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Visions for Pulsed Power as a driver for ICF, radiation, and fundamental HED Sciences

S.B. Hansen

for Sandia National Laboratories Pulsed Power Sciences Center

HED Community Self-Organization Workshop

August 10, 2017

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- What makes Pulsed Power unique and compelling for ICF/HED studies?
- Where are we now and where do we want to go in the next ten years?
  - Facilities:
    Sandia's Z, universities, China → Z-next, university++, Russia's Baikal
  - Diagnostics:
    integrated and space/time/energy resolved → extend resolution & analysis
  - Computations:
    Constitutive models and simulations → increase consistency and fidelity
  - Science:
    ICF/MIF: MagLIF → improve stability & energy coupling + new platforms
    Radiation sciences: wire arrays → non-thermal sources + new platforms
    Materials science: EOS → higher pressures, transport, new diagnostics
    Fundamental science: ZAPP/opacity → astrophysical applications + WDM

Why Pulsed Power?

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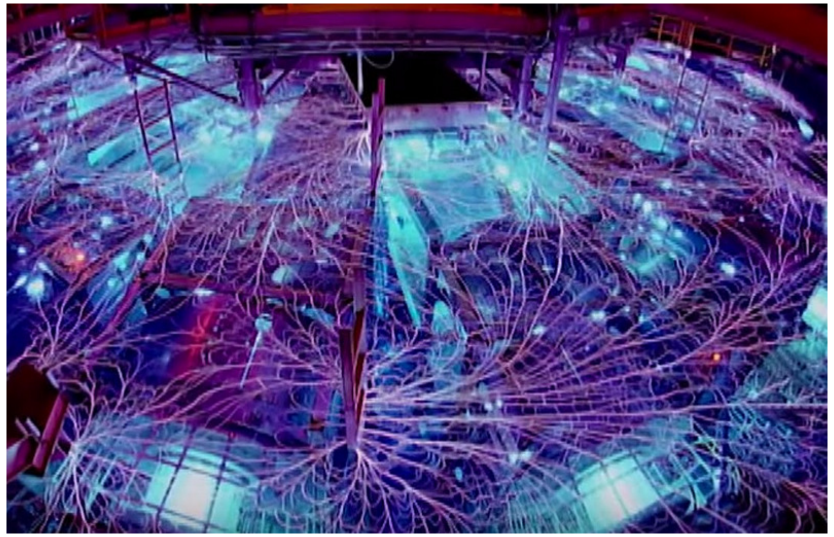
- Pulsed power offers *efficient* compression of energy in space (100 m → 1 mm) and time (100 s → 10 ns),delivering ~10% of ~20 MJ to targets
- Compression is achieved through JxB force with multifaceted applications to ICF, Radiation Science, Dynamic Materials Properties, and fundamental science
- Strong magnetic fields enable studies of regimes relevant to Mangeto-Inertial Fusion, atomic-scale physics in extreme environments, and astrophysics
- Disadvantages:
  20 MJ in chamber is destructive;
  Some applications and diagnostics require field-free environments



Facilities: Where are we now?

- Sandia's Z machine: 15 – 30 MA, ~20 MJ, ~150 shots/year:
  - 25% ICF (4 concepts including MagLIF)
  - 20% radiation sciences (GW-TW thermal and non-thermal sources)
  - 25% dynamic materials (isentropic and shock compression)
  - 10% fundamental HED & astrophysical science (opacities & photoionized plasma)

- University drivers: < 1 – 2 MA
  - Magpie at Imperial College, London
  - Maize (LTD) at U. Michigan
  - Cobra and XP at Cornell
  - Zebra at U. Nevada, Reno
  - Smaller drivers at UCSD, Texas Tech, USC, WSU….

