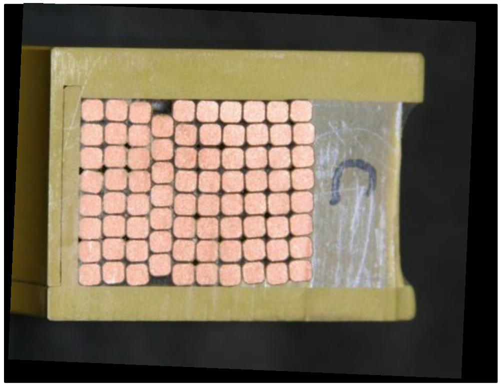


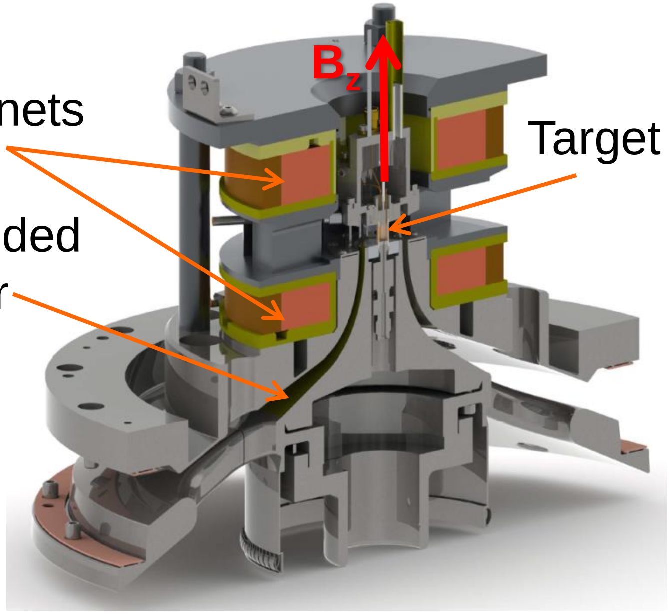
- In MagLIF, liner stability is critical because the liner provides confinement at stagnation
- Smooth beryllium liners were imploded and radiography was used to assess liner stability
- During the implosion, the magneto-Rayleigh-Taylor instability develops azimuthally correlated bubbles and spikes
- Based on experiments and simulations, aspect ratio 6 liners are at the limit of acceptable stability
  - Experiments are starting to explore thinner liners

R. D. McBride et al., PRL 109, 135004 (2012).

We developed the capability to apply uniform, pulsed magnetic fields to cm-scale targets







Applied B-field on Z

Capacitor bank: 900 kJ, 8 mF, 15 kV

Full diagnostic access coils: up to 10 T

Limited diagnostic access coils: 15-20 T

No diagnostic access coils: 25-30 T

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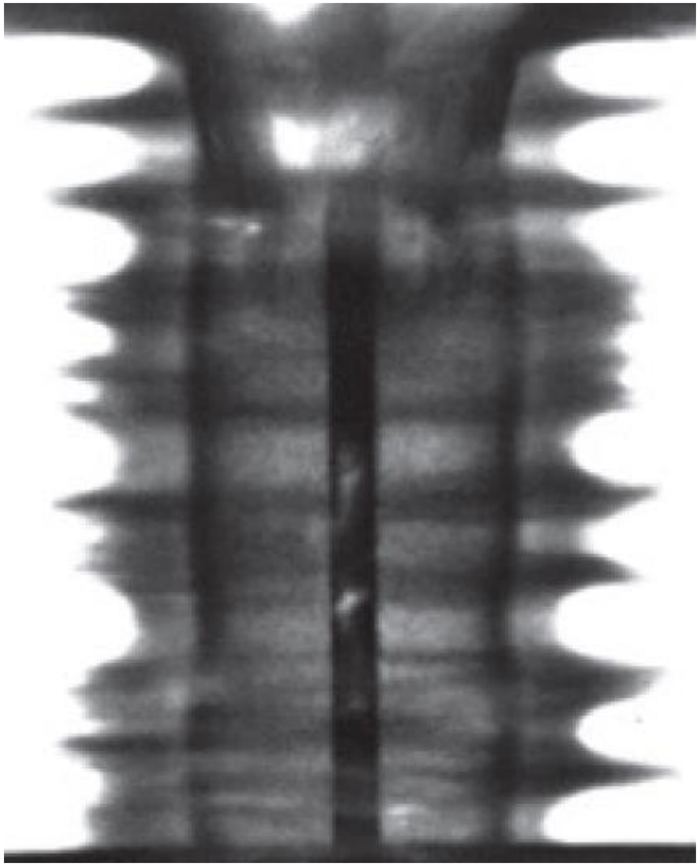
Rovang, Lamppa *et al.*, RSI **85**, 124701 (2014)

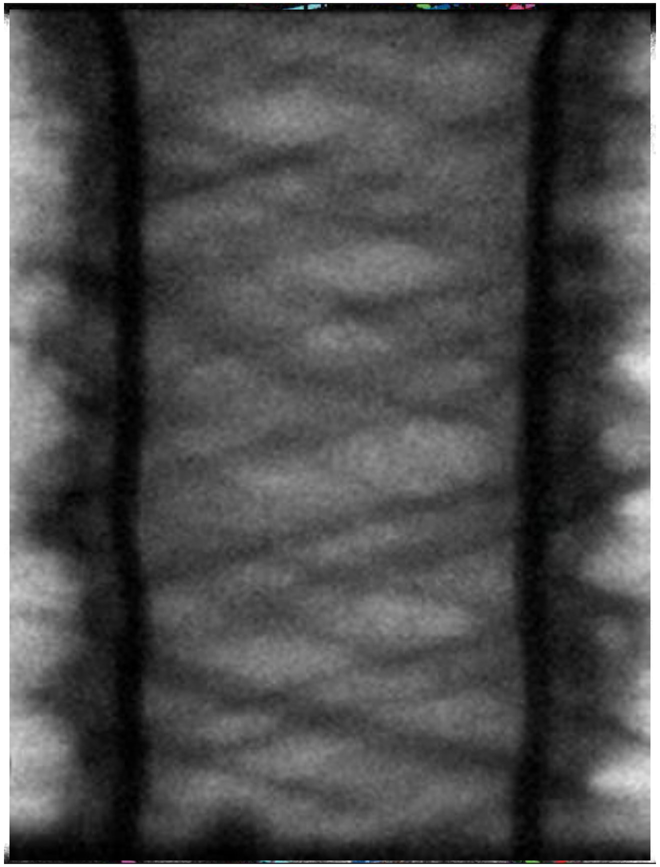
Addition of the axial B-field dramatically modified instability growth

Without axial B-field



Azimuthal MRT structure

With axial B-field



Helical MRT structure

17

T. J. Awe et al., Phys. Rev. Lett. 111, 235005 (2013).

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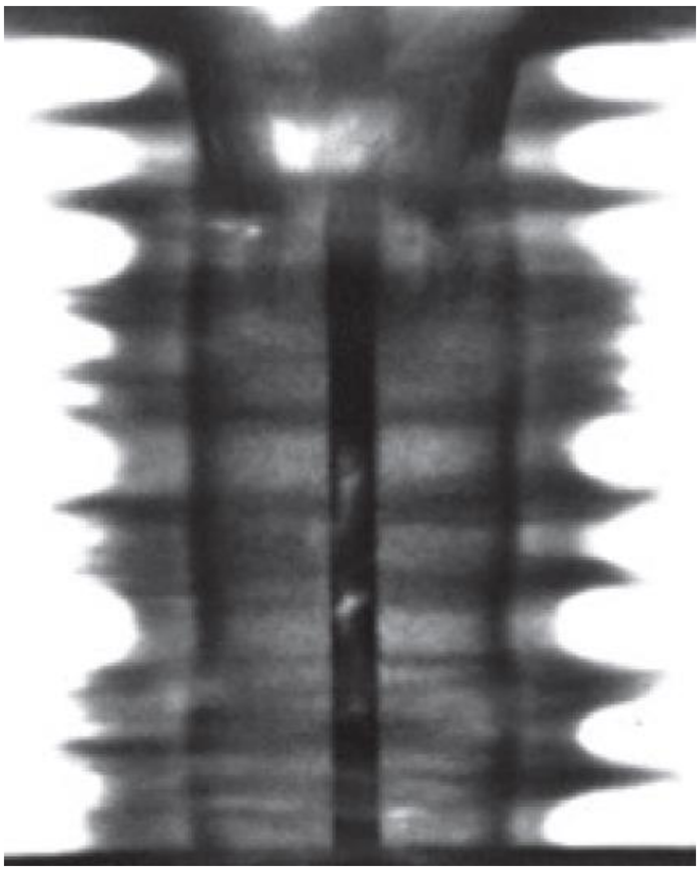

Azimuthal MRT structure

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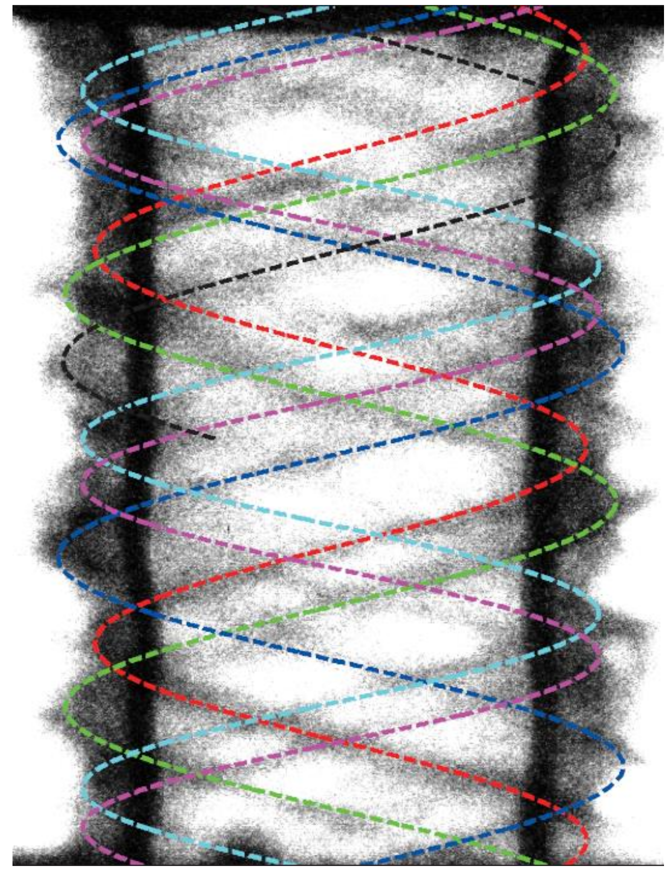

Helical MRT structure

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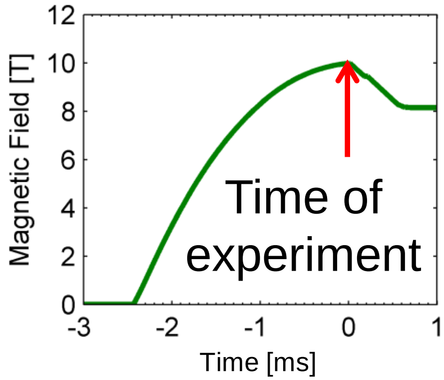
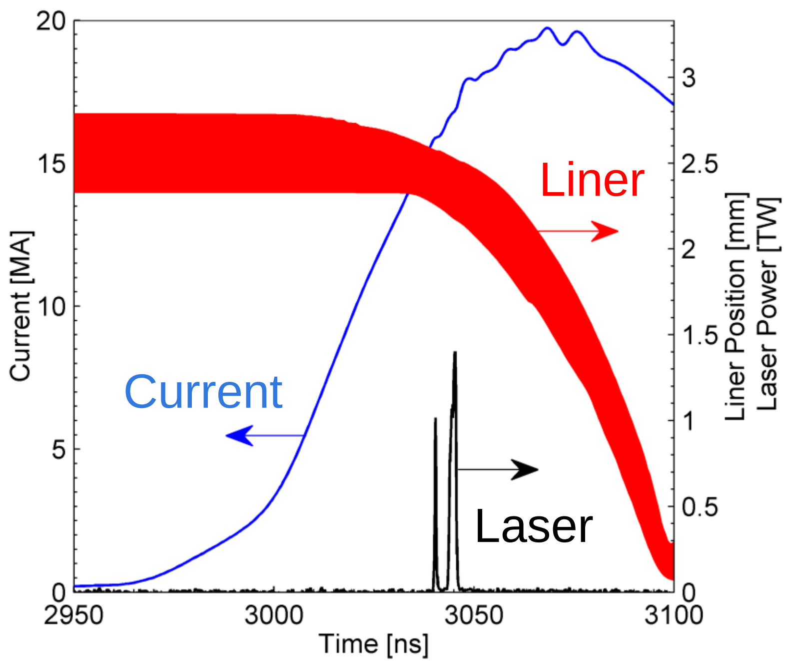
The initial experiments used the maximum magnetic field, current, and laser energy available



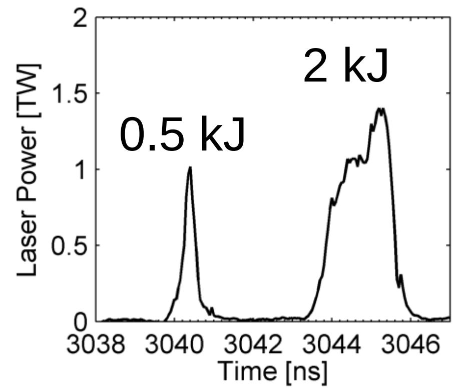
Magnetic field risetime is approximately 2 ms

B is constant over the timescale of the experiment

Magnetic field is 10 T
Peak current is 19 MA
Total laser energy is 2.5 kJ

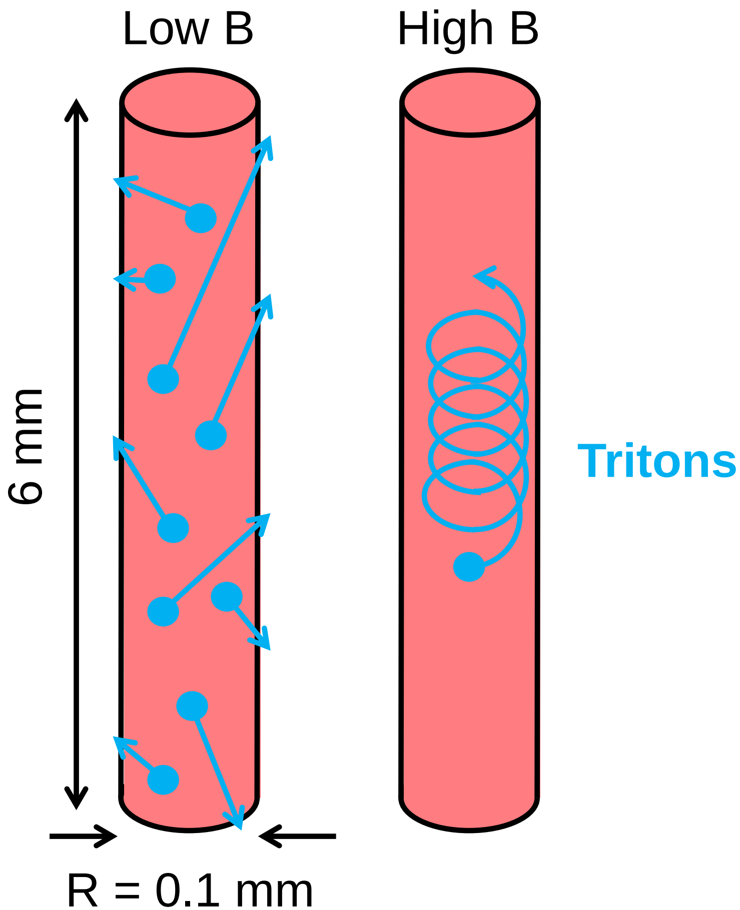


Laser energy is split into 2 pulses:
1st pulse intended to destroy LEH
2nd pulse intended to heat fuel



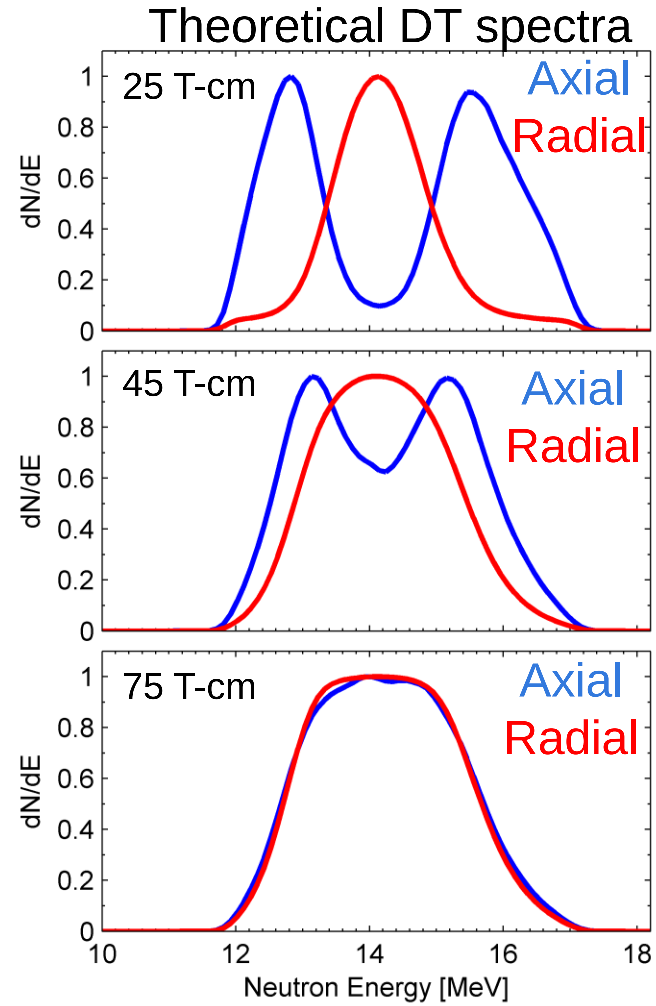
M. R. Gomez et al., Phys. Rev. Lett. 113, 155003 (2014).

