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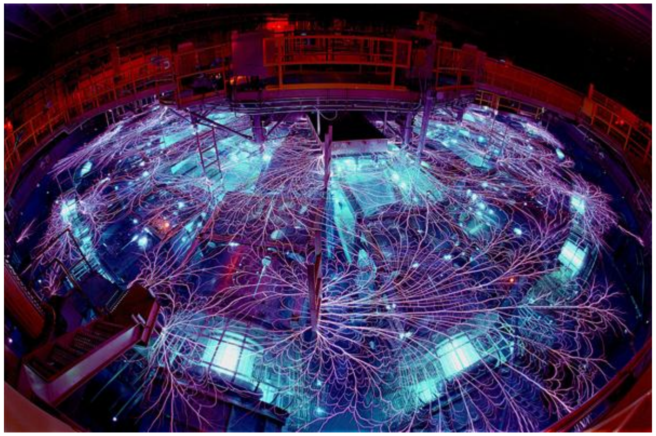
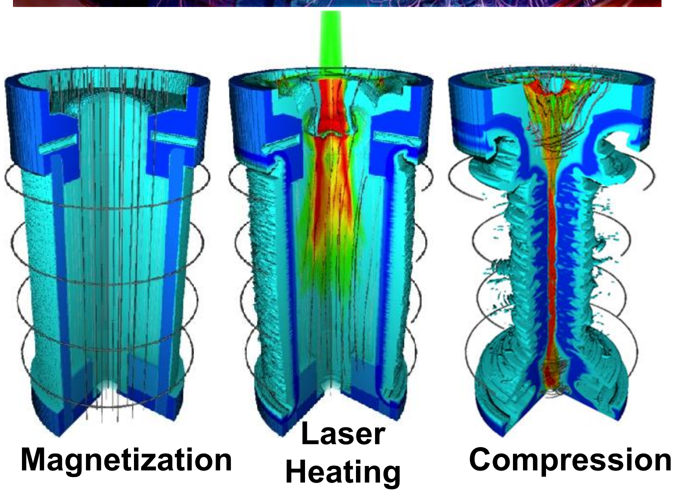


An overview of fusion, astrophysical experiments, and diagnostic development on Sandia's Z machine



Stephanie B. Hansen

Sandia National Laboratories

Presentation to the Laboratory for Plasma Studies
August 27, 2014

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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Outline

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- **Magnetized Liner Inertial Fusion (MagLIF)**
  Encouraging results from initial integrated experiments

- **Z Astrophysical Plasma Properties (ZAPP) Collaboration**
  Studies of emission and absorption from photoionized plasmas relevant to white dwarfs, accretion disks, and solar photosphere

- **Diagnostic development on Z**
  X-ray Thomson scattering and Zeeman splitting

There is a lot of interesting science going on at Z –
and many opportunities for significant contributions from Cornell's LPS.

The Sandia Z pulsed power facility uses magnetic pressure to efficiently couple energy to drive relatively large targets for a wide variety of stockpile stewardship applications

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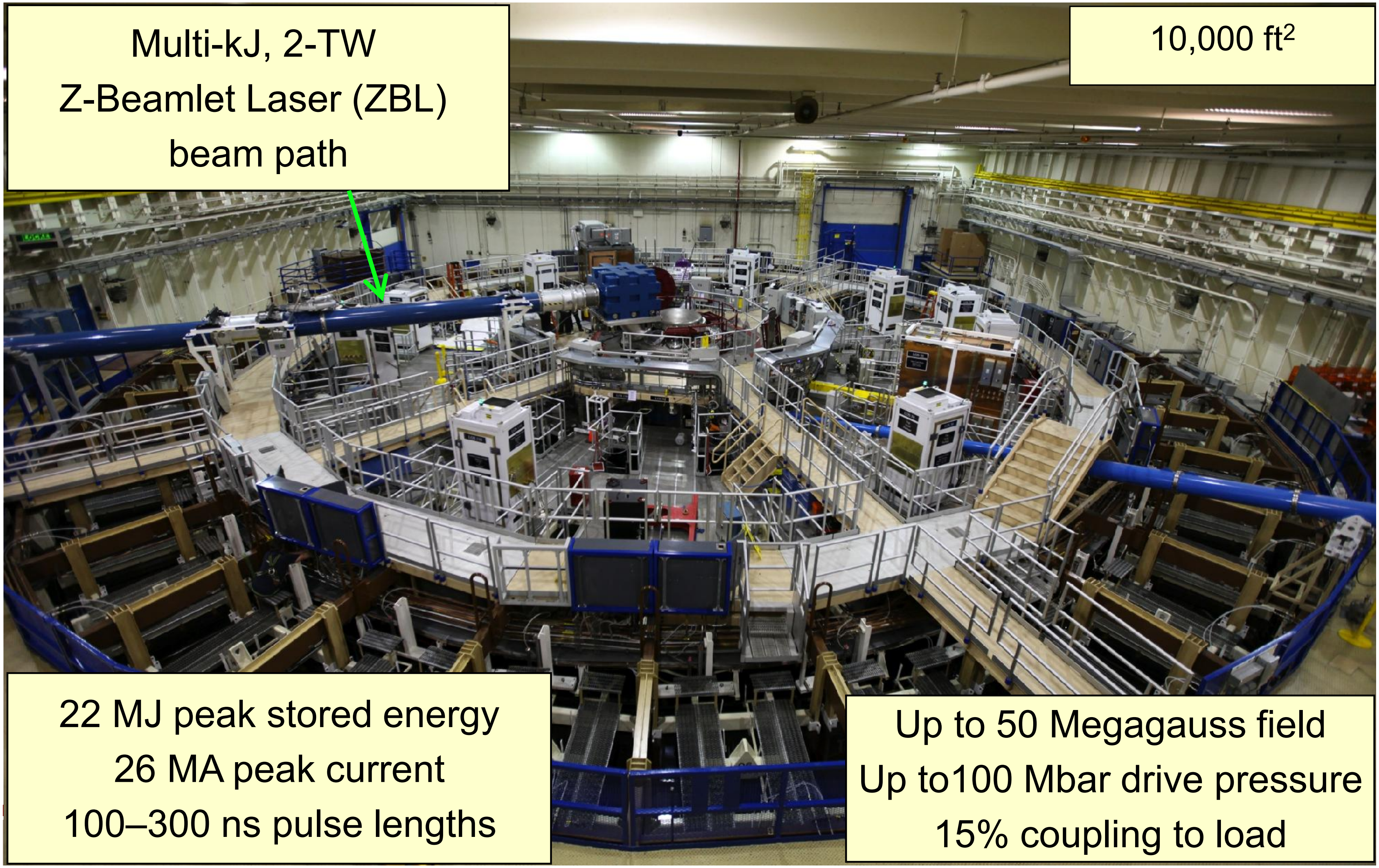
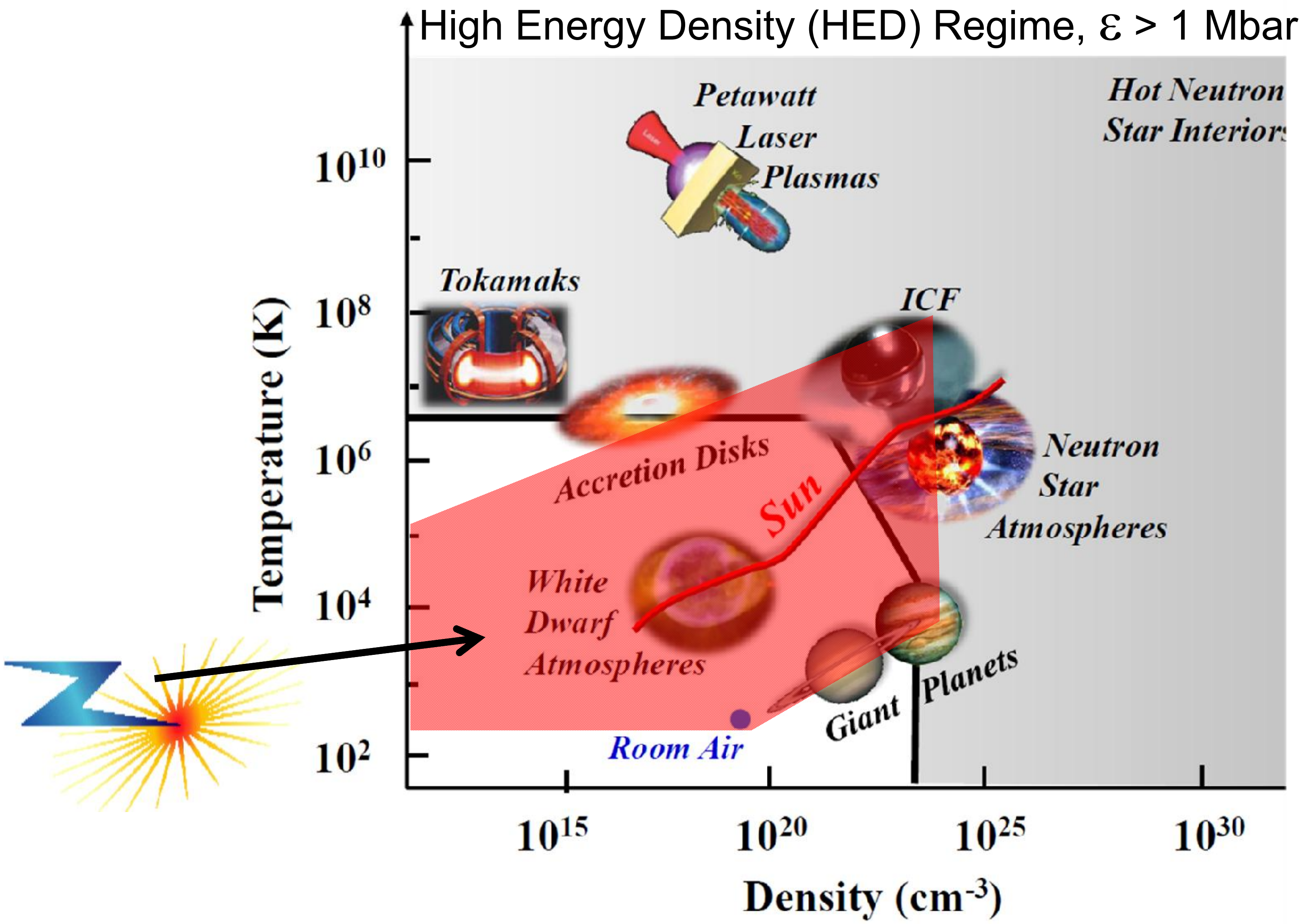


Experiments on Z access a broad range of the energy-density phase space



Many people are contributing to our Magnetized Liner Inertial Fusion (MagLIF) effort:

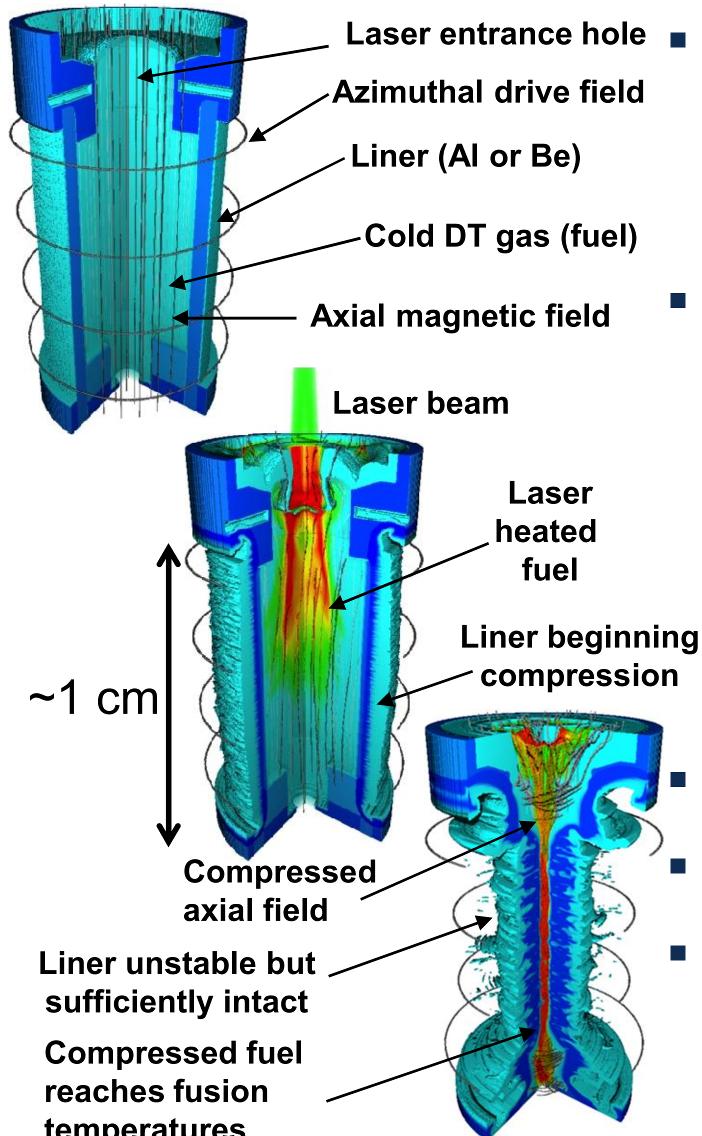
T.J. Awe, C.J. Bourdon, G.A. Chandler, P.J. Christenson, M.E. Cuneo, M. Geissel, **M.R. Gomez**, K.D. Hahn, S.B. Hansen, E.C. Harding, A.J. Harvey-Thompson, M.C. Herrmann, M.H. Hess, C.A. Jennings, B. Jones, M. Jones, R.J. Kaye, P.F. Knapp, D.C. Lamppa, M.R. Lopez, M.R. Martin, R.D. McBride, L.A. McPherson, J.S. Lash, K.J. Peterson, J.L. Porter, G.A. Rochau, D.C. Rovang, C.L. Ruiz, S.E. Rosenthal, M.E. Savage, P.F. Schmit, **A.B. Sefkow**, **D.B. Sinars**, **S.A. Slutz**, I.C. Smith, W.A. Stygar, R.A. Vesey, E.P. Yu

Sandia National Laboratories, Albuquerque, NM 87185 USA

B.E. Blue, D.G. Schroen, K. Tomlinson

General Atomics, San Diego, CA 92186 USA

We are evaluating a Magnetized Liner Inertial Fusion (MagLIF)* concept that may reduce fusion requirements

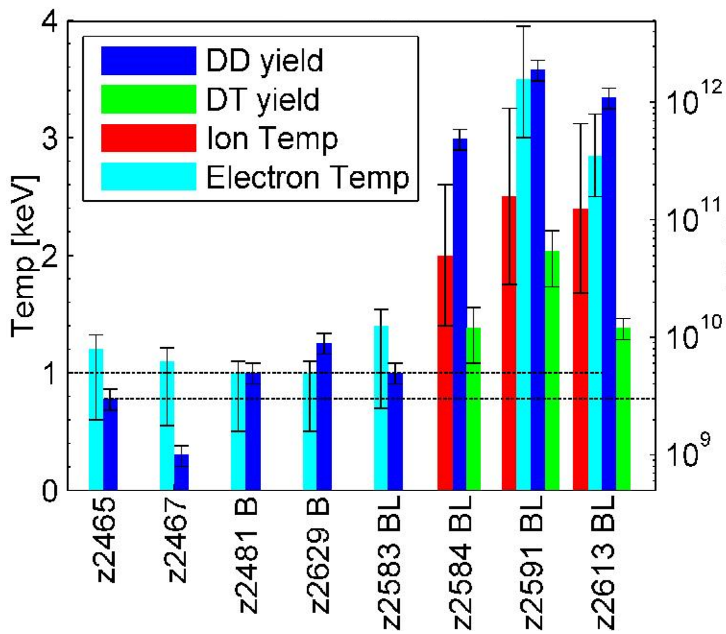


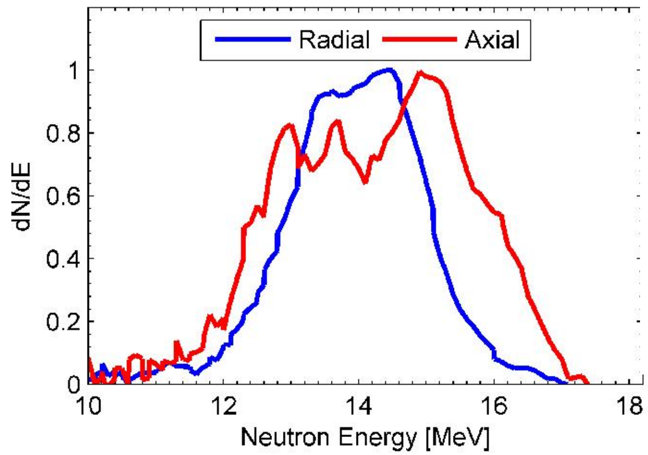
- An initial 30 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - Appears to stabilize implosion at late times
- During the ~100 ns implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ in designs)
  - Preheating to ~300 eV reduces the compression needed to obtain fusion temperatures to 23 on Z
  - Preheating reduces the implosion velocity needed to ~100 km/s, allowing us to use thick liners that are more robust against instabilities
- ~50-250 kJ energy in fuel; 0.2-1.4% of capacitor bank
- Stagnation pressure required is ~5 Gbar
- DD equivalent of 100 kJ DT yield may be possible on Z in the next few years—this will require enhanced drive upgrades that are in progress, e.g., 10 T → 30 T; 2 kJ → >6 kJ; 19 MA → >24 MA

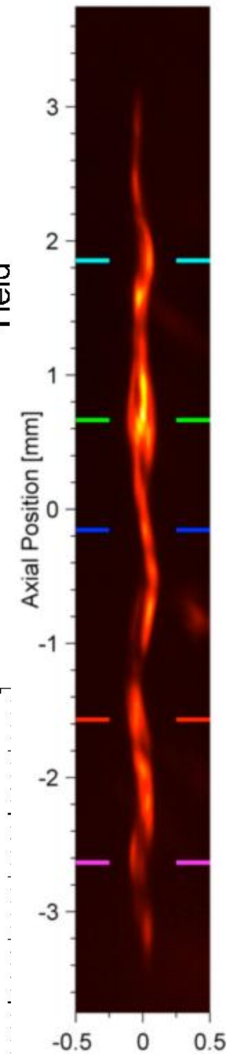
*S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010). S.A. Slutz and R.A. Vesey, Phys. Rev. Lett. (2012).