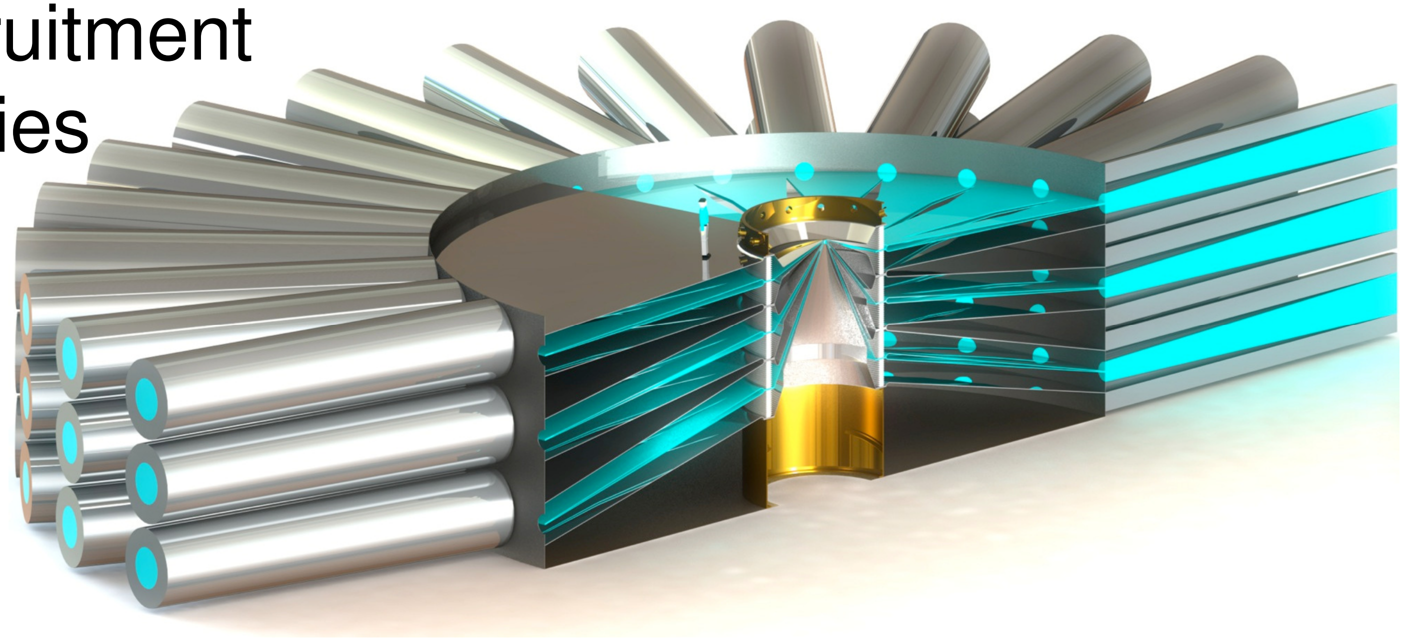
- China's PTS facility (~1/3 scale Z including laser!)

Facilities where are we going?

- Z: double shot rate by adding shifts (requires additional funding)
- Z-Beamlet and Petawatt: increase energies, co-injection

- Z-next: 50 – 60 MA, ~100 MJ stored energy
  - Potentially shift materials science experiments to alternate driver
  - Similar to (planned) Russian "Baikal" reactor
  - Requires strong science case for scaling