Magnetic flux compression demonstrated through secondary neutron yield and spectra



DT spectra are very sensitive to BR in this regime

As BR increases the distance between peaks in the axial spectra decreases



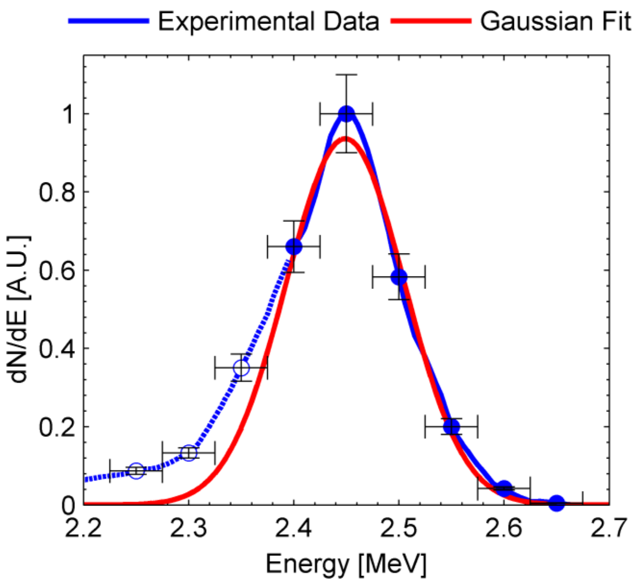
Measured DT/DD yield ratio and DT spectra are consistent with BR ≈ 40 ± 7 T-cm

P. F. Schmit, P. F. Knapp et al., Phys. Rev. Lett. 113, 155004 (2014).

20

MagLIF has successfully demonstrated key aspects of magneto-inertial fusion

Thermonuclear neutron generation

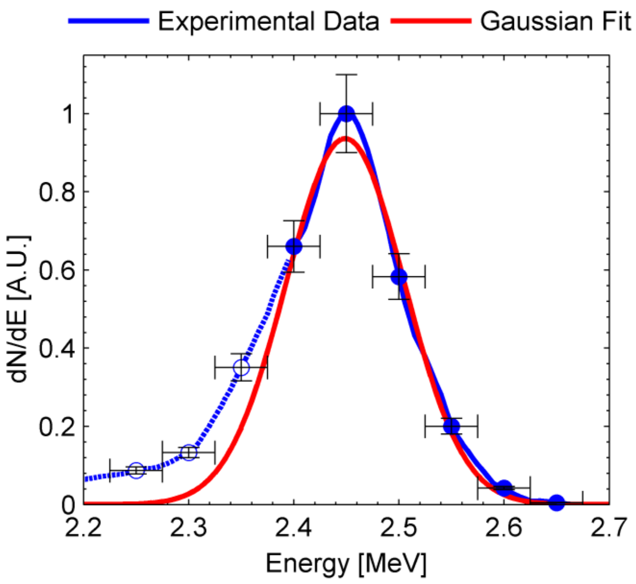


Isotropic, Gaussian DD neutron spectra

M. R. Gomez et al., Phys. Rev. Lett. 113, 155003 (2014). P. F. Schmit et al., Phys. Rev. Lett. 113, 155004 (2014).

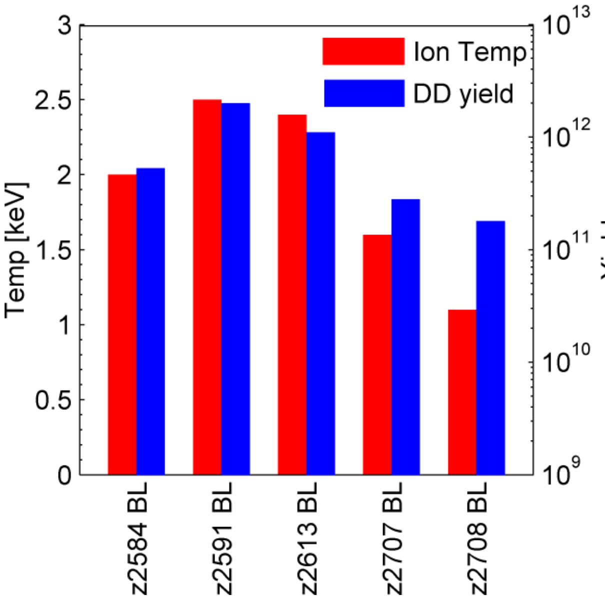
MagLIF has successfully demonstrated key aspects of magneto-inertial fusion

Thermonuclear neutron generation



Isotropic, Gaussian DD neutron spectra

High temperatures and yields

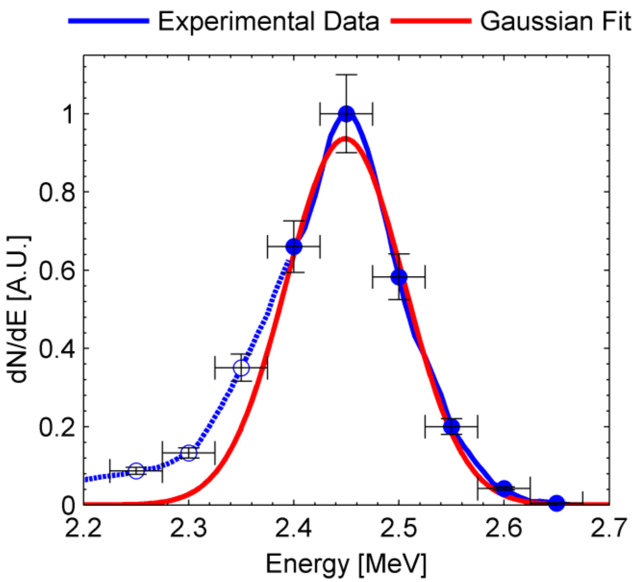


Max yield = 3e12
Max ion temp = 2.5 keV

M. R. Gomez et al., Phys. Rev. Lett. 113, 155003 (2014). P. F. Schmit et al., Phys. Rev. Lett. 113, 155004 (2014).

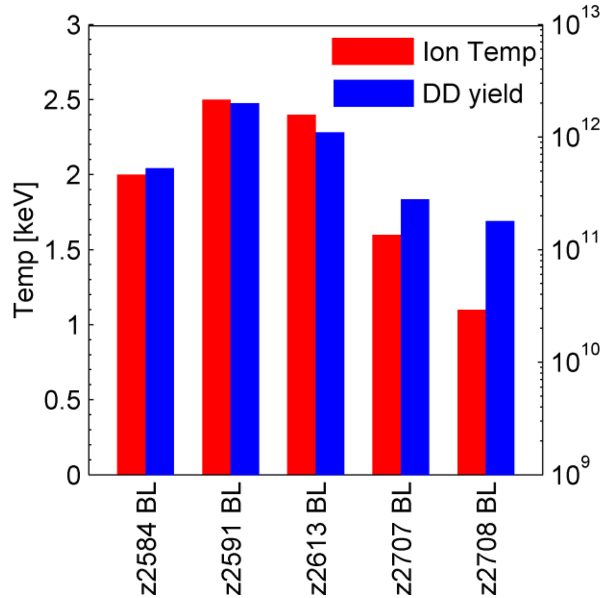
MagLIF has successfully demonstrated key aspects of magneto-inertial fusion

Thermonuclear neutron generation



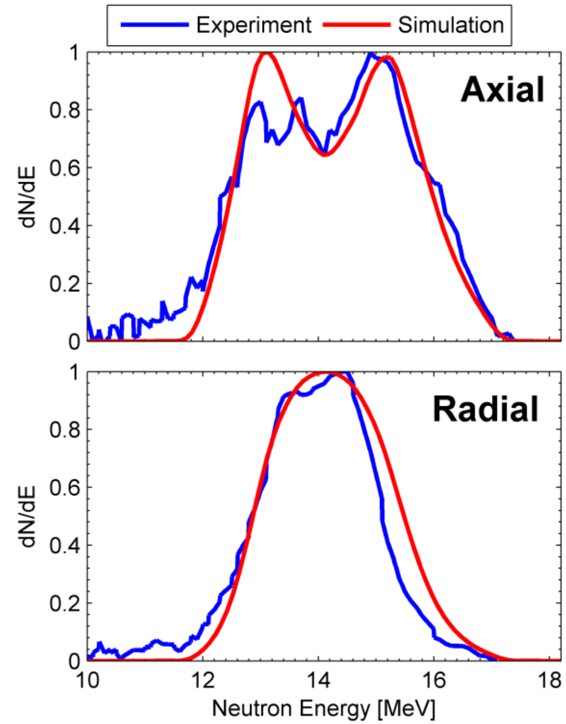
Isotropic, Gaussian DD neutron spectra

High temperatures and yields



Max yield = 3e12
Max ion temp = 2.5 keV

Magnetic flux compression



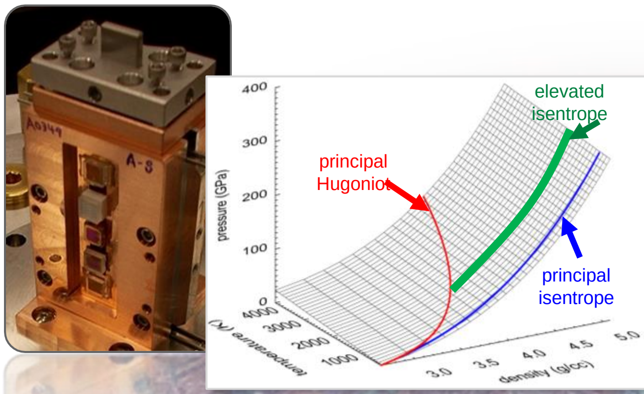
BR = 30-40 T-cm

M. R. Gomez et al., Phys. Rev. Lett. 113, 155003 (2014). P. F. Schmit et al., Phys. Rev. Lett. 113, 155004 (2014).

Z produces extreme conditions in numerous ways

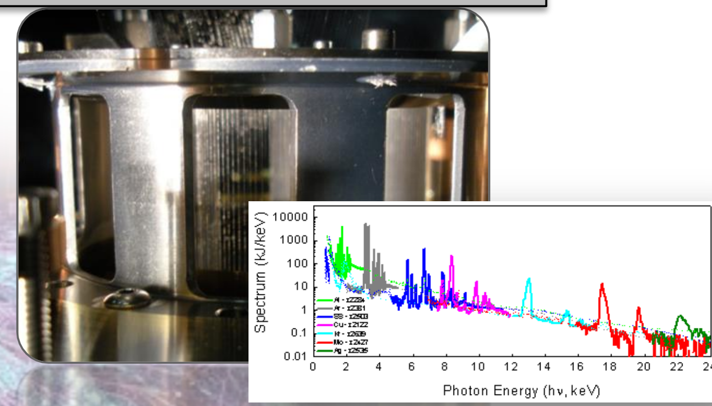
Dynamic Materials

Compress materials to 10^7 Atm.



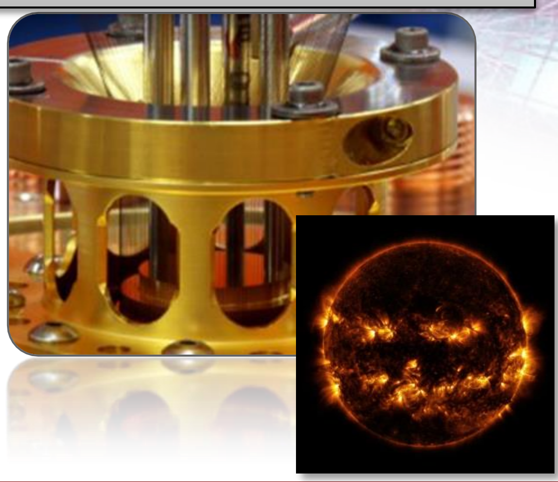
K-shell x-ray sources

100’s of kJ of multi-keV photons



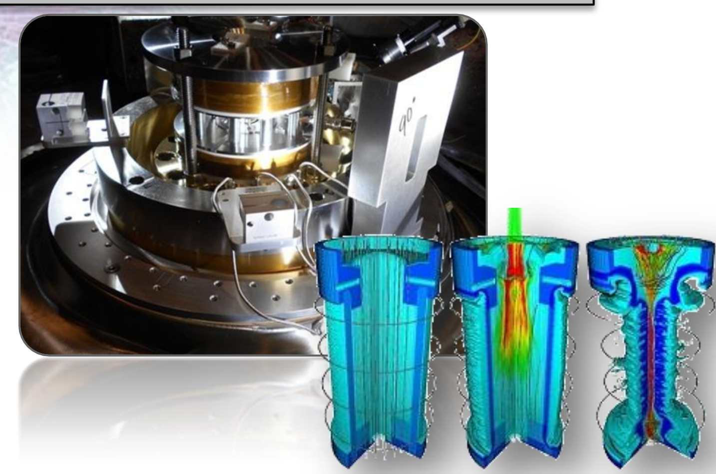
Stellar Opacities

Temperature/density of convection zone



MagLIF Fusion Plasmas

Fusion yields >10^{12} neutrons



K-shell line emission from z pinches is a very efficient source of multi-keV x-ray, but requires high velocities

