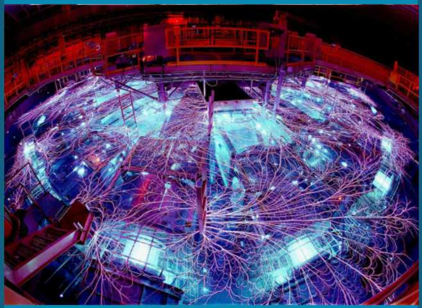
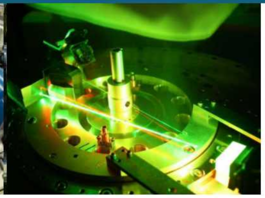
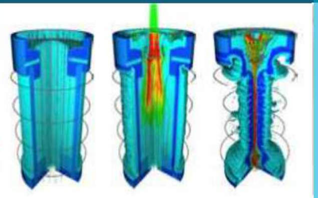
SAND2018-13638PE

Experiments at Sandia's Z Machine and Z Backlighter Laser Facility





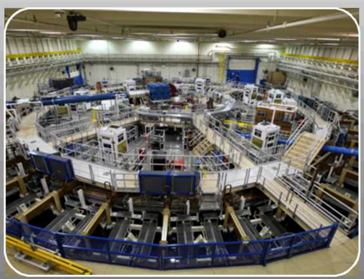


PRESENTED BY

Daniel Woodbury, University of Maryland, SSGF

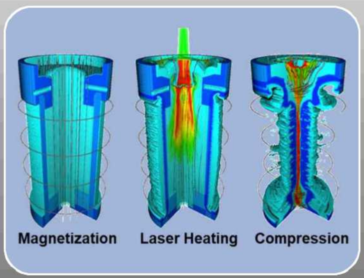
With support from the DOE NNSA SSGF Program, under grant DE-NA0002135.

Outline



Z/ Z Beamlet Pulsed Power Facility

- Overview & Capabilities, Key Research Areas



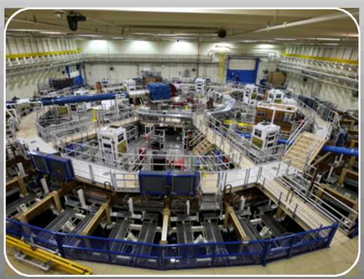
MagLIF Program

- Theoretical and Conceptual Basis, Experimental Progress

Optical Diagnostics on Pecos Test Stand

- Measurements of Laser Heated Fuel, My Contributions

Outline



Z/ Z Beamlet Pulsed Power Facility

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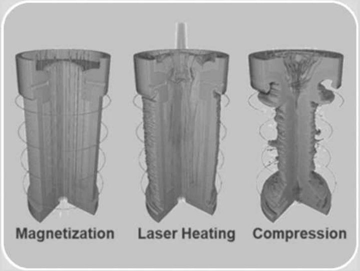

MagLIF Program

- Theoretical and Conceptual Basis, Experimental Progress

Optical Diagnostics on Pecos Test Stand

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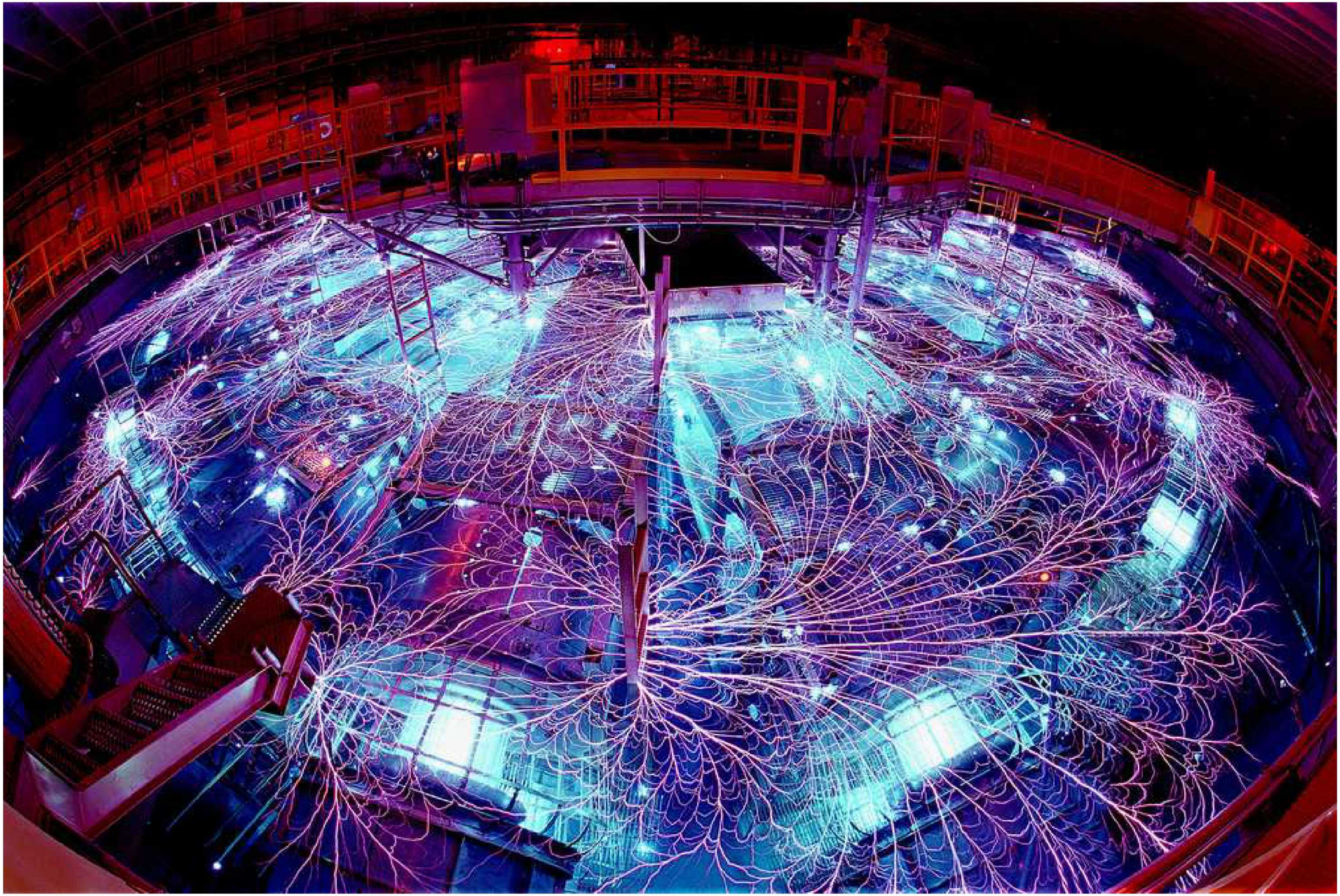
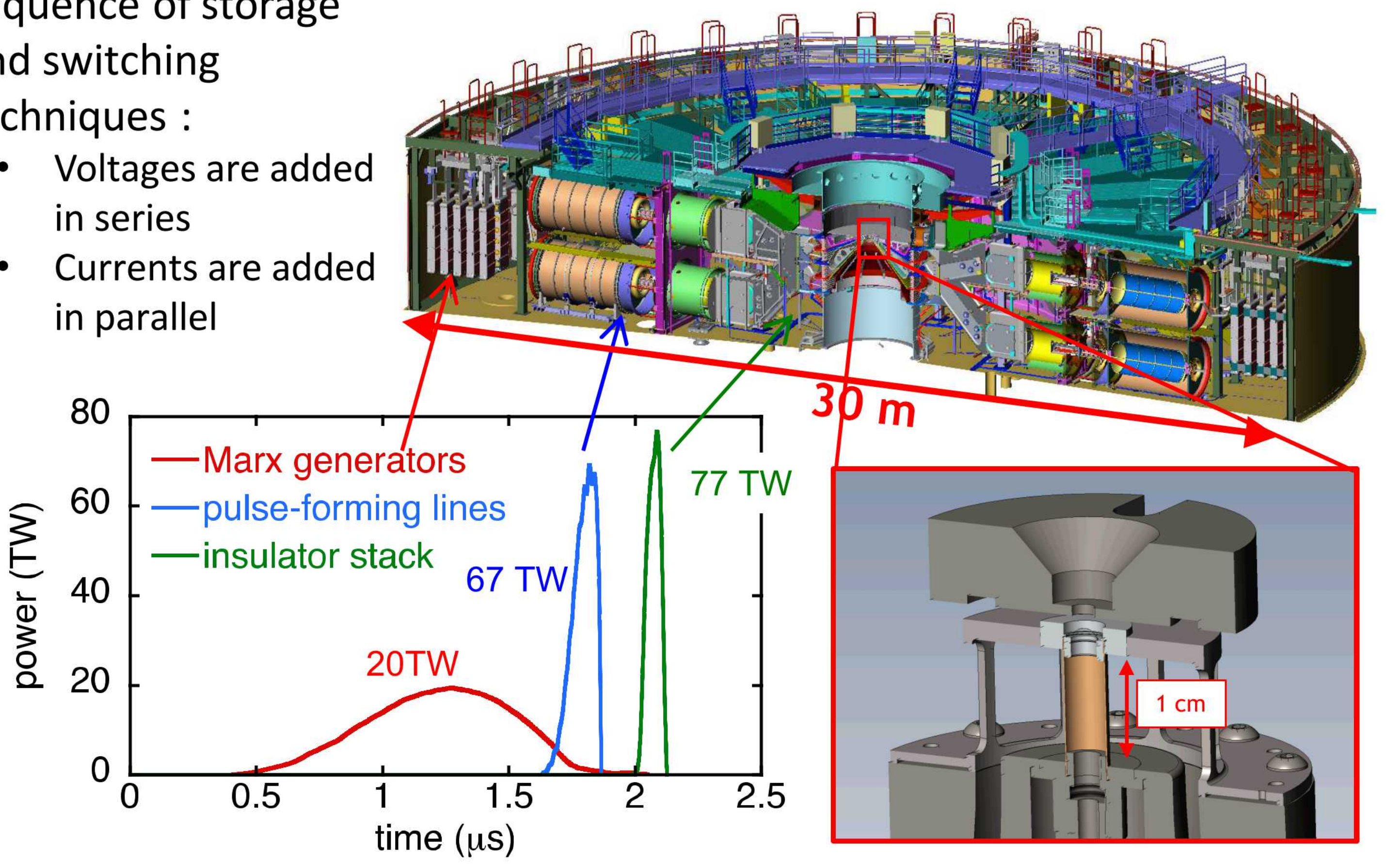
The Z Pulsed Power Facility is the world's largest pulsed power machine



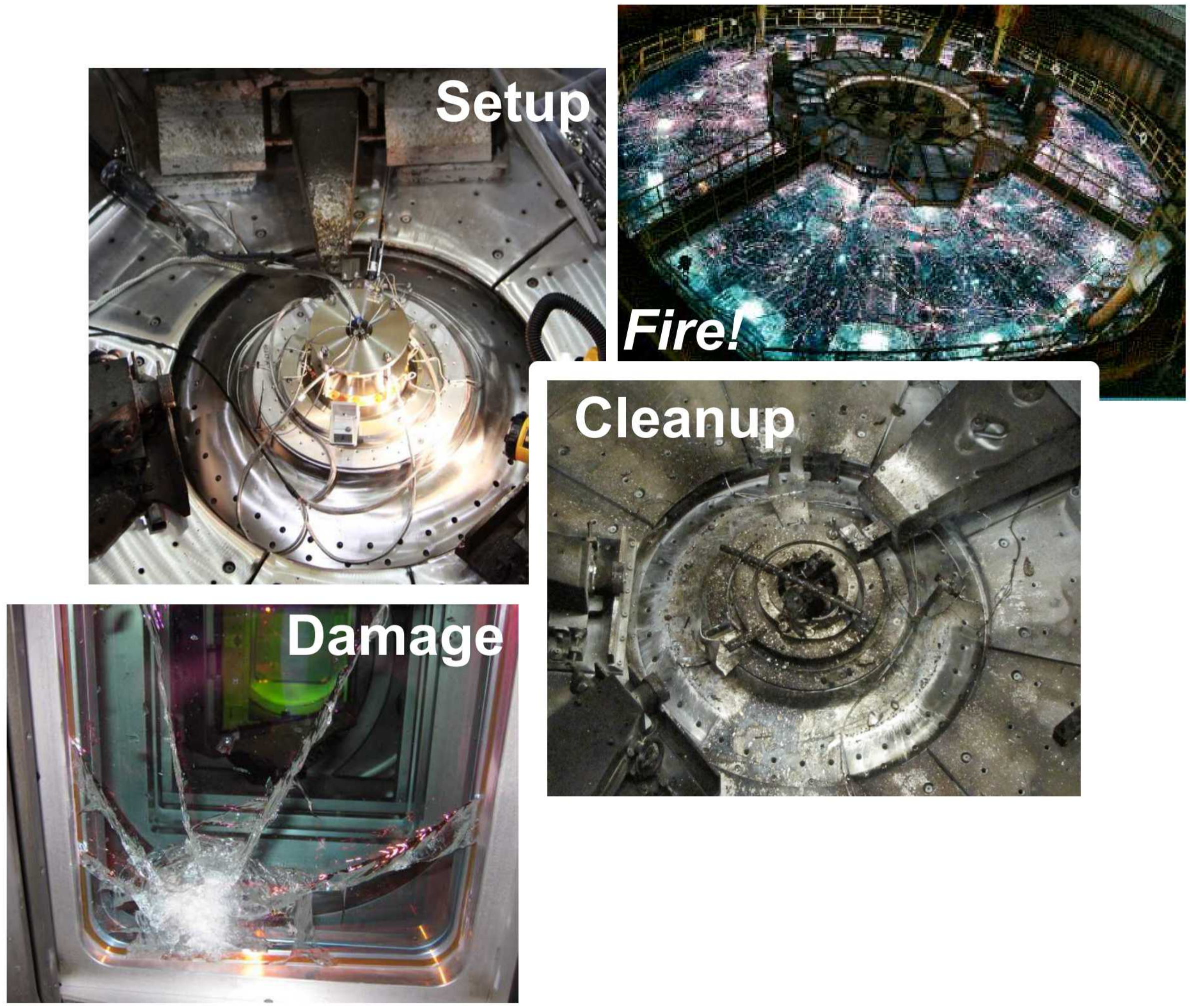
Pulsed-power is all about energy compression in both space and time

- Energy compression achieved by a sequence of storage and switching techniques :
  - Voltages are added in series
  - Currents are added in parallel

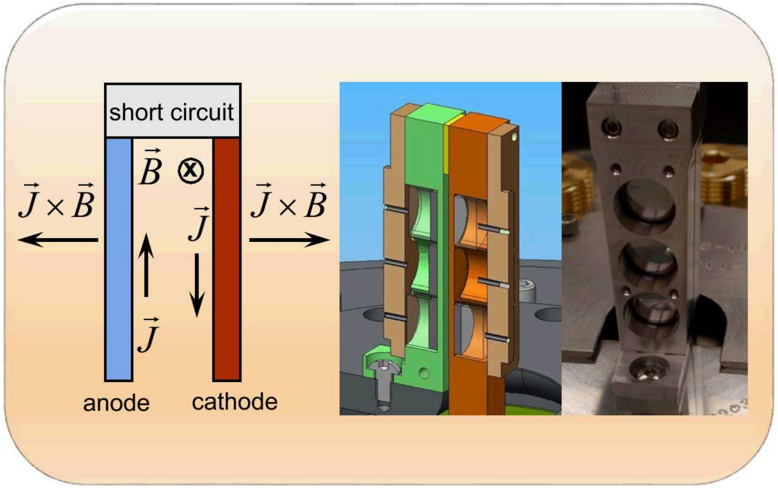


Z can be a challenging place to conduct high impact experiments

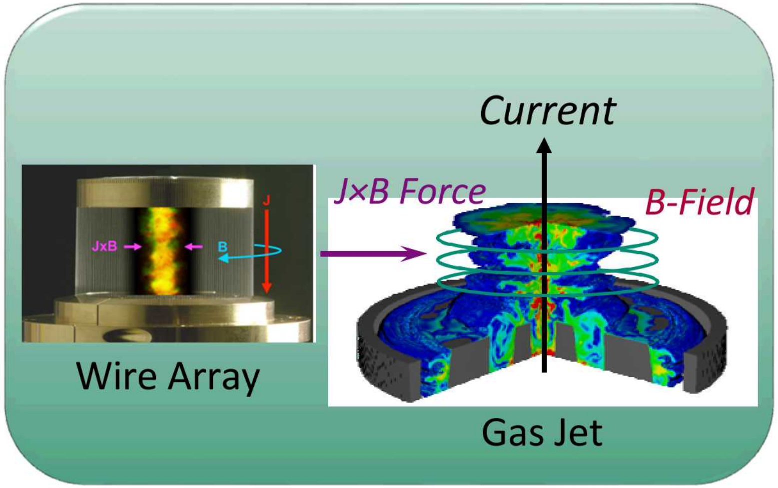
- Shot rate of ~1/day
- ~150 shots/year
- MJ's of magnetic energy to the load
- Equivalent to detonating a few sticks of dynamite
- Harsh debris, shock, and radiation environment make fielding experiments unique and challenging