We obtained promising initial results with MagLIF and are seeking to increase our understanding

- We achieved DD yields up to 2e12 (~0.3 kJ DT equivalent) in our first integrated tests of Magnetized Liner Inertial Fusion (MagLIF)
- A variety of data were collected that appear to show a <150 μm diameter, ~3 keV, highly magnetized plasma was produced—remarkable for a 70-100 km/s implosion!
- We are continuing to build on these results with a balanced combination of focused and integrated experiments
- In parallel we are improving capabilities to understand how this performance will scale with increasing drive parameters







Our path to studying the underlying science is a mixture of focused and integrated experiments to address key physics

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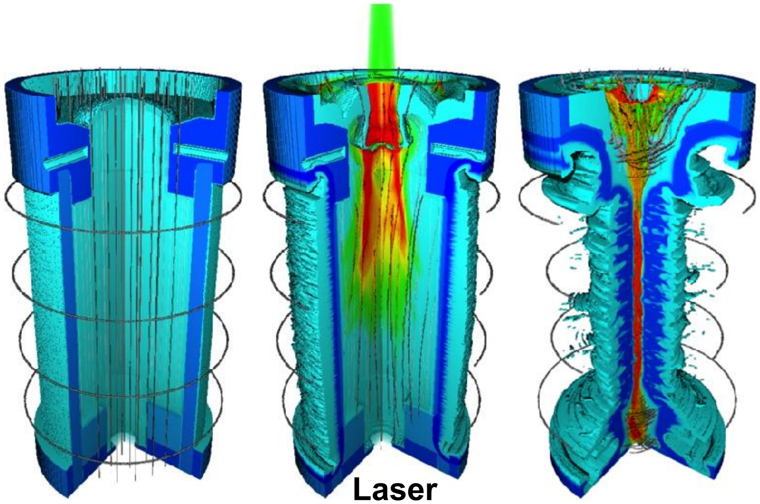


- Key target design elements
  - Liner compression
  - Magnetization
  - Laser heating

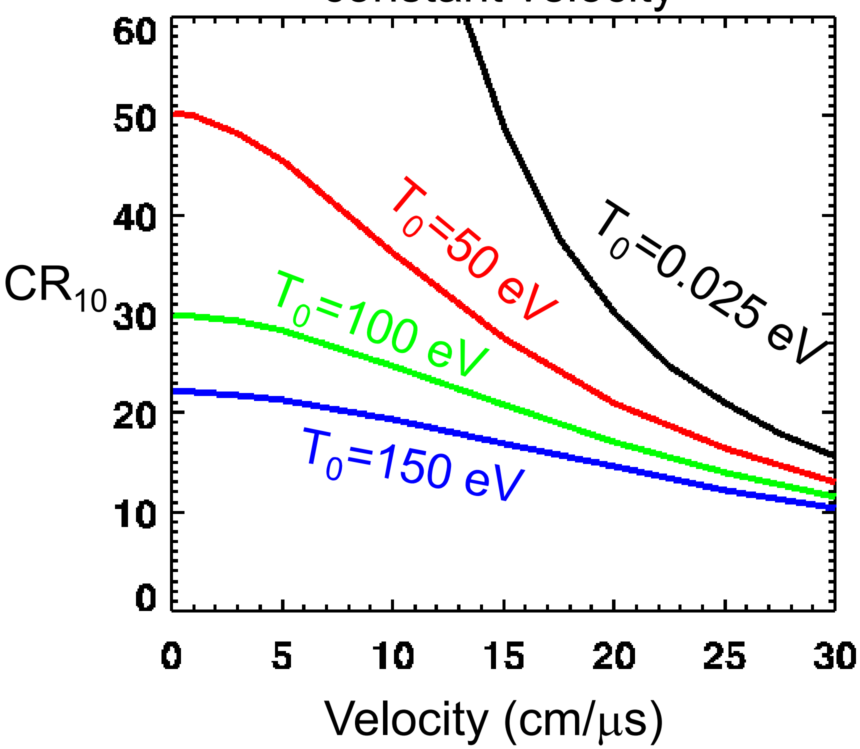
- Key physics uncertainties
  - Liner instabilities
    - Electro-thermal
    - Magneto-Rayleigh-Taylor
    - Deceleration RT
    - Impact of 3D fuel assembly
  - Liner/fuel interactions & mix
  - Laser-window and laser-fuel scattering, absorption, uniformity
  - Suppression of electron heat transport in dense plasma by magnetic fields
  - Magnetic flux compression
  - Magnetized burn

Experiments to address the key physics are planned for the Z pulsed power facility and the Z-Beamlet and Omega (and -EP) lasers.

Collaborative experiments on NIF may be helpful too!

Typical ICF implosions need high velocities to reach fusion temperatures—starting the implosion with heated fuel potentially reduces requirements

Lasnex simulation with constant velocity



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

Heating fuel to ignition temperatures is typically done with a high-velocity shock (or series of shocks)

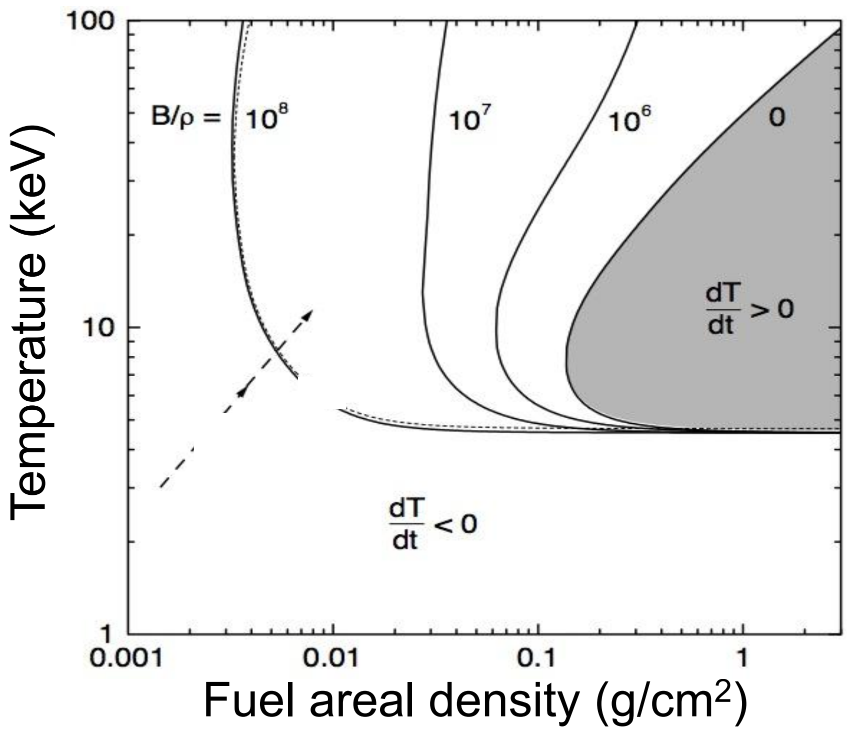
High velocities make it easier to reach fusion temperatures and also reduce the time available for losses (e.g., electron heat conduction or radiation)

Heating the fuel prior to the implosion *in the absence of losses* can allow low-velocity, low-convergence implosions to reach ignition temperatures

Is there a way to reduce losses?

A large, embedded magnetic field can significantly reduce electron conduction losses from heated fuel

*Basko et al. *Nuc. Fusion* 40, 59 (2000)



The ρr needed for ignition can be significantly reduced by the presence of a strong magnetic field largely through inhibiting electron conduction

Lower ρr reduces the required final fuel density (e.g., ~1 g/cc << 100g/cc), which also reduces bremsstrahlung radiation losses

This means the stagnation plasma pressure at ignition temperatures is significantly reduced (e.g., ~5 Gbar << ~500 Gbar for hot spot ignition)

Large values of B/ρ are needed and therefore large values of B are needed, B ~ 10,000 Tesla (Earth's B-field is ~0.00003 Tesla)

This field significantly exceeds pulsed coil technology (B_0 ~10-30 T), therefore flux compression is needed

Many groups want to use magnetic fields to relax inertial fusion stagnation requirements

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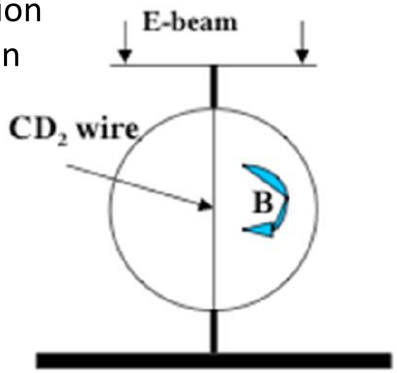
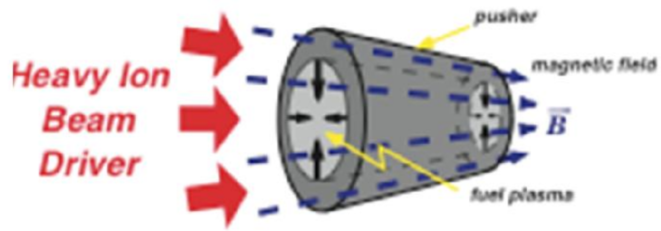
SNL Phi Target

1982 Demonstration of enhanced fusion yield with magnetization (~1e6 DD yield)



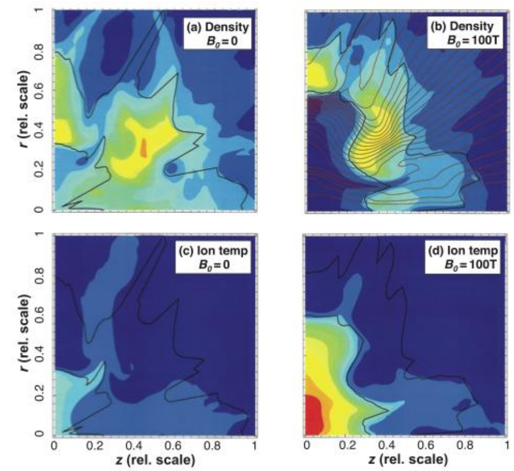
Max Planck/ITEP



Basko, Kemp, Meyer-ter-Vehn, *Nucl. Fusion* **40**, 59 (2000)
Kemp, Basko, Meyer-ter-Vehn, *Nucl. Fusion* **43**, 16 (2003)

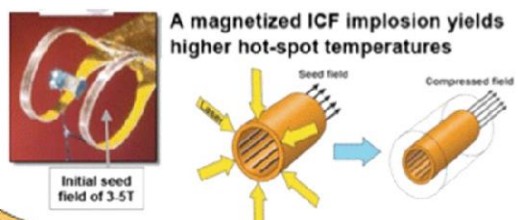
LLNL

(Perkins et al., Phys Plasmas 2013)

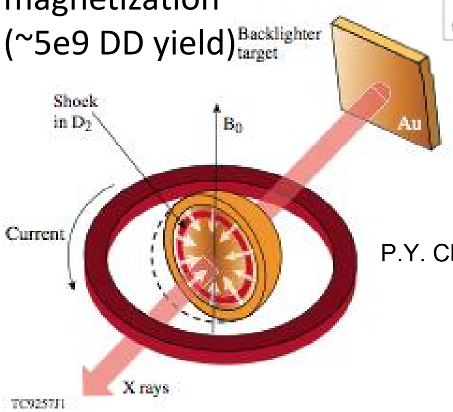


University of Rochester/LLE

2011 Demonstration of enhanced fusion yield with magnetization (~5e9 DD yield)



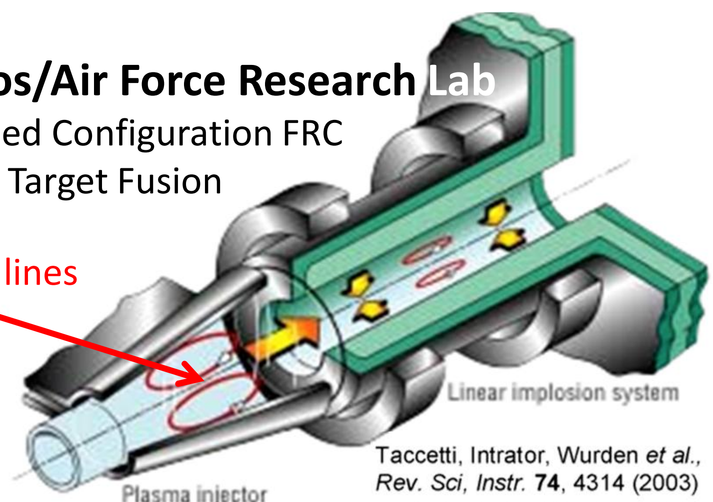
Gotchev *et al.*, *Rev. Sci. Instr.* **80**, 043504 (2009)



P.Y. Chang *et al.*, PRL (2011).

Los Alamos/Air Force Research Lab

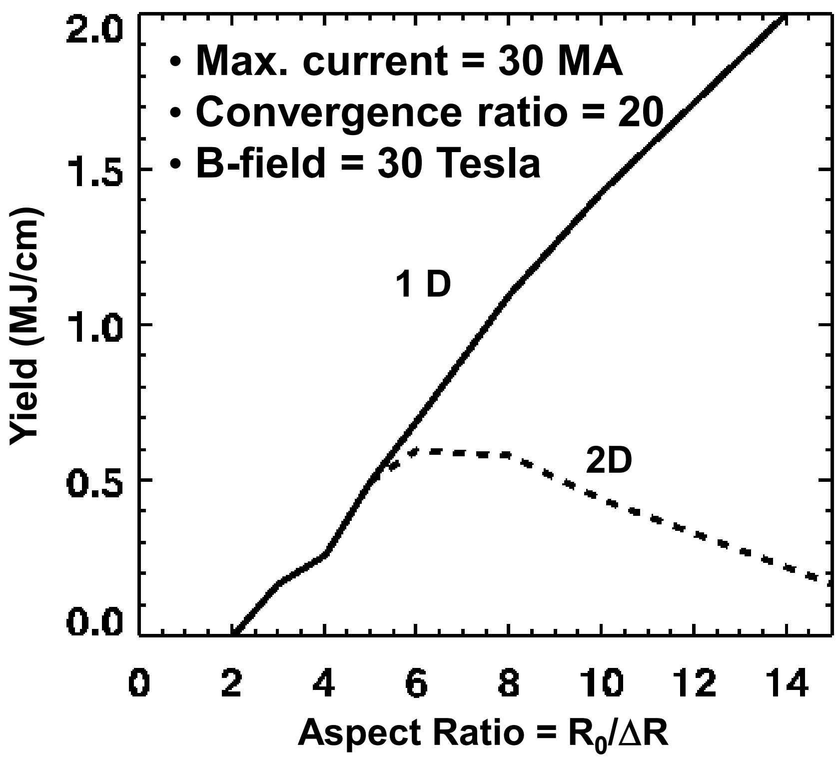
Field Reversed Configuration FRC
Magnetized Target Fusion
Shiva Star
closed field lines
FRC

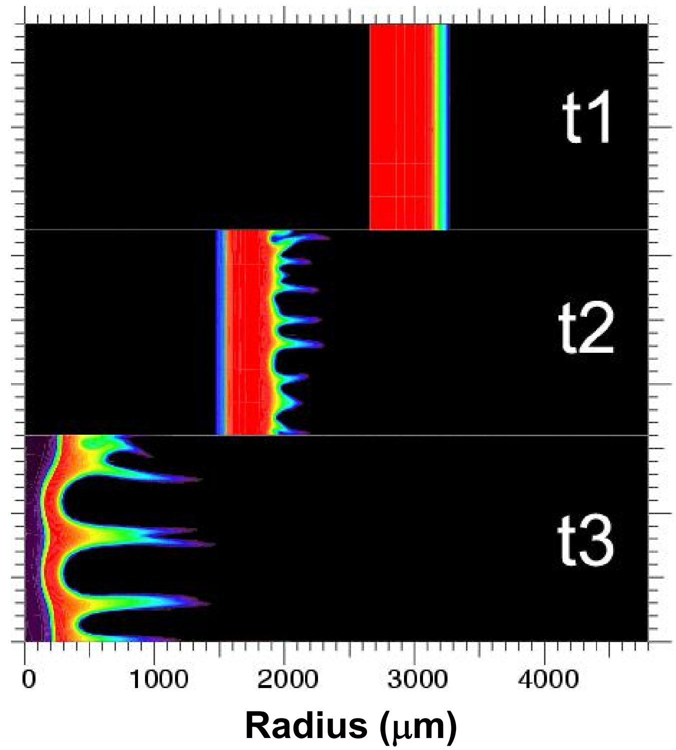


Taccetti, Intrator, Wurden *et al.*, *Rev. Sci, Instr.* **74**, 4314 (2003)
Degnan *et al.*, *IEEE Trans. Plas. Sci.* **36**, 80 (2008)

and many others…

Reducing the implosion velocity requirements through fuel heating and magnetization allows us to use thicker, more massive liners to compress the fuel that are more stable





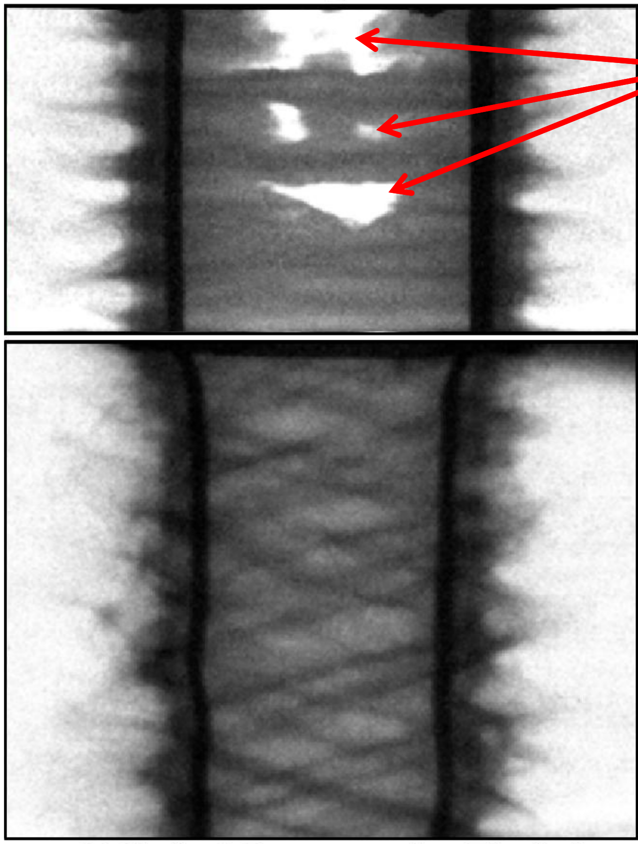
• The Magneto-Rayleigh-Taylor instability degrades the yield as the aspect ratio is increased (due to decreased liner ρR)

• Simulations of AR=6 Be liner show reasonably uniform fuel compression and sufficient liner ρR at stagnation to inertially confine the fuel—important because fuel density is low!