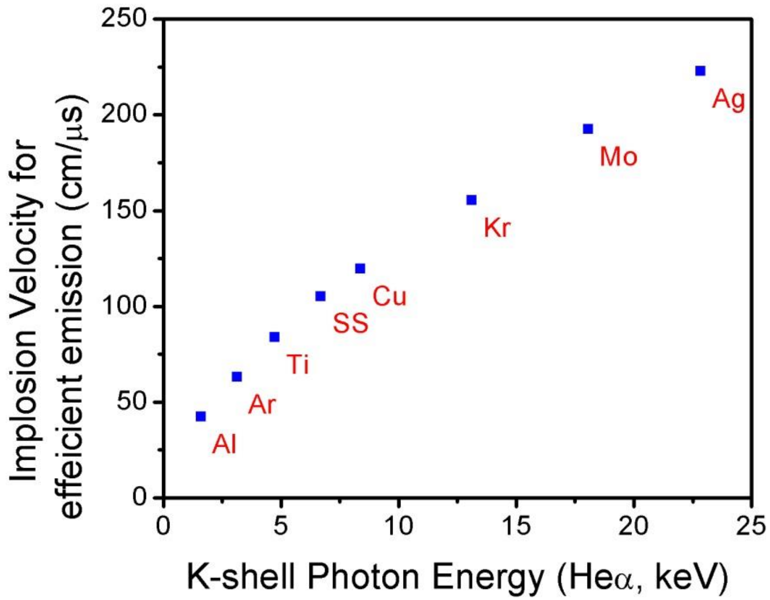
High implosion velocities
> 1000 km/s

↓

High electron temperatures
> Few keV

↓

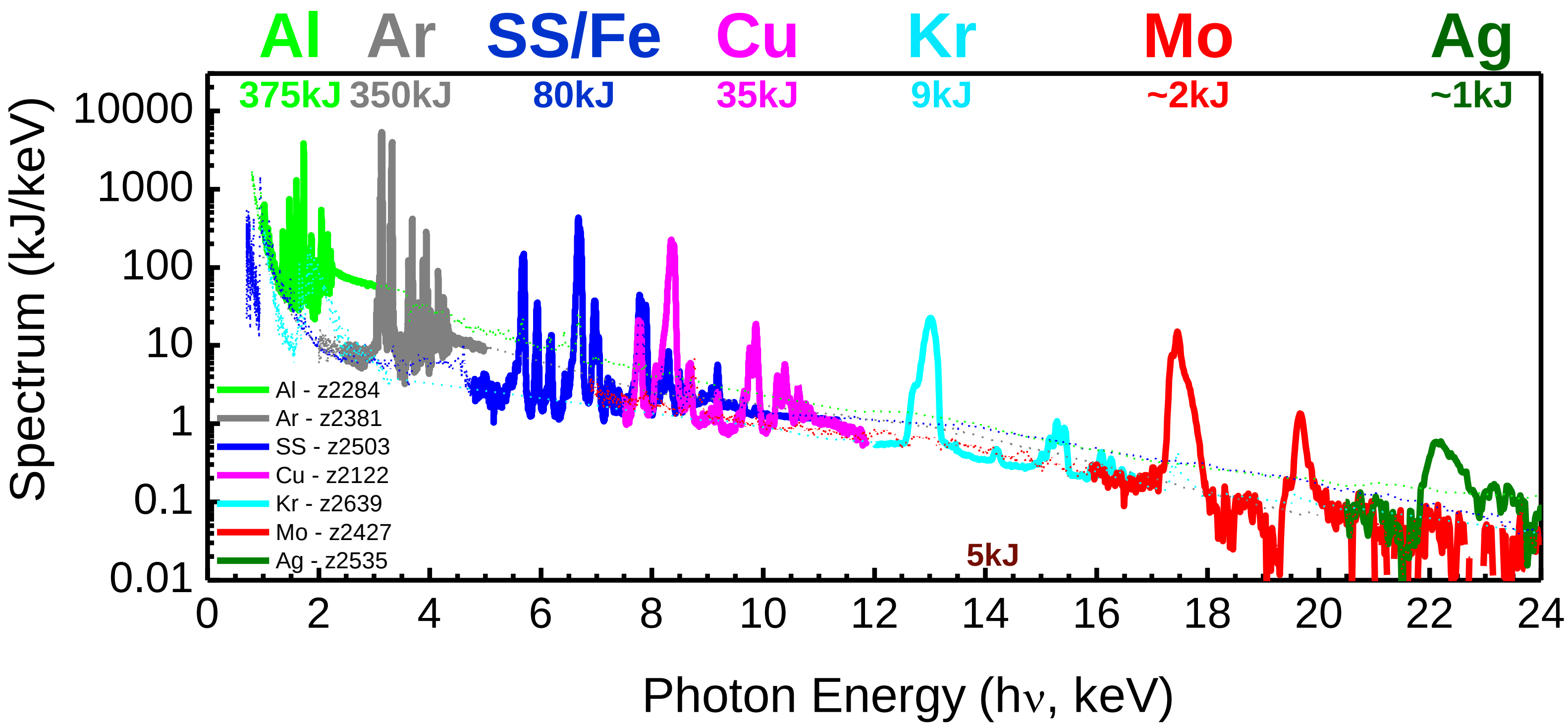
K-shell emission
10's or 100s of kJ at few keV



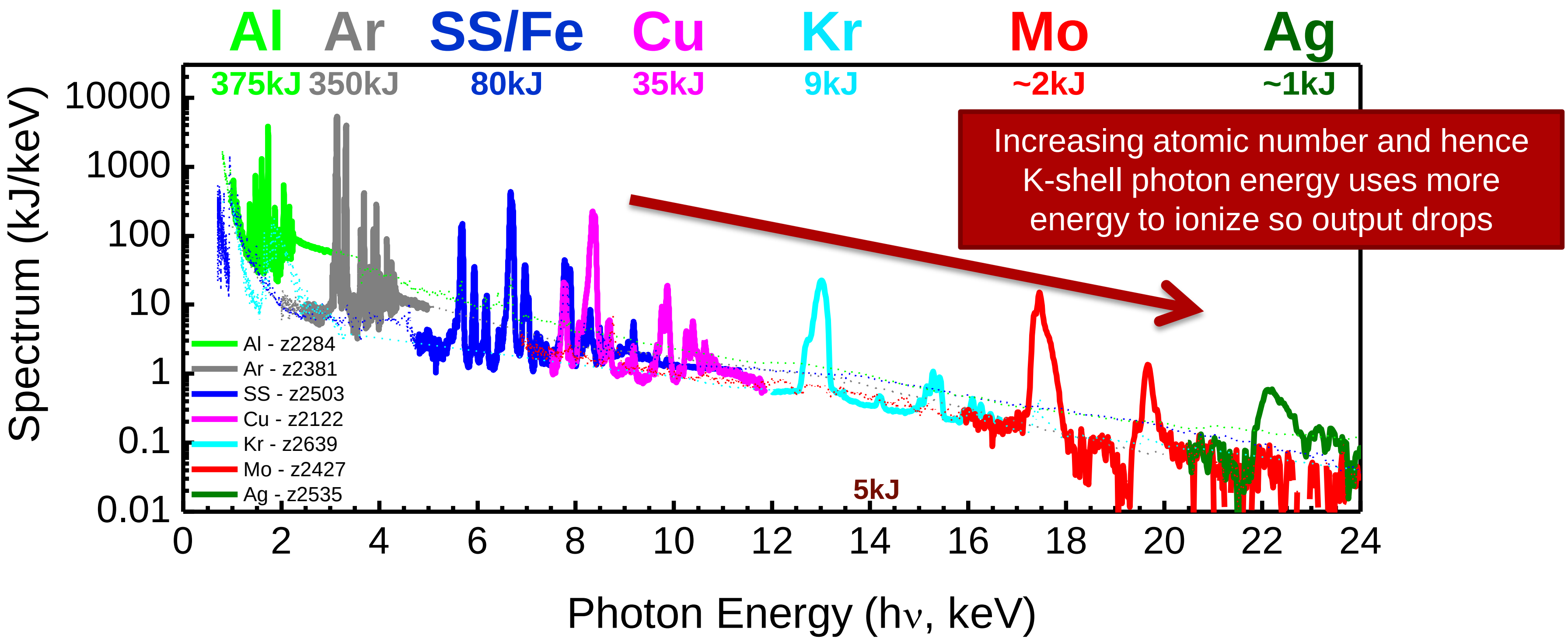
- Ionizing to the K-shell and producing bright K-shell line emission requires kinetic energy per ion and hence high velocities

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

High velocity, low mass imploding Z pinches on the Z generator create extremely bright plasmas at various photon energies

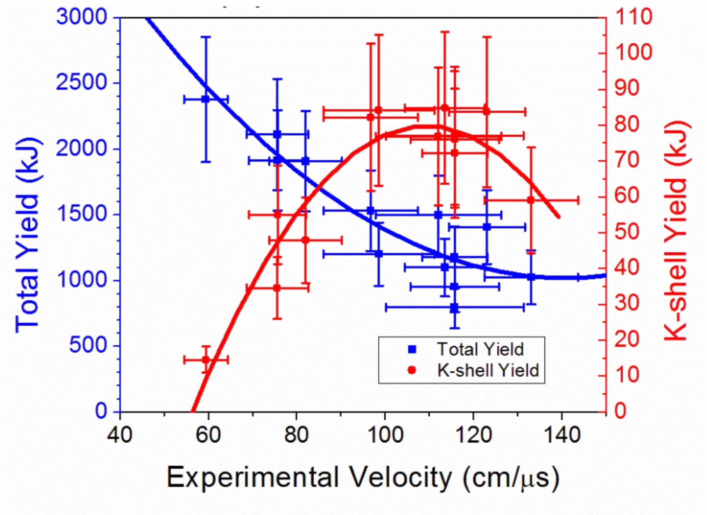


High velocity, low mass imploding Z pinches on the Z generator create extremely bright plasmas at various photon energies

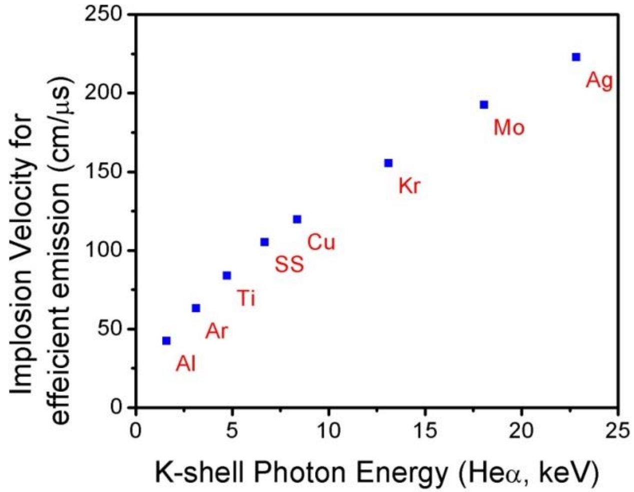


Experiments with Stainless steel demonstrate high implosion velocities needed for efficient K-shell emission

- Vary the initial wire array setup significantly varies implosion velocity
  - Total yield is highest for later/slower implosions, where more energy is coupled
  - K-shell yield is highest for ~110cm/µs implosions, consistent with analytic estimates

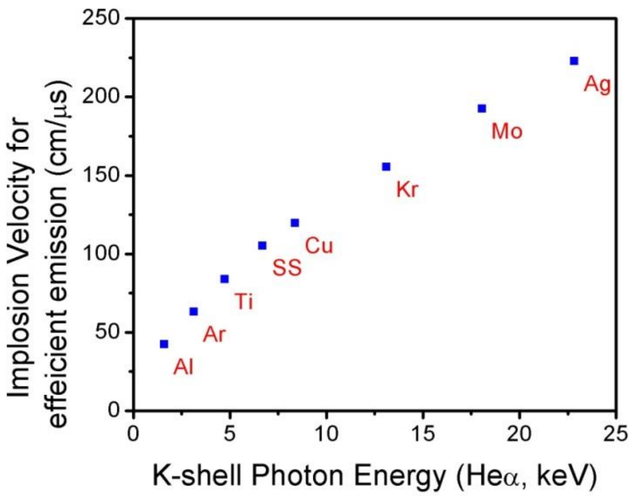


- For higher atomic number materials higher implosion velocities are required
  - Kr needs ~150cm/µs implosion velocities to provide 13 keV emission



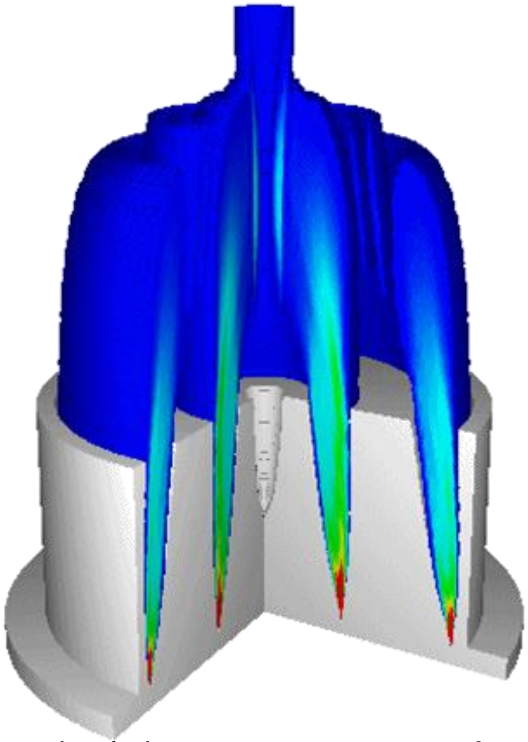
Kr K-shell emission at 13 keV requires >100 cm/μs velocities

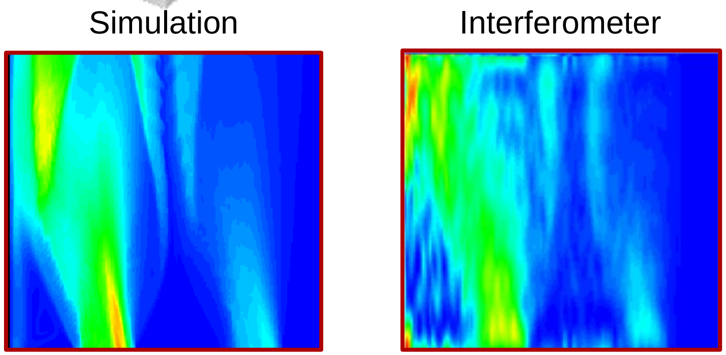
- To obtain high velocities on 100 ns generator start from very large diameters
  - 12 cm initial diameter!
- These velocities are very prone to instability growth
  - Work to mitigate instability growth



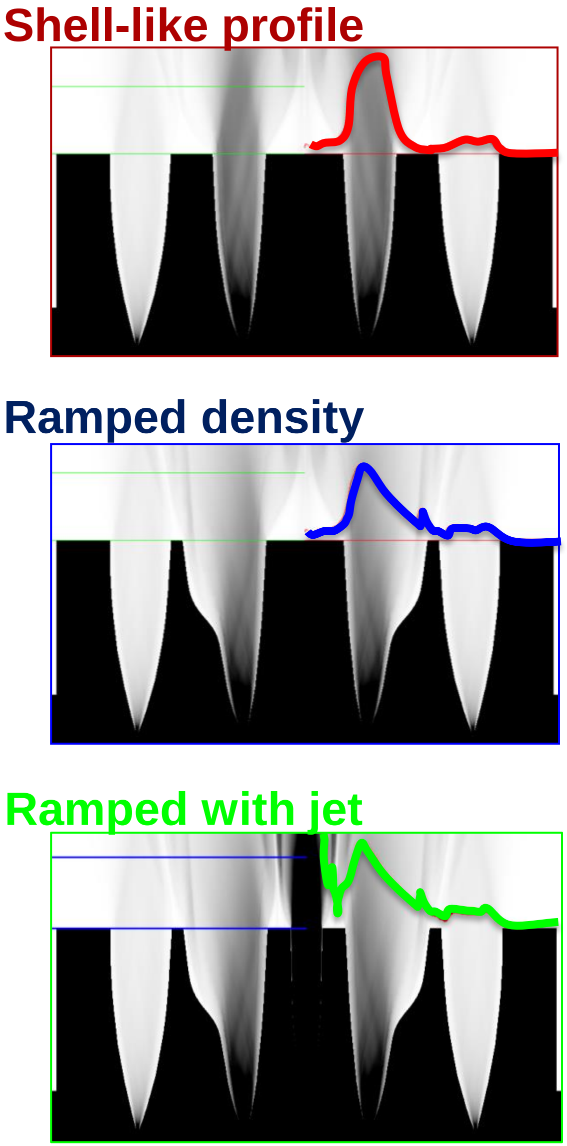
Simulations of gas flow from supersonic nozzles can be used to design initial conditions for gas puff z pinches

- Hydrodynamic simulations of gas flow are used to study the initial conditions for the experiments
  - Cold gas flow simulation of flow before Z fires
- Interferometry used for validation





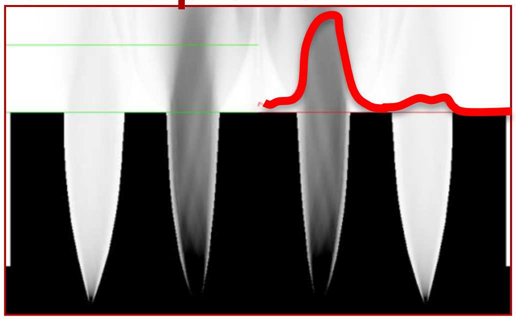
Can use hydrodynamic simulations as a design tool and test with 3-dimensional MHD implosion simulations



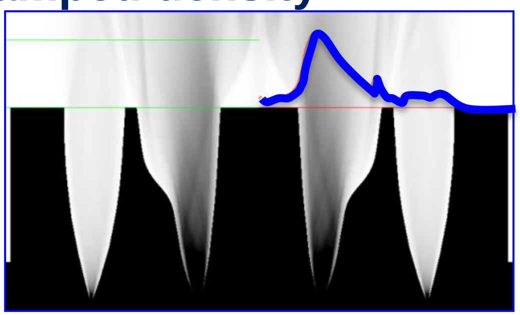
- To produce stable implosion want density continuously increasing towards the axis
- Constrains of real nozzles makes this harder
- Hydro simulations used to design various profiles from shell on shell through to near-ideal ramped with jet

Can use hydrodynamic simulations as a design tool and test with 3-dimensional MHD implosion simulations