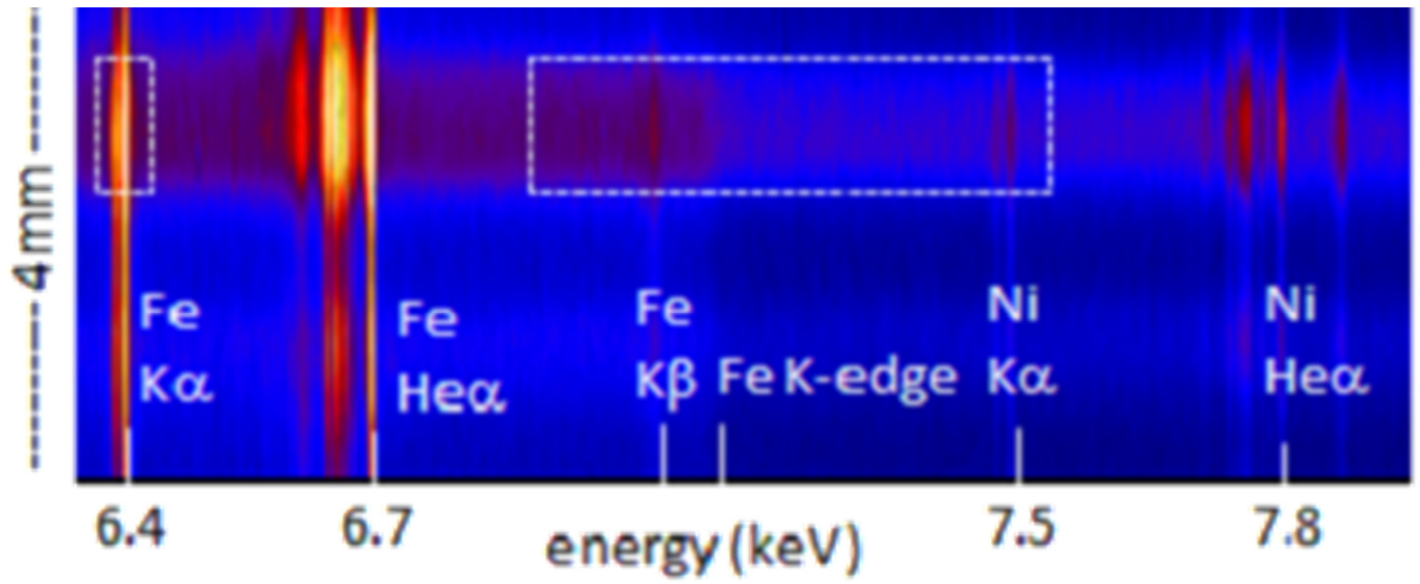
- University ++: Increase collaboration and recruitment
  - WDM/transport well-suited to small facilities
  - Study LTD performance
  - Possible pulsed power at LLE coupled to Omega laser facilities
  - Develop pipeline for HED theory and magneto-rad-hydro simulations



Diagnostics: Where are we now?

- X-ray diagnostics
  - High-resolution monochromatic imaging (~10 um time-integrated)
  - 1 – 9 keV backlighting using Z-Beamlet
  - Time-gated imaging through filters and multi-layer mirrors
  - ~10 spatially resolved spectrometers covering 1 – 100 keV photon energies with resolution $\lambda/\Delta\lambda$ = 500-5000, some time-gated
  - Optical streaked spectrometers
  - Filtered diodes for power and timing

- Neutron diagnostics
  - Neutron time-of flight
  - Neutron yields
  - Nascent neutron imaging



Diagnostics: Where are we going?

- X-ray diagnostics
  - Higher spatial resolution on spectrometers and imaging diagnostics
  - Combining temporal, spatial, and high spectral resolution for spectroscopy
  - Improved calibrations for diodes
  - X-ray diffraction and scattering
  - Time-gated/multiframe backlighting (exclude self-emission)

  Many of these advances will be enabled by hybrid-CMOS

hybrid CMOS sensor

- Neutron diagnostics
  - Improved neutron imaging (resolution, sensitivity)
  - Gamma-ray detectors/bang-time and burn duration
  - Improved analysis methods for charged particle-confinement through analysis

  Many of these advances will be enabled by trace tritium

- Enhancing diagnostics + analysis (e.g. Bayesian methods) enables science

Dynamic materials science: from hydrogen to plutonium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REPORT

Direct observation of an abrupt insulator-to-metal transition in dense liquid deuterium

M. D. Knudson[1,*], M. P. Desjarlais[1], A. Becker[2], R. W. Lemke[1], K. R. Cochrane[1], M. E. Savage[1], D. E. Bliss[1], T. R. Mattsson[1],...

+ See all authors and affiliations

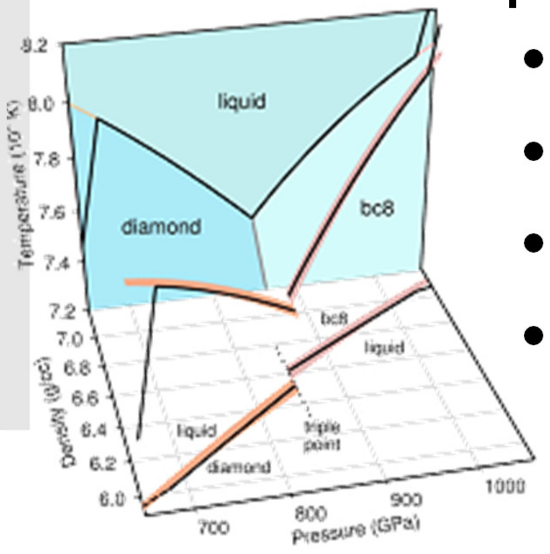
Science 26 Jun 2015:
Vol. 348, Issue 6242, pp. 1455-1460
DOI: 10.1126/science.aaa7471