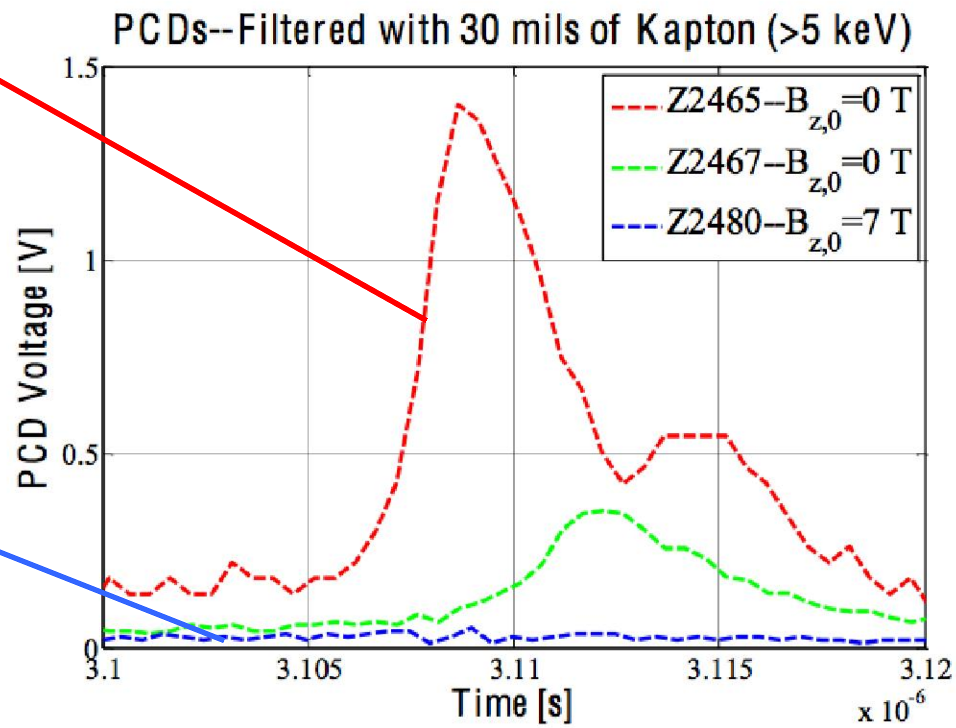
S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

Adding an axial magnetic field reduces hard x rays and hot spots, and changes the liner instability structure from cylindrical to helical—evidence it is doing something!

Without Magnetic Field



Time-integrated self-emission from liner implosion at 6151 eV; missing in shots with axial field



With Magnetic Field

If magnetic flux roughly conserved the additional magnetic pressure from the axial field will suppress micro-pinching—this is indirect evidence for flux compression

T.J. Awe *et al.*, Phys. Rev. Lett. (2013); *ibid.*, Phys. Plasmas (2014).

The target design for our initial experiments incorporates the knowledge gained from focused experiments and extensive simulations

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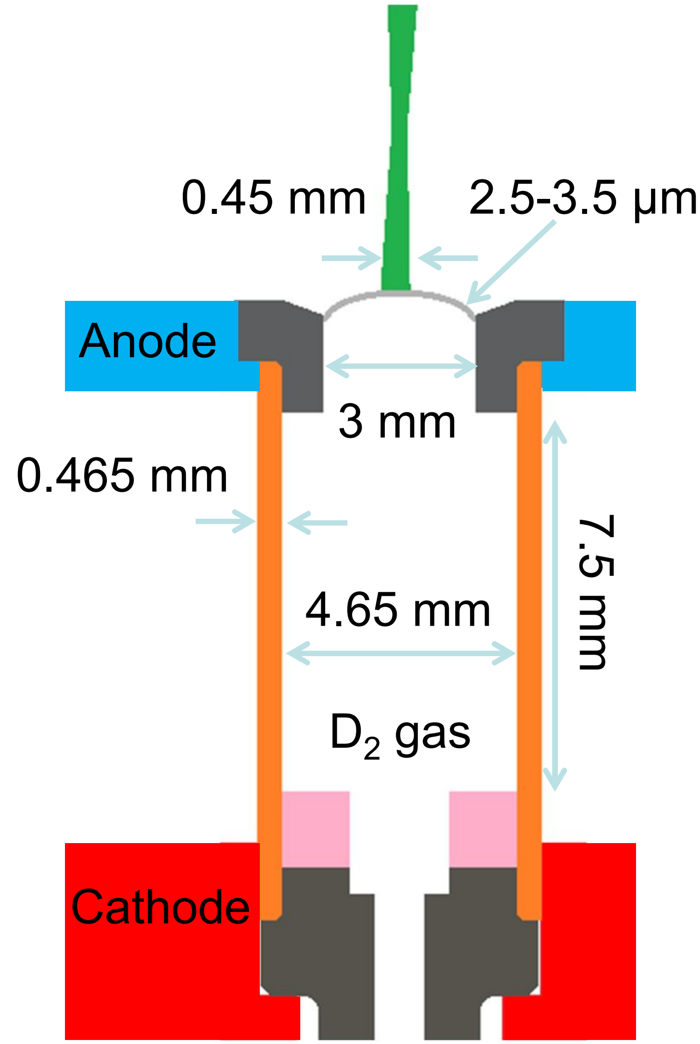
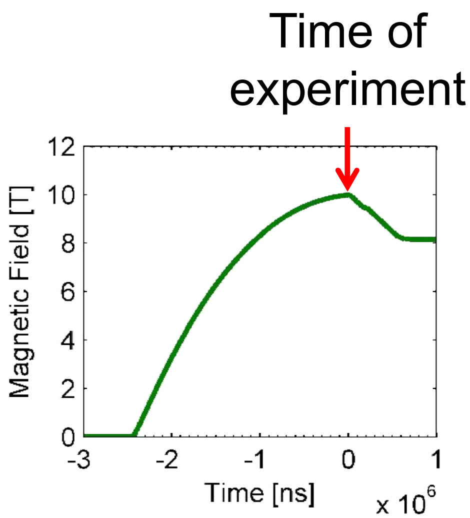
- **Beryllium liner with aspect ratio 6**
  - **Thick liner is more robust to instabilities**
  - **Still allows diagnostic access > 5 keV**
- **Top and bottom implosion cushions**
  - **Mitigates wall instability**
- **Standoff between LEH and imploding region**
  - **Avoid window material mixing with fuel**
- **Exit hole at bottom of target**
  - **Avoid interaction with bottom of target**

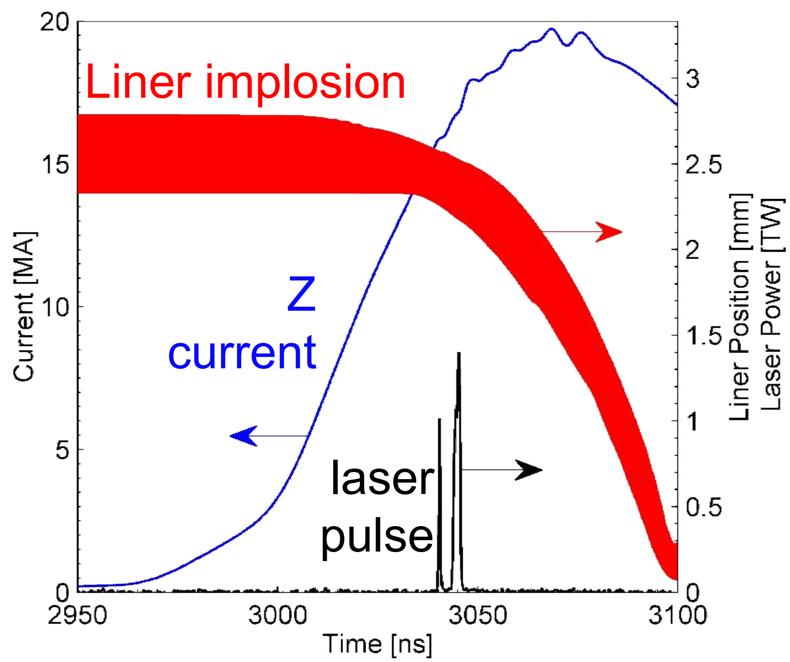


Initial experiments were conducted at I = 19 MA, B = 10 T, and Laser = 2.5 kJ



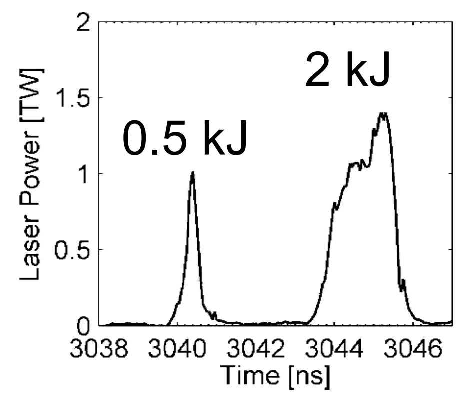
Magnetic field risetime is approximately 2 ms

B is constant over the timescale of the experiment

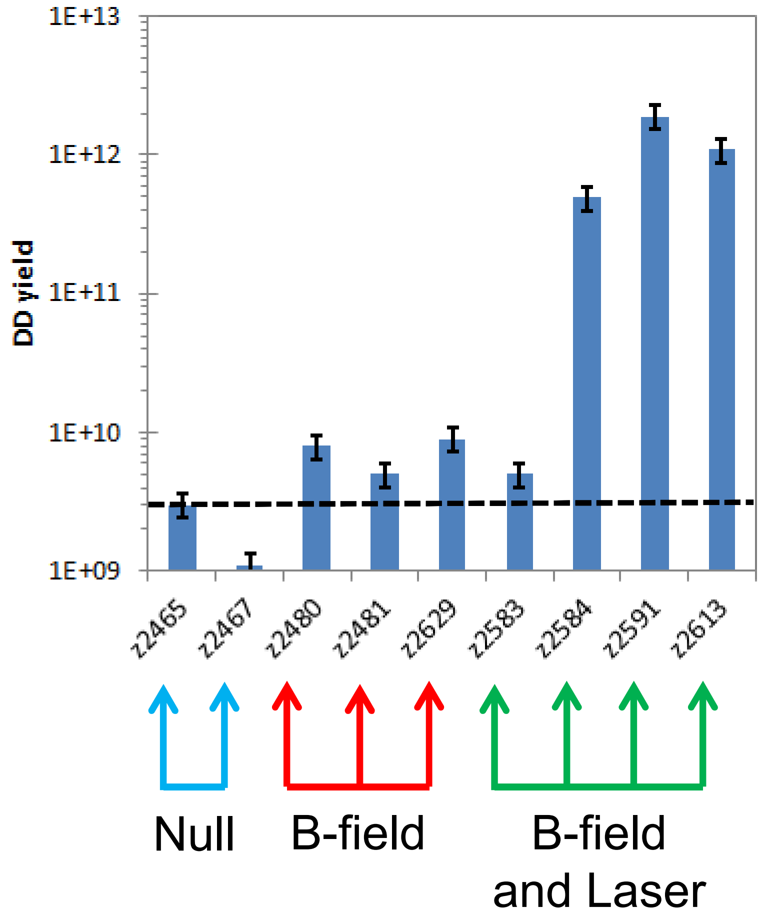


Peak current is 19 MA
Magnetic field is 10 T
Total laser energy is 2.5 kJ

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



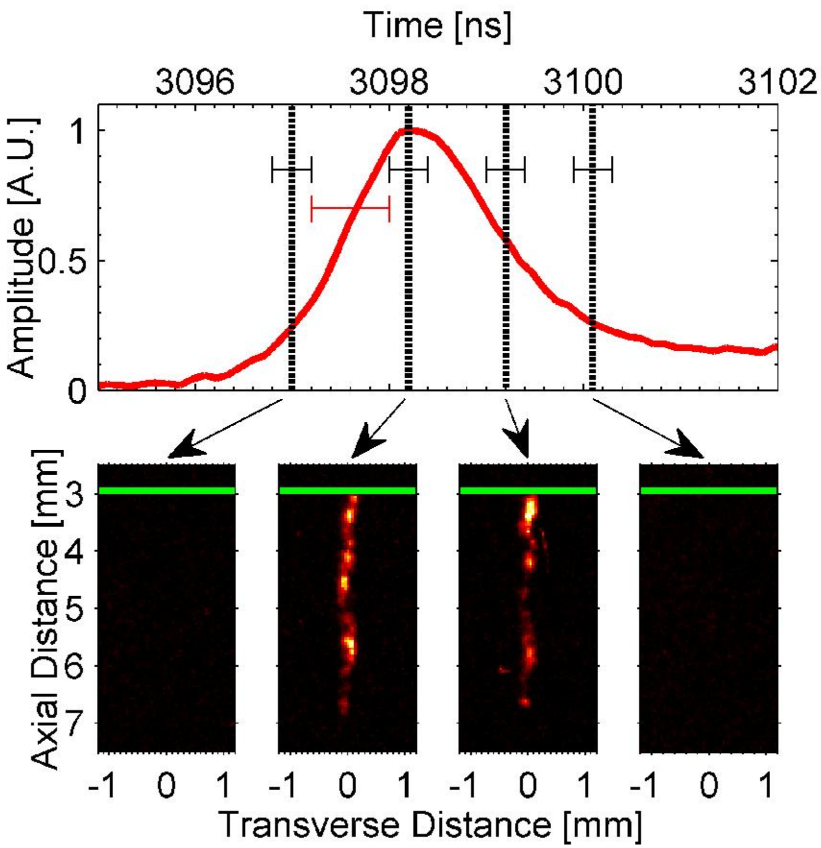
Z shots producing DD yields in excess of 10^{12} were only observed in experiments with laser and B-field



- High yields were only observed on experiments incorporating both applied magnetic field and laser heating
- A series of experiments without laser and/or B-field produced yields at the background level of the measurement
- Result of z2583 is not well understood nor reproduced at this time

M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, to be published in PRL (2014).

Time-resolved x-ray pinhole imaging (hν > 2.8 keV) shows a narrow emission column during peak in X-ray signal

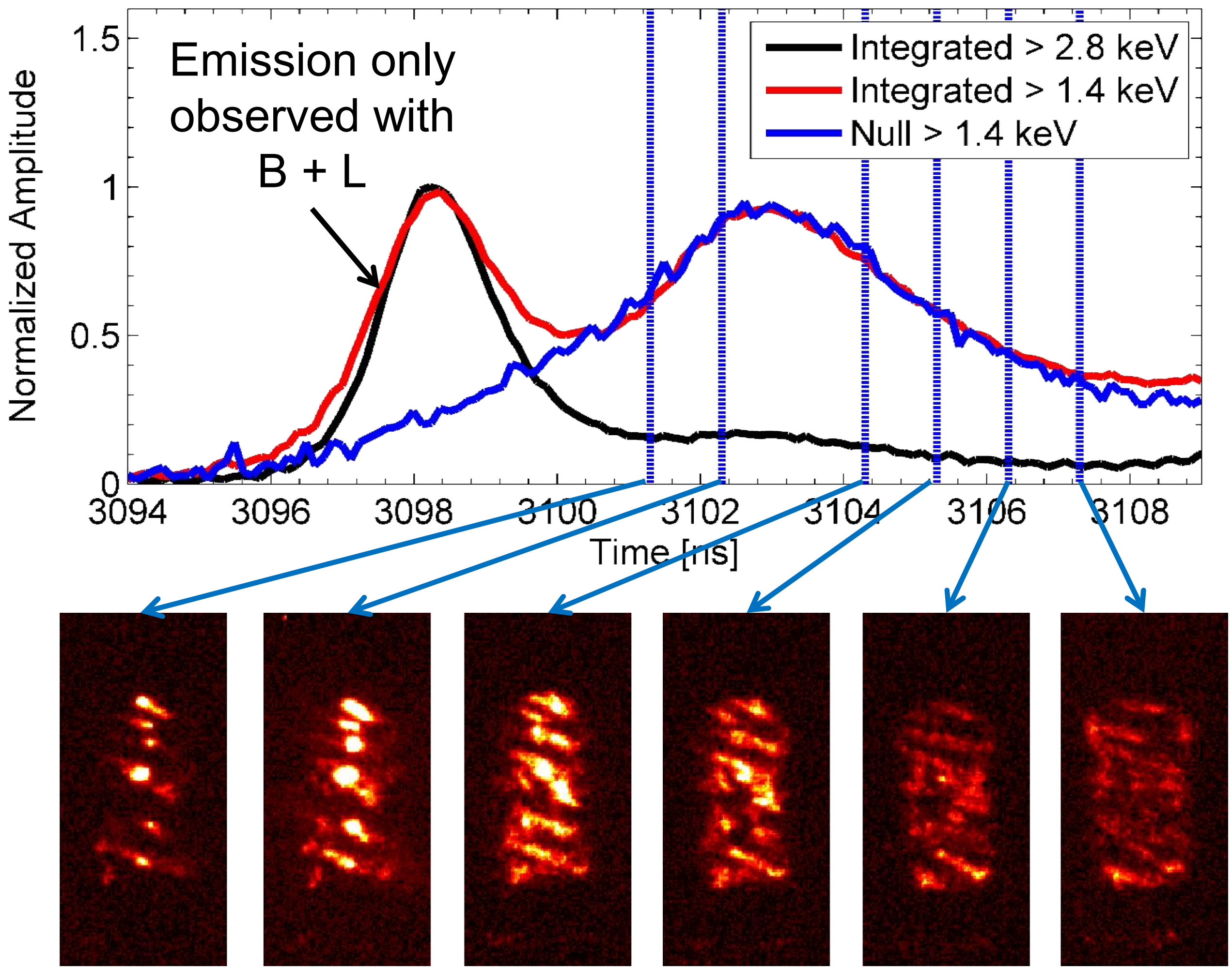


- Emission column is observed only during the peak in the x-ray signal
- Emission column is only observed on experiments with high neutron yield
- Stagnation column width is at the resolution limit of this instrument (~150 microns)

M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, to be published in PRL (2014).