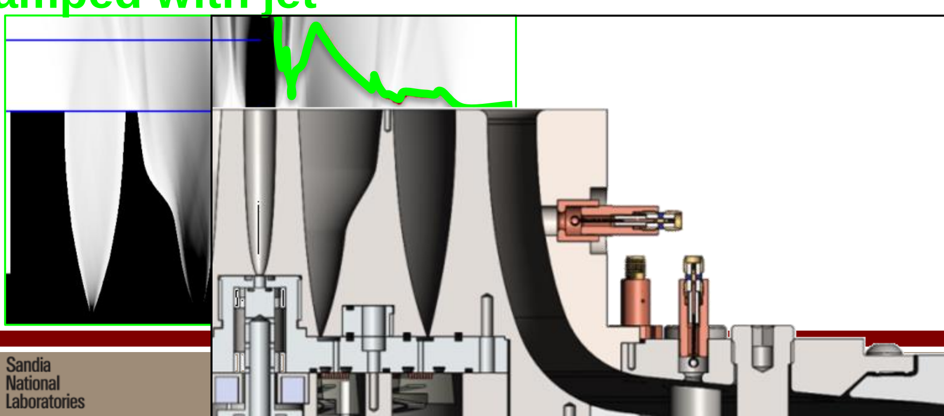
Shell-like profile



Ramped density



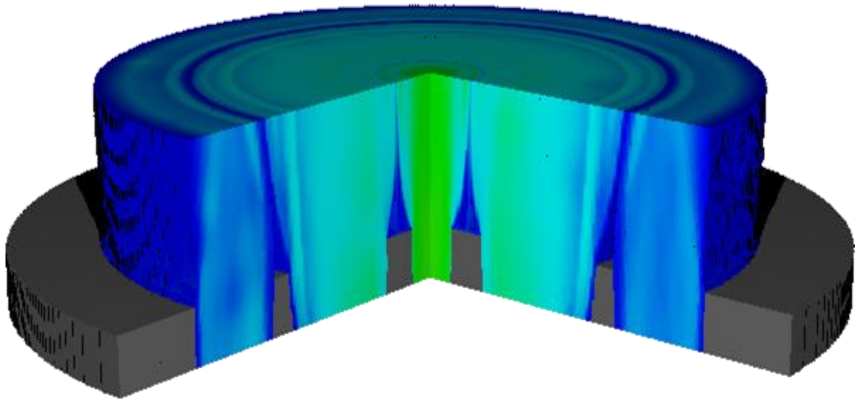
Ramped with jet

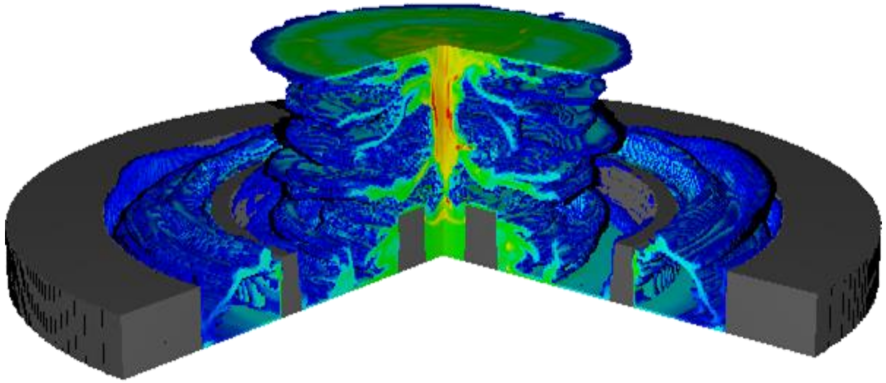


- To produce stable implosion want density continuously increasing towards the axis
- Constrains of real nozzles makes this harder
- Hydro simulations used to design various profiles from shell on shell through to near-ideal ramped with jet

Full 3D MHD simulations can be initiated with output from cold gas flow simulations

- 3D Gorgon simulations using initial conditions from gas flow simulations
- Resistive MHD simulations using tabulated K-shell emissivities
- Simulations enable exploration of different gas profiles

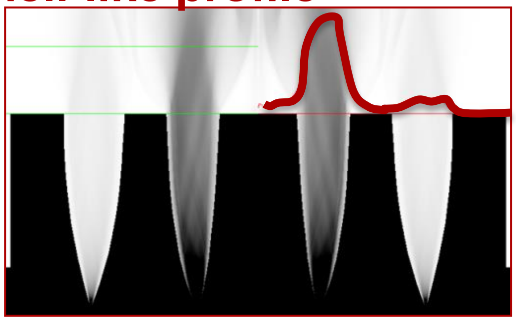


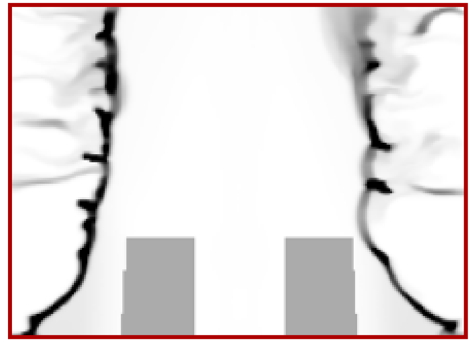


Can use hydrodynamic simulations as a design tool and test with 3-dimensional MHD implosion simulations

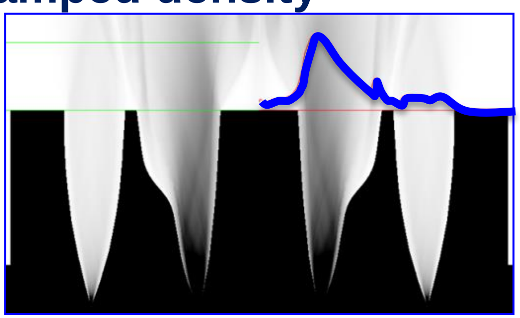
Mid-implosion

Shell-like profile

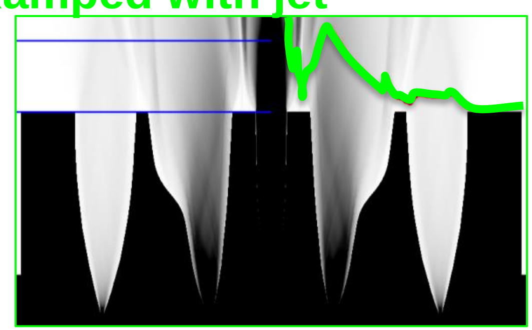


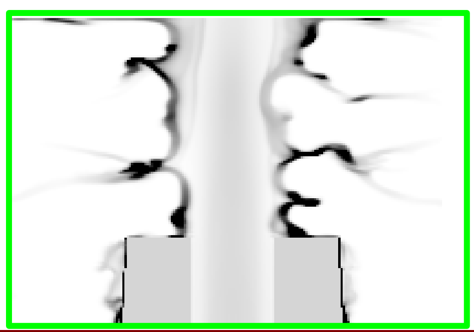


Ramped density



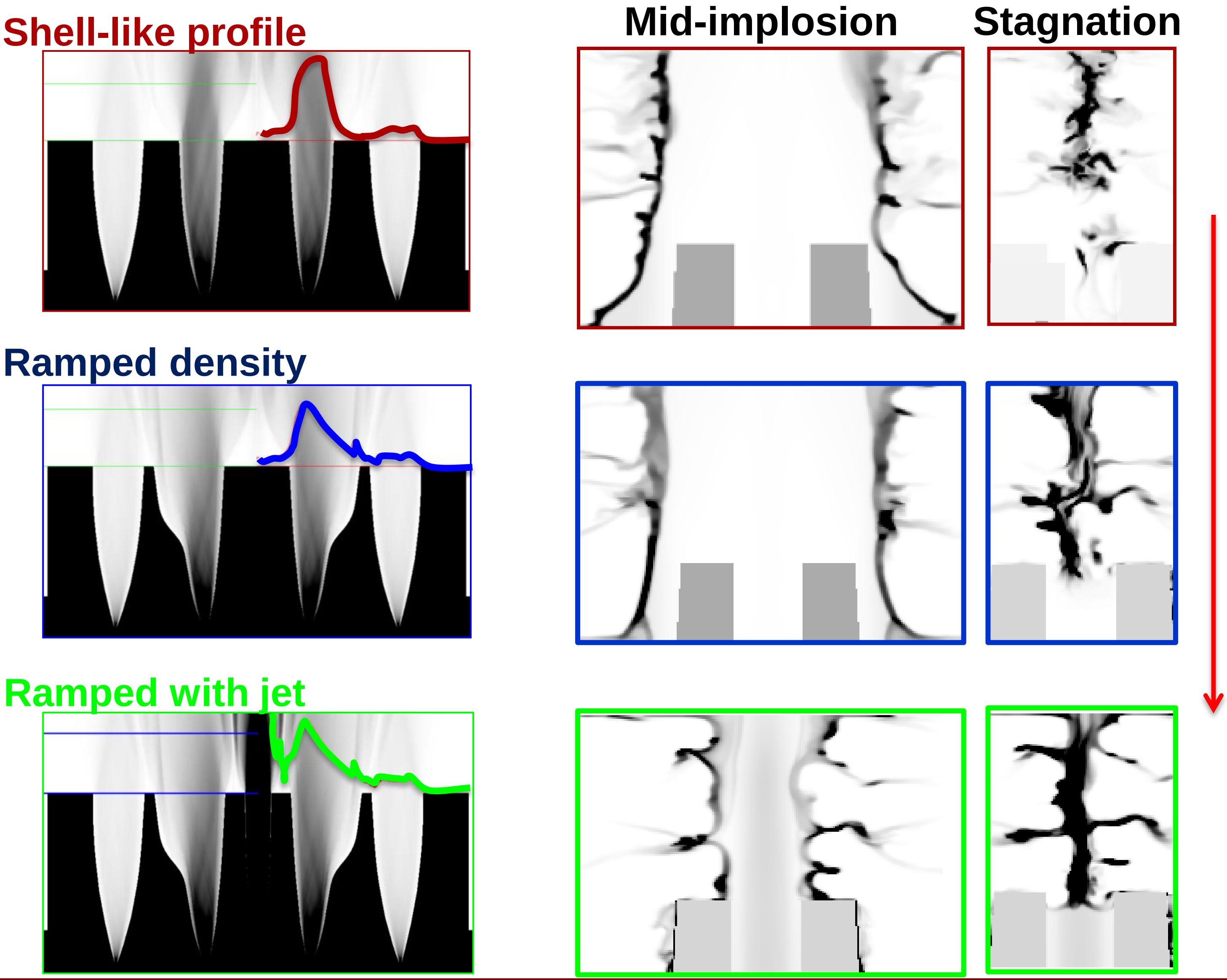
Ramped with jet





Implosion is more stable for more ideal initial profiles

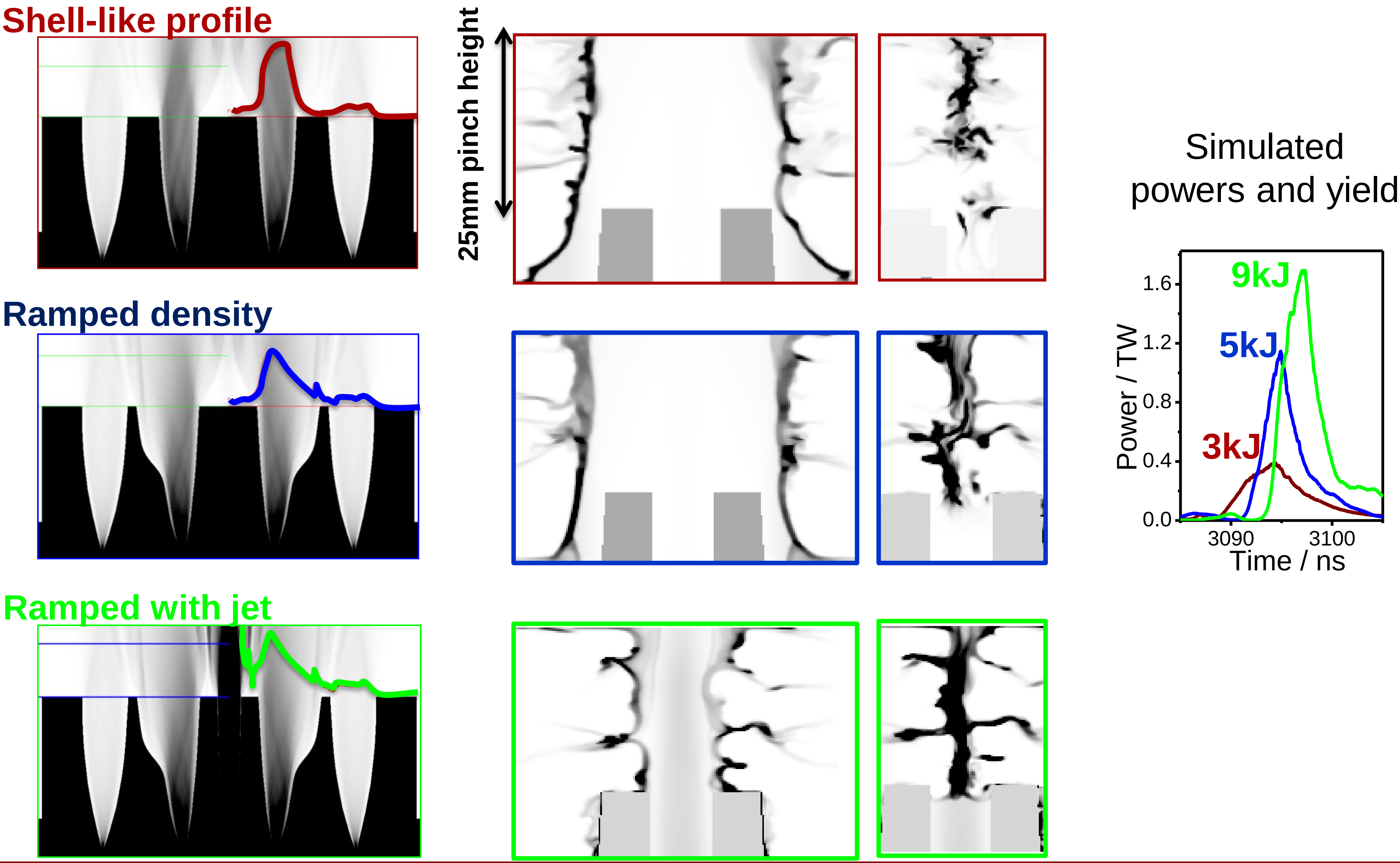
Can use hydrodynamic simulations as a design tool and test with 3-dimensional MHD implosion simulations



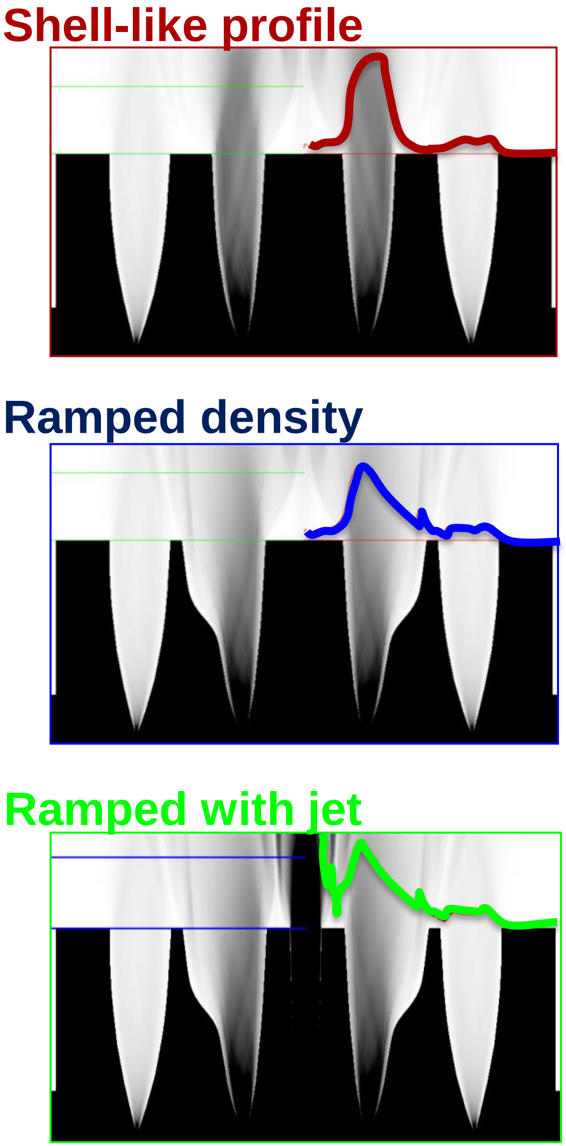
Stagnation is more stable for more ideal initial profiles