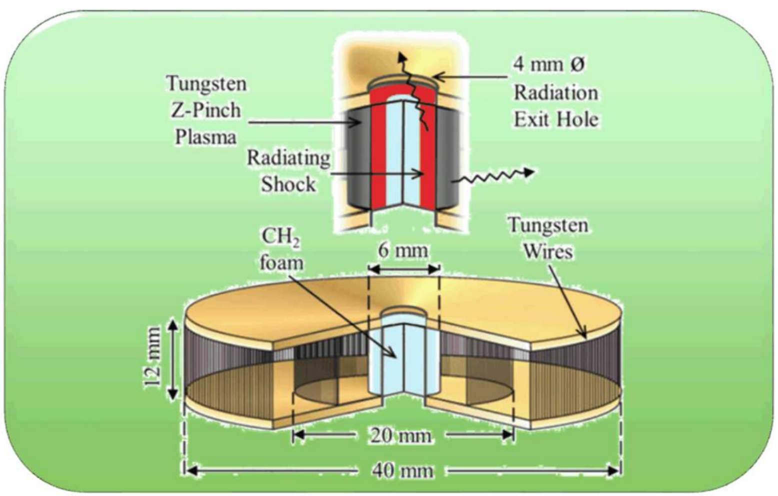
We use Z in several ways to create HED matter for various physics applications



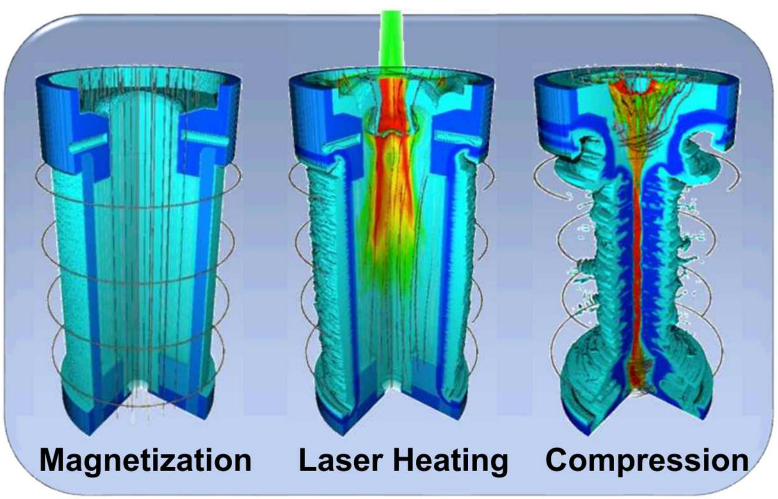
Dynamic Material Properties



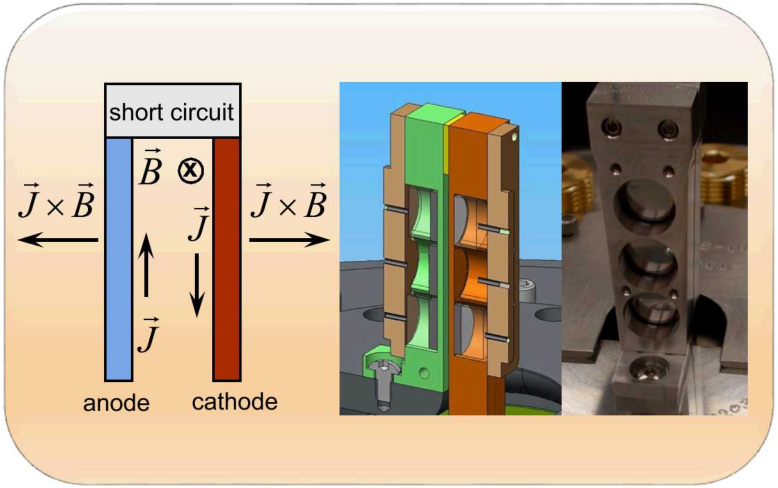
Z-Pinch X-Ray Sources



Astrophysical Plasmas



Inertial Confinement Fusion



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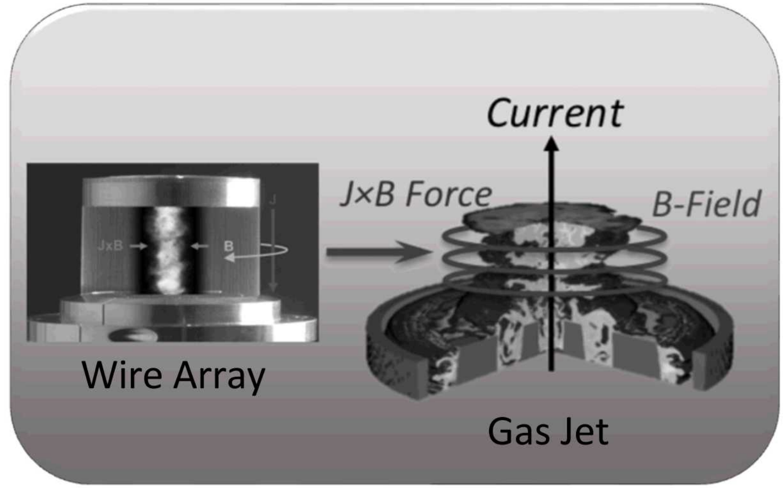

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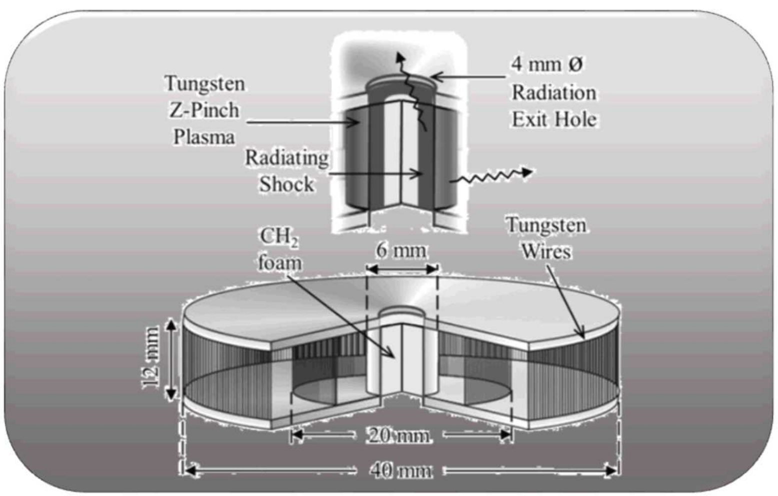

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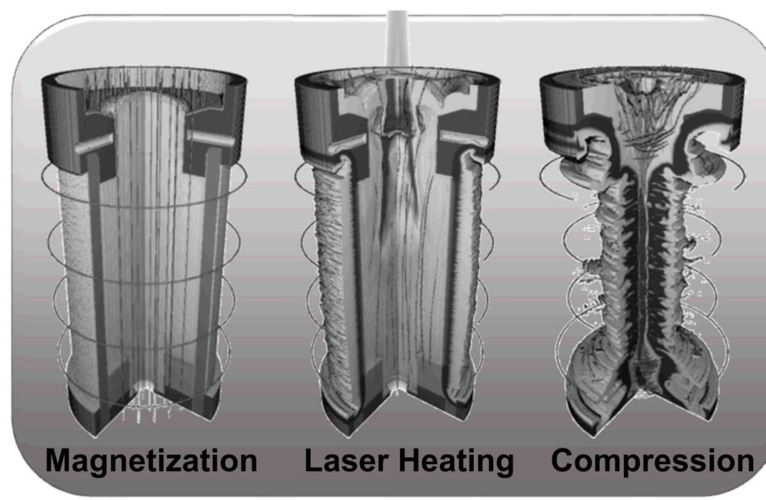
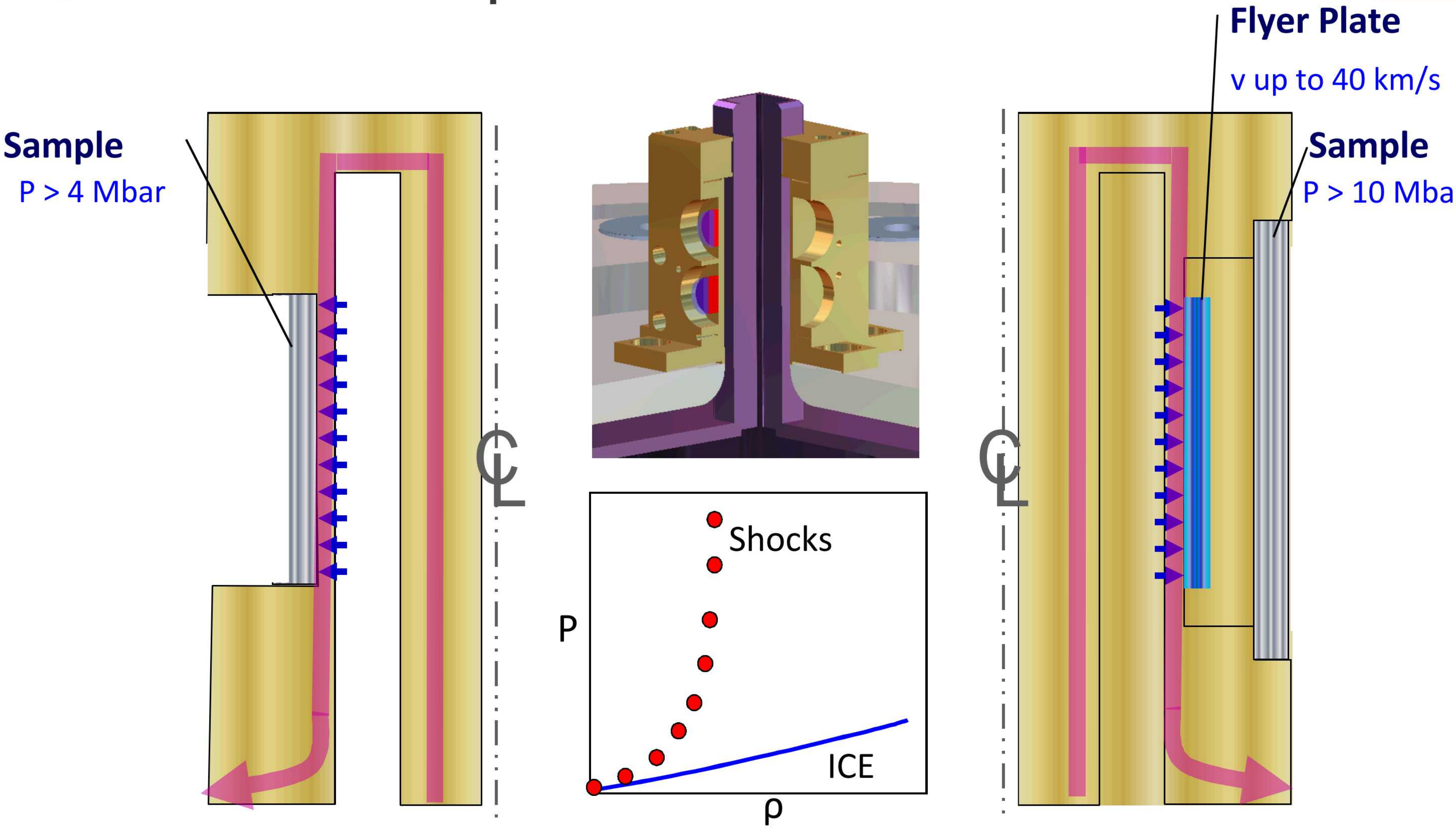


Inertial Confinement Fusion

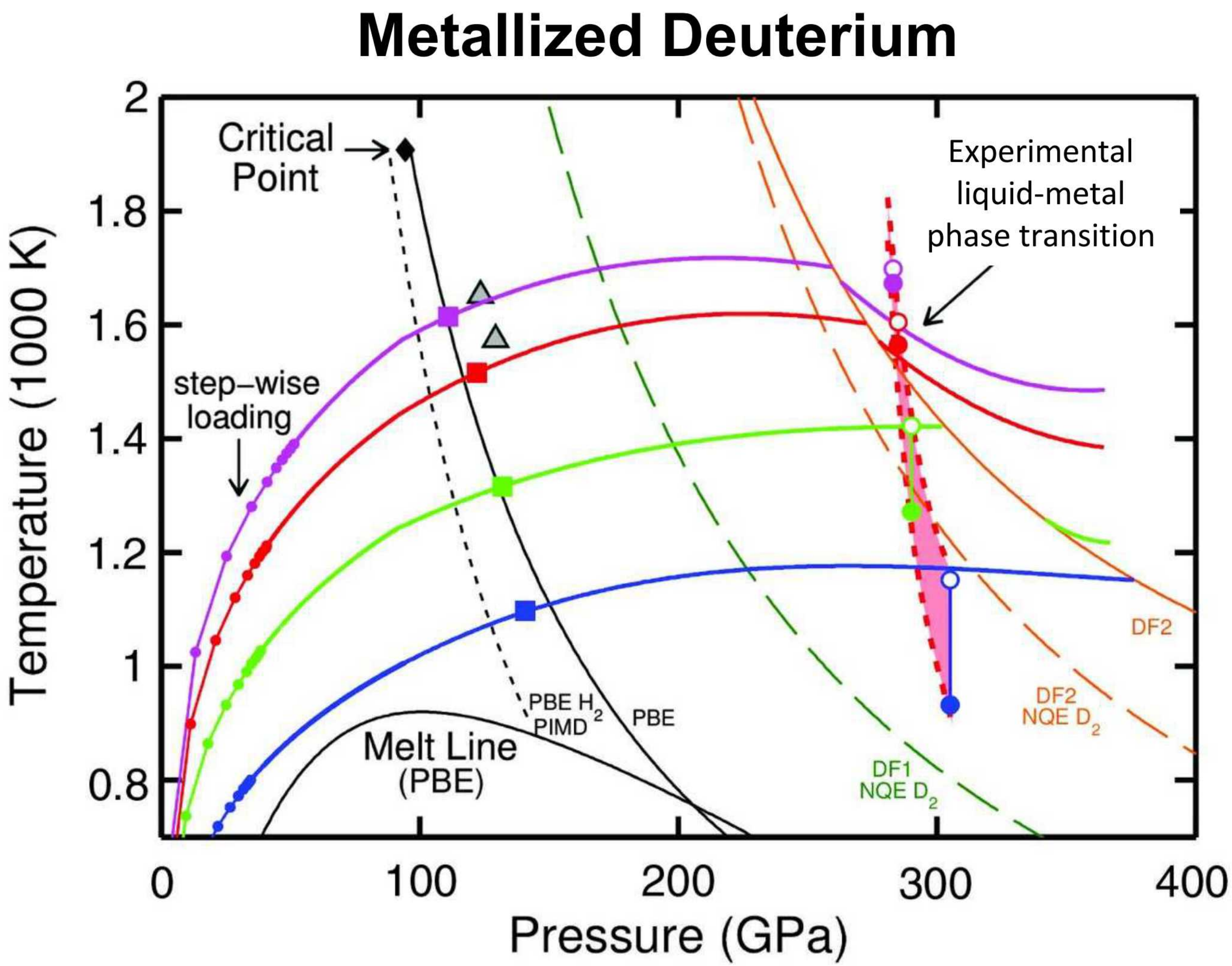
Z can perform both shockless compression and shock wave experiments



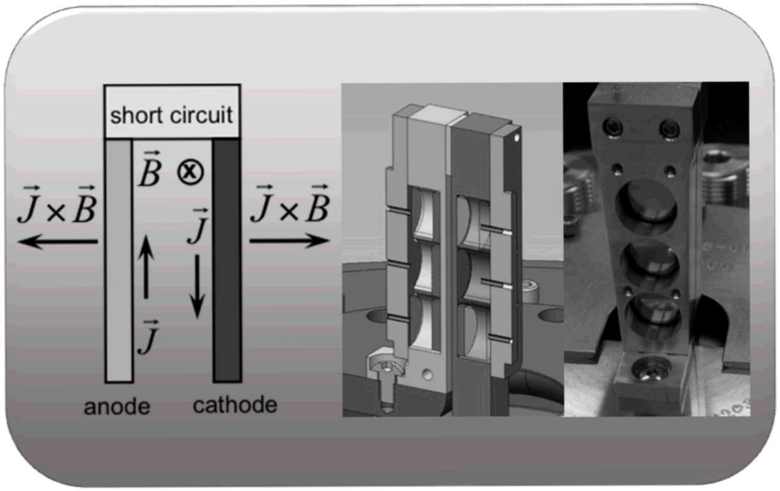
Shockless/Isentropic Compression Experiments (ICE):
gradual pressure rise in sample