High energy x-ray signal and narrow emission region are absent in null experiments

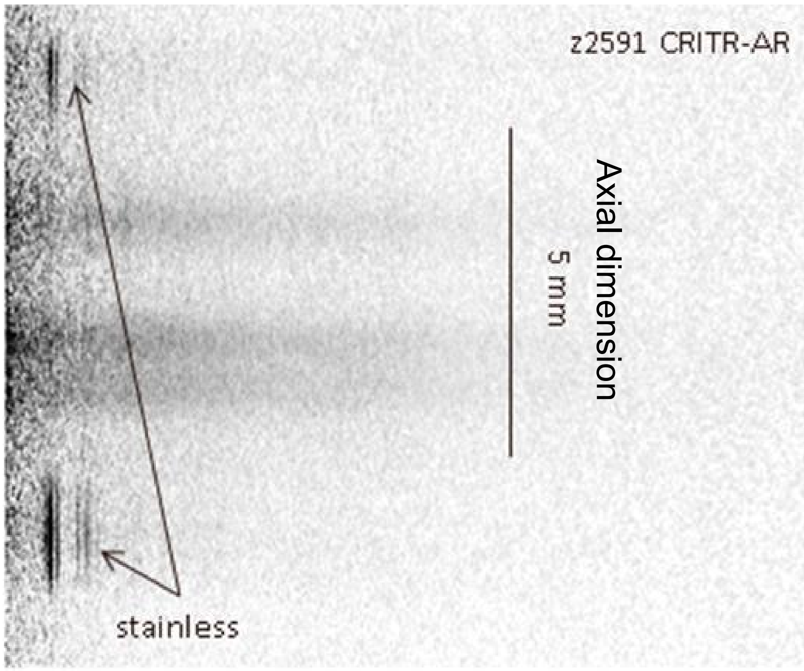
- **Liner emission is observed in all experiments**
- **Liner emission is at a lower photon energy (< 2.8 keV)**
- **Liner emission is getting larger at late times**



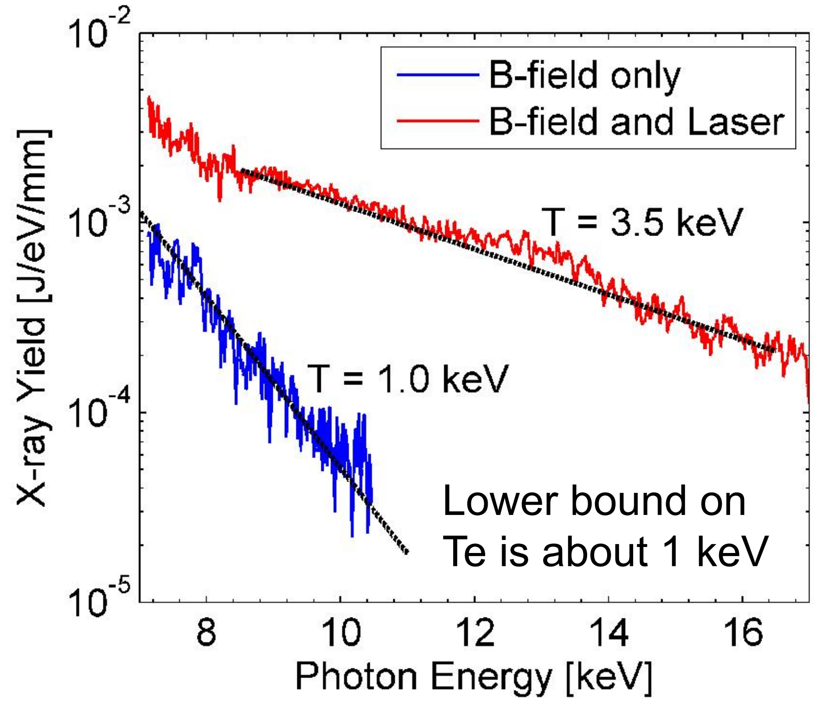
M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, to be published in PRL (2014).

High-energy spectra show axial variations in temperature and composition, with ~3.5 keV electron temperature in the pinch region—remarkable for a 70-100 km/s implosion!

Emission lines from stainless steel (Fe, Cr, Ni) appear at the anode and cathode, but minimal high-Z contamination is observed in hot central regions



The slope of the high-energy continuum emission implies Te ~ 1.5 keV at the anode and cathode, and T ~ 3.5 keV in the central regions

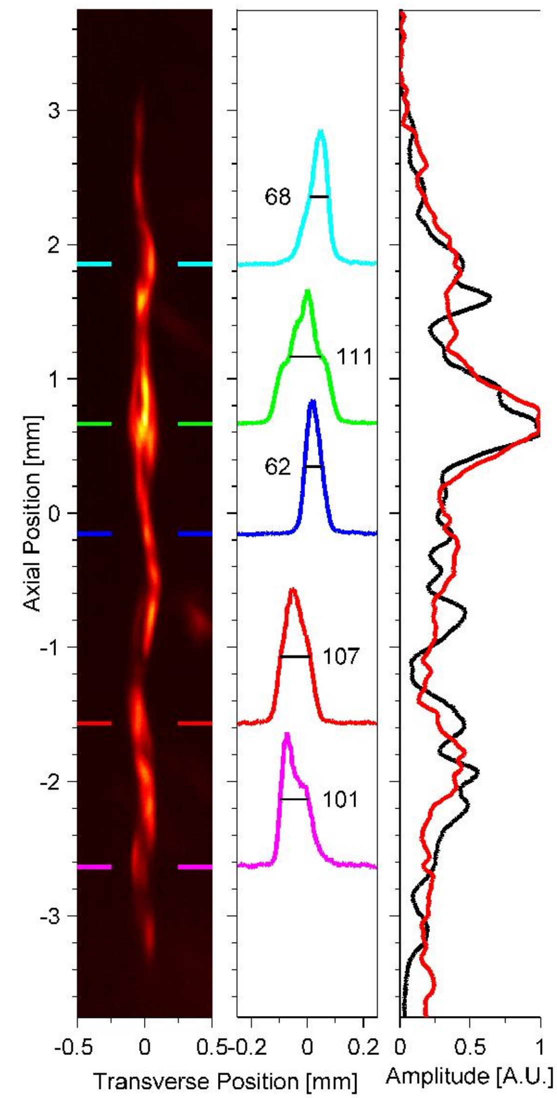


The measured electron temperature is close to the ion temperature obtained from neutron time-of-flight data; x-ray emission yields are consistent with fuel ρ ~ 0.4 g/cm^3

M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, to be published in PRL (2014).

High-resolution monochromatic imaging of the x-ray emission shows a narrow, hot plasma column with weakly helical structure

- Lineouts of stagnation column vary from 60 to 120 μm FWHM (resolution about 60 μm)
- Emission is observed from about 6 mm of the 7.5 mm axial extent
- Note that the emission doesn't necessarily define the fuel-liner boundary, but only the hot fuel region
- The stagnation column is weakly helical with a wavelength of about 1.3 mm and a 0.05 mm horizontal offset
- Axial lineouts of image (black) agree with 9.3 keV 1D spectrometer lineouts (red), suggesting features are due to emission and not liner opacity (Be opacity >9 keV small).
- With $\rho \sim 0.4$ g/cm^3, $\rho r \sim 2$ mg/cm^2



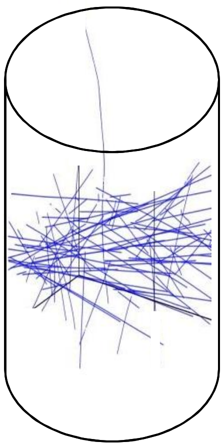
M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, to be published in PRL (2014).

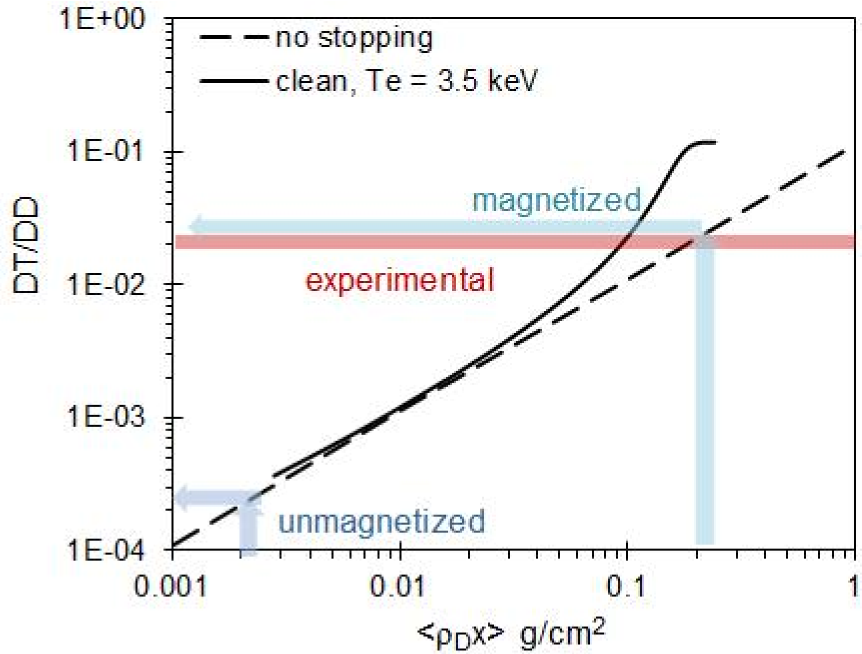
In addition to the significant ~2x10^{12} DD neutron yields, we measure a remarkable ~5x10^{10} DT neutrons

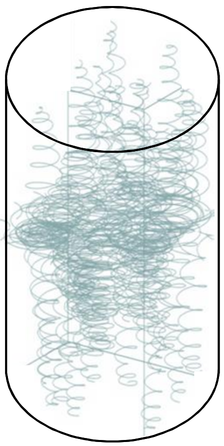
“Secondary” 14 MeV neutrons can be produced by 1 MeV tritons interacting with D fuel

D + D $\xrightarrow{50\%}$ 0.8 MeV He^3 + 2.5 MeV n

$\searrow^{50\%}$ 1.0 MeV T + 3 .0 MeV p





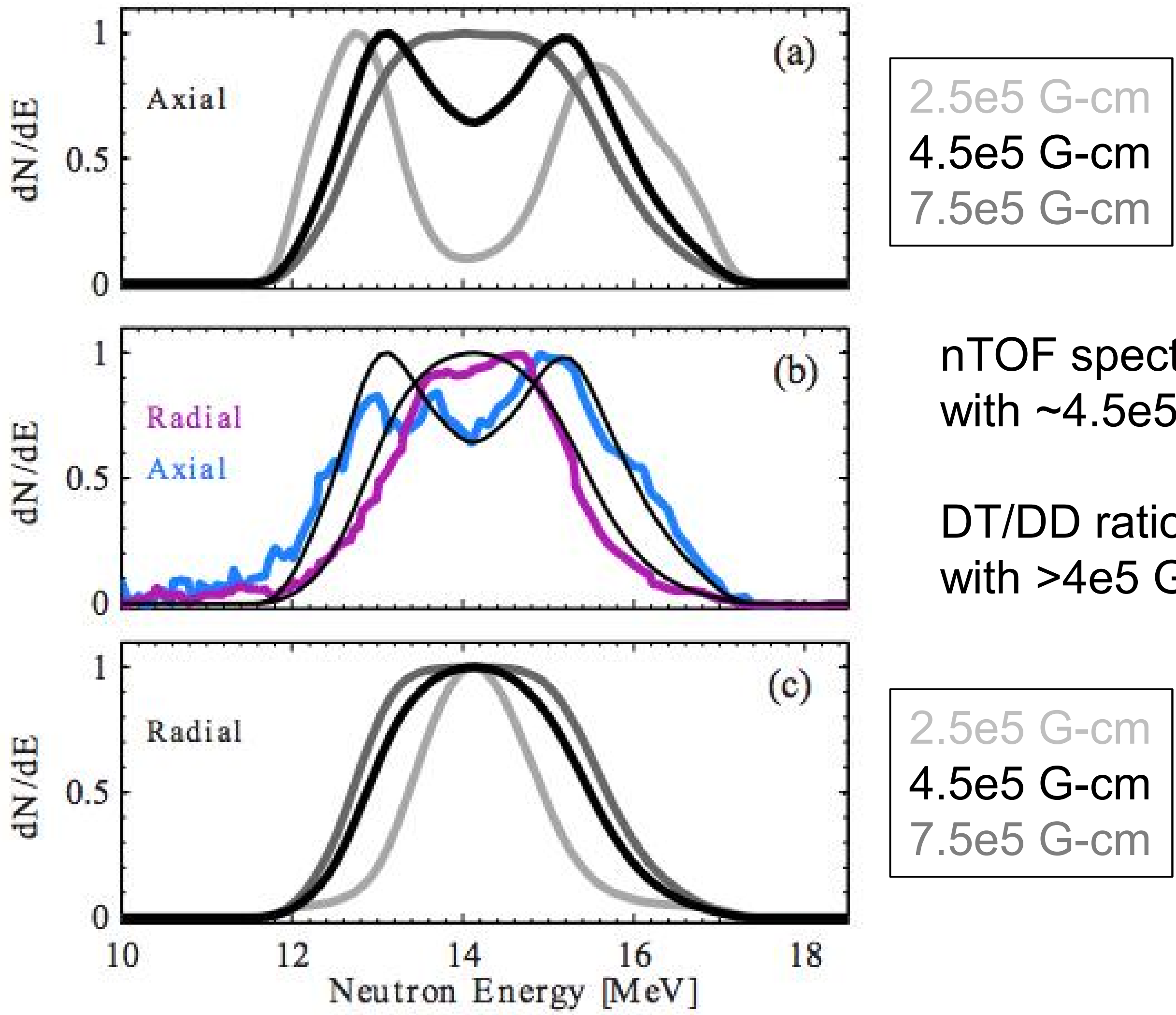


Unmagnetized plasmas must reach pressures of ~500 Gbar and ρR > 0.2 g/cm^2 to achieve the α-particle confinement required for ignition

In magnetized plasmas, thermal confinement and α-deposition are both enhanced by B, reducing pressure and ρR requirements by factors of ~100.

A field that confines tritons also confines electrons -- and will confine alphas!

Neutron time-of-flight data are consistent with high magnetization



nTOF spectra consistent with ~4.5e5 G-cm

DT/DD ratio consistent with >4e5 G-cm

P.F. Schmit, P.F. Knapp, S.B. Hansen *et al.,* to be published in PRL (2014).

MagLIF Summary

- Results from initial MagLIF experiments have been encouraging, with significant DD and DT yields and strong evidence for good stability, confinement, and scaling
- A helical stagnation column with T~3 keV, r~0.4 g/cc, r ~ 50 um, and Bz ~ 10 kT is consistent with an extensive collection of neutron and x-ray data
- Both integrated and focused experiments are ongoing
- Better understanding of how high magnetic fields affect thermal transport and stopping power will increase confidence in our predictions for yield scaling with increasing current, external field, and laser power

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- **Magnetized Liner Inertial Fusion (MagLIF)**
  Encouraging results from initial integrated experiments

- **Z Astrophysical Plasma Properties (ZAPP) Collaboration**
  Studies of emission and absorption from photoionized plasmas relevant to white dwarfs, accretion disks, and solar photosphere

- **Diagnostic development on Z**
  X-ray Thomson scattering and Zeeman splitting

There is a lot of interesting science going on at Z –
and many opportunities for significant contributions from Cornell's LPS.