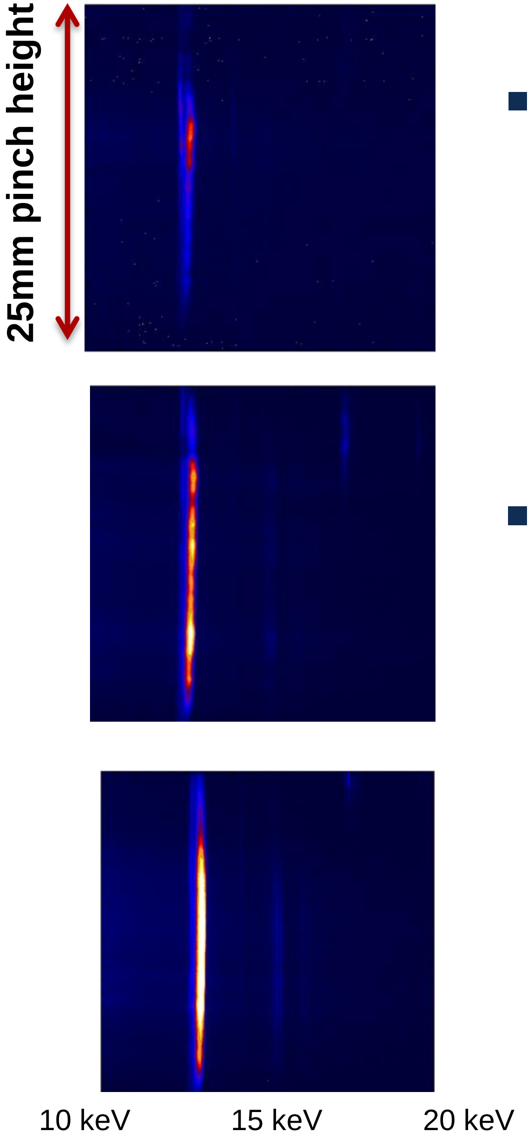
Better stability enables high temperatures in stagnated column

Can use hydrodynamic simulations as a design tool and test with 3-dimensional MHD implosion simulations



In experiments axially resolved spectra show change of structure due to stability



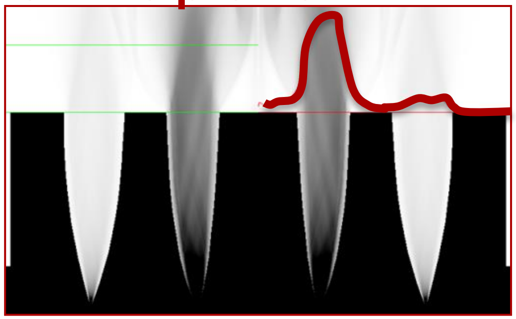


- Axially resolved spectra provide information of axial uniformity of emission
- Uniformity of emission increases considerably with theoretically more stable profiles

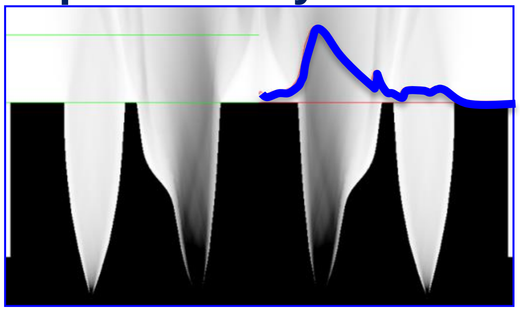
D.J. Ampleford *et al.*, APS DPP 2014, manuscript in preparation

In experiments axially resolved spectra show change of structure due to stability

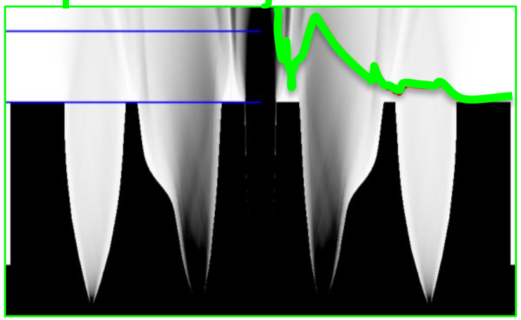
Shell-like profile

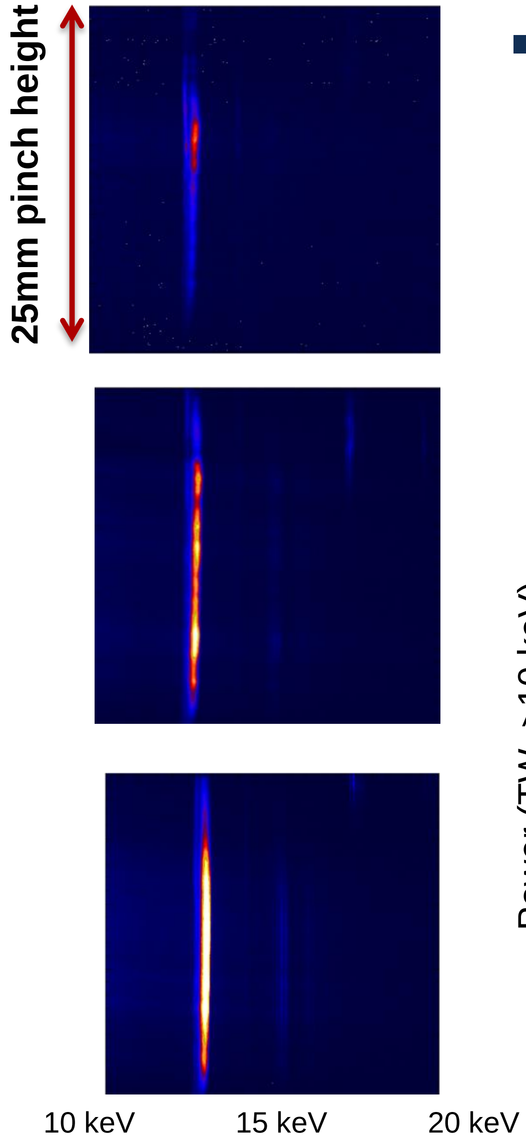


Ramped density



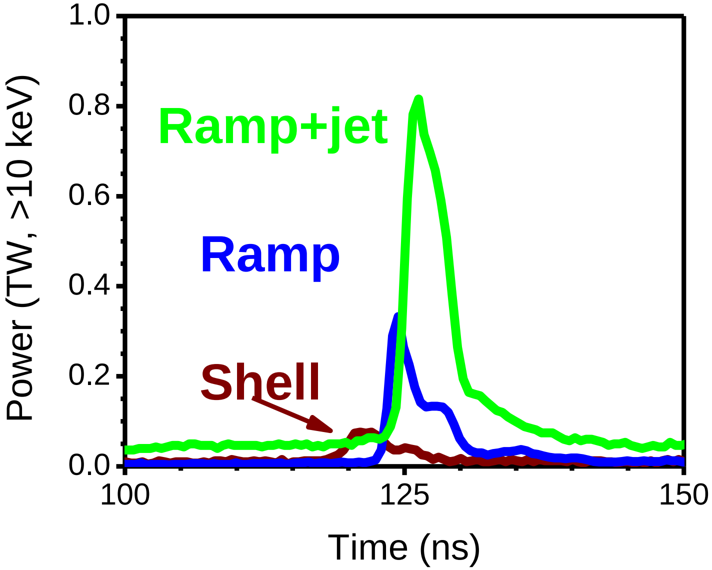
Ramped with jet





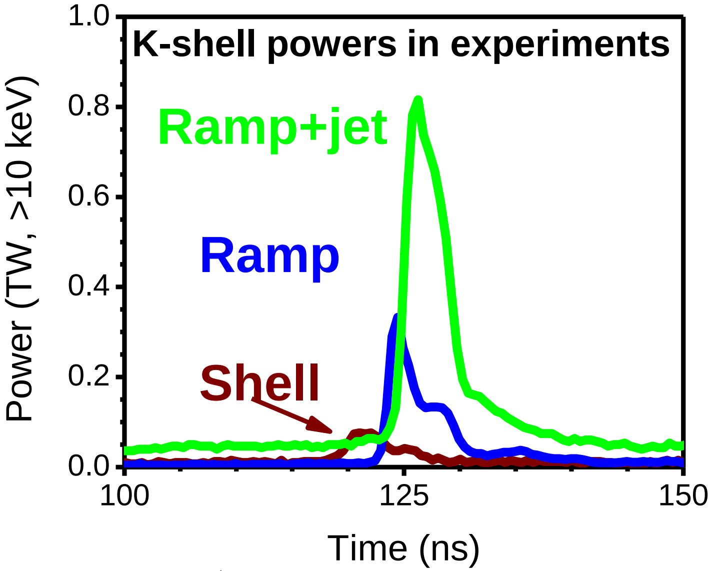
- Power pulses measured in experiments confirm importance of stability on radiated output

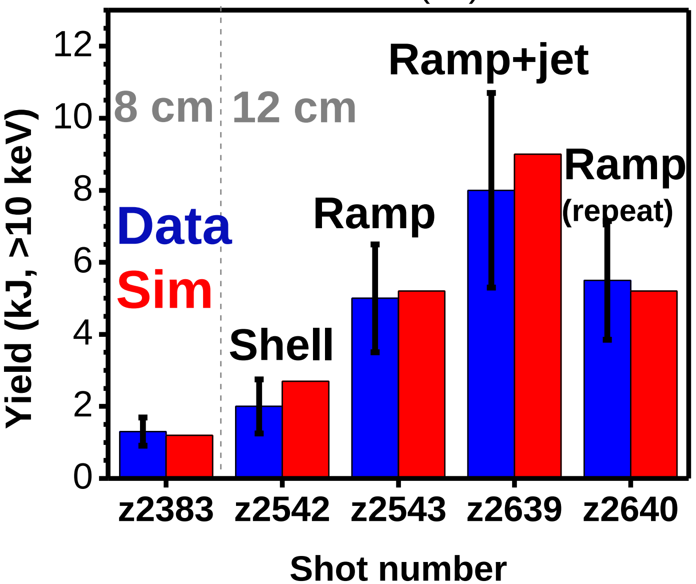
K-shell powers in experiments



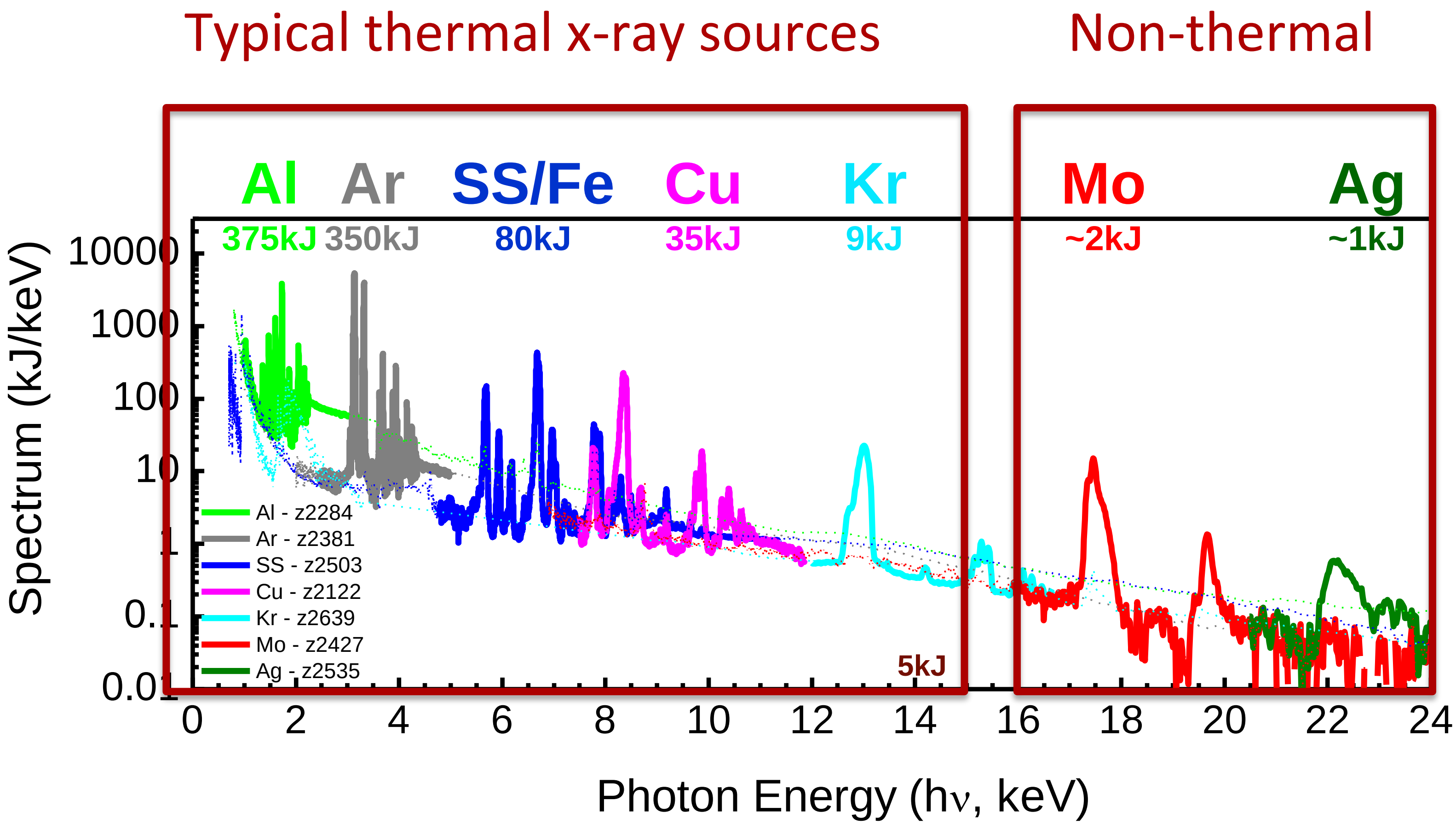
Experiments show that, with correct initial conditions can produce, 8 kJ of 13-keV Kr K-shell emission

- High velocity implosion that is stable is needed
- Output is very sensitive to initial gas profile
- Simulations correctly predict trends



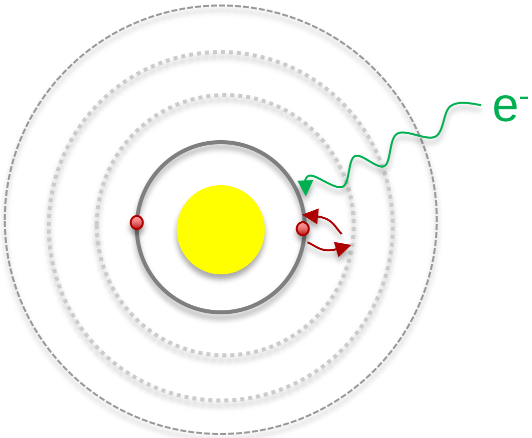


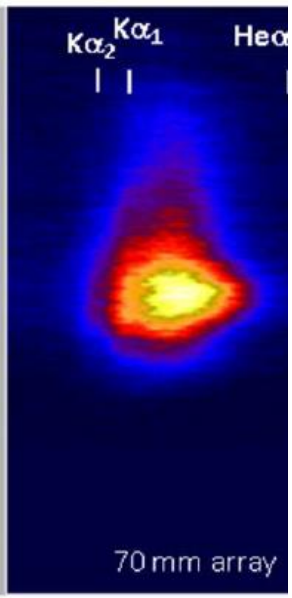
To go to higher photon energies not practical to keep increasing implosion velocities; recent experiments investigated non-thermal emission processes



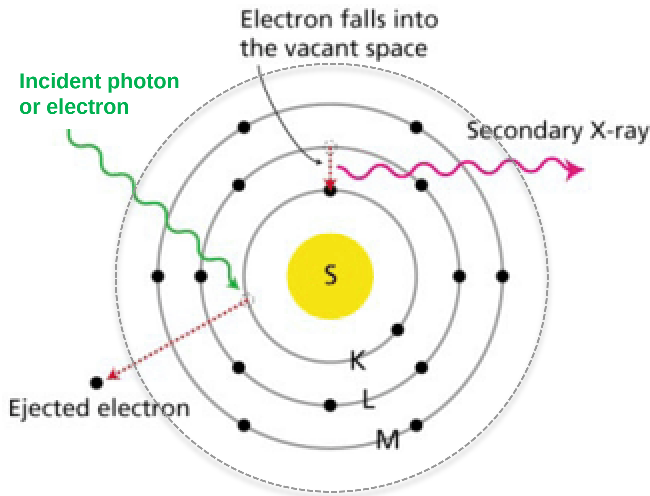
For higher photon energies non-thermal inner shell ionization becomes a more effective emission mechanism