Shock Hugoniot Experiments:
shock wave in sample on impact

Shock experiments on Z were able to measure a metallic phase of deuterium



M.D. Knudson, M.P. Desjarlais, A. Becker, R.W. Lemke, K.R. Cochrane, M.E. Savage, D.E. Bliss, T.R. Mattsson, and R. Redmer, Science **348,** 1455, (2015). Collaboration with Prof. Ronald Redmer's group at University of Rostock



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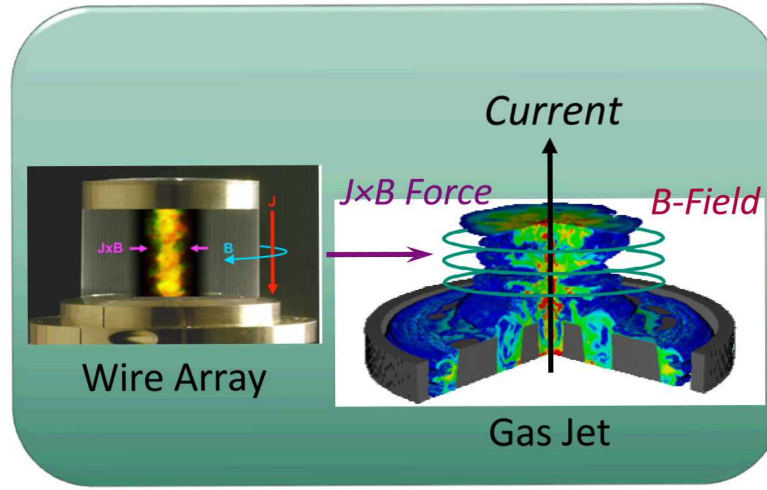

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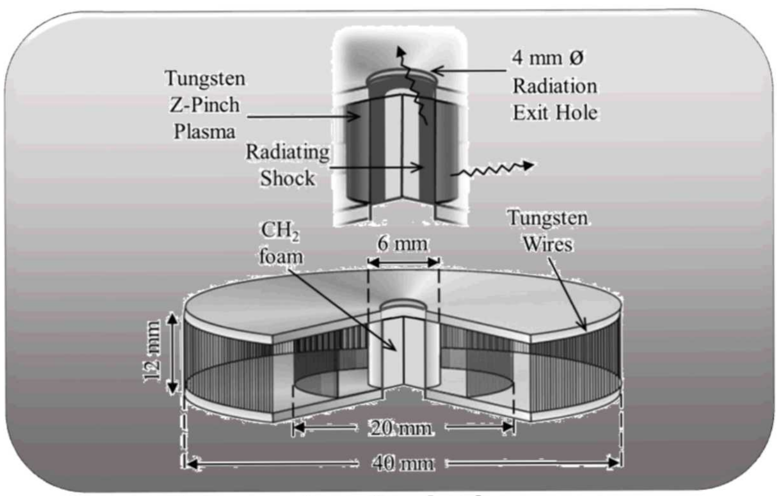
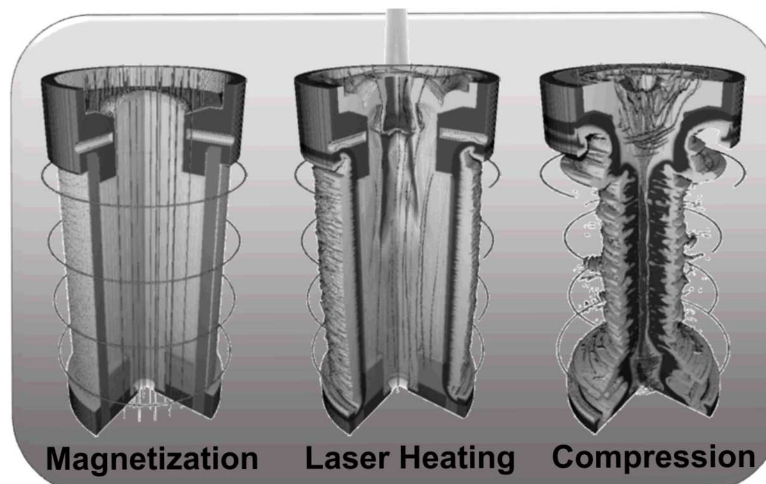
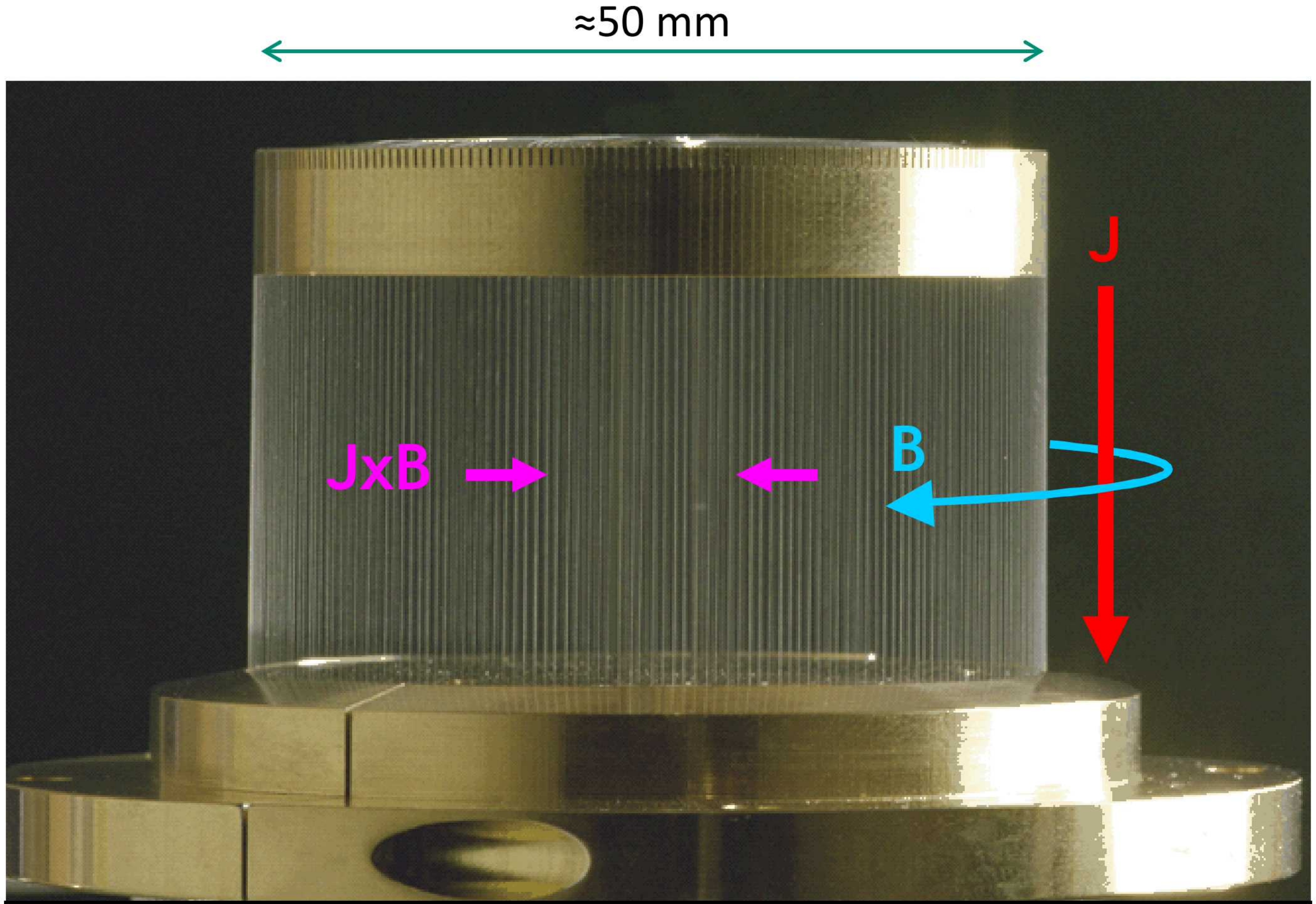


Astrophysical Plasmas



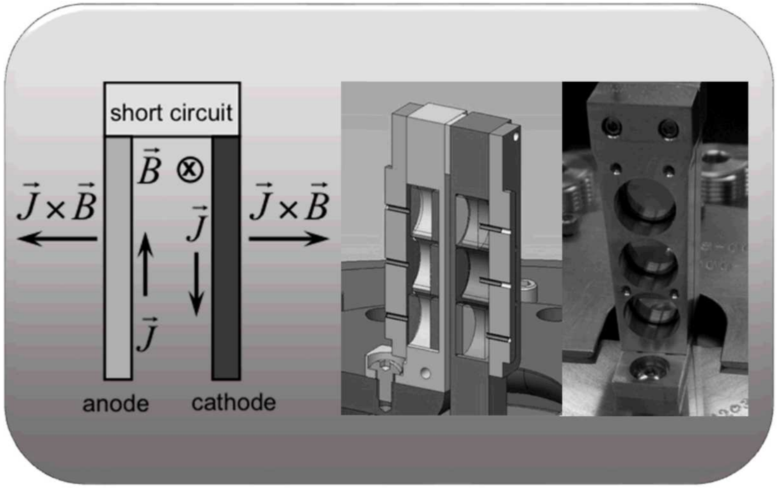
Inertial Confinement Fusion

(Nested) wire array Z pinches



P_{rad} ≈ 400 TW, Y_{rad} ≈ 2.5 MJ (total)

≈ 10-15% efficiency



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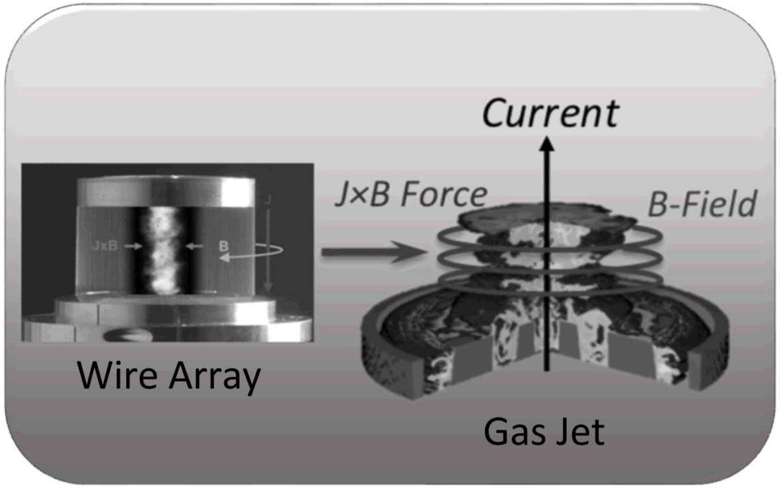

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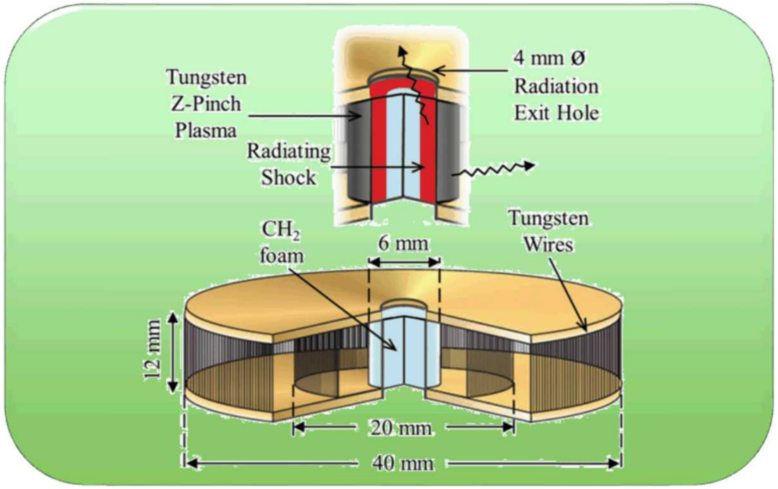

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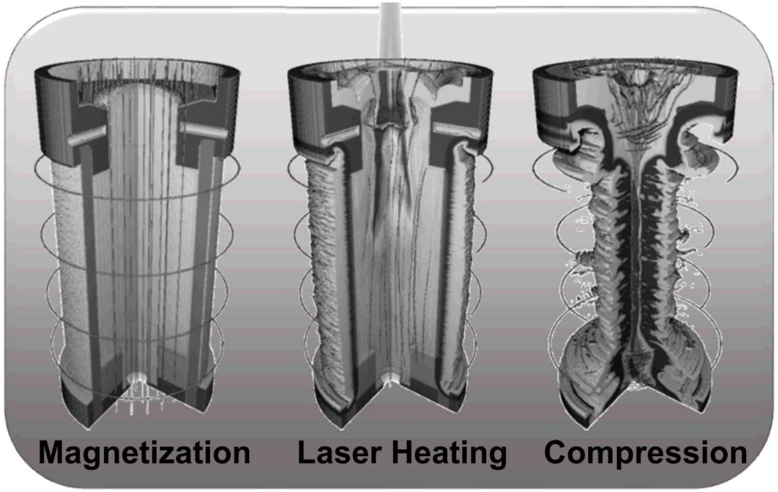


Inertial Confinement Fusion

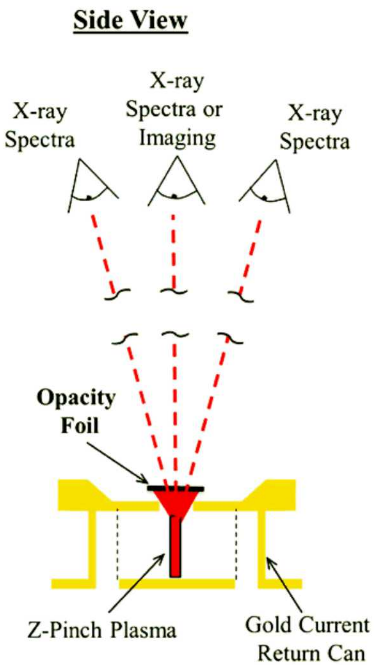
Z Astrophysical Plasma Properties (ZAPP) collaboration uses single x-ray source to conduct multiple experiments

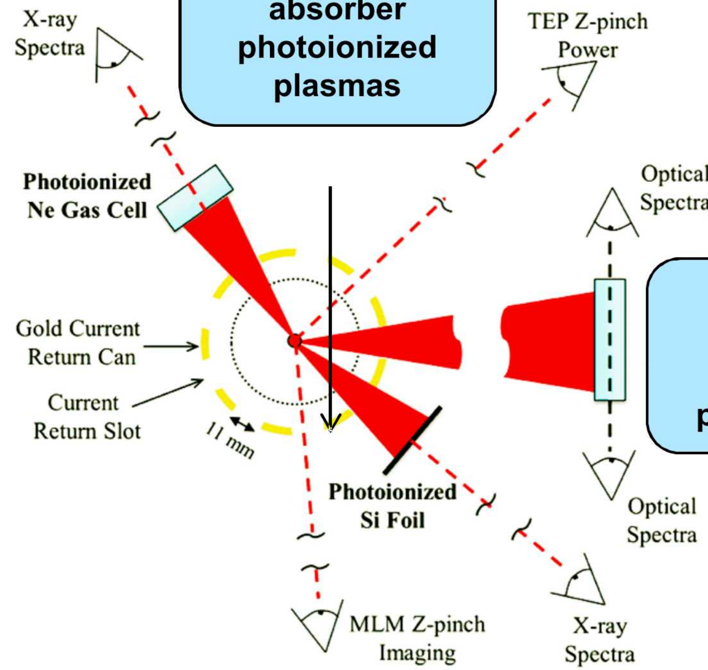
Stellar interior opacity*

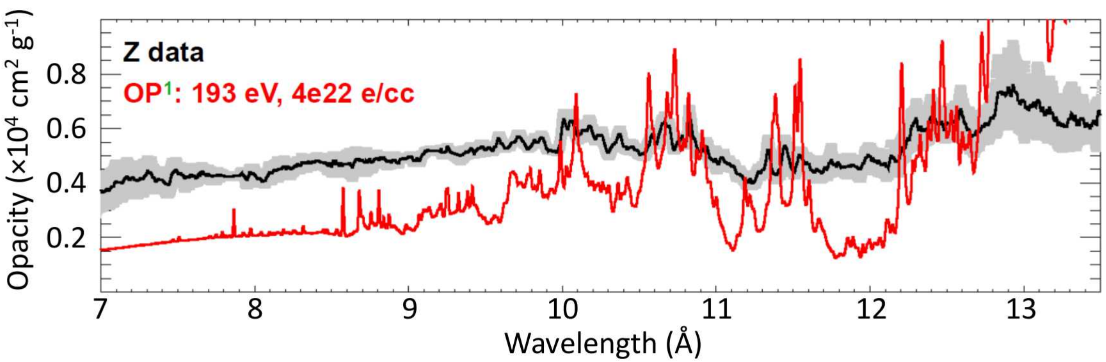
Atomic kinetics in warm absorber photoionized plasmas