These efforts represents a large collaboration between the NNSA labs and the academic community

Sandia National Laboratories

Jim Bailey, Taisuke Nagayama, Guillaume Loisel, Stephanie Hansen, Dave Bliss, Tom Nash, Tom Ao, Eric Harding, Greg Rochau, Matt Gomez, Michael Desjarlais
Sandia National Laboratories

Roberto Mancini, Iain Hall, Tom Lockard, Dan Mayes
University of Nevada – Reno

Don Winget, Mike Montgomery, Ross Falcon, Thomas Gomez, Alan Wootton, Jennifer Ellis, Sean Moorhead, Roger Bengtson
University of Texas – Austin

Anhil Pradhan, C. Orban, Mark Pinsonneault, and S.N. Nahar
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Mark Koepke, Ted Lane, Matt Flaugh
West Virginia University

Duane Leidahl, Carlos Iglesias, Brian Wilson
Lawrence Livermore National Laboratory

Manolo Sherrill, Heidi Tierney ,Chris Fontes, James Colgan, Dave Kilcrease
Los Alamos National Laboratory

C. Blancard, Ph. Cosse, G. Faussurier, F. Gilleron, J.C. Pain
French Alternative Energies and Atomic Energy Commission (CEA)

Joe MacFarlane, Igor Golovkin
Prism Computational Sciences

Laura Johnson
Cornell University

We are interested in developing new collaborations

ZAPP experiments measure the fundamental properties of atoms in plasmas to solve important astrophysical puzzles:

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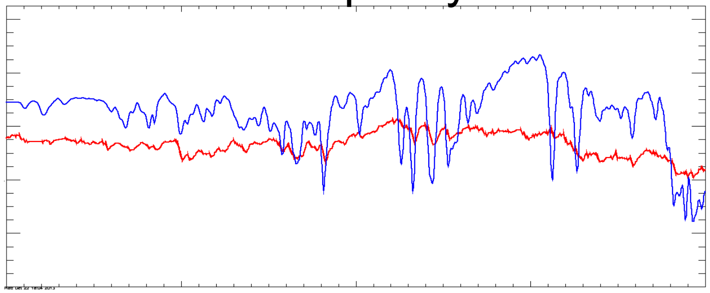
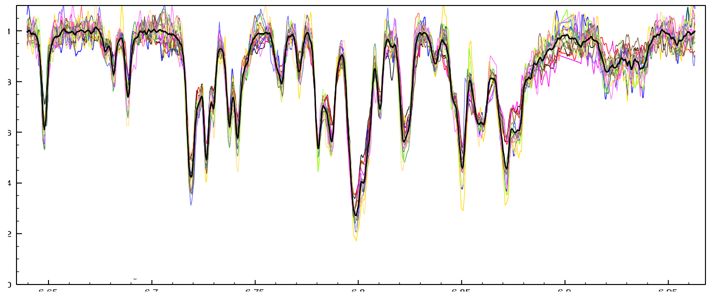
- Why can't we predict the location of the convection zone boundary in the Sun?
  - ➢ Opacity of Fe at T~200 eV
- How does ionization and line formation occur in accreting objects and warm absorbers?
  - ➢ Ionization distribution and spectral properties of photoionized Ne and Si
- Why doesn't spectral fitting provide the correct properties for White Dwarfs?
  - ➢ Stark-broadened H-Balmer line profiles

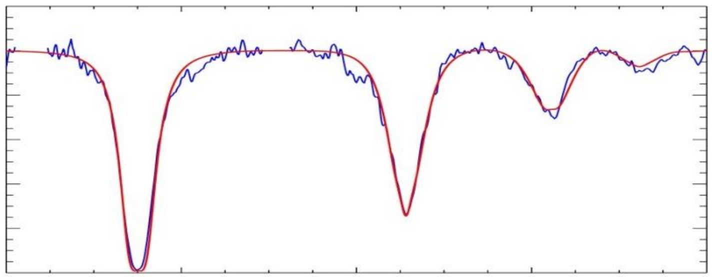
Fe Opacity



Si Photoionization



H-Balmer Line shapes



The ZPDH x-ray emission is reproducible to ± 10% in peak power and ± 7% in energy

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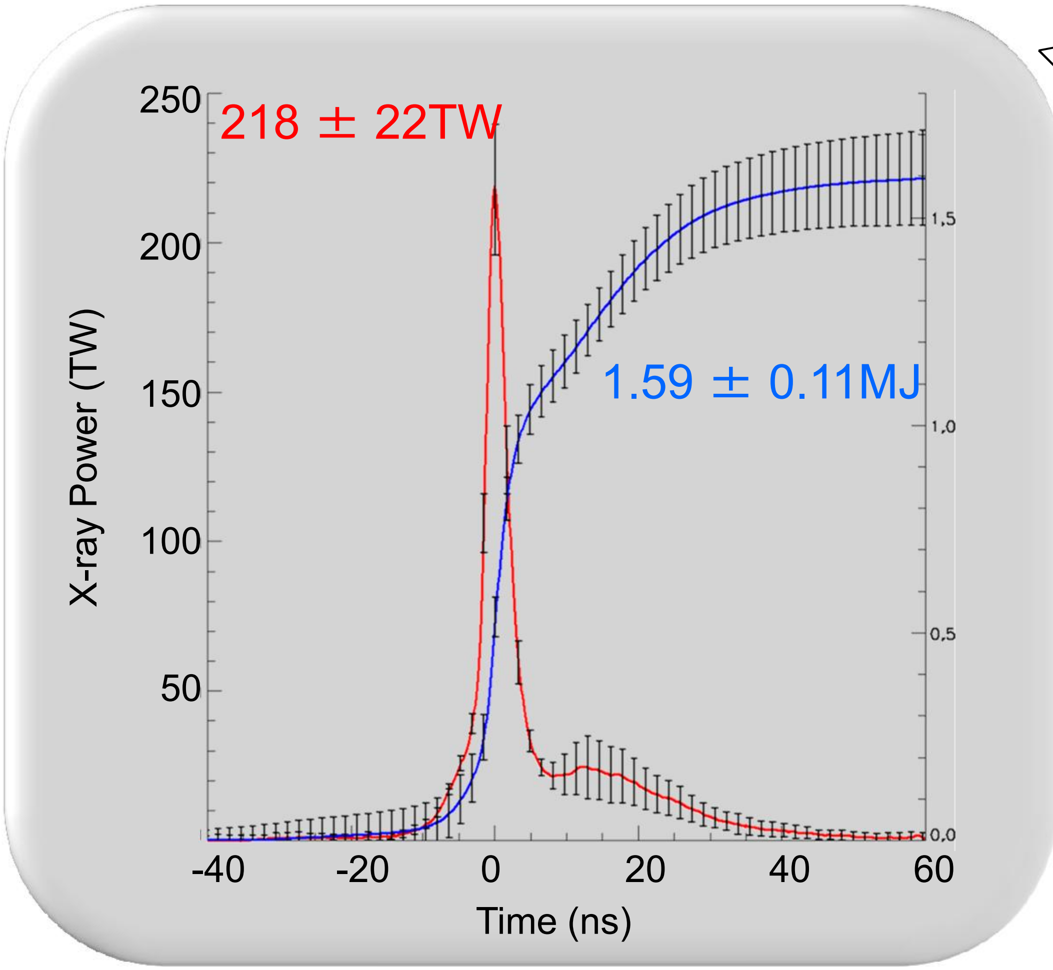
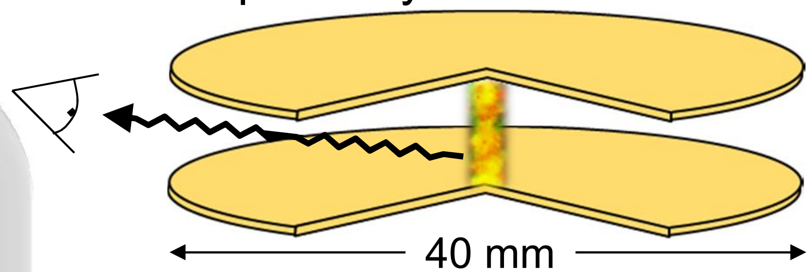
Radial X-ray Power and Energy (20 shot average)



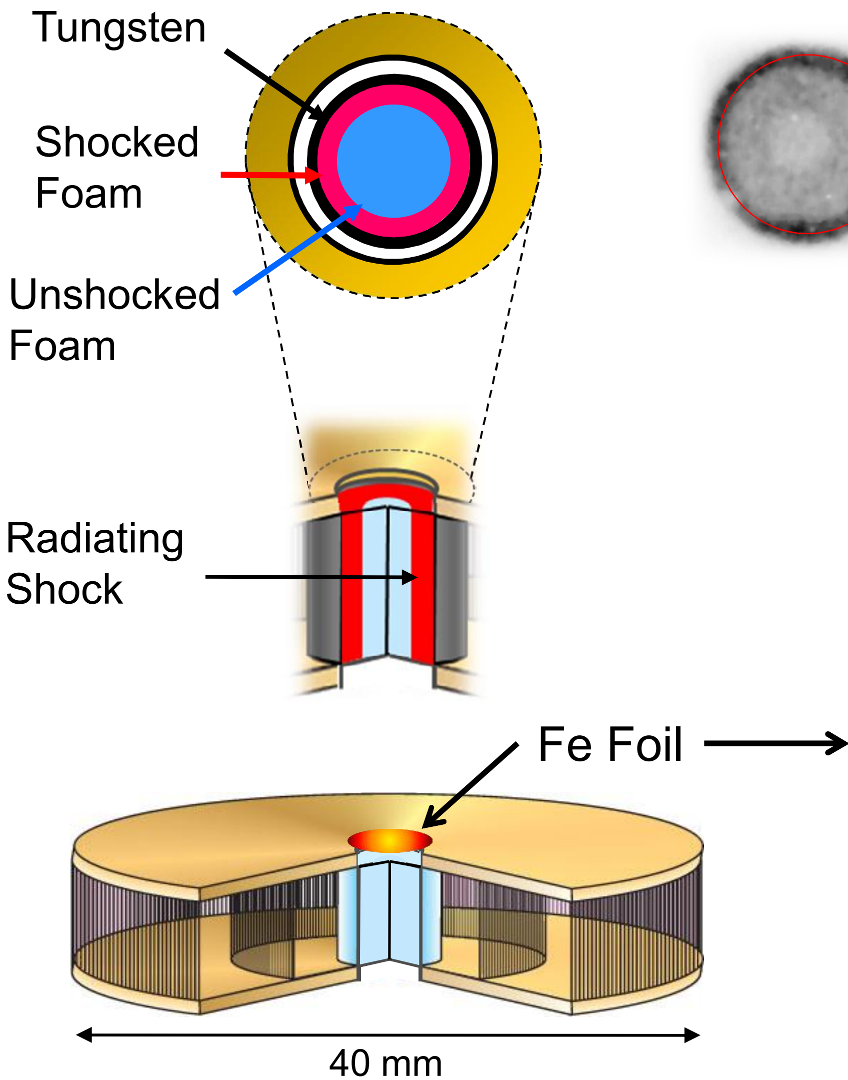
Z-pinch Dynamic Hohlraum



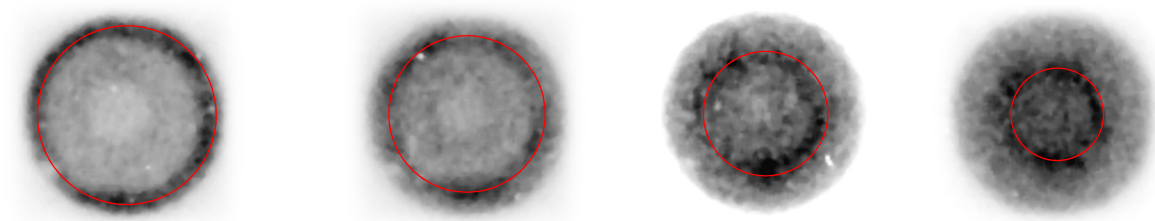
	ZR >2011	Z <2007
Marx Energy	20.3 MJ	11.4 MJ
Ipeak	25.8 MA (1.5%)	21.7 MA* (2.1%)
Mass	8.5 mg	3.8 mg
Peak Power	220 TW (10%)	120 TW (14%)
Radiated Energy	1.6 MJ (7%)	0.82 MJ (17%)

*Wagoner, PRSTAB 11 (2008)

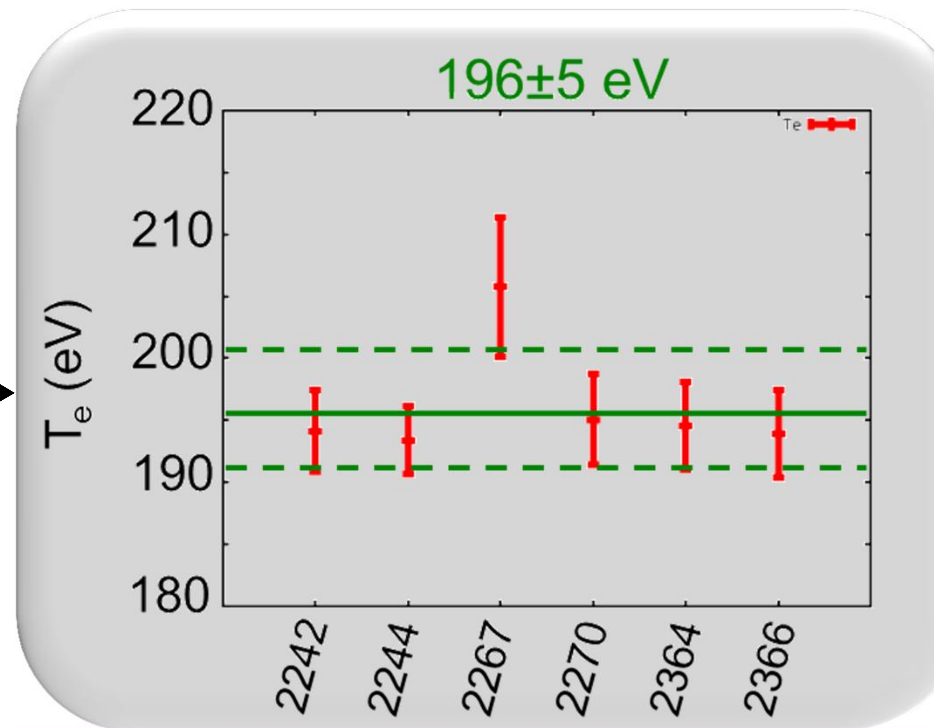
The ZPDH can also radiatively heat samples placed above the z-pinch to T_e~200 eV.



Framing Pinhole Camera Images

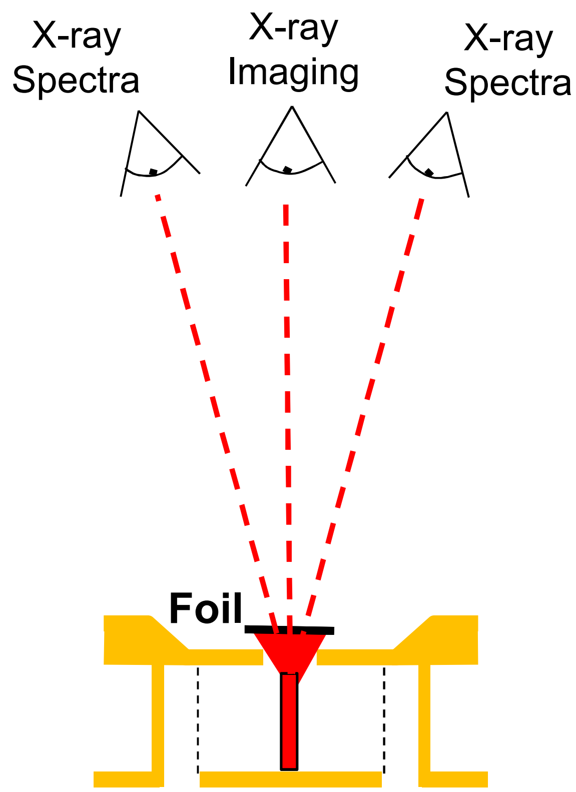


Axial Fe Foil Temperature

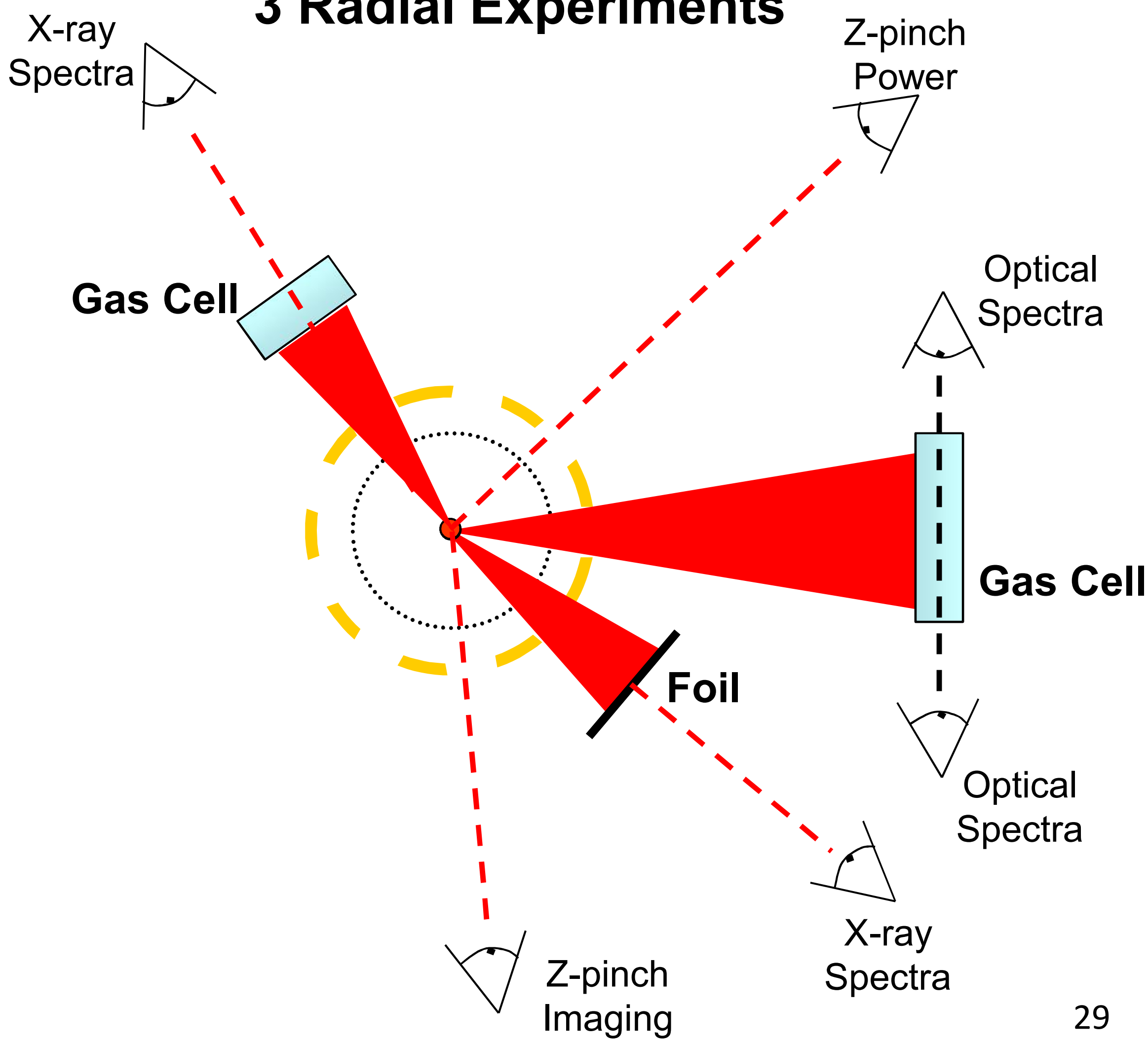


The ZPDH simultaneously drives four independent experiments on a single ZAPP shot