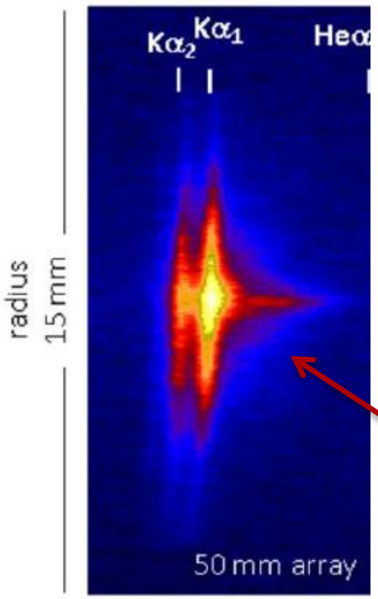
- Thermal K-shell
  - He-like and H-like lines
  - Need to ionize to the K-shell





- Non-thermal K-shell
  - Cold K-lines
  - Need hot electrons/photons
  - Don't need to ionize bulk plasma

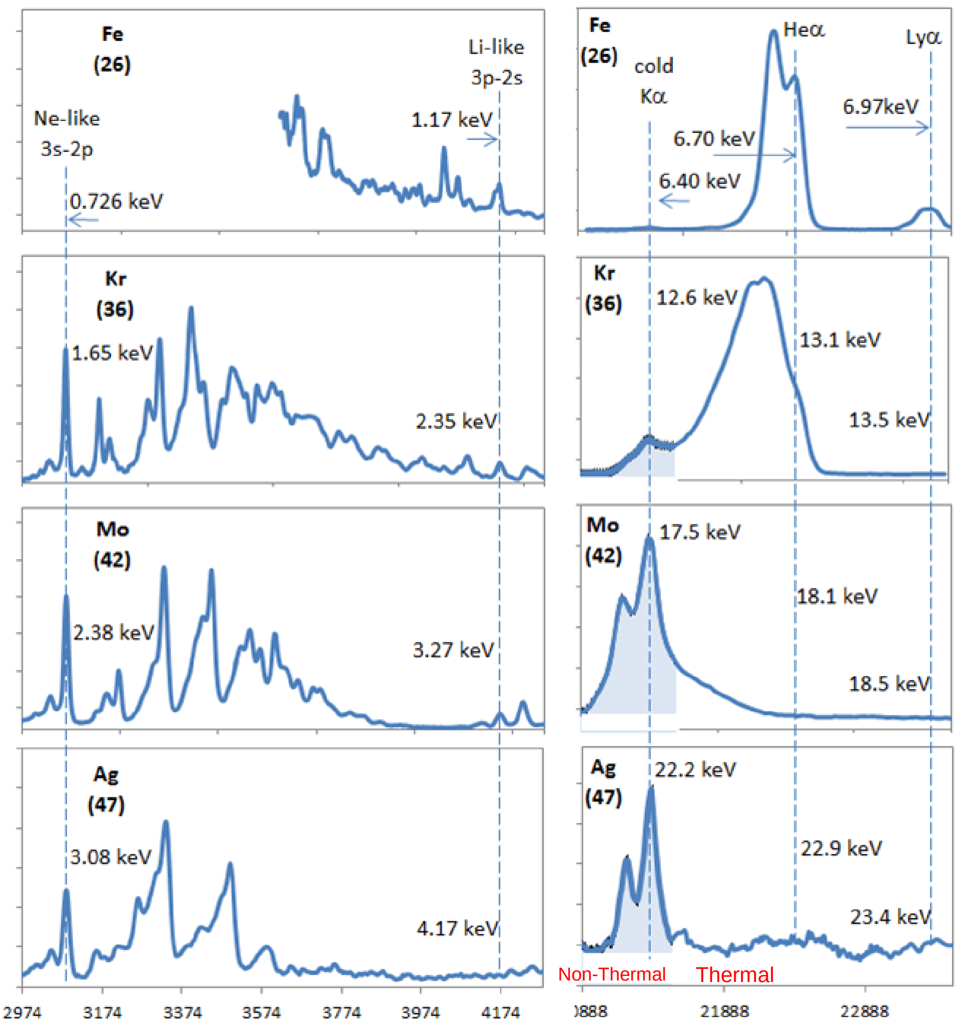




High resolution spectroscopy resolves different in wavelength of Heα and cold Kα lines

S.B. Hansen, D.J. Ampleford *et al.*, Physics of Plasmas 21 031202 (2014)
D.J. Ampleford, S.B. Hansen *et al.*, Sandia Report SAND2015-10453 (2015)

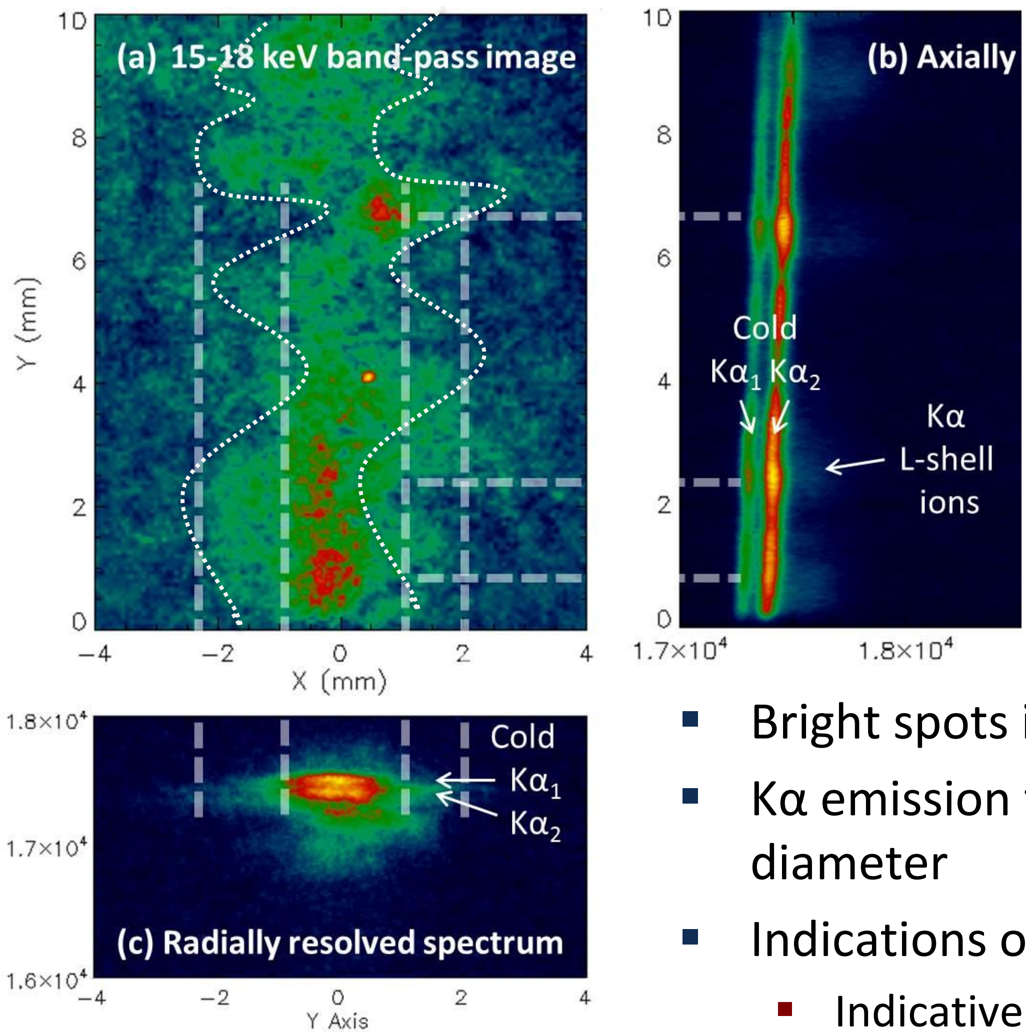
Spectra from Z experiments using different materials shows transition from thermal to non-thermal emission

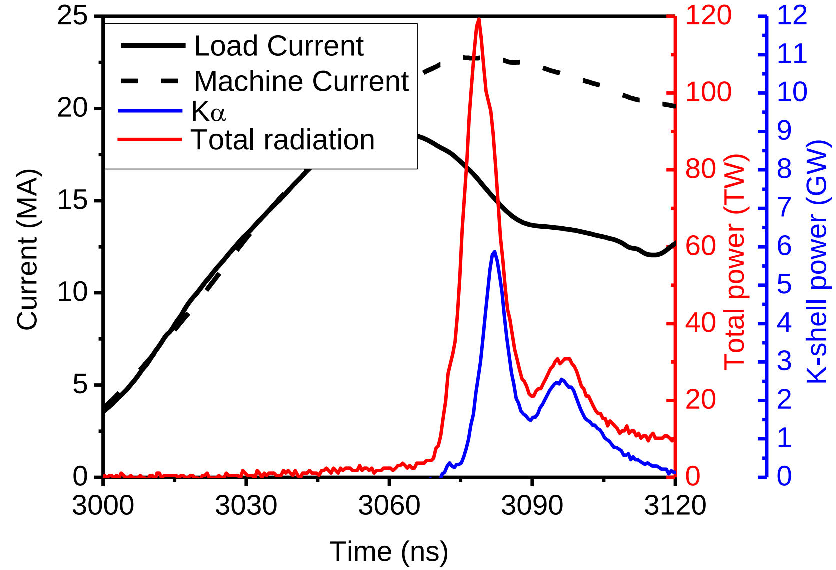


- As atomic number increases see transition from thermal K-shell (Heα) to non-thermal K-shell (cold Kα)
  - Fe almost entirely Heα
  - Ag entirely cold Kα

D.J. Ampleford, S.B. Hansen *et al.*, Sandia Report SAND2015-10453 (2015)
Manuscript in preparation

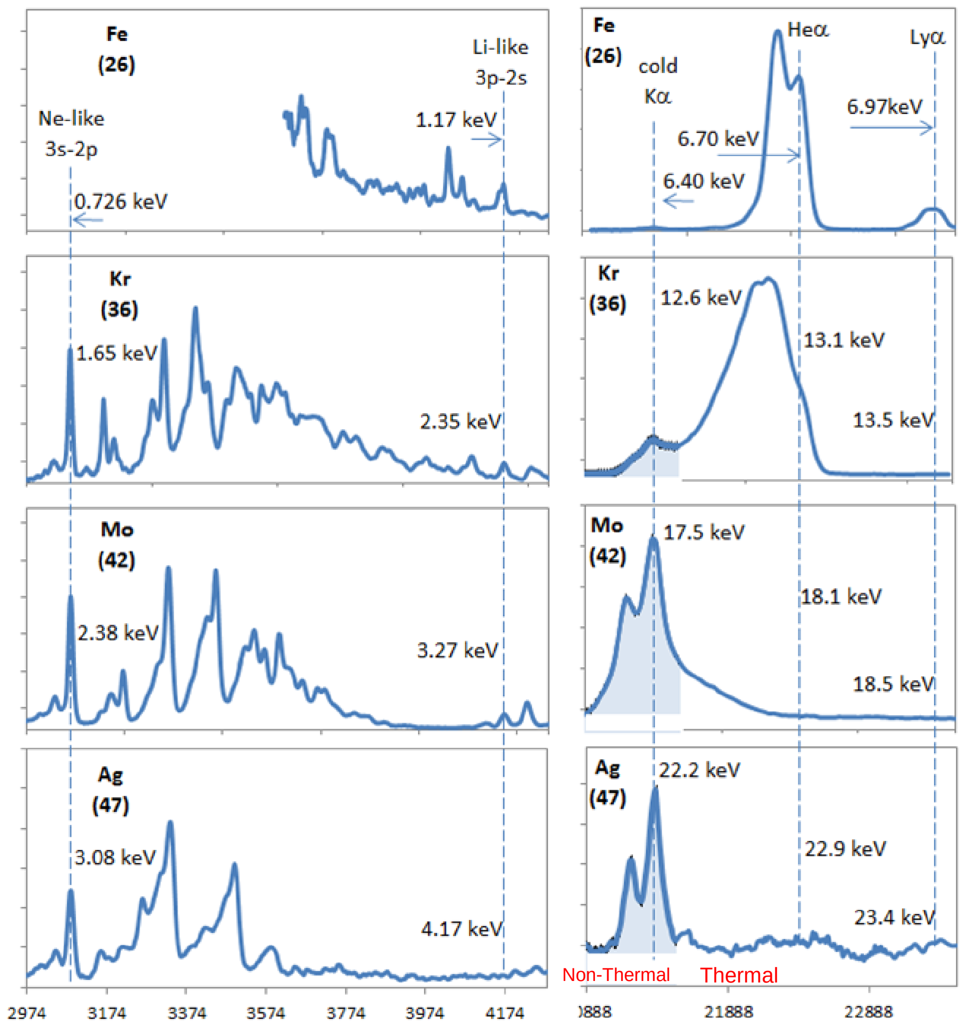
Using imaging and spectroscopy of Kα line from a Mo wire array indicates Kα linked to pinch disruption

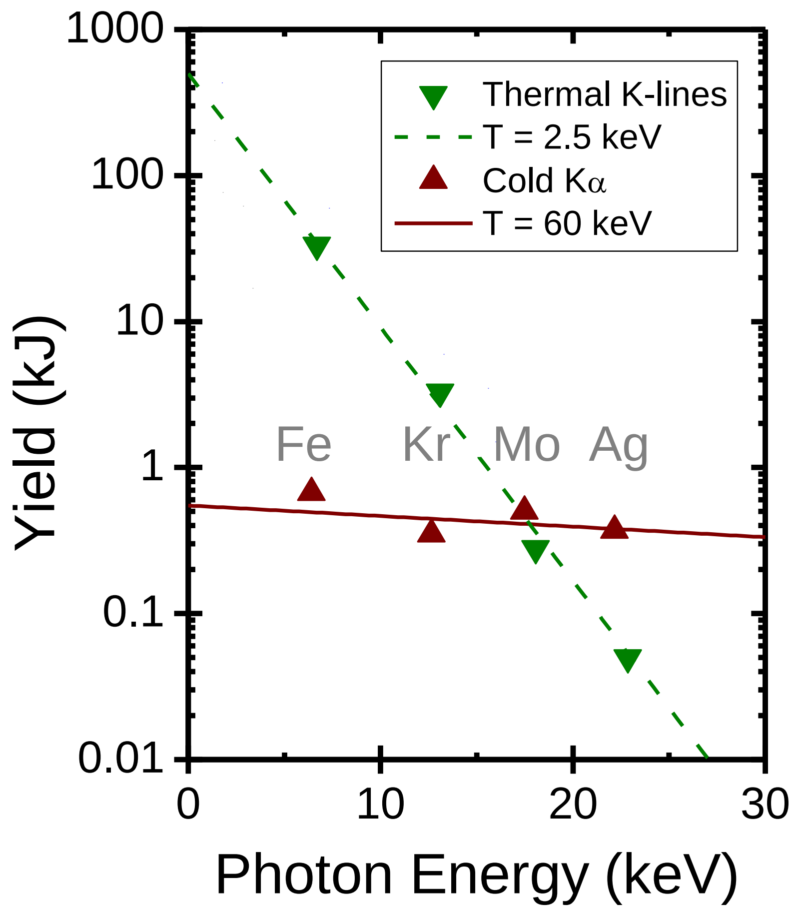




- Bright spots in 2D image and spectrum
- Kα emission from most of pinch height and few mm diameter
- Indications of quasi-helical structure
  - Indicative of pinch breakup
  - Consistent with late time emission of Kα

Spectra from Z experiments using different materials shows transition from thermal to non-thermal emission