Spectral line formation in white dwarf photo spheres

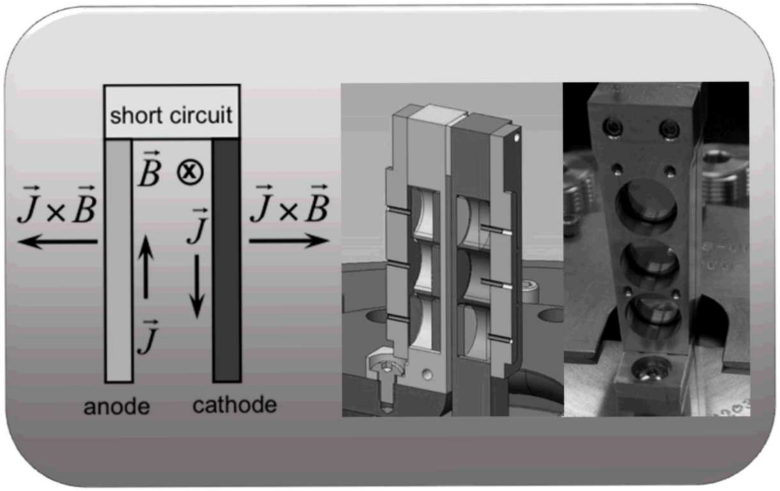
Resonant Auger destruction in accretion powered objects (black holes)







G.A. Rochau et al., Phys. Plasmas 21, 056308 (2014) *J. Bailey et al., *Nature* 517, 56 (2015)



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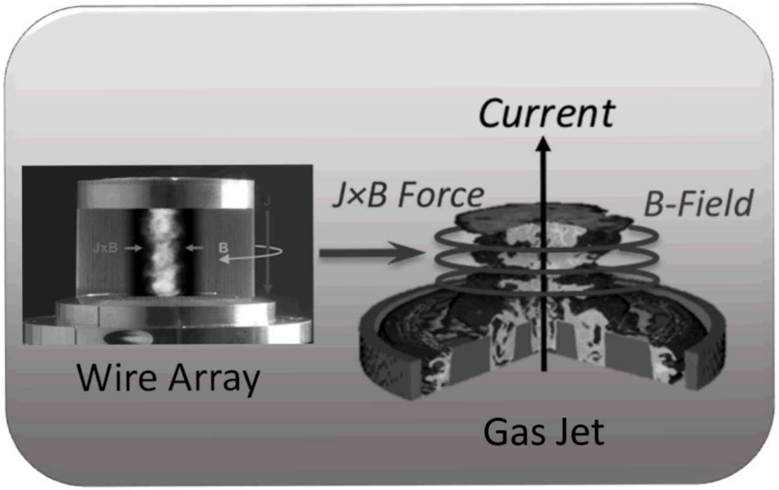
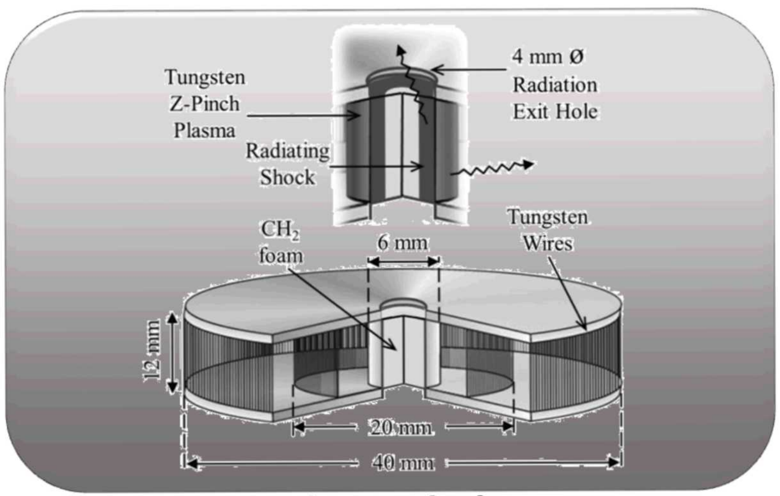


Z-Pinch X-Ray Sources



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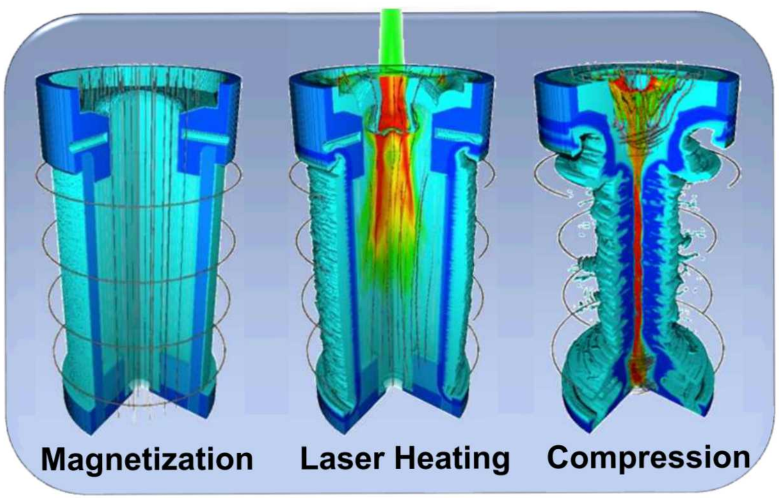
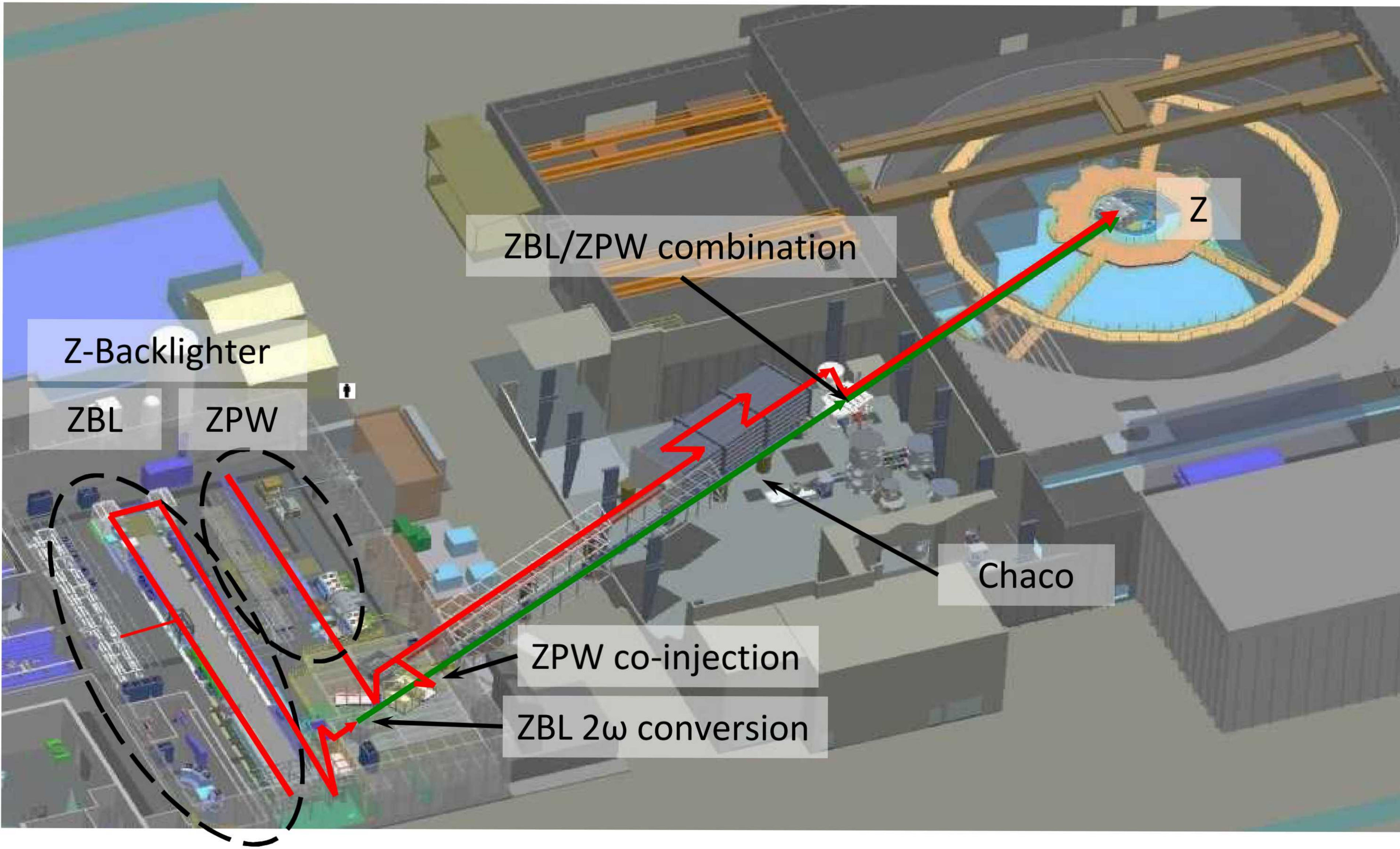


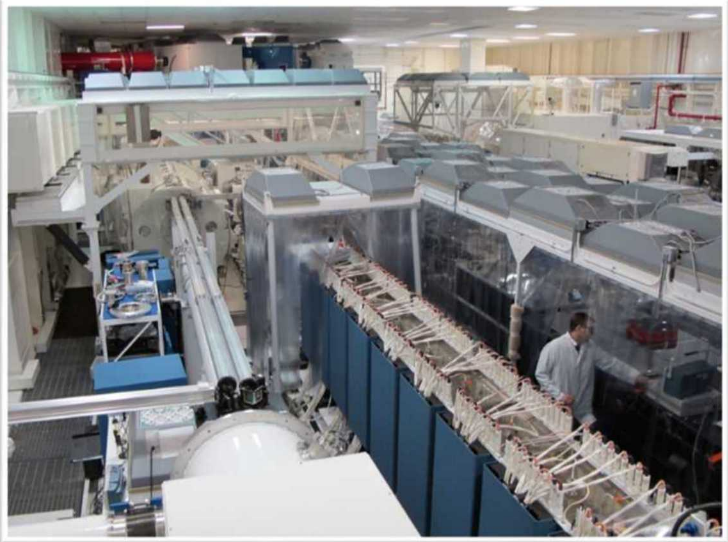
Inertial Confinement Fusion

Z-Backlighter Facility Overview

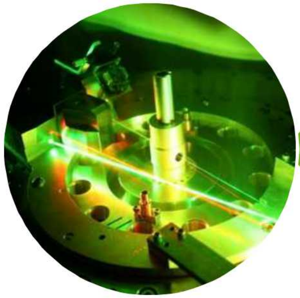


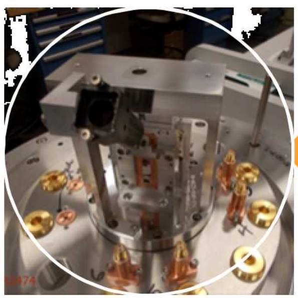
Z- Backlighter Facility Lasers

- Z-Beamlet
  - NIF prototype beamline
  - Delivers several kJ in few ns pulse
  - 1054 nm or 527 nm operation
  - Primarily used for x-ray backlighting and fuel preheat

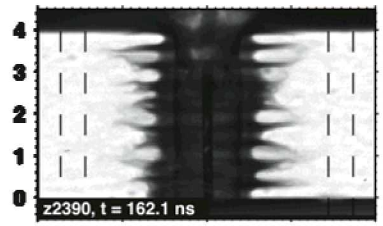


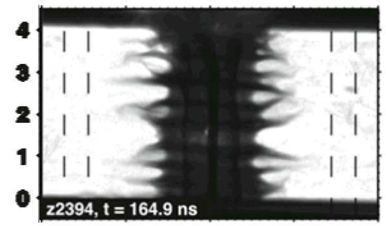
Key research areas at the Z-Backlighter Facility

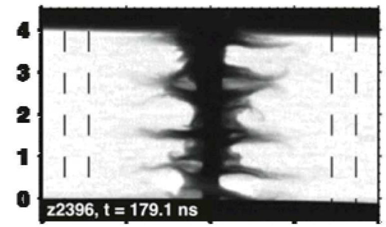




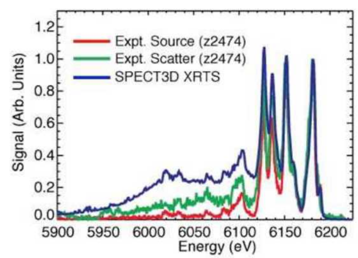
Improve x-ray backlighting for radiography of imploding liners or wire arrays

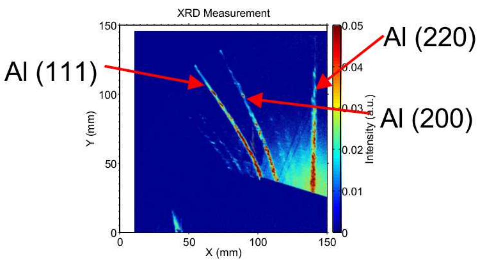






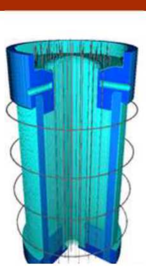
Develop sources for x-ray scattering and diffraction on compressed matter



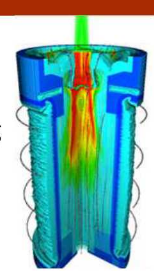


Investigate preheating on MagLIF targets

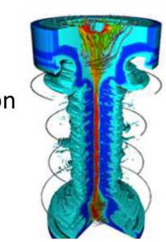
Magnetization



Laser heating



Compression



Outline

Z/ Z Beamlet Pulsed Power Facility

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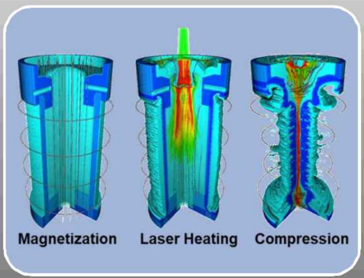

MagLIF Program

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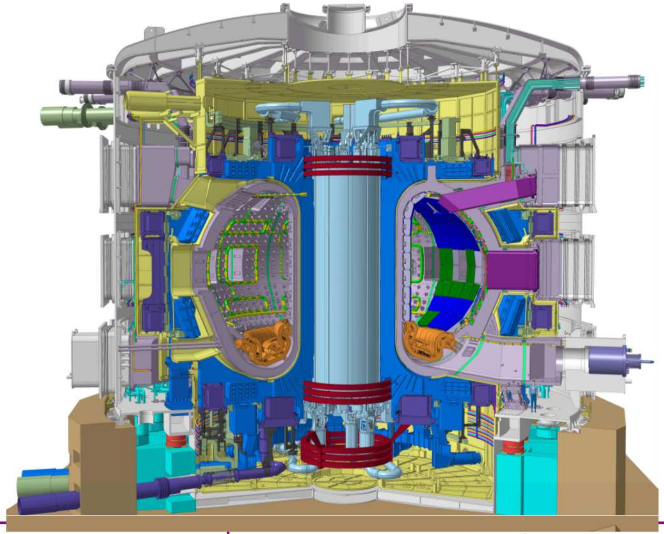
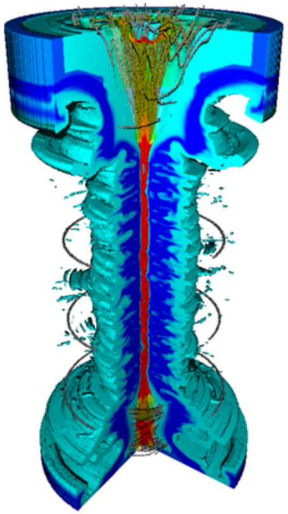
- Measurements of Laser Heated Fuel, My Contributions

Magneto-inertial fusion sits in the space between magnetic and inertial confinement fusion