1 Axial Experiment

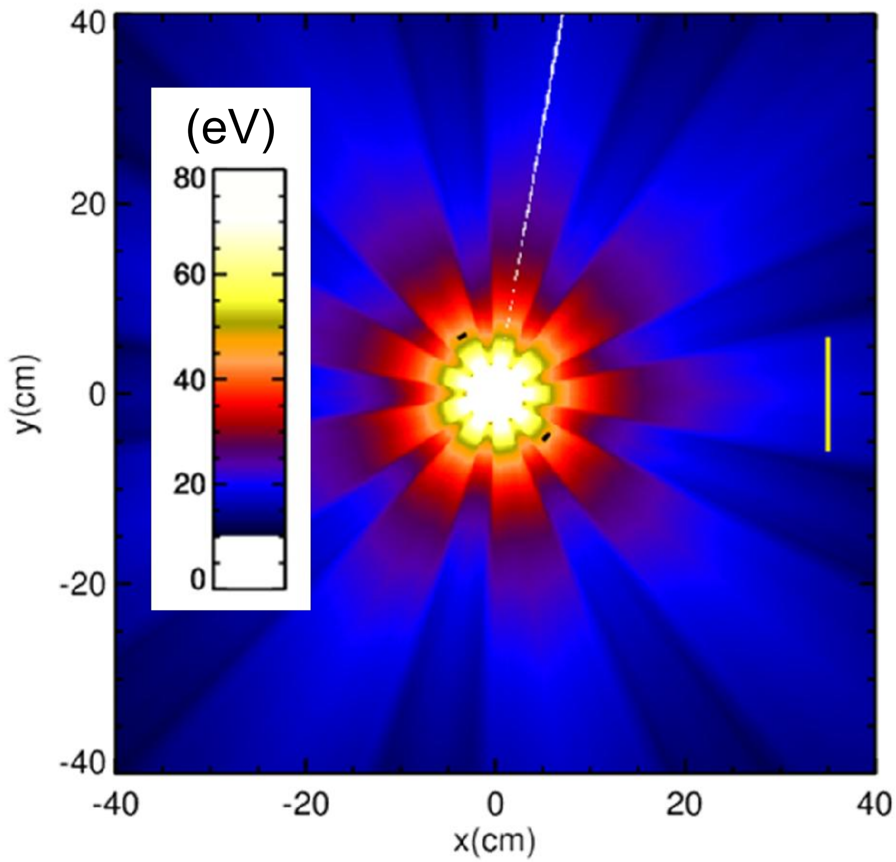


3 Radial Experiments

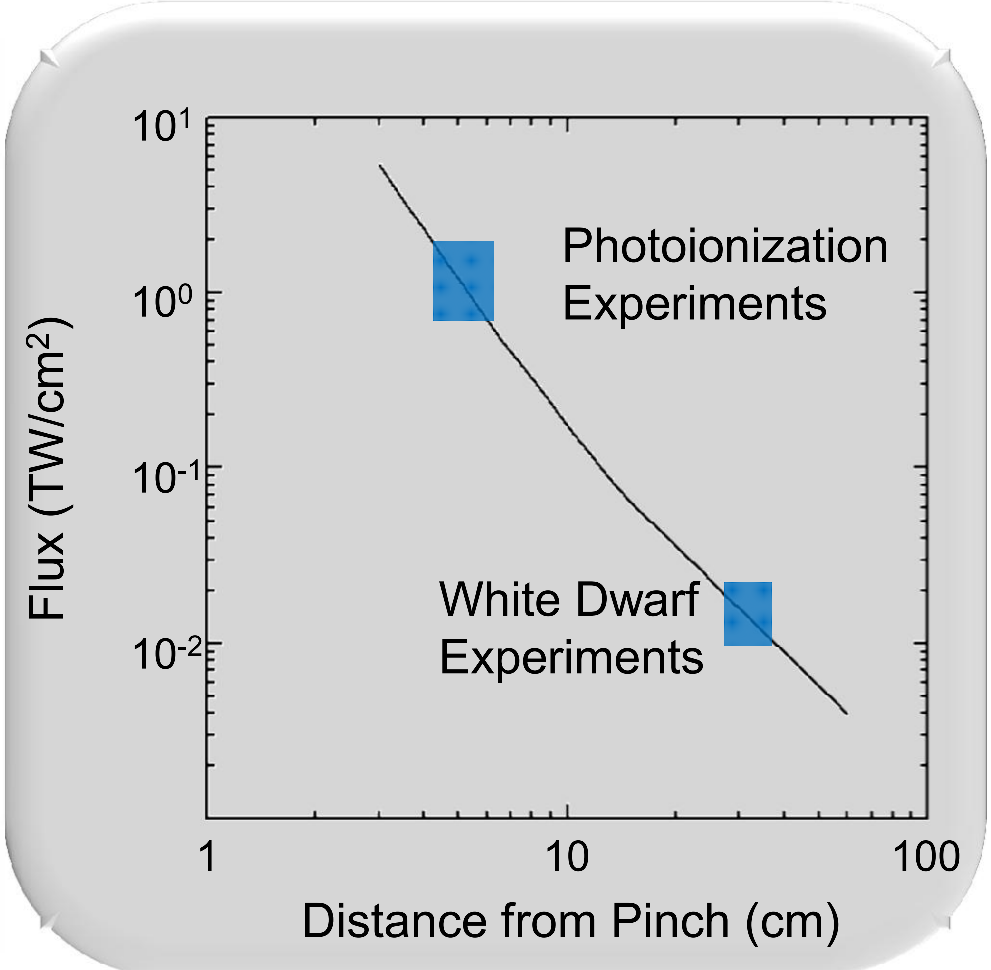


Placing samples at multiple distances from the z pinch provides a broad range of drive flux.

r-θ Peak Brightness Temperature Contours Around Z Pinch



Peak Drive Flux on a Sample



ZAPP campaigns simultaneously study multiple issues spanning 200x in temperature and 10^6x in density

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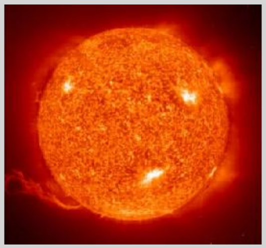
Solar Opacity



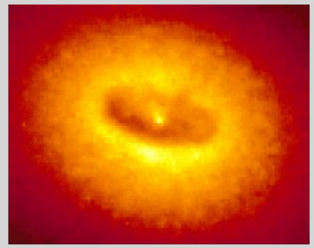
Question:
Why can't we predict the location of the convection zone boundary in the Sun?

Achieved Conditions:
$T_e \sim 200$ eV, $n_e \sim 10^{23}$ cm^{-3}

Los Alamos NATIONAL LABORATORY EST. 1943

cea

Photoionized Plasmas



Question:
How does ionization and line formation occur in accreting objects?

Achieved Conditions:
$T_e \sim 20$ eV, $n_e \sim 10^{18}$ cm^{-3}

N

White Dwarf Line-Shapes

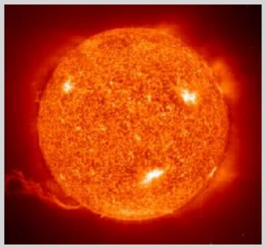
Question:
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

Acheived Conditions:
$T_e \sim 1$ eV, $n_e \sim 10^{17}$ cm^{-3}

THE UNIVERSITY OF TEXAS AT AUSTIN

ZAPP campaigns simultaneously study multiple issues spanning 200x in temperature and 10^6x in density

Solar Opacity



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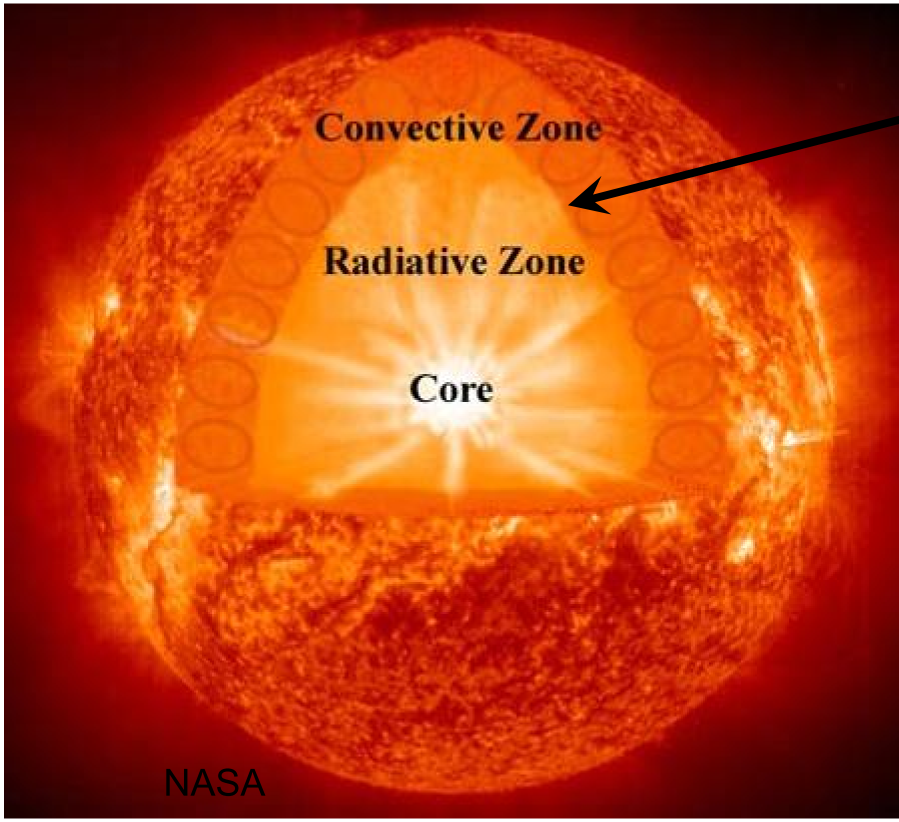
Models for solar interior structure disagree with helioseismology observations.



Convection-Zone (CZ) Boundary
Models are off by 10-30 σ

Models depend on:

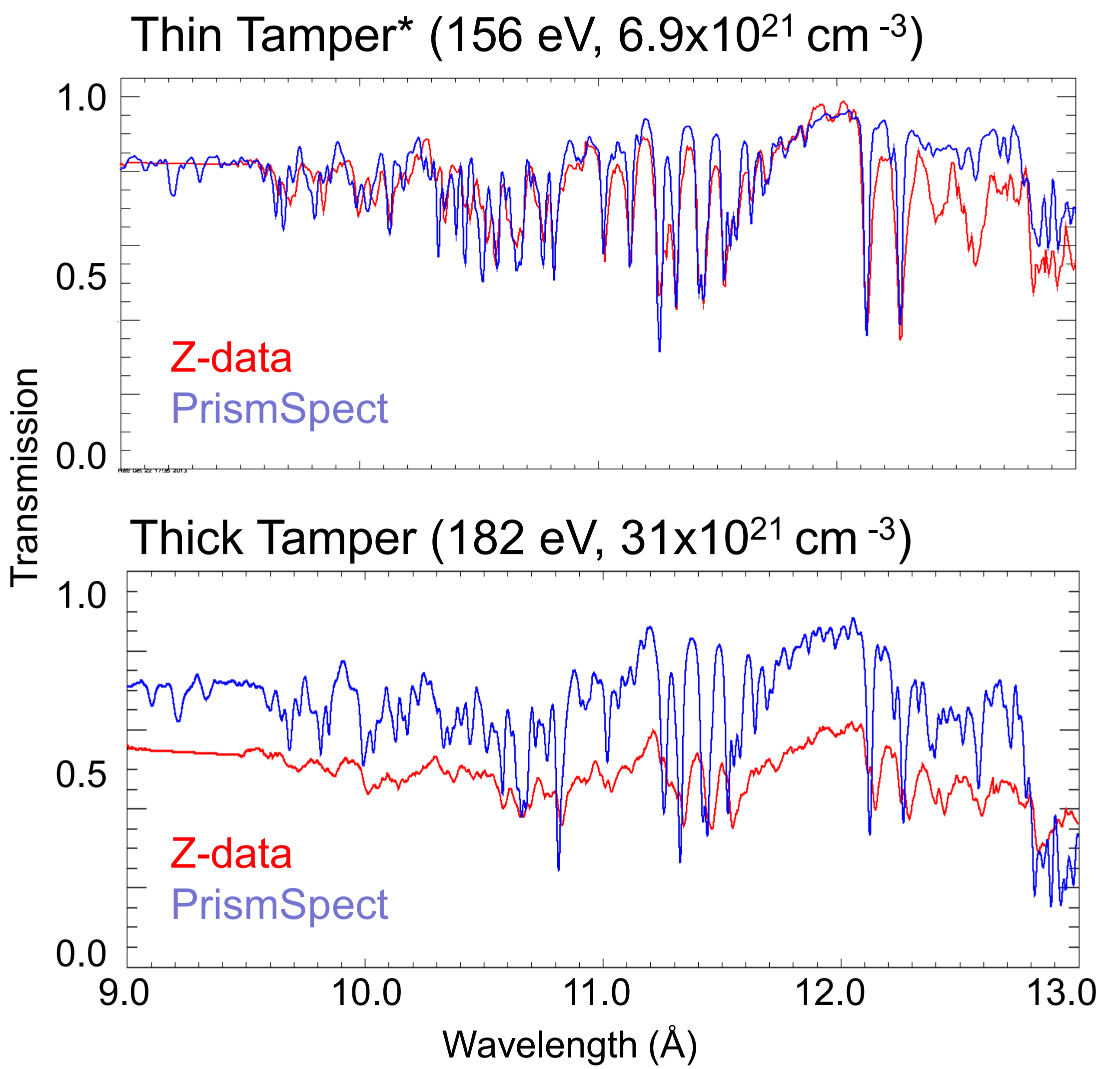
- **Composition (revised in 2005*)**
- **EOS as a function of radius**
- **The solar matter *opacity***
- **Nuclear cross sections**

Question: **Is opacity uncertainty the cause of the disagreement?**

Objective: **Measure Fe opacity at CZ base conditions.**

*M. Asplund *et al*, Annu. Rev. Astro. Astrophys. **43**, 481 (2005).

Modern computations of Fe opacity show large disagreements with data at CZ base conditions



Present Status

- Agreement between data and computation becomes worse at increasing temp. and dens.
- Disagreements at CZ base conditions can partially explain the CZ boundary problem.
- The differences are probably not unique to Fe… more scrutiny of the data is prudent.

*Bailey et al., PRL 100 (2008)

ZAPP campaigns simultaneously study multiple issues spanning 200x in temperature and 10^6x in density

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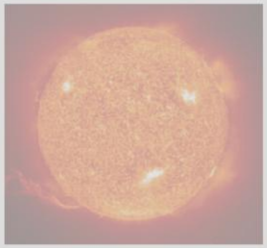
Solar Opacity



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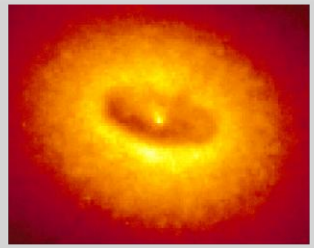

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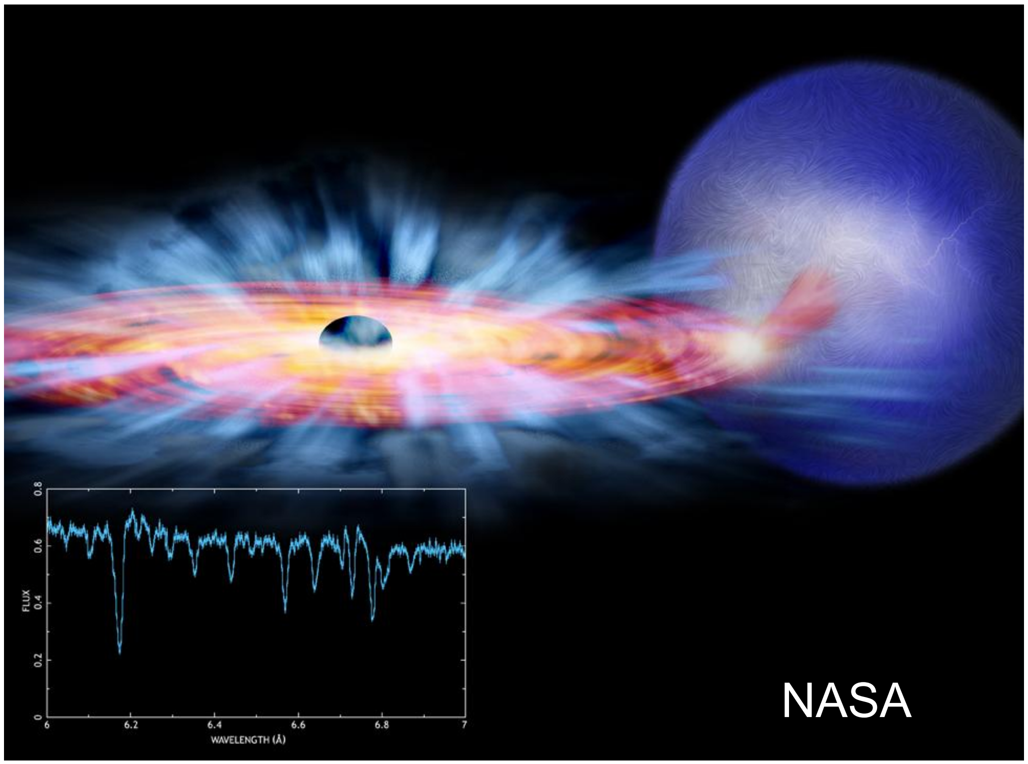
We learn about black holes from the matter falling into them – these are photoionized plasmas

Conceptual Picture of a Black-Hole Accretion Disk
ξ ~ 10 – 10,000 erg.cm.s^{-1}



Photoionization parameter

$$\xi \equiv \frac{4\pi F}{n_e} \ [\mathrm{erg.cm.s^{-1}}]$$

Laboratory Plasmas

n_e ~ 10^{19} cm^{-3}

F > 1 TW/cm^2 for ξ > 10

- Can we model the ionization?
- Can we model the line emission?