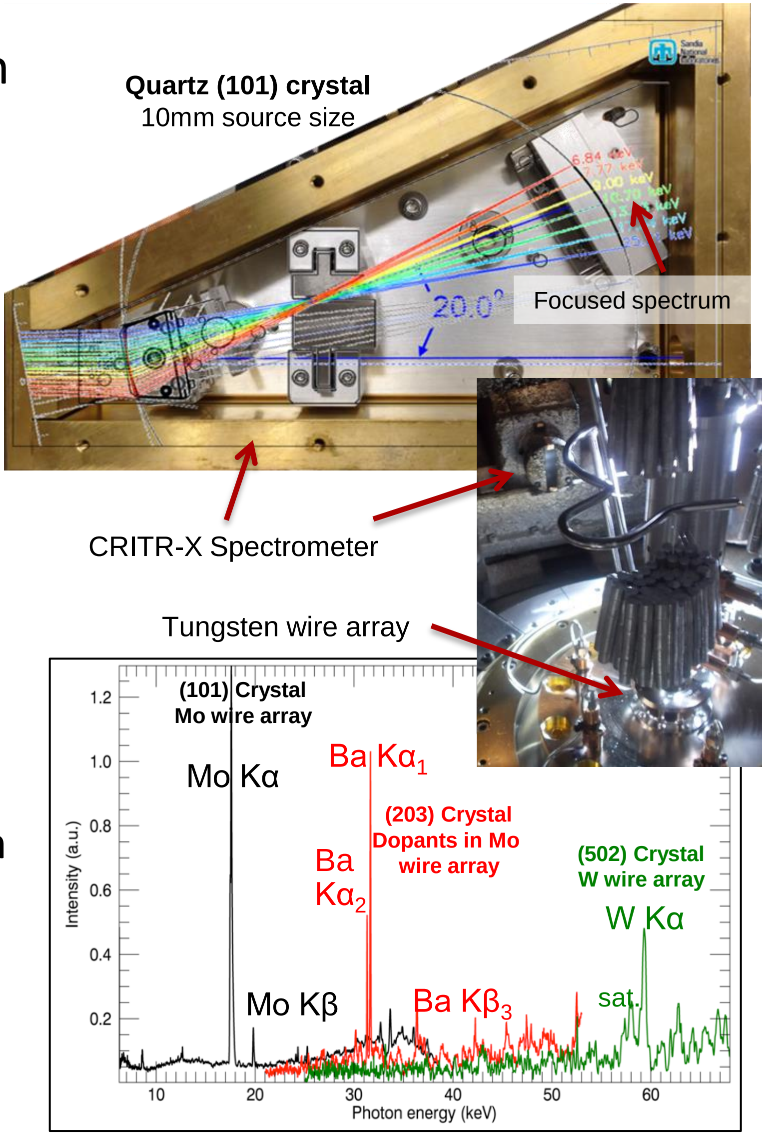
Scaling to higher photon energies much better with cold Kα

A new spectrometer provides first absolute spectral measurements on Z at 7-80 keV for Radiation Science

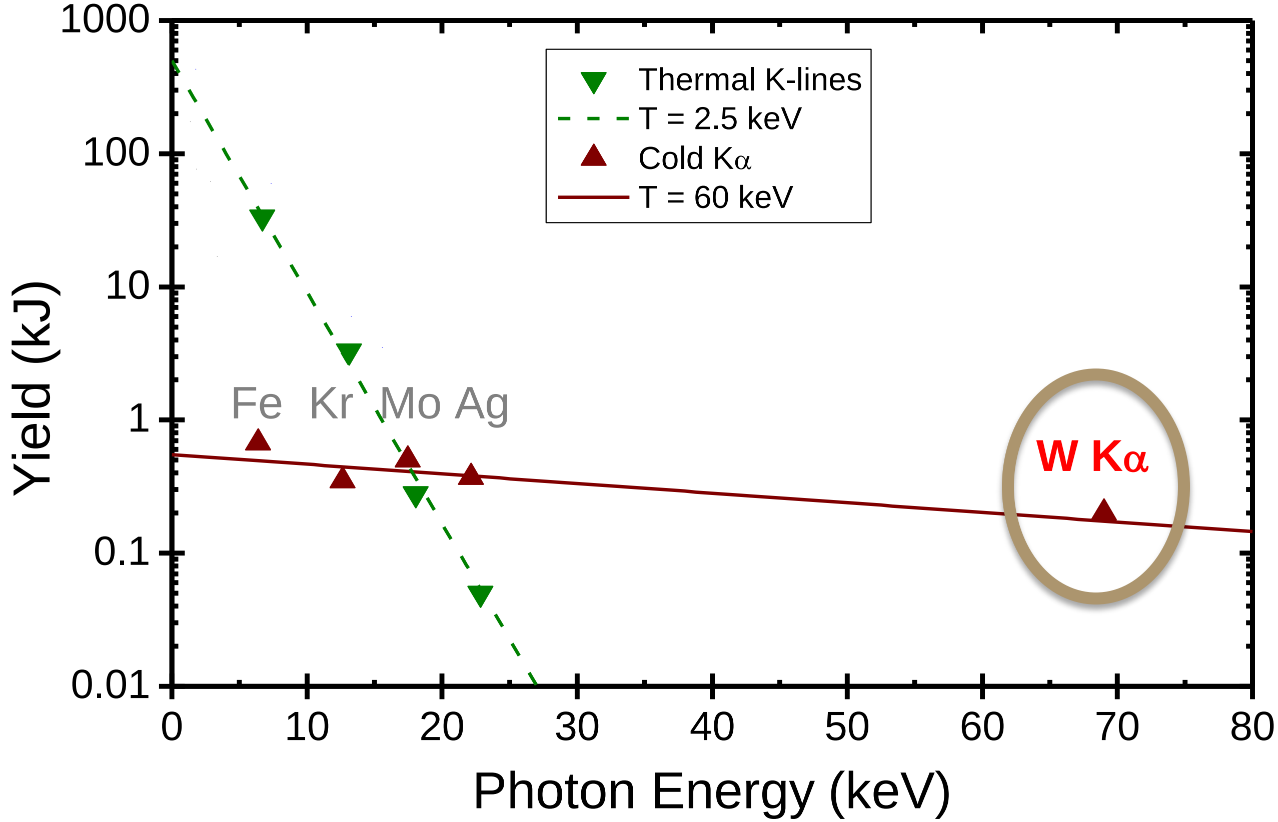
- New spectrometer (CRITR-X) developed based on existing housing
  - Improved signal to noise using baffling
  - Crystals sensitivity calibrated at NIST
  - New crystal options provide 7-80 keV coverage

Quartz cut (Miller indices)	2d lattice spacing (Å)	Spectral range (keV)
(101)	6.68	7-26
(203)	2.75	16-51
(502)	1.62	28-80

- On recent Z shots (z2891 & z2893) we obtained data with each of the three new crystal cuts.
  - Spectroscopic dopants provided numerous lines in the spectral range
  - First data spectrally resolving W Kα in a z pinch
  - First calibrated data of line emission at >10 keV



Recent experiments have demonstrated ability to generate 69 keV W emission

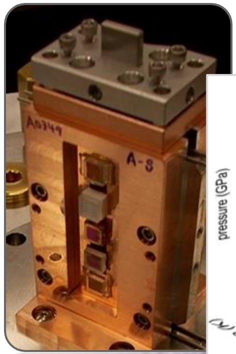


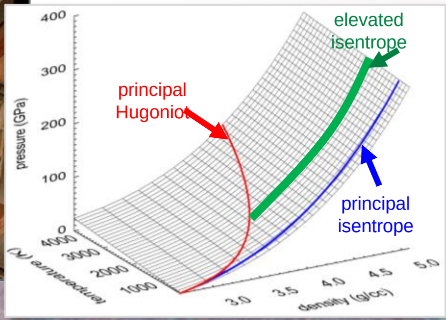
- Scaling to W cold Kα at 69 keV consistent with lower energies
- First demonstration of W Kα emission from a z pinch

Z produces extreme conditions in numerous ways

Dynamic Materials

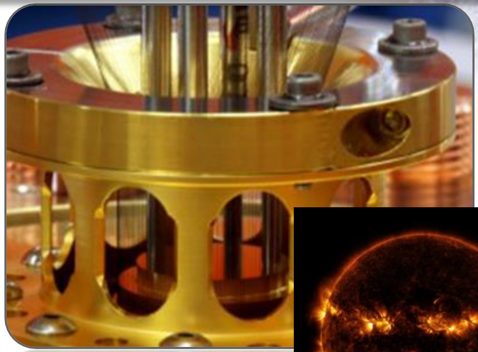
Compress materials to 10^7 Atm.





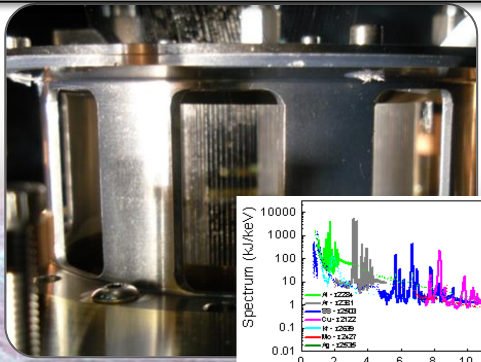
Stellar Opacities

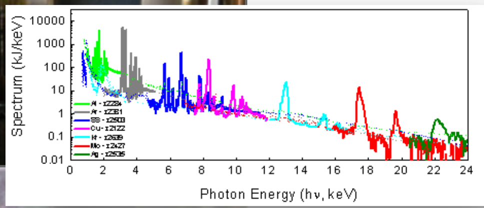
Temperature/density of convection zone



K-shell x-ray sources

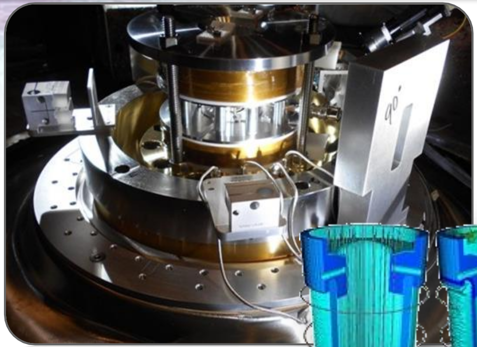
100's of kJ of multi-keV photons

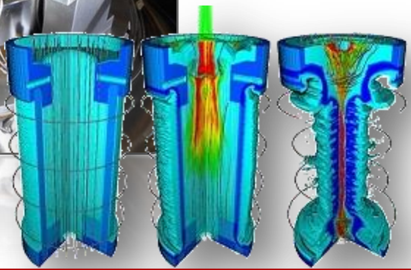




MagLIF Fusion Plasmas

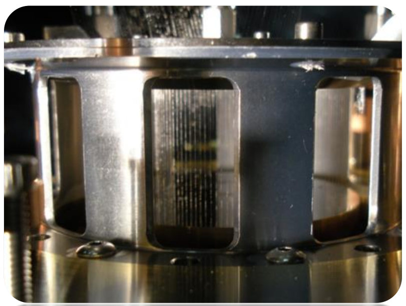
Fusion yields $>10^{12}$ neutrons



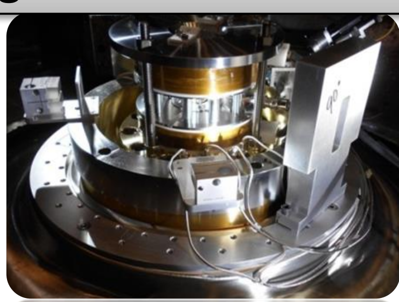


The diagnostics used to study these experiments are similar

K-shell x-ray sources

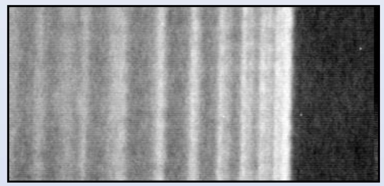


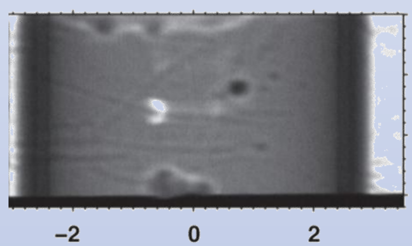
MagLIF Fusion Plasmas



Radiography

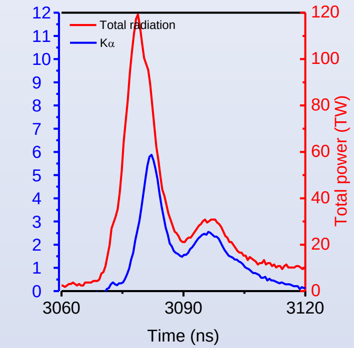
Monochromatic two-frame using ZBL laser

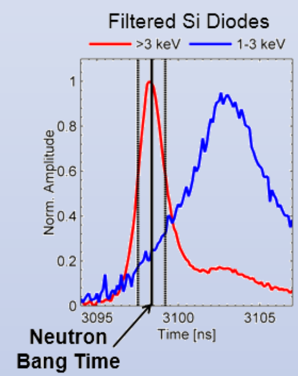




X-ray time history

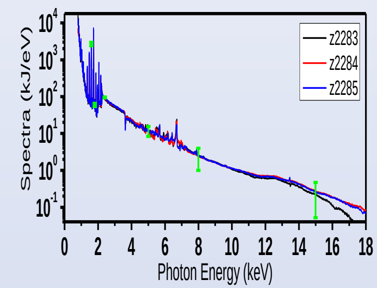
PCDs, SiDs, XRDs

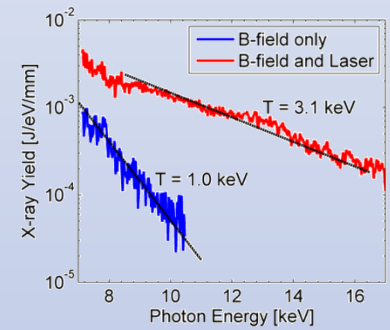




Spectroscopy

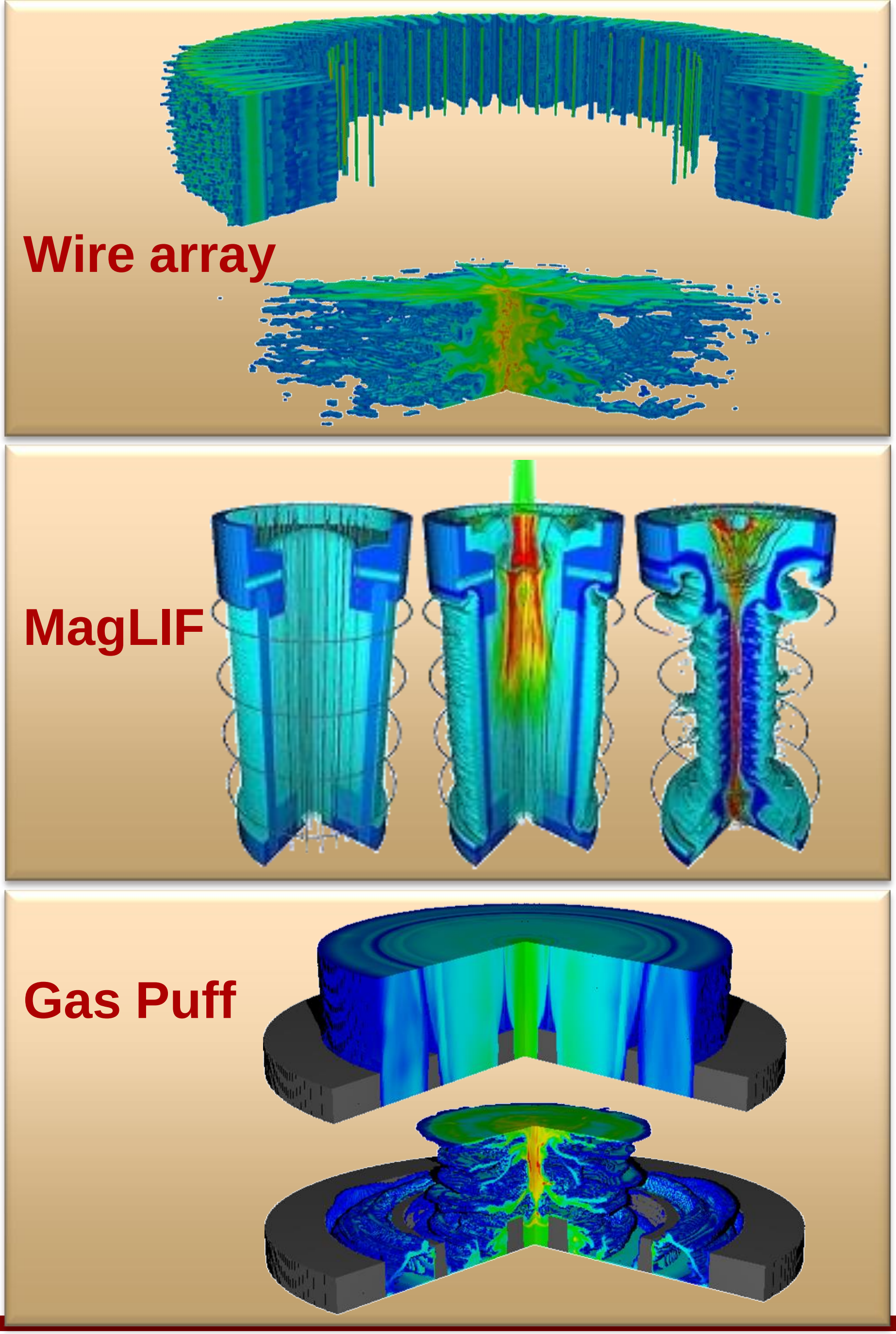
Spatially resolved, various energies





The same codes are used to model radiation producing wire arrays and gas puffs as well as MagLIF plasmas