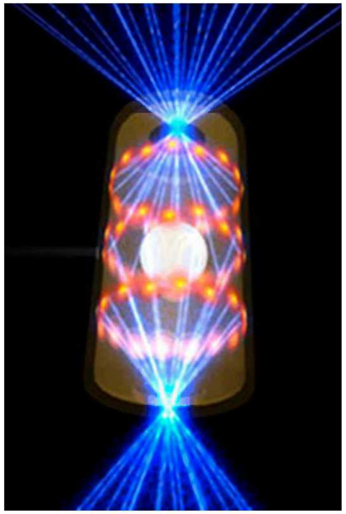
ITER



MIF concept

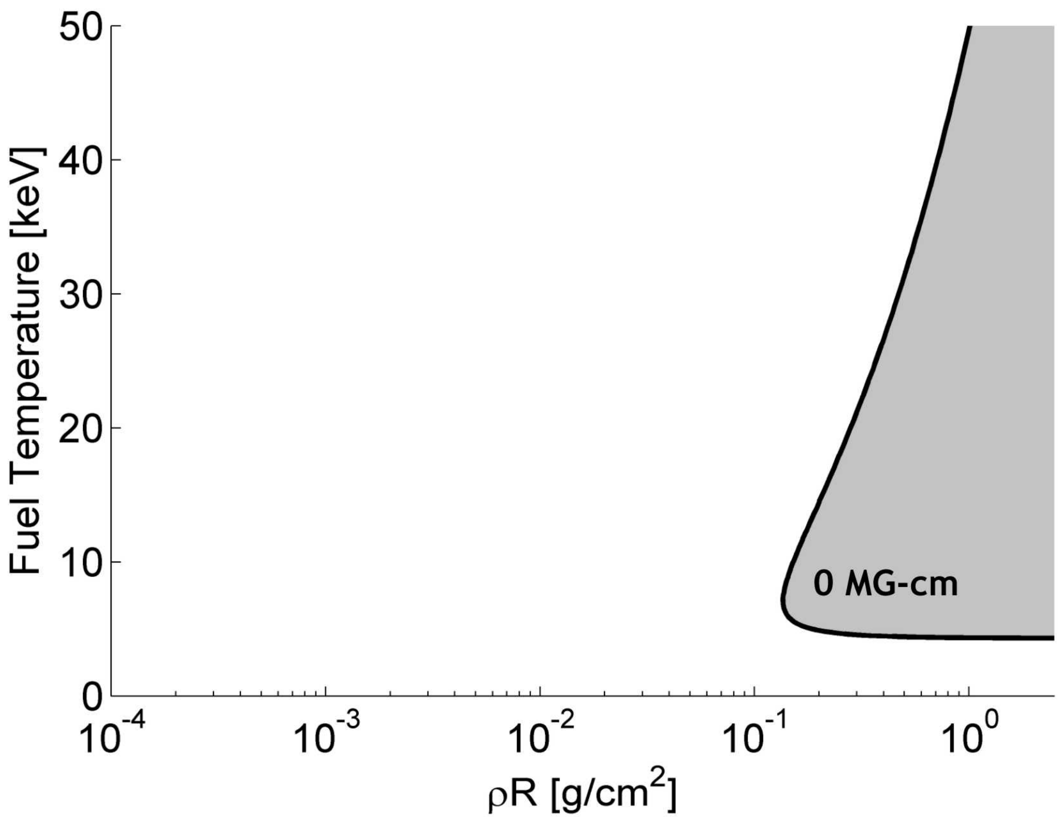


NIF hohlraum



Density	1 x 10^{14} cm^{-3}	1 x 10^{23} cm^{-3}	2-20 x 10^{25} cm^{-3}
Volume	8 x 10^{8} cm^{3}	8 x 10^{-5} cm^{3}	6 x 10^{-8} cm^{3}
Duration	300-500 s	1-2 x 10^{-9} s	5-10 x 10^{-11} s
Magnetic field	100 kG	50-100 MG	0 kG

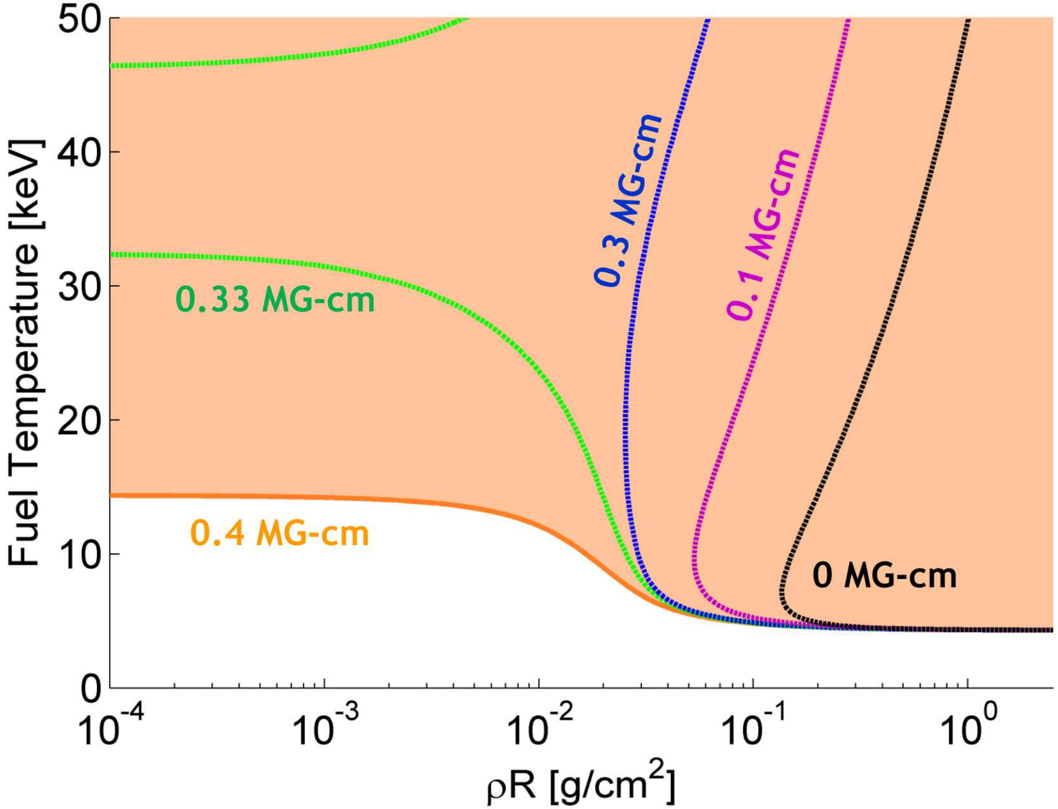
ICF has requirements on fuel temperature and areal density for gains to exceed losses



- There is a minimum fuel temperature of about 4.5 keV
  - This is where fusion heating outpaces radiation losses
- The minimum fuel areal density is around 0.2 g/cm^2
- Traditional ICF concepts attempt to operate in this minimum

P. F. Knapp, et al., Phys. Plasmas 22, 056312 (2015).

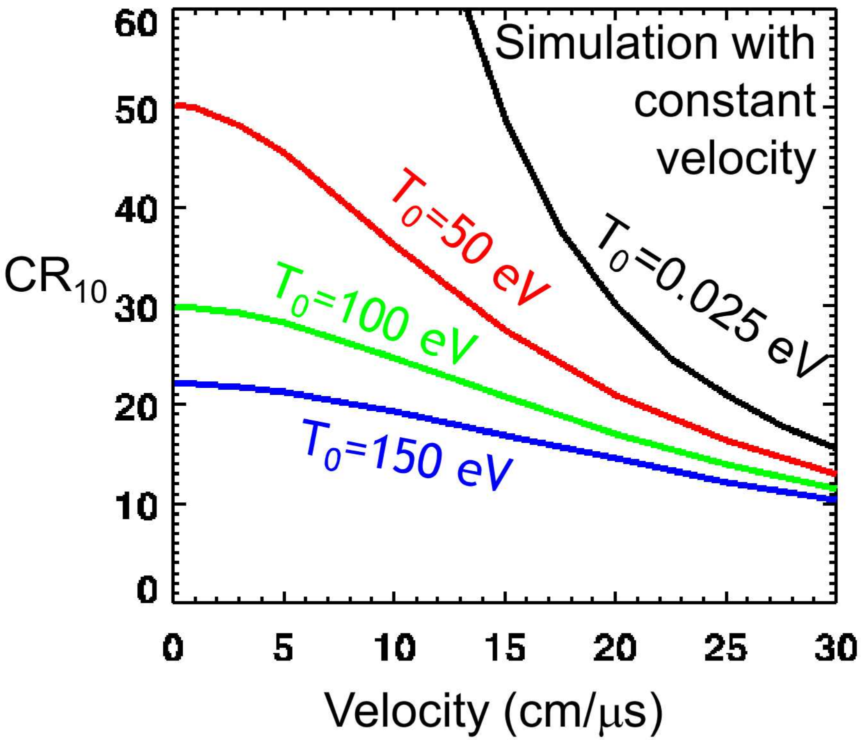
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- As the field is increased, particle magnetization reduces thermal conduction
- Performance increases dramatically once the Larmor radius of alphas is equal to the fuel radius
- In this regime, particle trapping is achieved through magnetization rather than areal density

P. F. Knapp, et al., Phys. Plasmas 22, 056312 (2015).

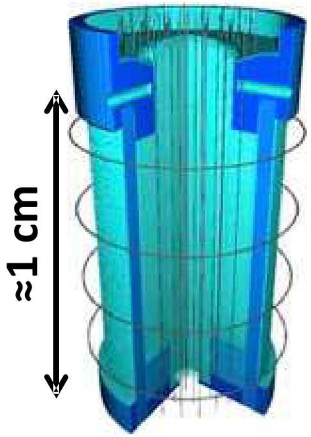
Preheating fuel may also reduce implosion requirements



CR_{10} = Convergence Ratio (R_0/R_f) needed to obtain 10 keV (ignition) with no radiation losses or conductivity

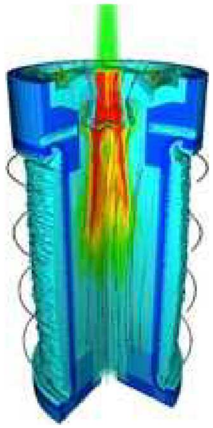
- Laser heating of fuel (6-10 kJ) offers one way to reach pre-compression temperatures of ~200 eV
- Detailed simulations suggest we can reach fusion temperatures through cylindrical implosions at R_0/R_f of 25

Magnetized Liner Inertial Fusion (MagLIF)



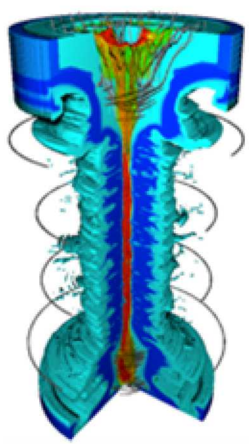
Initialize axial magnetic field (B_0 = 10-30 T)

- Inhibits thermal losses from fuel to liner
- May help stabilize liner during compression
- Flux compression increases field to kT and trap α particles



Laser heating of fuel (E_L = 2-4 kJ)

- Initial fuel temperature 150-200 eV → 10 keV at compression
- Fuel heating achieved by compression against fuel pressure rather than high convergence and high velocity

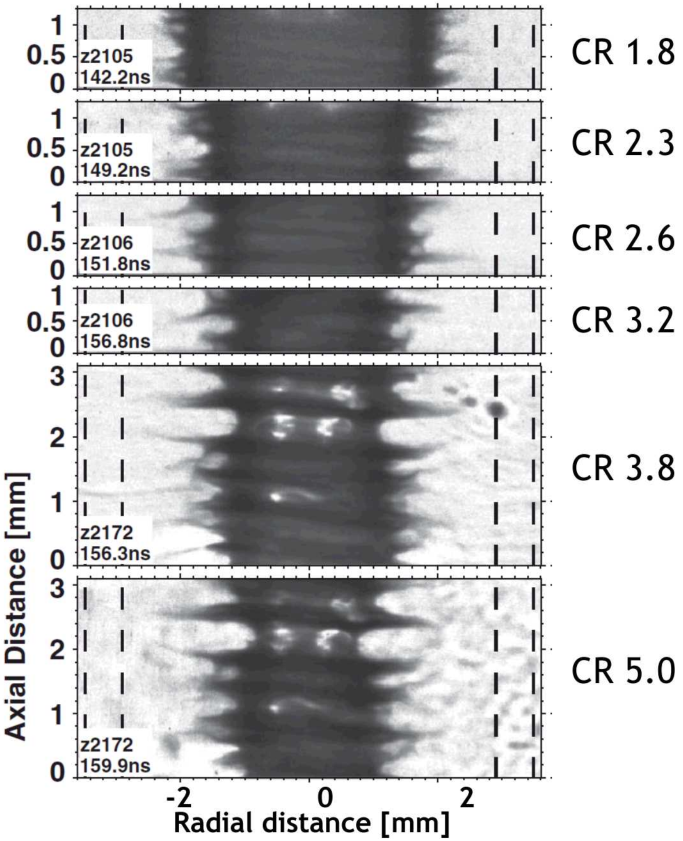


Magnetic compression of fuel

- 70-100 km/s, quasi-adiabatic fuel compression
- Low aspect liners ($r/\Delta r \approx 6$) are robust to hydrodynamic instabilities
- **Significantly lower implosion velocity and final pressure/density than NIF ICF because preheat and magnetization relax requirements**

S.A. Slutz et al., Phys. Plasmas (2010); S.A. Slutz & R.A. Vesey, Phys. Rev. Lett (2012); A.B. Sefkow et al., Phys. Plasmas (2014)

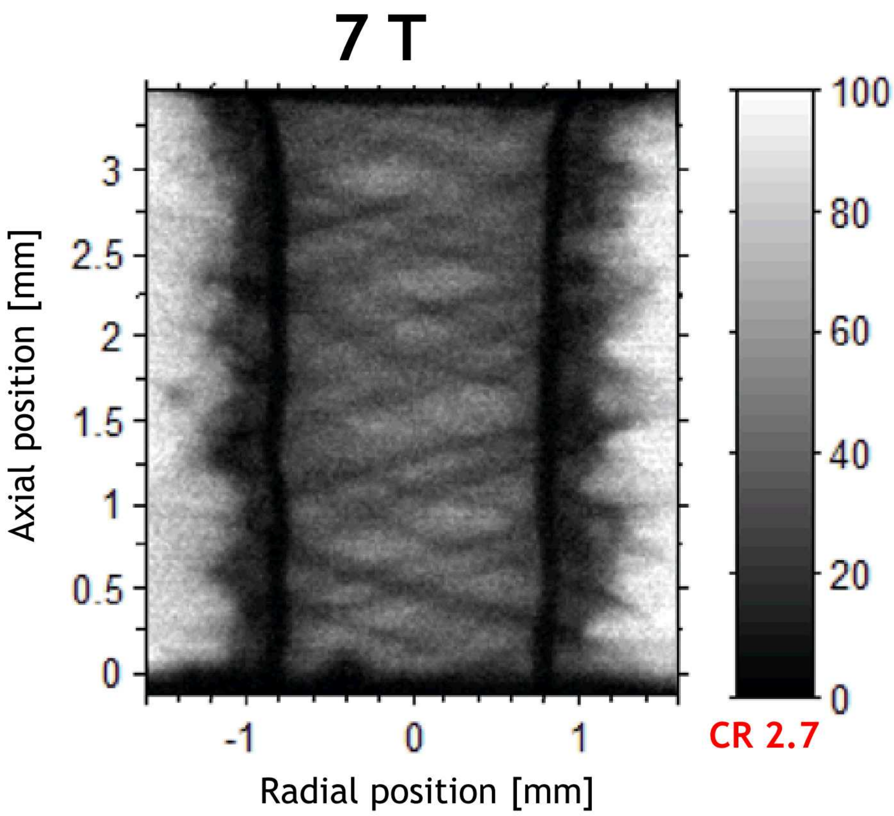
First steps: Radiographs throughout the implosion were collected on a series of implosion only experiments

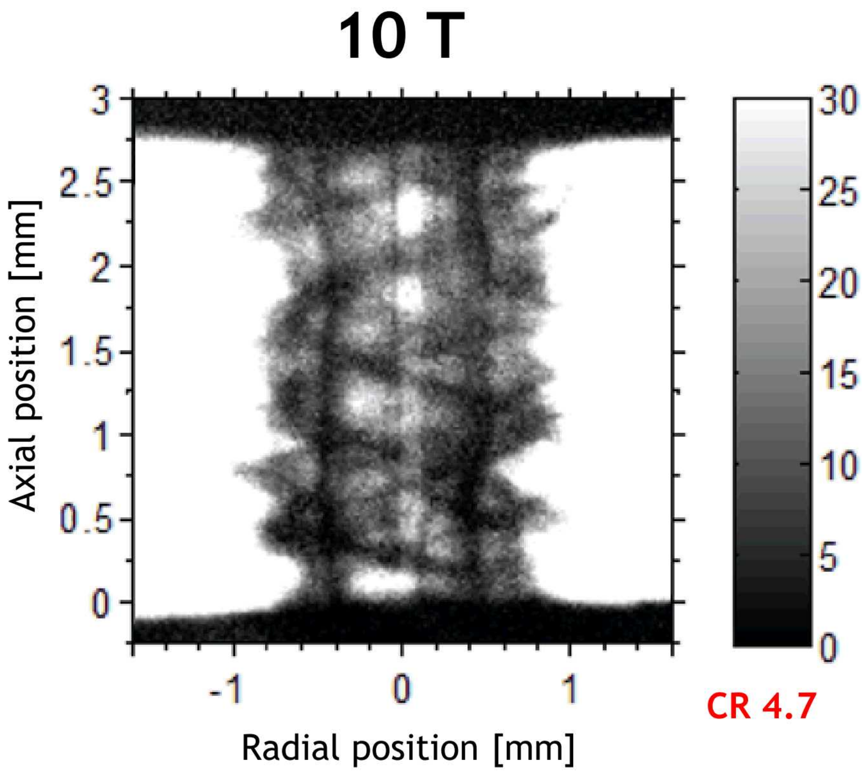


- Magneto-Rayleigh-Taylor instabilities develop and grow
  - Azimuthal correlation of instabilities
  - Use thick liners to limit feedthrough to inner surface
  - Massive liners implode on a relatively slow time scale compared to traditional ICF
- Relatively happy with liner stability
  - Inner surface is relatively straight at a convergence ratio of 5
    - 82% of implosion distance to CR 40