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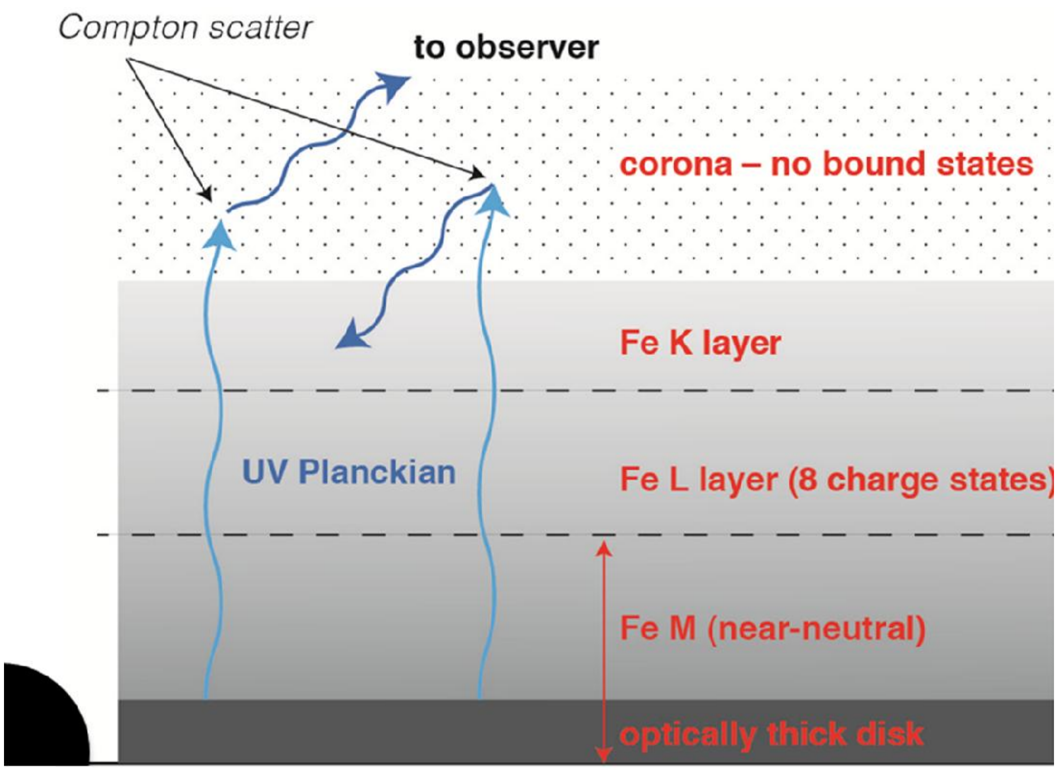

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Laboratory Plasmas

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- Can we model the ionization?
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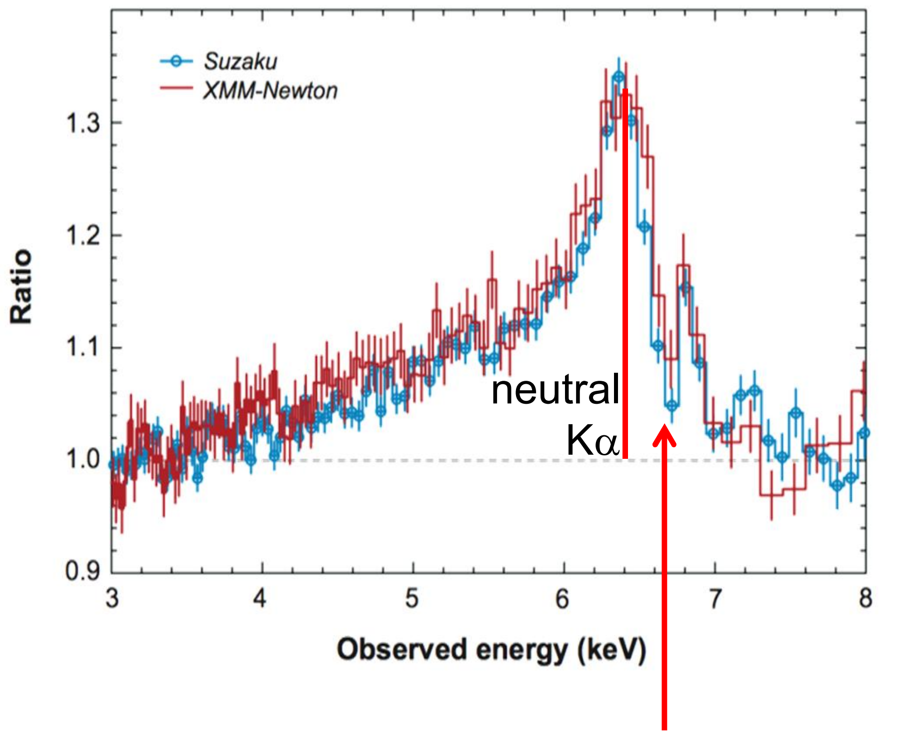
A Specific Problem: Emission from L-shell ions is not seen in some prominent black-hole accretion disks.

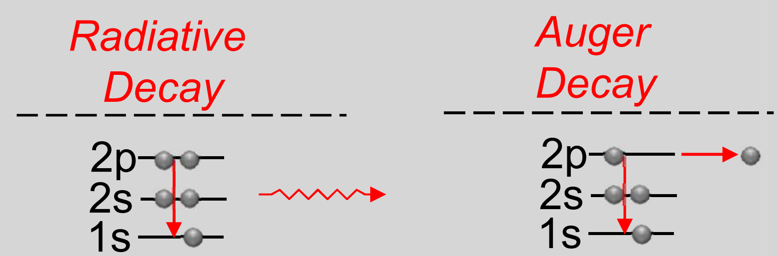
Measured Fe Emission from MCG 6-30-15



No observed emission from Fe ionized to the L-shell

Resonant Auger Destruction (RAD) was accepted as the reason*

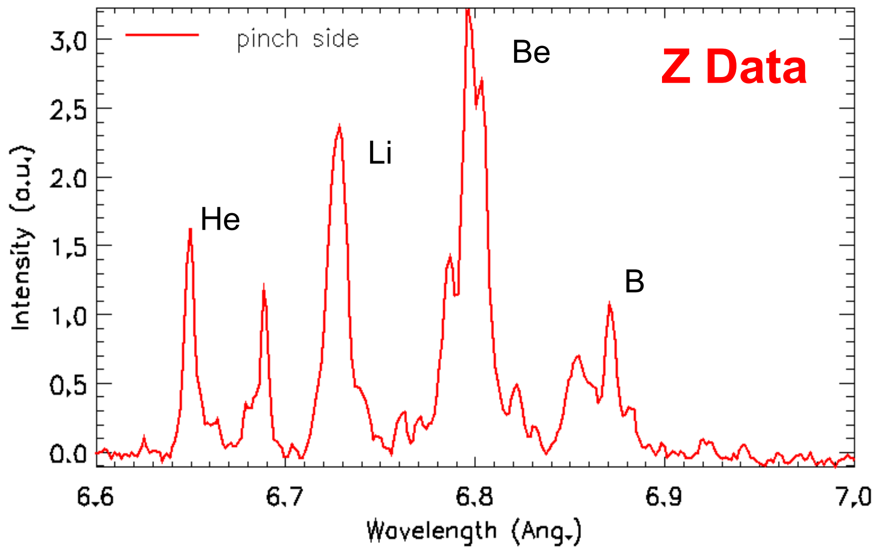
- 2 competing processes for the de-excitation of L-shell ions:

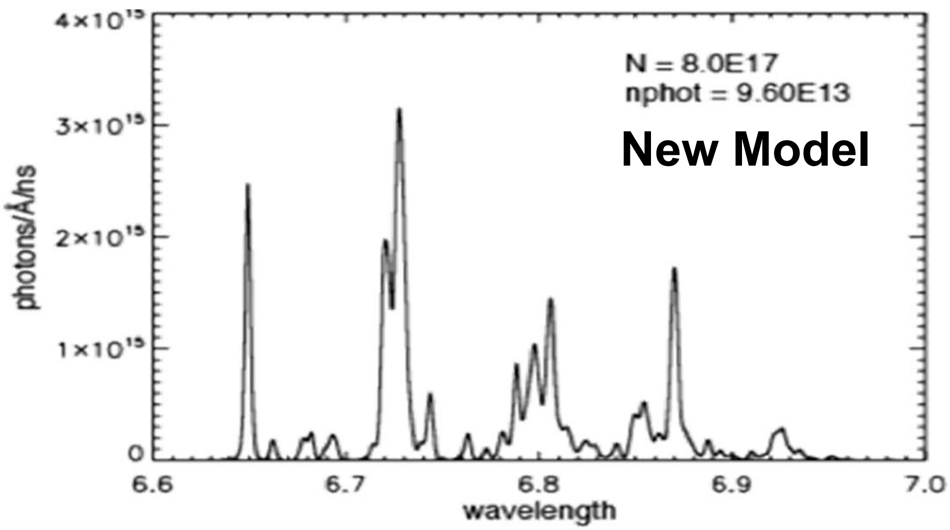


- **Thin Plasma:** high probability of observing the photon
- **Thick Plasma:** high probability of the photon being resonantly absorbed
  → Higher probability of Auger Decay for the ensemble

*Ross, Fabian and Brandt, MNRAS, 1996

Recent emission measurements demonstrate that L-shell emission is not 100% quenched by RAD.



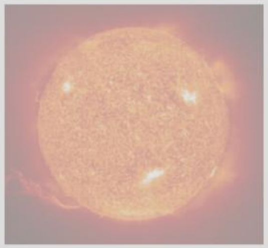


Present Status

- Z Data demonstrates that L-shell emission does escape at column depths >1E17 at/cm^2.
- Present data can discriminate between models of the ionization distribution AND relative line strengths.
- Absolute intensity is needed to determine efficiency of RAD process.

ZAPP campaigns simultaneously study multiple issues spanning 200x in temperature and 10^6x in density

Solar Opacity



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T_e ~ 20 eV, n_e ~ 10^{18} cm^{-3}

White Dwarf Line-Shapes

Question:
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

Acheived Conditions:
T_e ~ 1 eV, n_e ~ 10^{17} cm^{-3}

The properties of White Dwarfs are determined by spectral fitting, but disagrees with other methods

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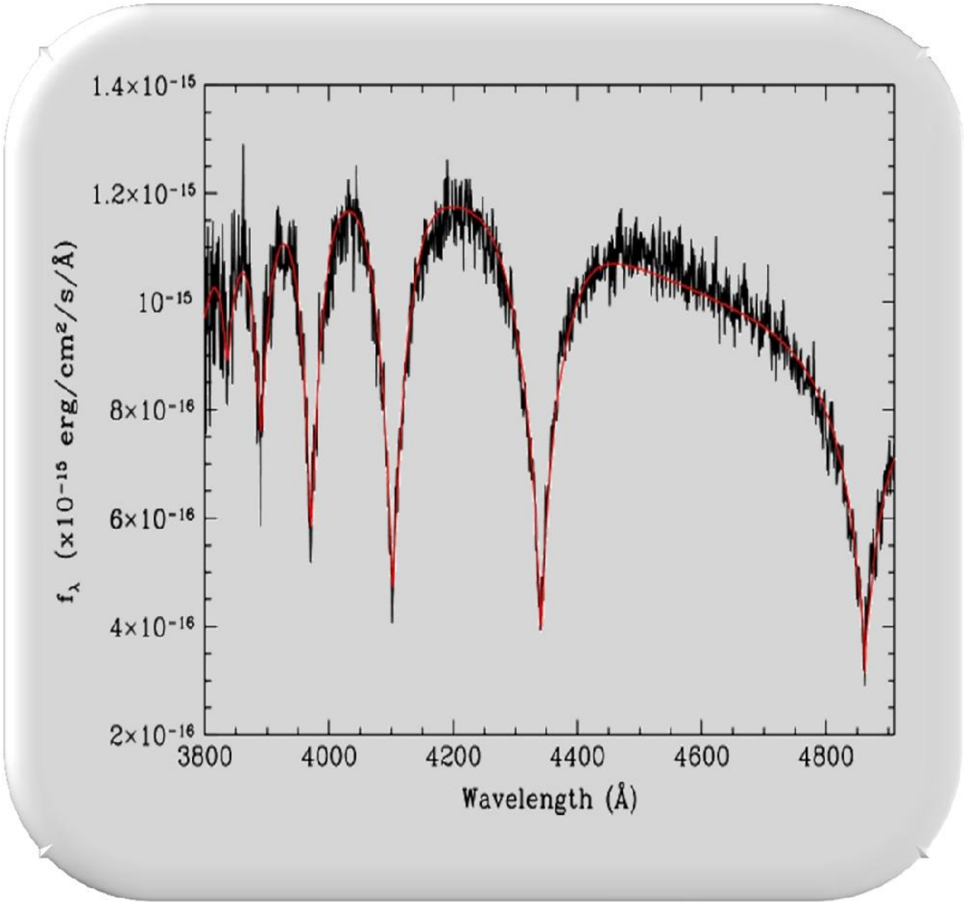
- White Dwarfs are fundamentally important
  - ➢ Evolutionary endpoint for ~98% of stars
  - ➢ Simple in structure and evolution
  - ➢ Cosmic laboratories (cosmochronology)

- WD surface temperature and total mass are usually determined by fitting the observed spectra

- The spectroscopic method and gravitational redshift disagree by >10% in the stellar mass

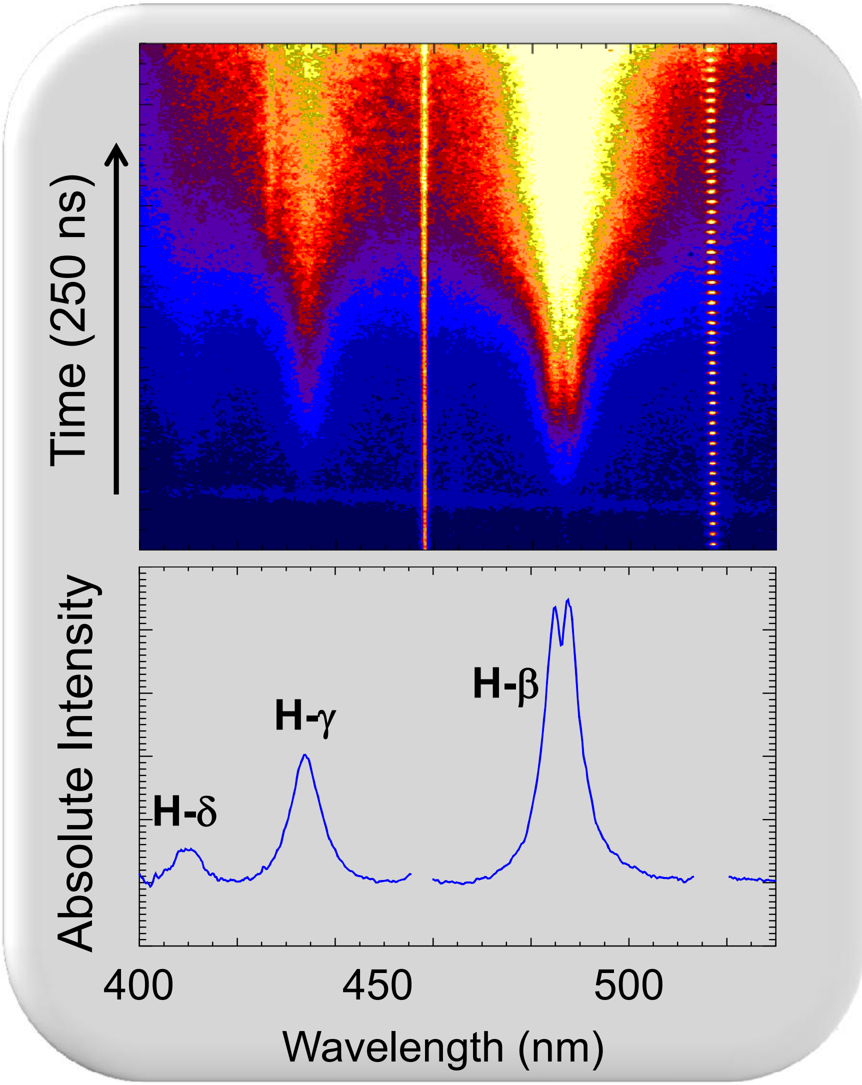
Spectral fit of WD J1916+3938*



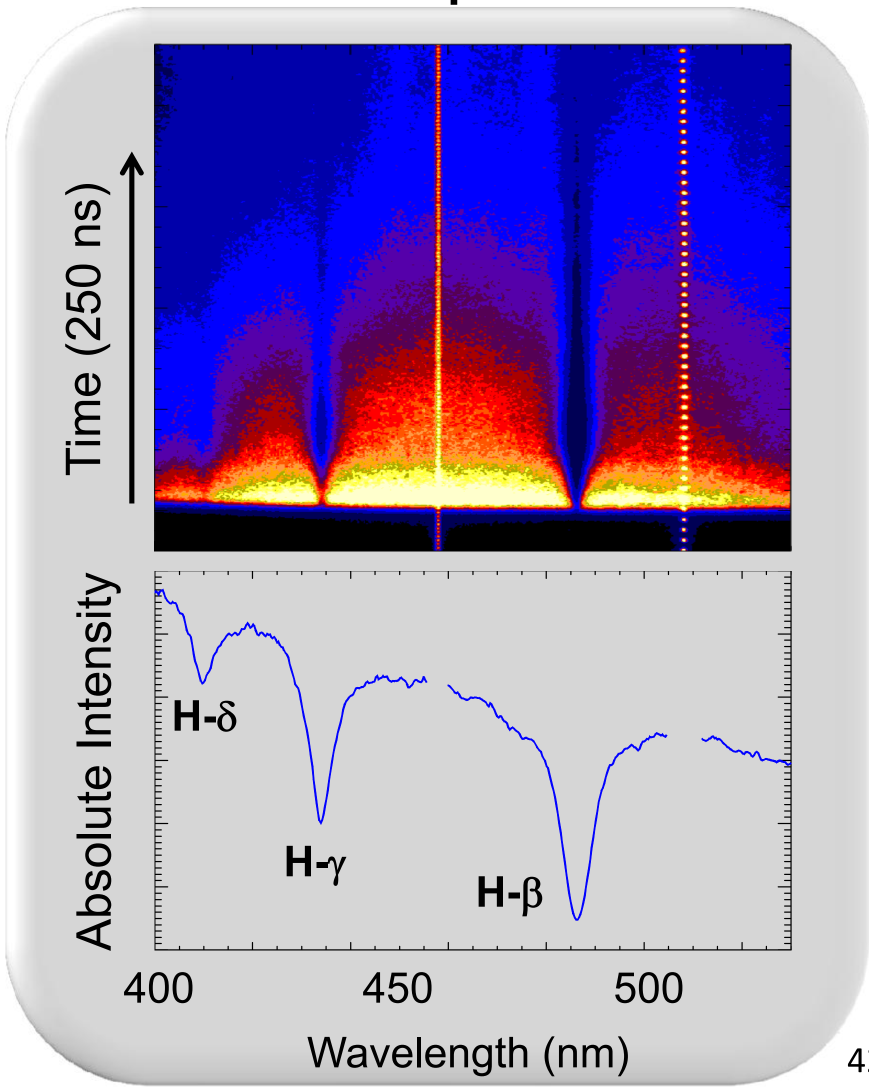
*Hermes et al. (2011)

Simultaneous streaked absorption and emission provide a unique capability to measure lineshapes

Emission



Absorption



Outline

- **Magnetized Liner Inertial Fusion (MagLIF)**
  Encouraging results from initial integrated experiments

- **Z Astrophysical Plasma Properties (ZAPP) Collaboration**
  Studies of emission and absorption from photoionized plasmas relevant to white dwarfs, accretion disks, and solar photosphere

- **Diagnostic development on Z**
  X-ray Thomson scattering and Zeeman splitting

There is a lot of interesting science going on at Z –
and many opportunities for significant contributions from Cornell's LPS.