- Using same MHD codes used to model various magnetically driven implosions provides confidence in
  - Plasma dynamics models
  - Atomic physics models
  - Circuit model
- Gorgon 3D MHD simulations shown of all three systems

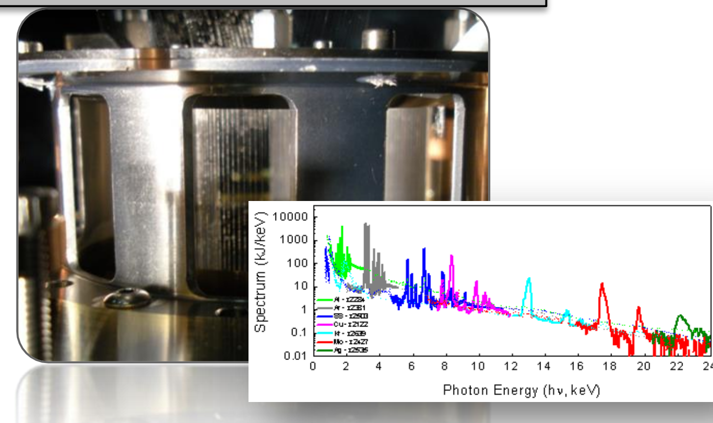


Summary: MagLIF and wire arrays very different, very similar

- Significant overlap and contrast between multi-keV x-ray source experiments and MagLIF
  - Diagnostics similar
  - Same simulation tools used on each
  - Both challenging on the generator
- K-shell sources and MagLIF have made significant progress in last 4 years
  - K-shell sources
    - Previously only source for <10 keV,
    - Now 13 keV Kr gas puffs and 17-59 keV non-thermal sources
  - MagLIF
    - Initial experiments very promising
    - Physics and optimization experiments continuing

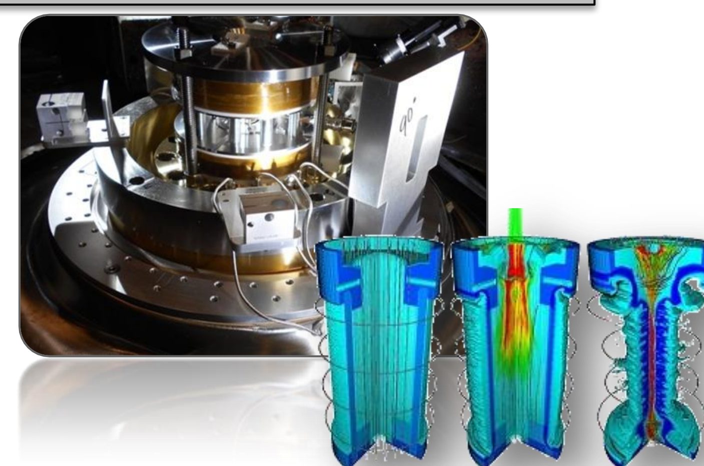
K-shell x-ray sources

100's of kJ of multi-keV photons



MagLIF Fusion Plasmas

Fusion yields >10^{12} neutrons



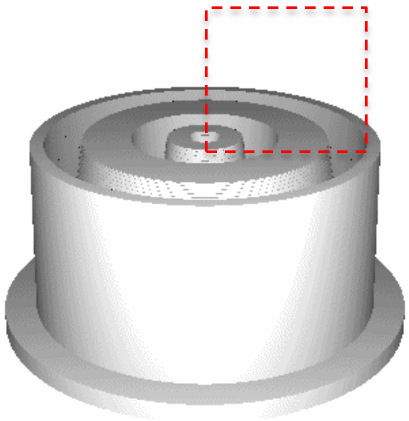
Backup

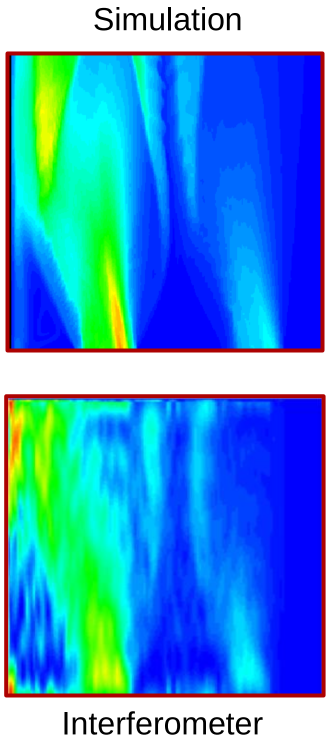
Despite huge difference in scales, K-shell sources and MagLIF have similar implosion kinetic energies but produce similar pressures

		MagLIF	K-shell
Velocity	cm/us	6	100
Atomic Number	Z (low)	1	13
	Z (high)	4	74
Mass	mg/mm	10	0.01
Number density	per cc	1.18E+23	2.00E+20
Stagnation Density	g/cm3	0.4	0.0196
Stagnation Temp	eV	3000	6000
Kinetic Energy	Joues/cm	180	100
Stag Pressure (ZNkT)	Bar	1.13E+09	4.80E+07
	GBar	1.13E+03	4.80E+01
Temperature	(K)	3E+07	6E+07

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

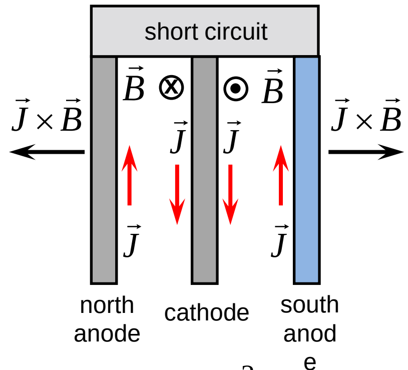
- Many tools have been developed to provide customizable gas profiles
  - Interferometry of profiles
  - Hydrodynamic simulations
  - Rapid-prototyping of nozzle parts
- Combined capabilities allows
  - Control of density distribution
    - Test implosion stability
  - Eliminate need for cathode grid
    - Better azimuthal symmetry
  - Self-consistent initiation of MHD

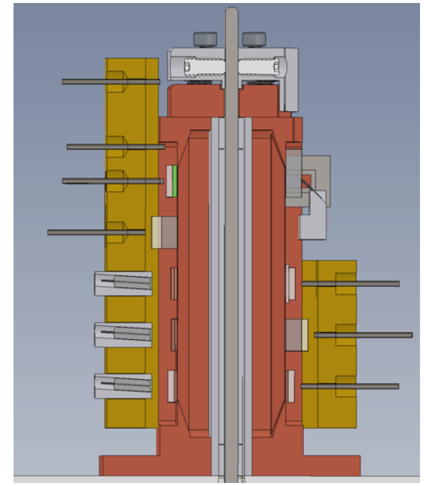


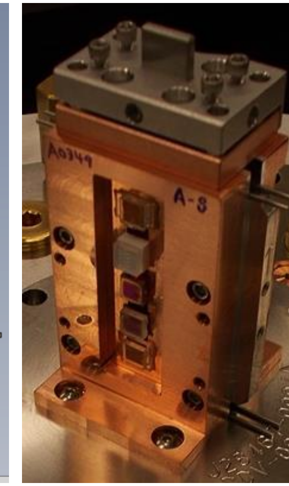


Z-DMP planar experiments

- Coaxial load
  - Cathode stalk surrounded by anode panels
  - Dual pressures possible on north and south panels
  - Enclosed magnetic fields
  - More sample locations
  - Optimal for (flyer plate) shock compression

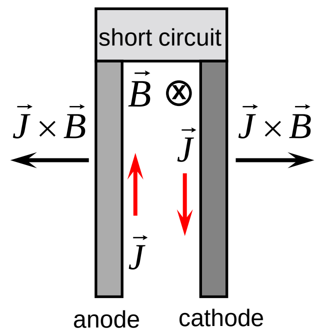


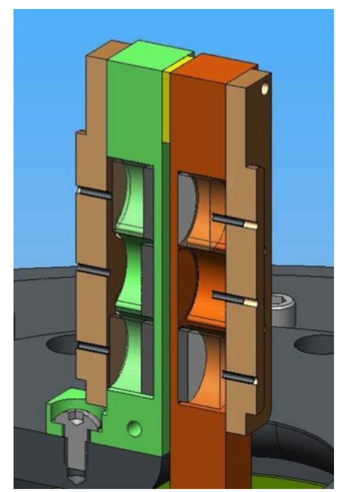




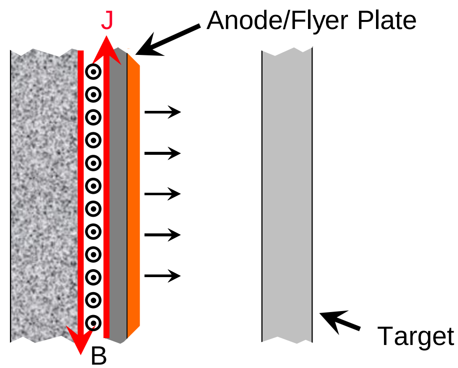
$$P = \frac{B^2}{2\mu_0}$$

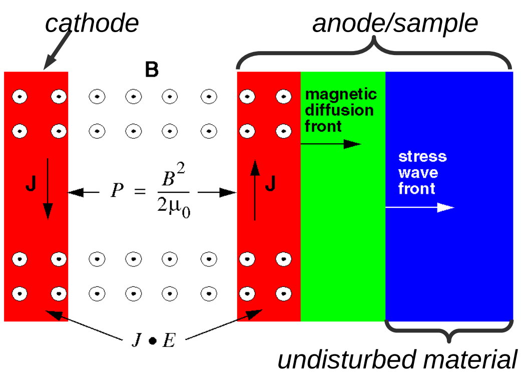
- Stripline load
  - Identical pressure on both cathode and anode panels
  - Higher current density and pressure
  - Open magnetic fields
  - Optimal for high-pressure ramp compression

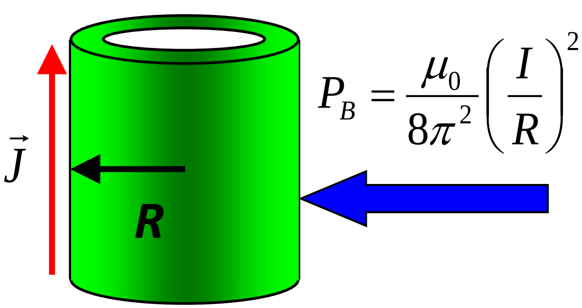




Dynamic Material Properties (DMP) experiments on Z enable unique equation-of-state studies





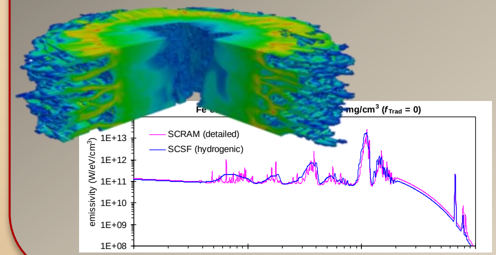


- Shock compression
  - Flyer impact velocities to ~40 km/s
  - Hugoniot states to ~10 Mbar; T ~10,000–50,000 K
- Ramp (quasi-isentropic) compression
  - Continuous compression to ~5 Mbar
  - Lower strain rates ~10^6–10^7 /s; T ~1000–5000 K
- Shock-ramp compression
  - Complex loading path access off-Hugoniot states
  - Shock melt and ramp refreeze
- Cylindrical compression
  - Extreme pressure states: ramp to ~20 Mbar
- Containment experiments
  - Restricted diagnostic access to load

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

Pre-shot design

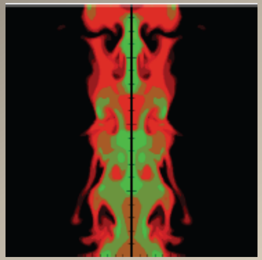
3D Gorgon MHD coupled to tabulated non-LTE emissivities



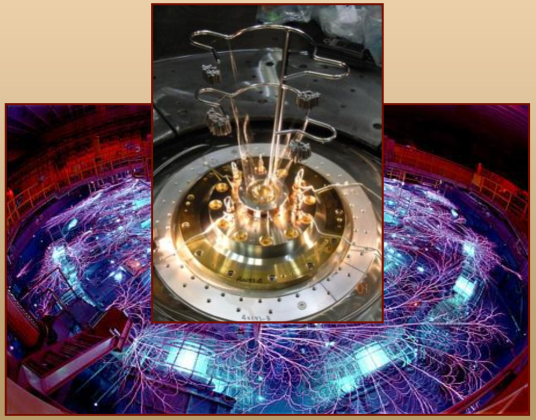
Energy balance arguments

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

2D rad-MHD
Mach2 with DDTCRE



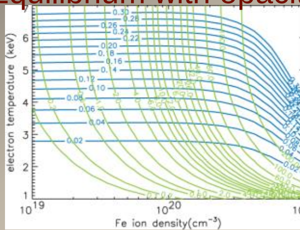
Experiment



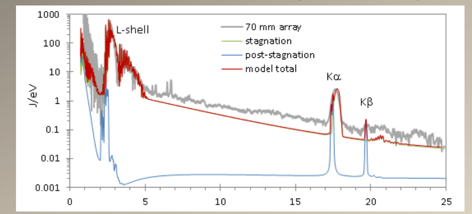
Feedback into design models

Analysis

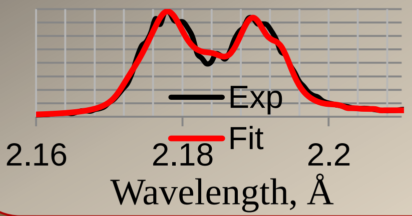
Static Collisional Radiative Equilibrium with opacity



Hybrid structure Collision Radiative model (SCRAM)

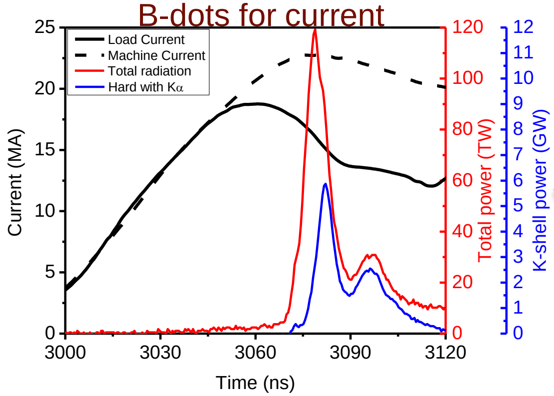


Collisional Radiative modeling of specific features

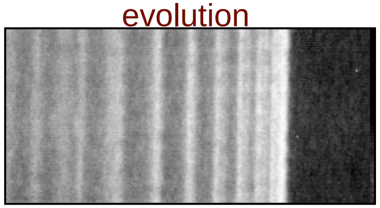


GENERALIZE TO INCLUDE MAGLIF High velocity implosions on Z provide a rich dataset from spectral, imaging and current diagnostics

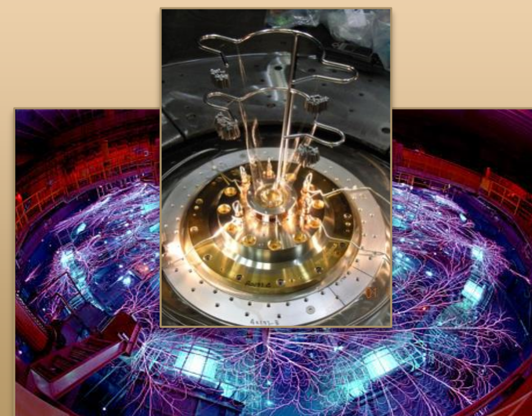
PCDs for K-shell power
XRD/TEP/Bolo for total emission
B-dots for current



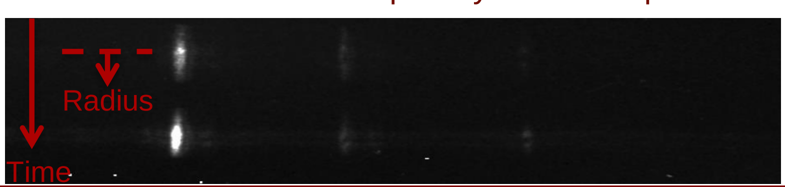
Radiography of early-time evolution



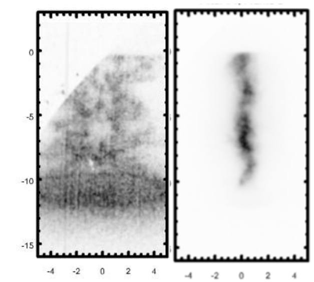
Experiment



Time-resolved 1D-spatially-resolved spectra



Time-resolved imaging of soft and K-shell emission



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