R. D. McBride, et al., Phys. Rev. Lett. 109, 135004 (2012).

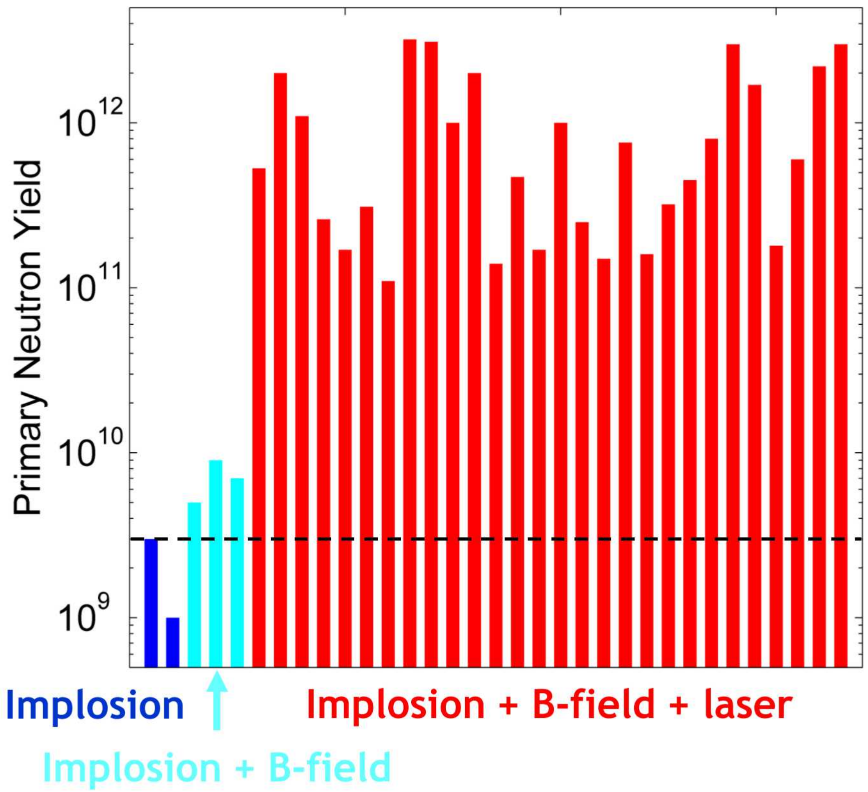
The axial B-field converted the azimuthal MRT structure into helical; stabilized the implosion?





T. J. Awe, et al., Phys. Plasmas 21, 056303 (2014).

First integrated experiments show primary neutron yield is highly dependent on magnetization *and* laser heating

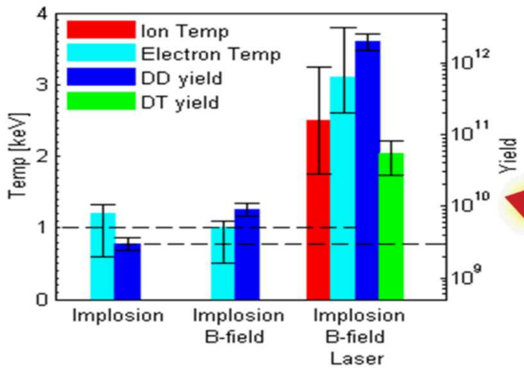


- Experiments without the magnetic field and laser produce yields at the typical background level
- Adding just the magnetic field had a marginal change in yield
- In experiments where the magnetic field was applied and the laser heated the fuel, the yield increased by about 2 orders of magnitude

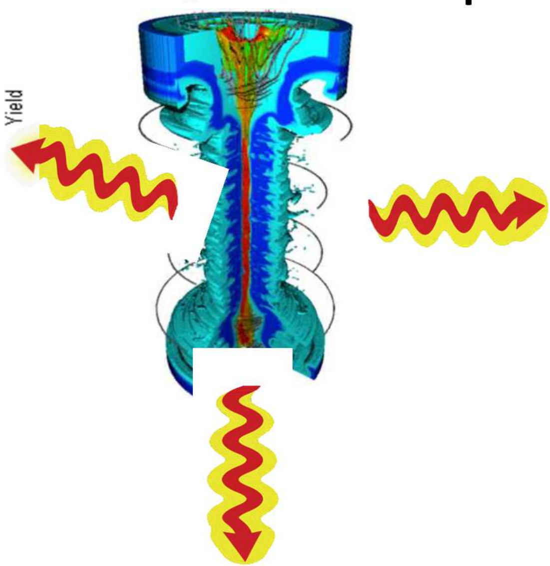
M. R. Gomez, et al., Phys. Rev. Lett. 113, 155003 (2014).

An ensemble of measurements from MagLIF experiments are consistent with a magnetized, thermonuclear plasma

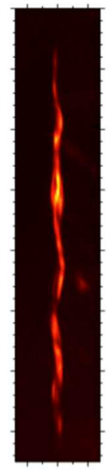
Nuclear Activation (yield)



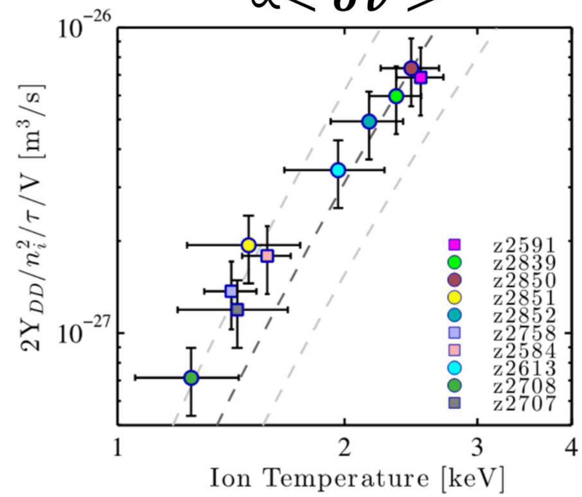
MagLIF Z pinch



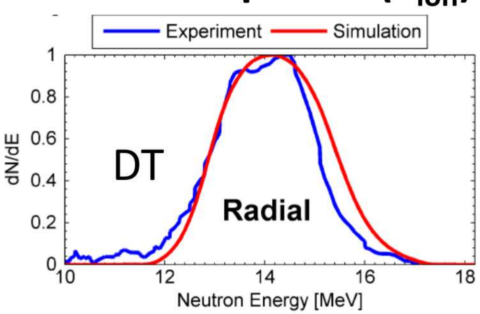
X-ray Imaging (hot plasma shape)

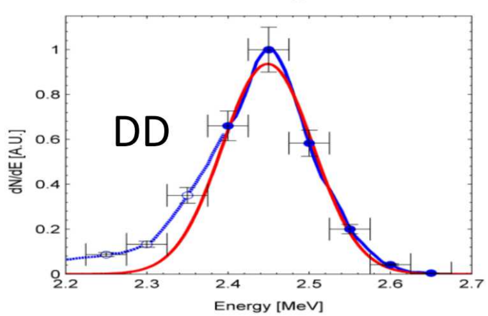


Scaling with ion temperature $\propto \langle \sigma v \rangle$

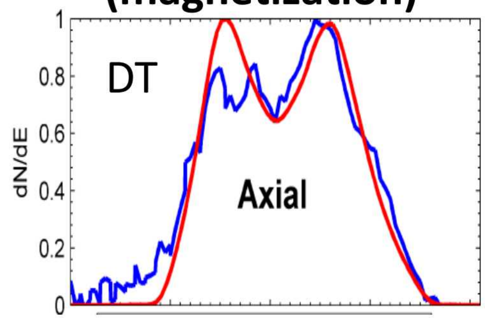


Neutron spectra (T_{ion})

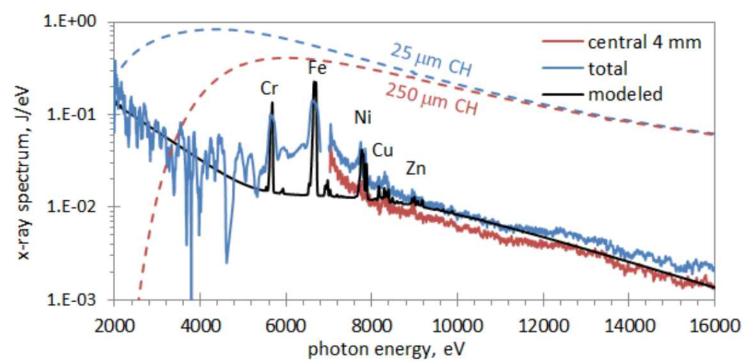




DT Neutron spectra (magnetization)



X-ray Spectra (T_e, mix)

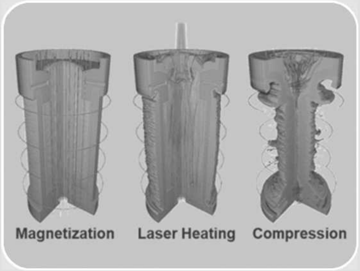


M.R. Gomez *et al.* PRL (2014). P.F. Schmit *et al.*, PRL (2014). P.F. Knapp *et al.*, PoP (2015). M.R. Gomez *et al.*, PoP (2015). S.B. Hansen *et al.*, PoP (2015).

Outline

Z/ Z Beamlet Pulsed Power Facility

- Overview & Capabilities, Key Research Areas



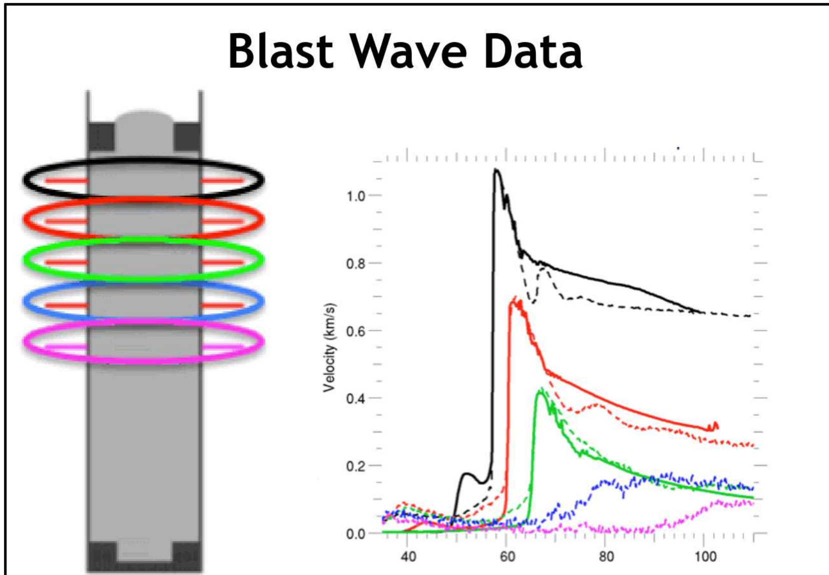
MagLIF Program

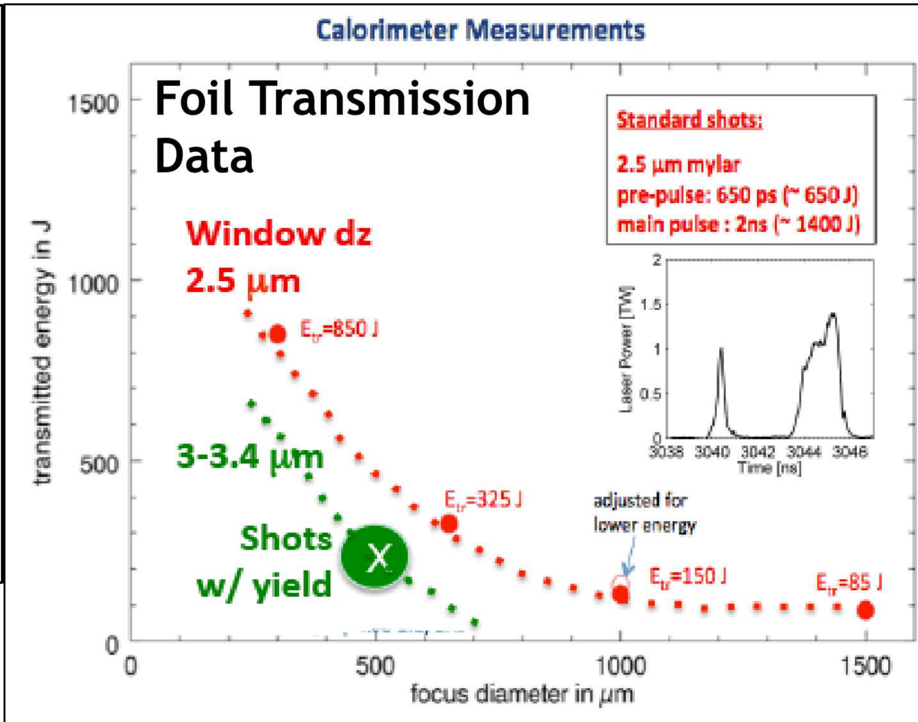
- Theoretical and Conceptual Basis, Experimental Progress

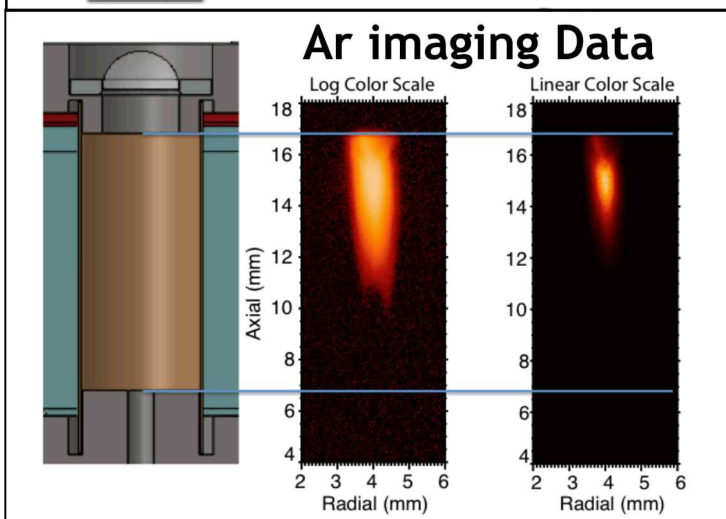
Optical Diagnostics on Pecos Test Stand

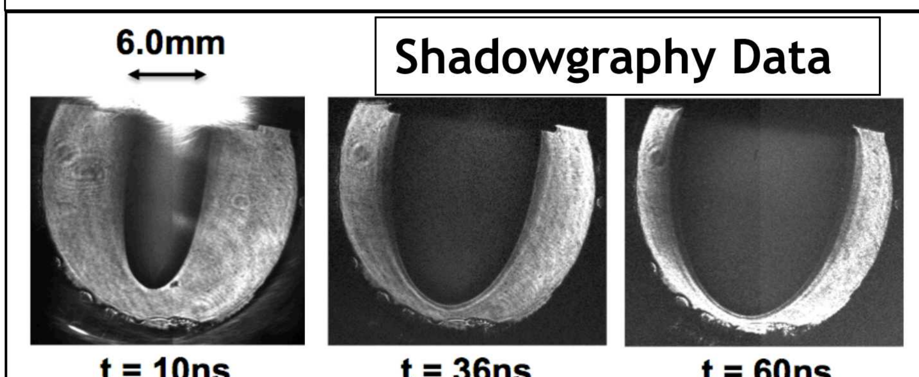
- Measurements of Laser Heated Fuel, My Contributions

Early experiments identified laser heating as area of concern (only ~10-20% coupling)





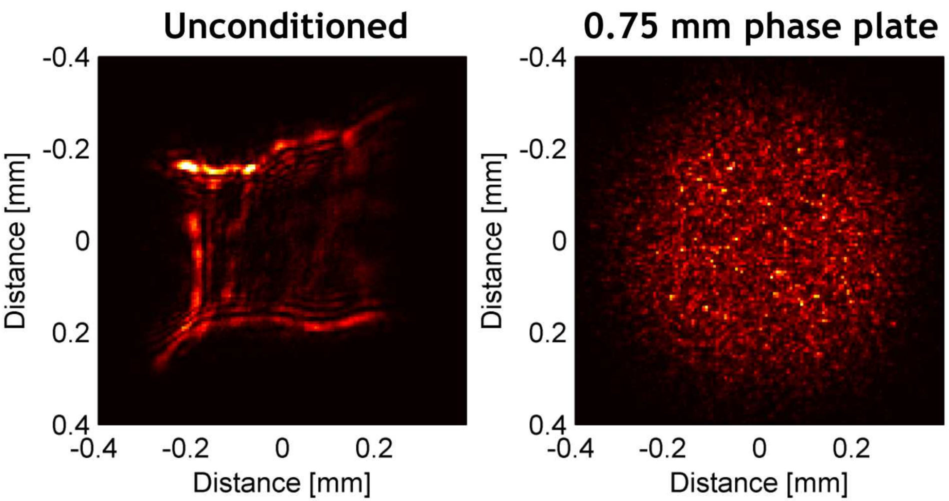




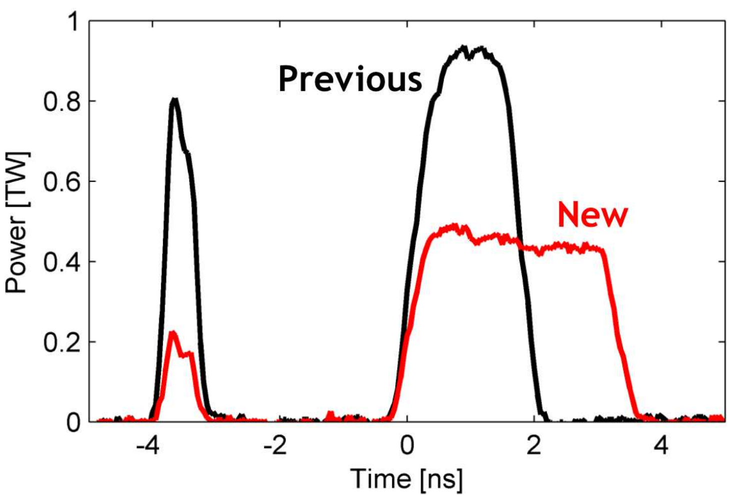
D. B. Sinars, ICOPS (2015).