Article | Figures & Data | Info & Metrics | eLetters | PDF

Driving liquid deuterium into metal

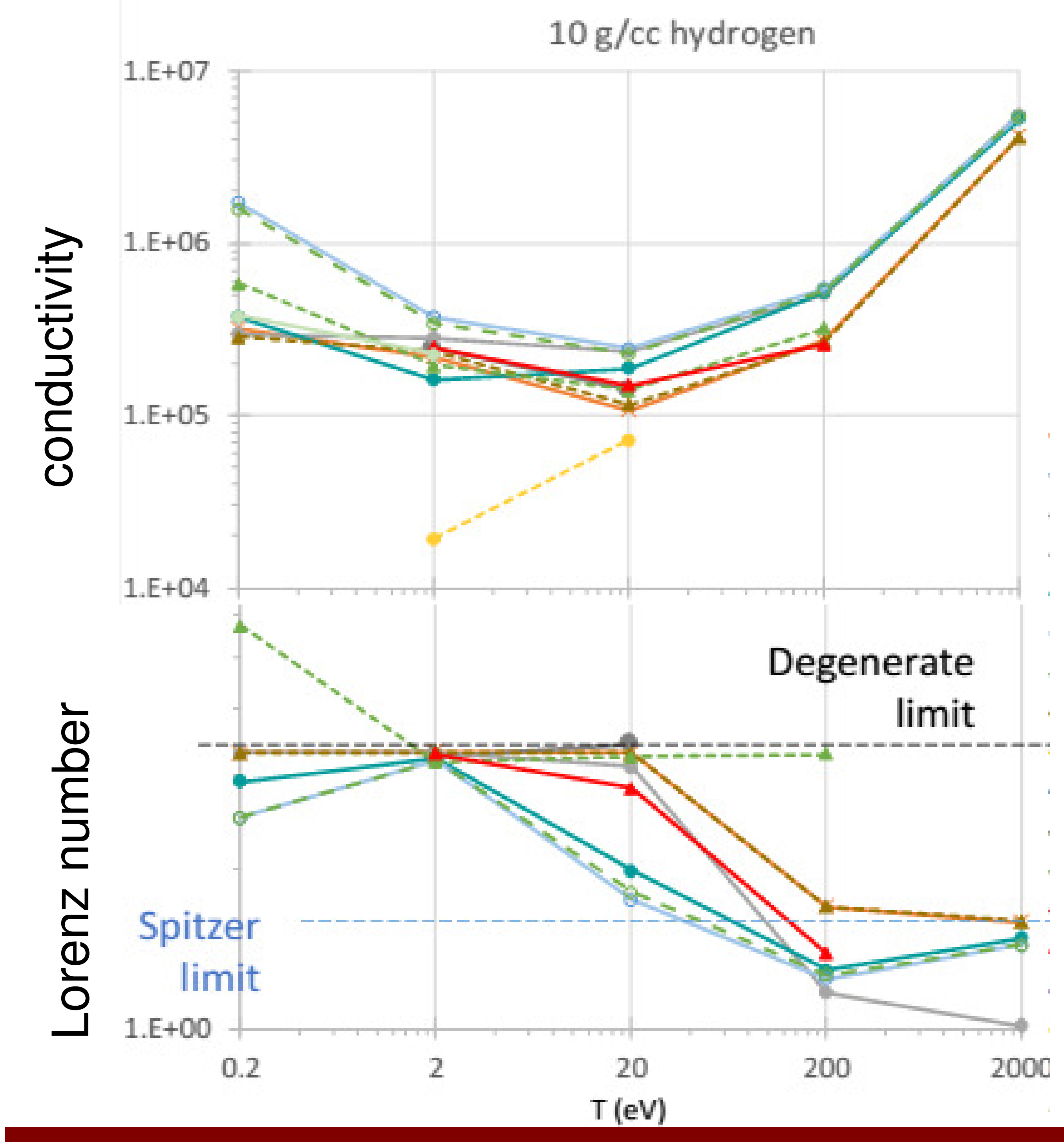
Quick and powerful compression can force materials to change their properties dramatically. Knudson *et al.* compressed liquid deuterium to extreme temperatures and pressures using high-energy magnetic pulses at the Sandia Z-machine (see the Perspective by Ackland). Deuterium began to reflect like a mirror during compression, as the electrical conductivity sharply increased. The observed conditions for metallization of deuterium and hydrogen help us to build theoretical models for the universe's most abundant element. This a our understanding of the internal layering of gas giant planets such as Jupiter and Saturn.