X-ray Thomson Scattering has recently emerged as a potential diagnostic for warm dense matter (WDM)

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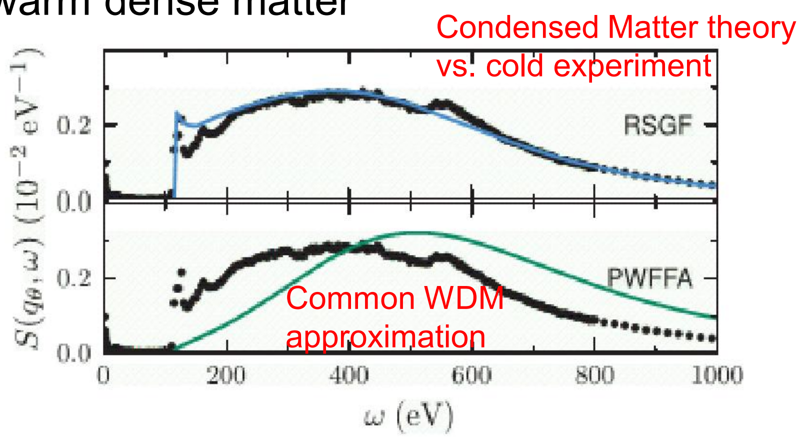
- Warm Dense Matter is difficult to both model and diagnose:
  - Since the kinetic energy of the plasma particles is of the same order as their potential energy, one cannot make the simplifying assumptions appropriate for Condensed Matter or Ideal Plasmas
  - Since Warm Dense Matter emits weakly and absorbs strongly, optical diagnostics only probe its surface; an external x-ray source is required for bulk characterization

- Seven recent PRLs have been devoted to the use of XRTS as a diagnostic for electron density, temperature, and ionization
  - However, the models used to predict scattering signals make significant assumptions about the electronic and ionic properties of warm dense matter

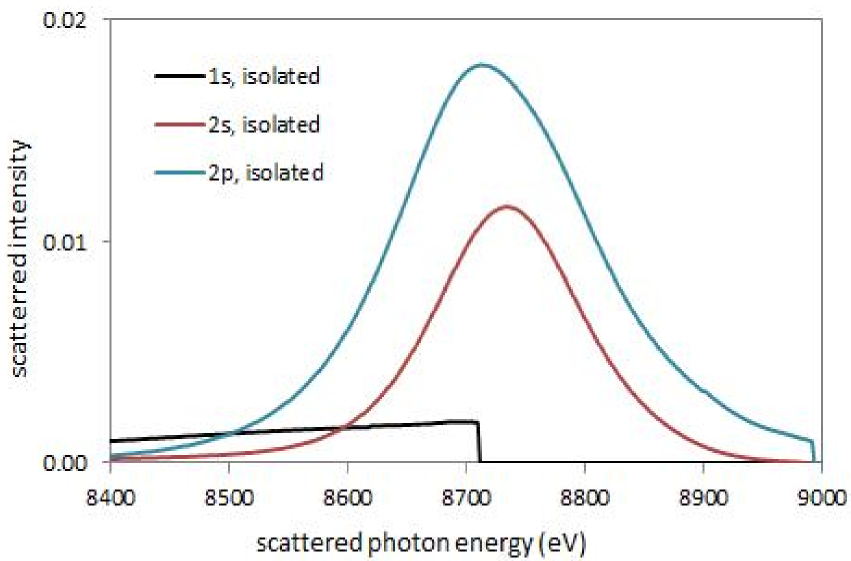
- Experimental studies with uniform, well-characterized sample conditions and high signal-to-noise scattering measurements are needed to augment existing cold scattering data



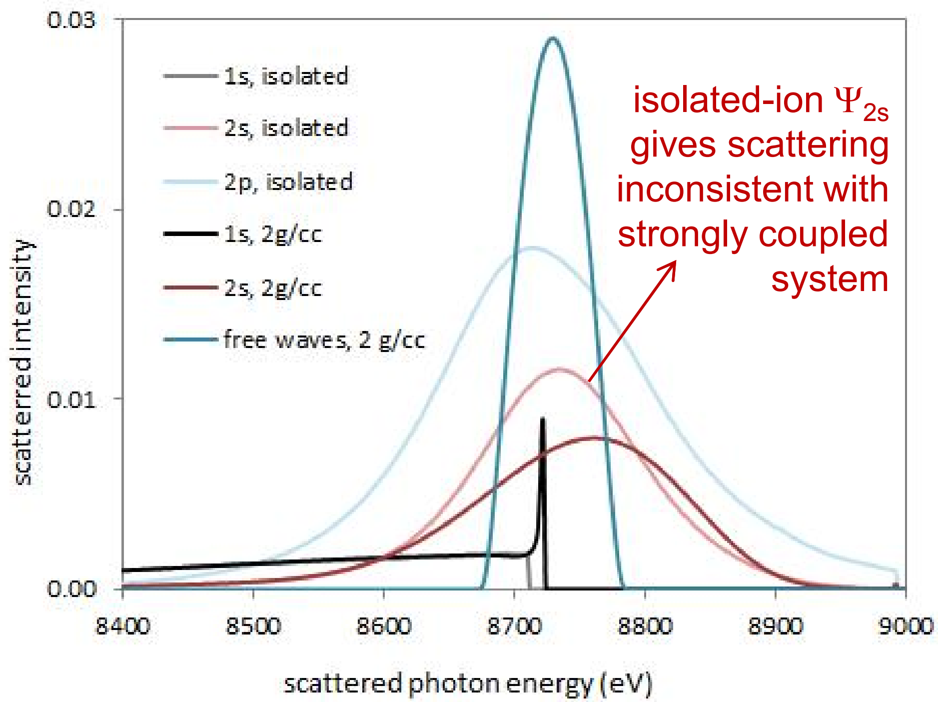
B.A. Mattern & G.T. Seidler, *Phys Plas* **20**, 022706 (2013)

Key question: what happens to the scattering signal as bound electrons become pressure ionized?

135° scattering from cold, isolated carbon:
Valence 2p state is bound



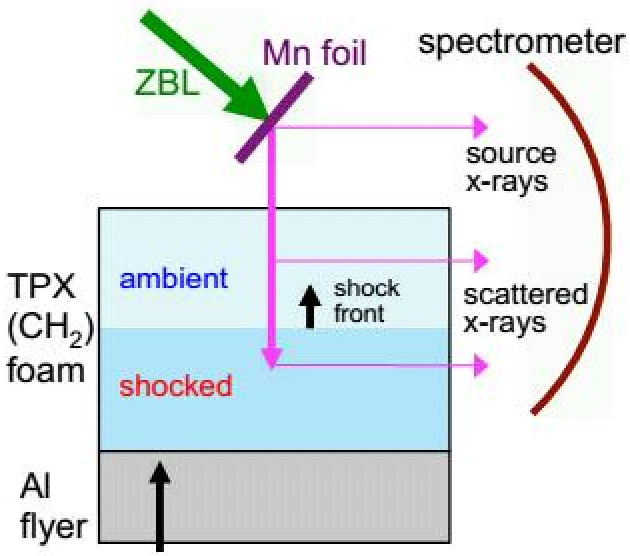
Scattering from cold carbon at 2 g/cc:
2p is pressure ionized (but not to a plane wave!)
1s and 2s scattering signals are modified

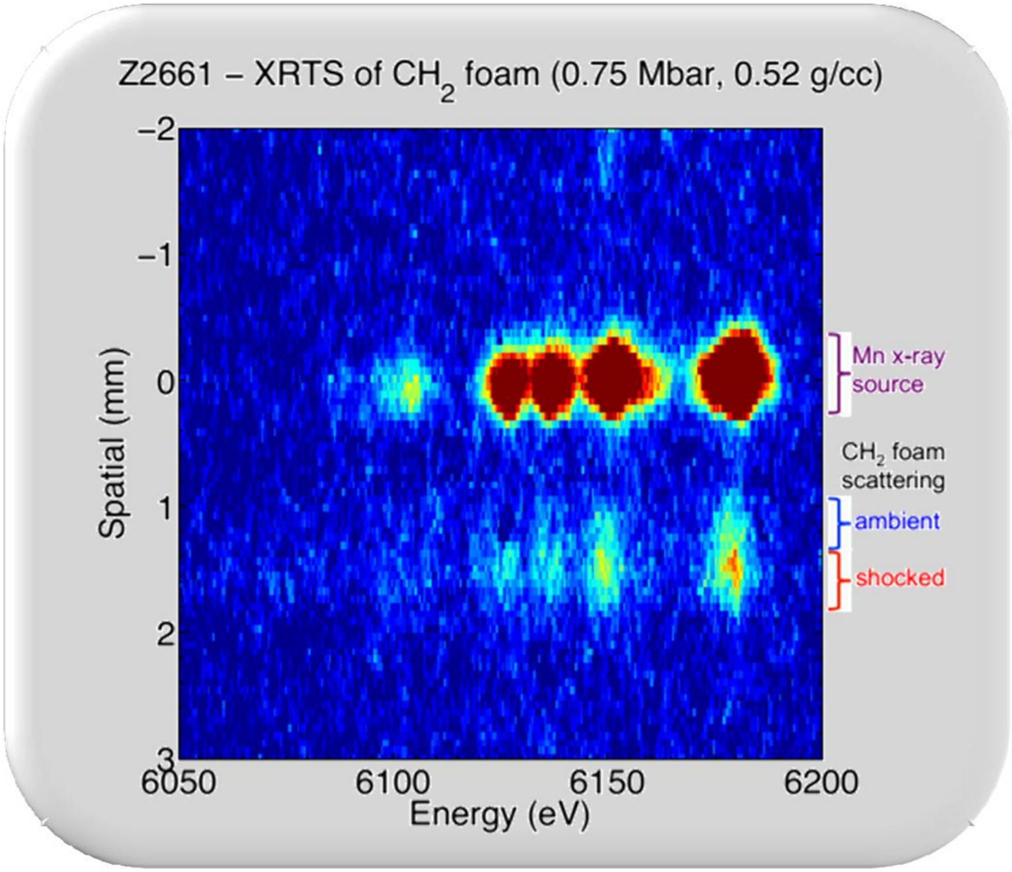


Laura Johnson is investigating the effect of continuum-wave distortion on free-free scattering signals.

We recently obtained scattering data from both shocked and unshocked foam on Z

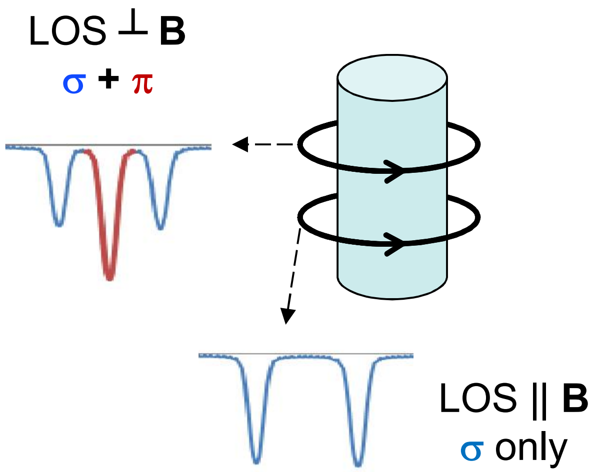
- Z experiments provide:
  - Uniform, long-lived, well-defined shock state
  - *In-situ* comparison with ambient state
  - Source spectrum measured for each shot
  - Potential for high S/N



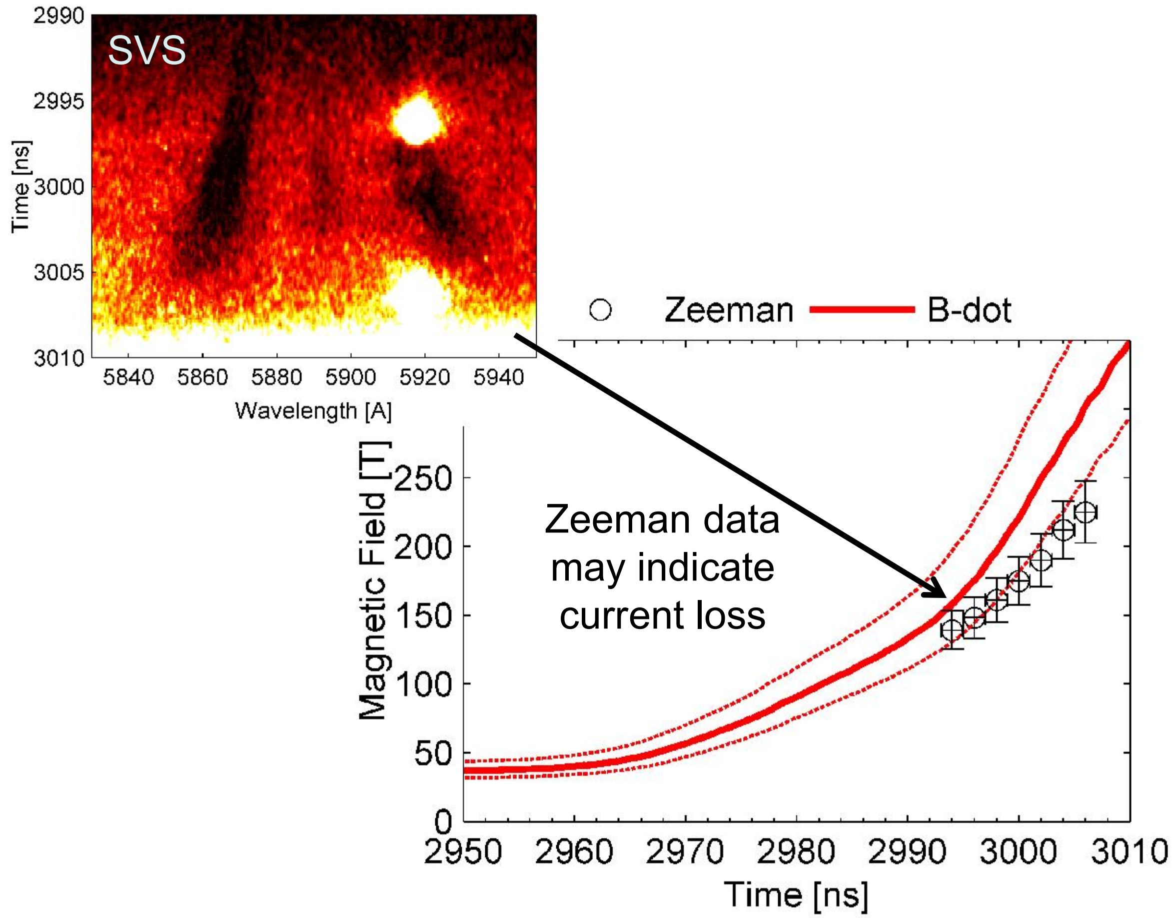


Zeeman splitting is being used to characterize Z's current drive and flux compression in Magnetized Liner Inertial Fusion (MagLIF) experiments

- Sodium deposits vaporized and backlit by current-carrying surfaces signal both the magnitude and direction of the local magnetic field:



The relative strength of σ and π components indicates field direction



Summary: We are using Z to explore new frontiers in laboratory astrophysics and diagnostics

- The Z Astrophysical Plasma Properties (ZAPP) collaboration uses the intense x-ray flux from wire arrays to create mm-scale regions of material with properties similar to those found in accretion objects, white dwarfs, and the solar photosphere, and measures their properties with extensive x-ray and optical spectrometers

- X-ray spectrometers are being fielded on dynamic materials experiments to help advance understanding of x-ray scattering in warm dense matter, with the potential to provide critical tests of scattering theory and temperature diagnostics

- Streaked optical spectrometers are being used to measure Zeeman splitting of optical absorption features to diagnose local magnetic fields important for understanding flux compression and current loss

We welcome ideas for additional collaborations!