Reasons for poor laser coupling

Beam smoothing with phase plates

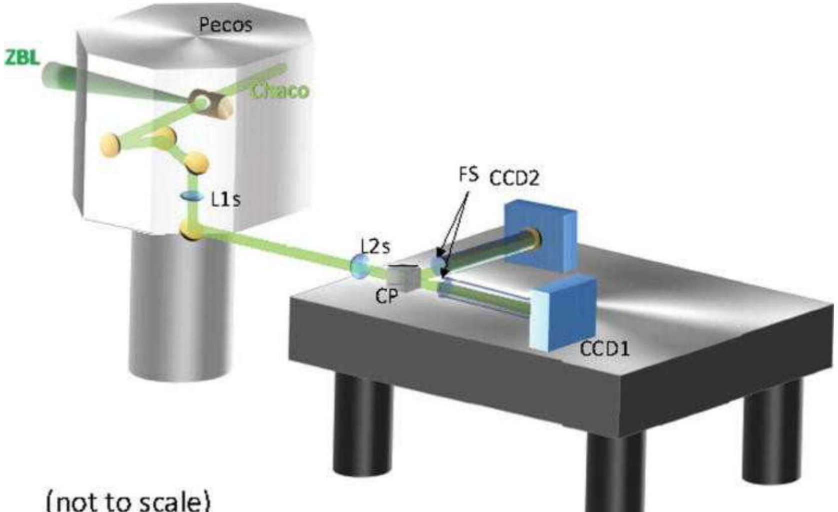


Pulse shaping for intensity control

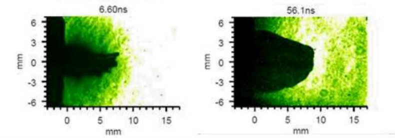


- Initial experiments used thick windows, an unconditioned defocused beam with high intensity variations, and high intensities that led to strong laser plasma instabilities
- Several techniques were used to mitigate these problems, including beam smoothing with phase plates, and redesigned temporal shapes
- Unfortunately, Z does not provide a good environment for testing variations in preheat due to a low shot rate (shot/day) and shot allocation (few shots/year)

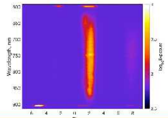
Experiments in the Pecos chamber measure laser heated fuel with a variety of diagnostics at a high(er) shot rate



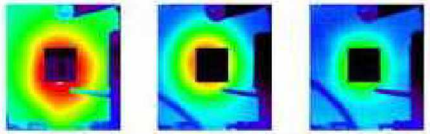
Shadowgraphy – Blast wave and total energy coupling



Stimulated Raman scattering (SRS) spectroscopy – Density evolution in areas of high SRS gain, filamentation



Near beam imaging – Energy loss to laser plasma instabilities (SBS, SRS)

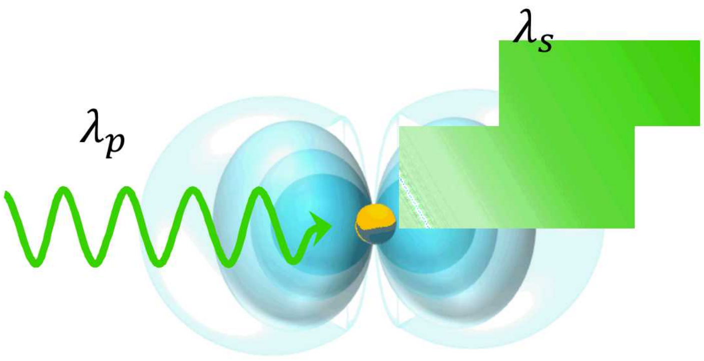


Optical Thomson scattering imaging and spectroscopy–
Spatially resolved laser fluence
Temperature and mix

M. Geissel, et al. Phys. Plasmas 25, 022706 (2018)

We measure optical Thomson scattering (OTS) in the collective regime

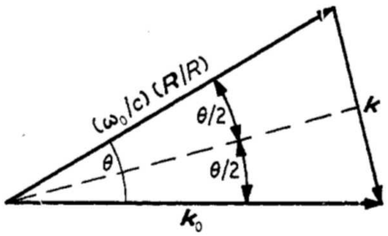
- Thomson scatter comes from dipole radiation of electrons moving in the incident electric field



- The scattering parameter α gives the ratio of the scattered wave vector k' to the plasma Debye length, λ_D

- For $\alpha \ll 1$, light is scattered off of individual electrons with a temperature dependent Doppler profile

$$|\boldsymbol{k}| = 2(\omega_0/c)\sin(\theta/2)$$



- For $\alpha \gg 1$, light is scattered from collective structures (fluctuations), primarily ion acoustic features

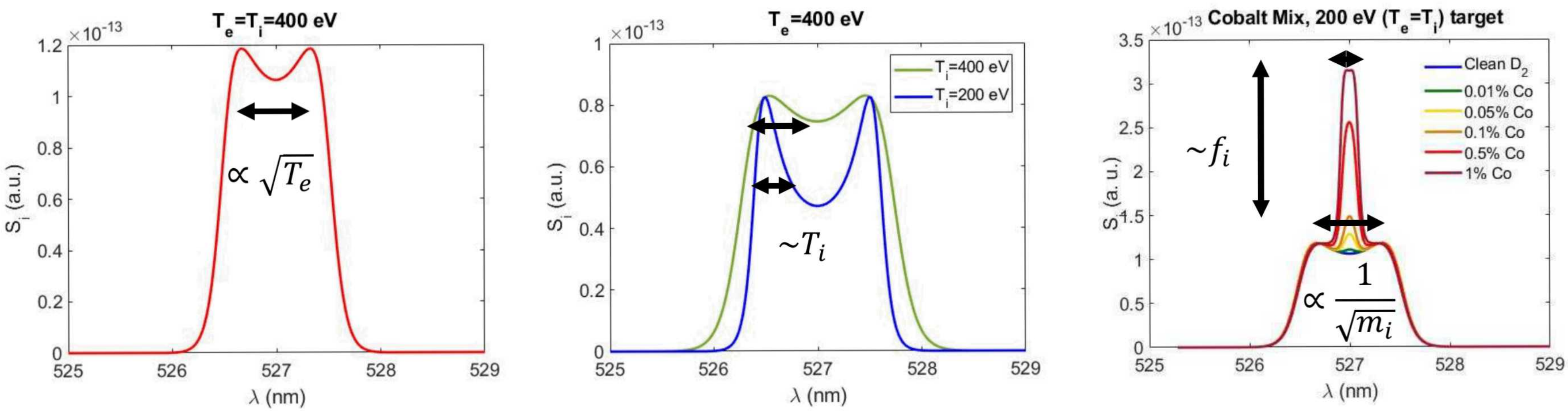
Collective OTS provides way to measure temperature and mix

- The separation of the blue-shifted and red-shifted scattering peaks is given by the ion acoustic frequency:

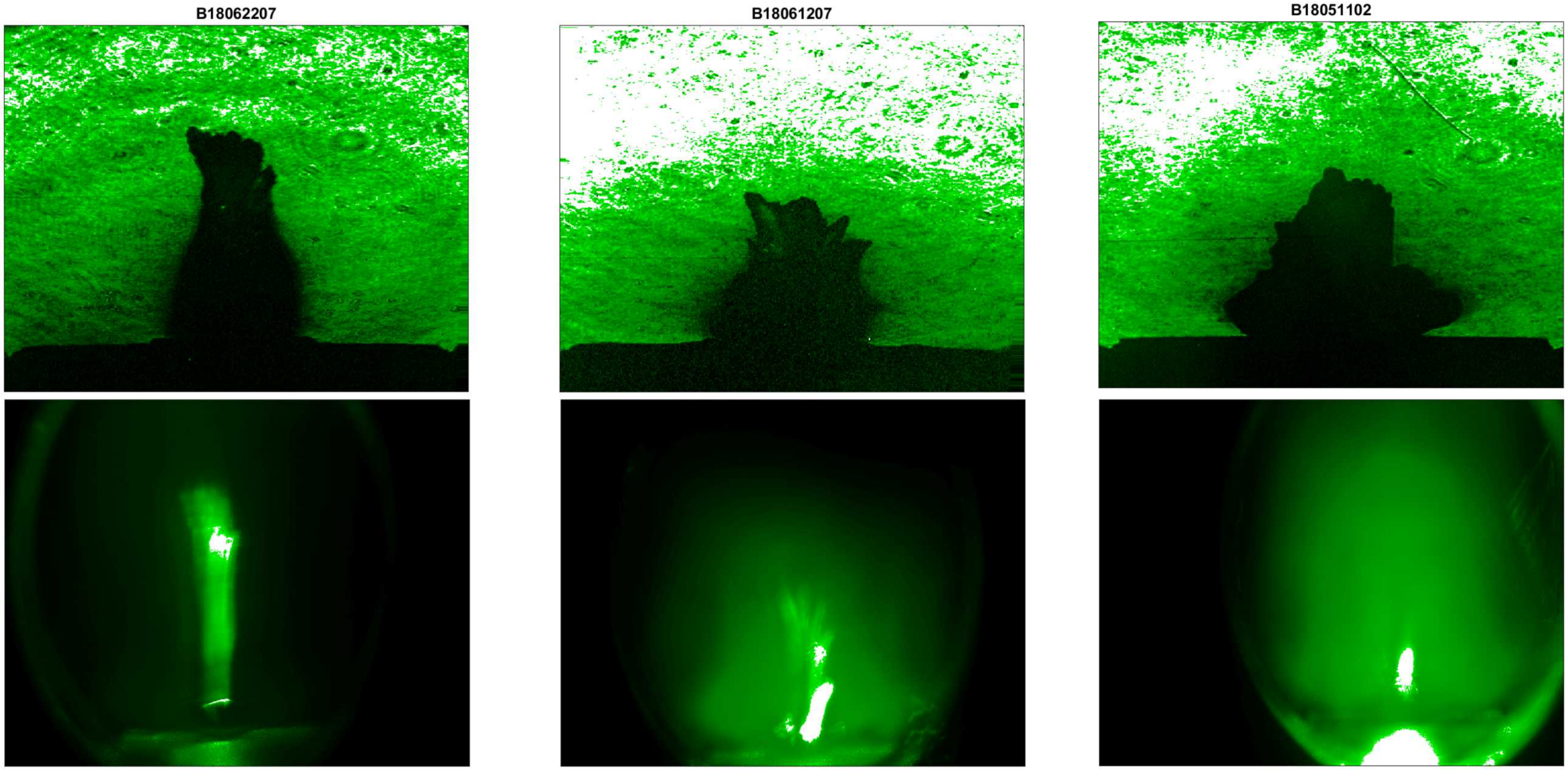
$$\Delta\omega \cong k' c_s \approx k' \sqrt{\frac{ZT_e}{m_i}} \quad \text{(with corrections } \sigma \sim T_i/T_e\text{)}$$

- The width of theses peaks is related to the ion temperature

Thomson Spectra for 120 psi (4×10^{20} cm^{-3}) D_2 targets



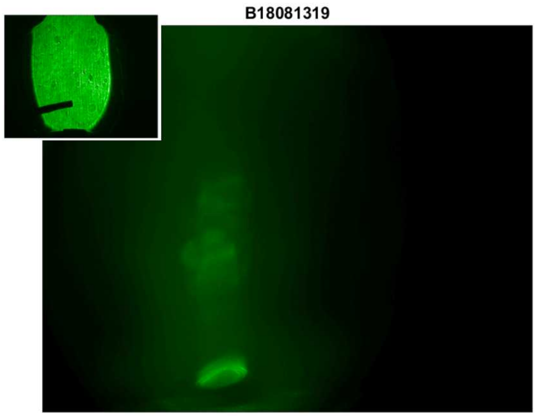
Thomson scatter images are encouraging, but show less energy than expected

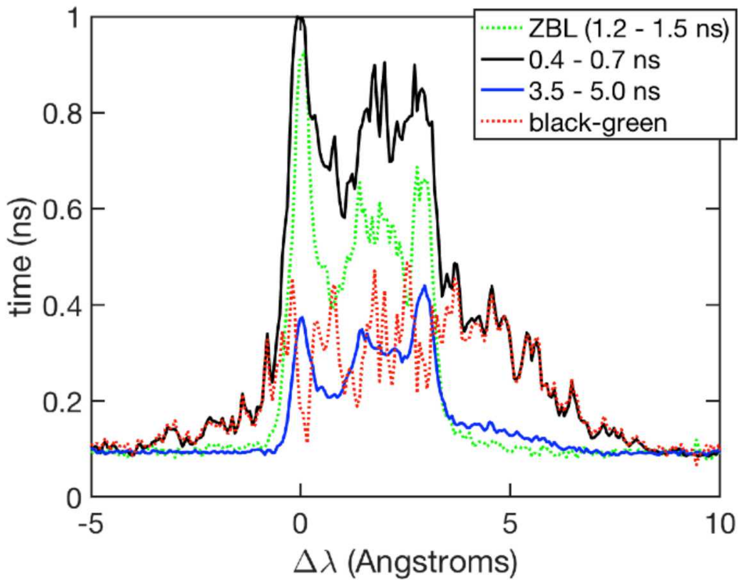


120 psi co-injection | 120 psi co-injection, misaligned | 60 psi No-DPP

- Features correlate with shadowgraphy and show distinction between different preheat protocols
- Integrated scattering energy is ≲1-2 mJ, 2 to 3 orders of magnitude smaller than calculated based on geometry, indicating strong absorption

Scatter spectra (to date) show primarily laser scatter





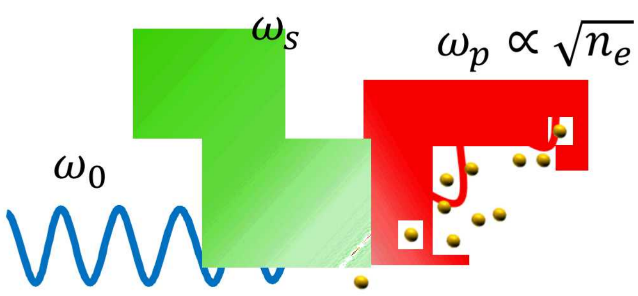
- Scatter spectra (separate from 3 peak modulated ZBL spectrum) do not show the expected double peak, but rather only a red-shifted feature.
- May indicate SBS side scattering or Doppler shifted Thomson scattering (or both)
- Without an idea of possible Doppler shifting between ion acoustic (SBS) peak and laser fundamental, it is not possible to assign a temperature.
- A complete (double peaked) Thomson spectra would avoid this problem
- Prominence (and minimal blurring) of laser spectrum may indicate we are mainly collecting reflections in the chamber
- Additional testing needed to eliminate failure modes

Stimulated Raman scatter (SRS) provide measure of density in areas of high gain

- SRS comes from scattering off of electron plasma wave features that are driven by the incident beam

$$n_e = n_c \left(1 - \frac{\lambda_0}{\lambda_s}\right)^2$$

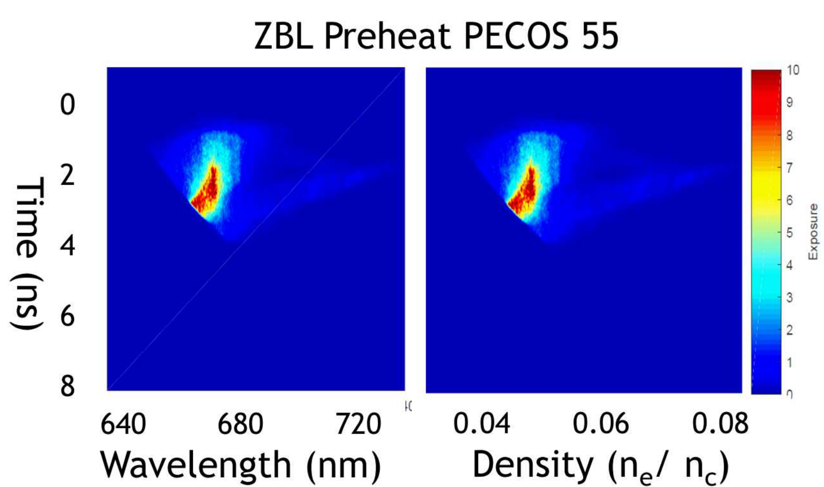
- For direct backscatter, the downshifted frequency gives the local electron density



- Backscatter primarily comes from areas of high gain (high intensity and density, long scale length)

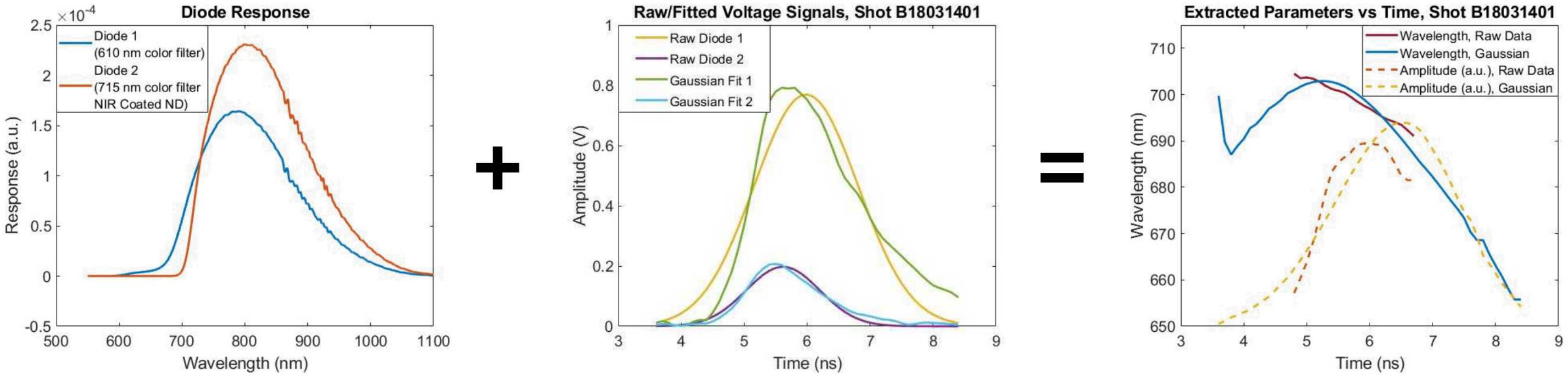
$$I\left(\frac{W}{cm^2}\right) > \frac{1x10^{17}}{L\lambda}\frac{n_c}{n_e}$$

- SRS is observed on a streaked visible spectroscopy (SVS) system consisting of a streak camera coupled to a spectrometer



Diodes provide easy way to track SRS evolution when SVS is unavailable (often…)

- Two diodes facing a scatter plate are individually filtered, giving different responses for different wavelengths
- Assuming a Gaussian SRS spectrum with σ=10 nm, we perform a nonlinear least squares fit to extract the mean wavelength and amplitude at each time step (original analysis model developed by Daniel Davis, UNM)



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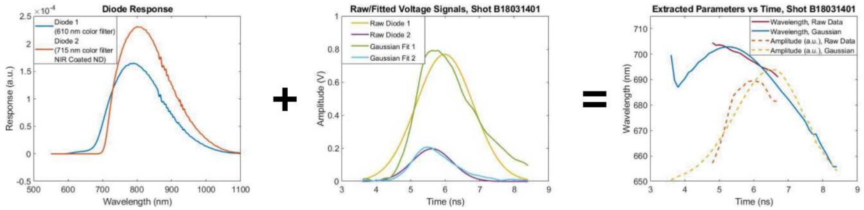
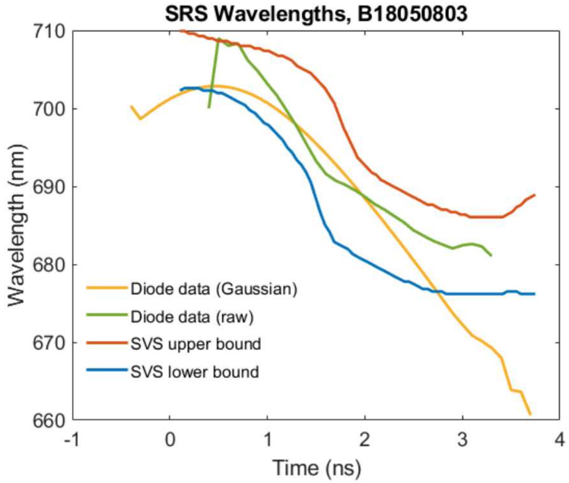
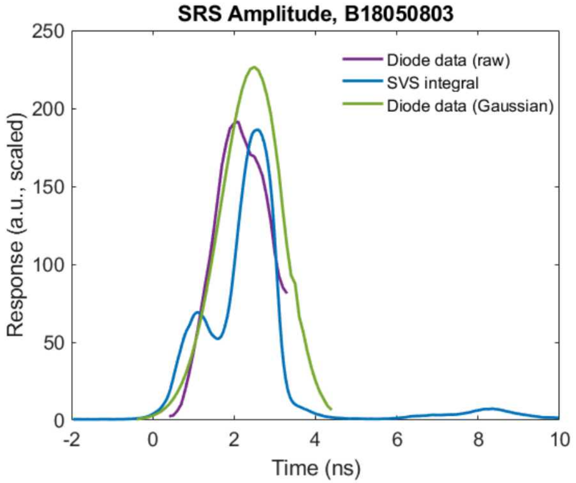


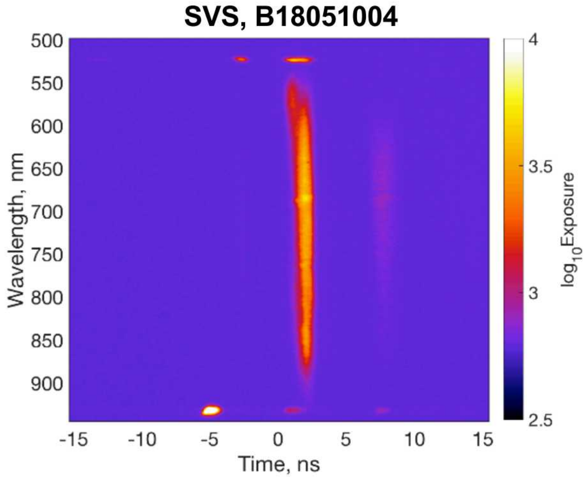
- Extracted values show good agreement with SVS data, but only for some shots…
  - SVS analysis by Jeff Fein

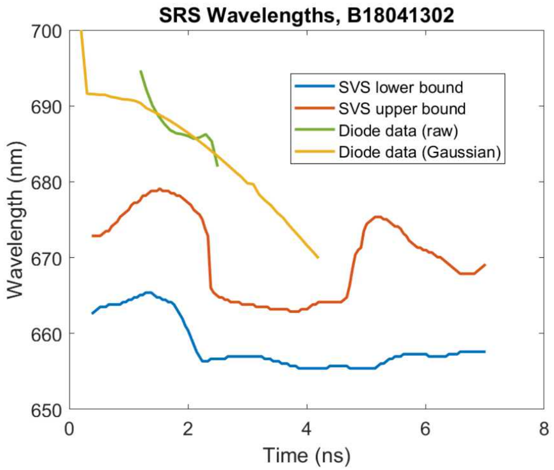




Extraction fails for non-Gaussian spectra and wavelengths outside the second diode's sensitivity

- Shots with a broad supercontinuum background or broad multipeaked spectra are not well handled by the model (no DPP shot below, diode's return constant wavelength ~700 nm)
- The second SRS diode has effectively zero response below 690 nm because of the color filter
- This means many of the lower density shots are unreliable (60 psi density corresponds to ~680 nm scattering)



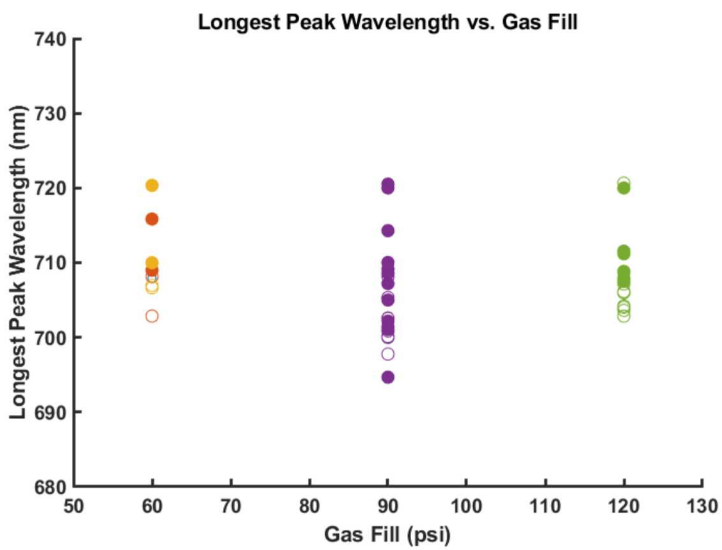


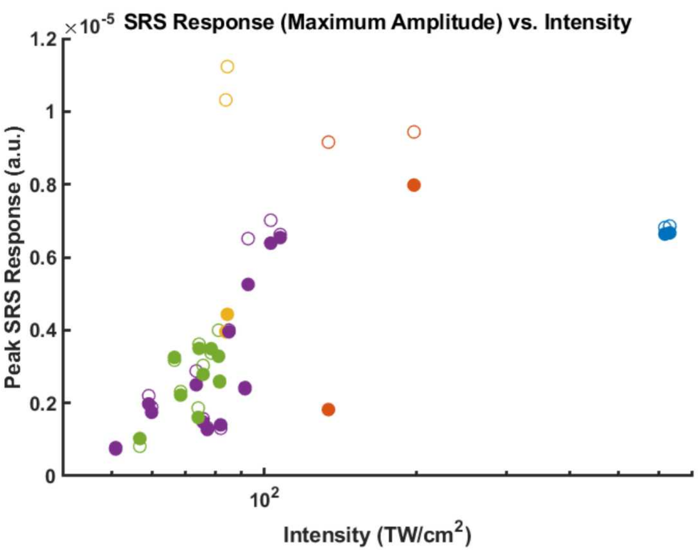
Analysis of full diode dataset shows interesting trends, with caveat that some shots are unreliable

- Co-injection shots consistently show scattering corresponding to densities below the fill pressure, indicating early gas/window expansion after the co-injection pre-pulse
- SRS increases with intensity and then saturates
  - Numbers may only be good to a factor of ~2-3x based on comparison of select shots with SVS

- Initial MagLIF Design (60 psi)
- DPP750 Config A (60 psi He)
- DPP1100 Config A (60 psi)
- DPP1100 co-injection (90 psi)
- DPP1100 co-injection (120 psi)

Open circles: Gaussian model

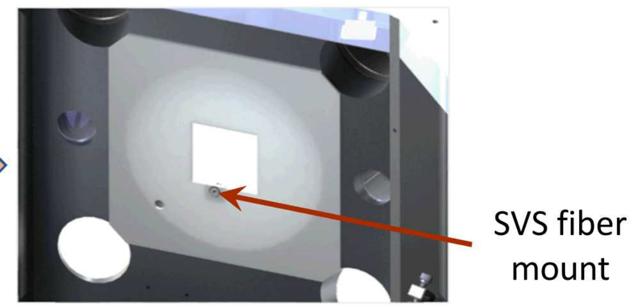




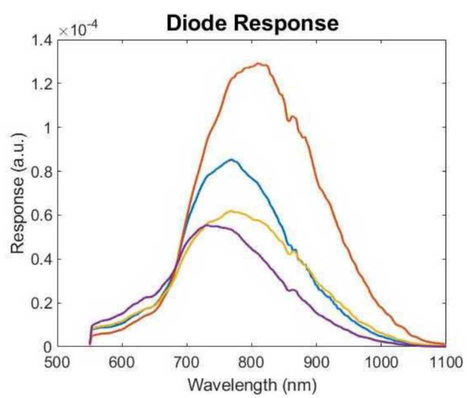
Plans to upgrade diode assembly to extend useful time window and better constrain spectra

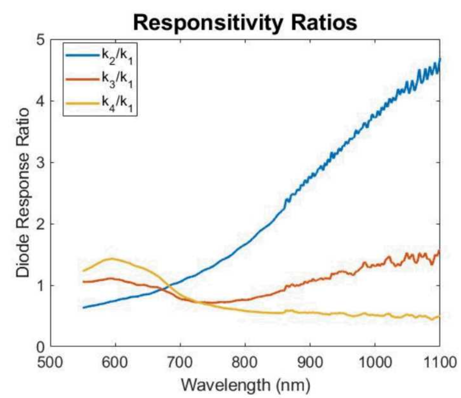
- Four diodes mounted on two lines of sight to scatter plate with beam-splitter cubes allows fit of more spectral parameters
- Wavelength dependence achieved with different combinations of ND filters
  - Each diode covers full range, preventing covariance matrix from diverging

External diode mounting



LOS to scatter plate





Summary

- Experiments on the Z Machine and related Z Backlighter facility support a wide range of scientific interests and national needs, including laboratory astrophysics, stockpile stewardship, inertial confinement fusion, materials physics and high energy density science

- MagLIF provides a possible route to high yield ICF by using fuel preheat and magnetization to relax requirements on implosion velocity and final hot spot conditions

- Experiments on the Pecos target chamber support preheat objectives for the MagLIF program and allow detailed diagnostics of high energy laser energy deposition in a plasma target

The work presented is the collective effort of many scientists and engineers (necessarily an incomplete list)

D.J. Ampleford, T.J. Awe, J.E. Bailey, D.E. Bliss, C.J. Bourdon, G.A. Chandler, P.J. Christenson, M.E. Cuneo, J.R. Fein, B.R. Galloway, M. Geissel, M.R. Gomez, K.D. Hahn, S.B. Hansen, E.C. Harding, A.J. Harvey-Thompson, M.H. Hess, B.T. Hutsel, C.A. Jennings, B. Jones, M.C. Jones, R.J. Kaye, M.W. Kimmel, P.F. Knapp, M.D. Knudson, G. Laity, D.C. Lamppa, M.R. Lopez, M.R. Martin, M. K. Matzen, L.A. McPherson, T. Nagayama, J.S. Lash, S. Patel, K.J. Peterson, J.L. Porter, G.A. Rochau, D.C. Rovang, C.L. Ruiz, M.E. Savage, P.F. Schmit, D. Scoglietti, M. Schollmeier, J. Schwarz, J.E. Shores, D.B. Sinars, S.A. Slutz, I.C. Smith, W.A. Stygar, R.A. Vesey, M.R. Weis, E.P. Yu, *Sandia National Laboratories*

R.R. Paguio, D.G. Schroen, G. Smith, K. Tomlinson, *General Atomics*

B.E. Blue, M.C. Herrmann, *Lawrence Livermore National Laboratories*

R.D. McBride, *University of Michigan*

A. B. Sefkow, *Laboratory for Laser Energetics*

D. Davis, *University of New Mexico*

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R.D. McBride, *University of Michigan*

A. B. Sefkow, *Laboratory for Laser Energetics*

D. Davis, *University of New Mexico*

Those directly involved in my work, or who contributed slides about Z/ZBL/MagLIF

Questions?

- About the science?
- About Sandia and the Z Facility?
- About working in a national lab?
- About the SSGF fellowship (provided support for this internship)?

Backup Slides

Density depression

- The decrease in density during preheat may indicate thermally driven expansion or filamentation (or both)
- This decrease shows a weak correlation with intensity, and differences in preheat protocols
- Too preliminary to make conclusions: new diode array needed