Science, this issue p. 1455; see also p. 1429



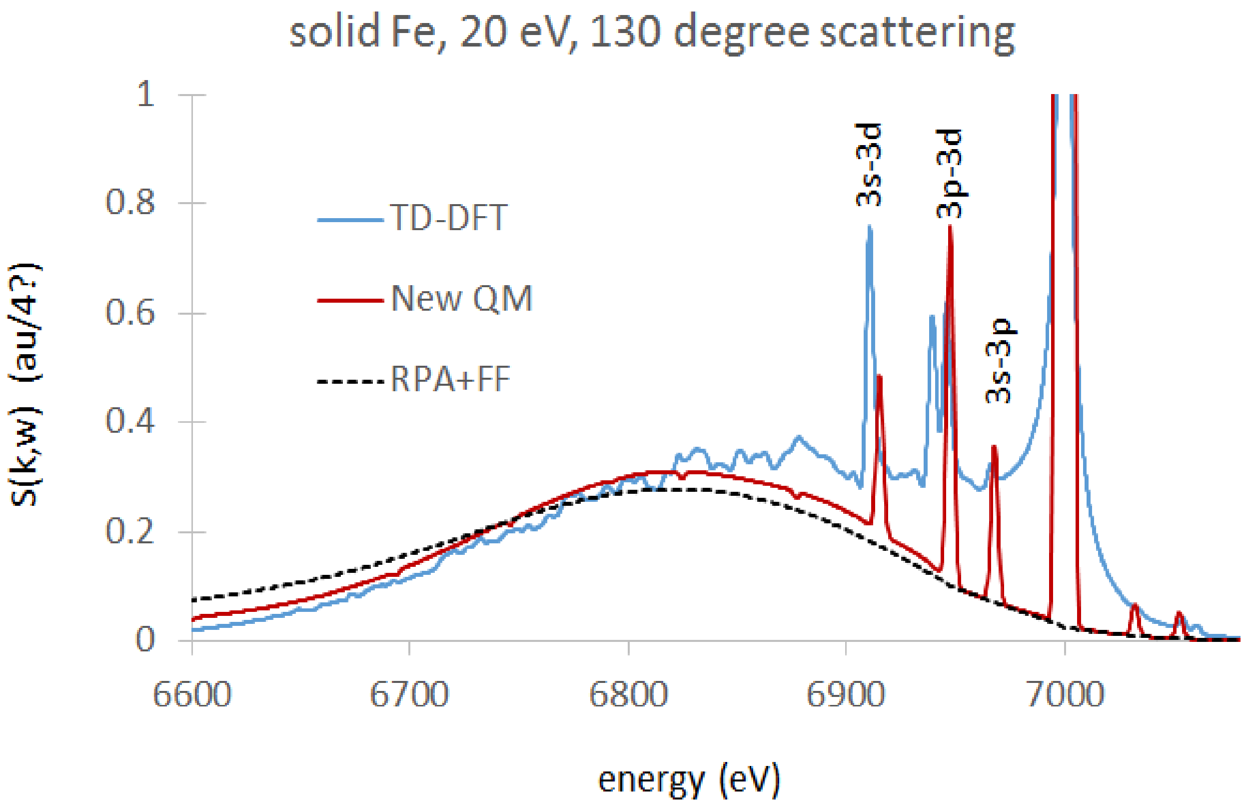
- Shock compression and isentropic compression of materials
- High-pressure material properties diagnosed primarily with VISAR and supported by intense *ab-initio* computational efforts
- Future prospects are exciting in both experiments and theory:
  - X-ray diffraction diagnostics
  - X-ray Thomson scattering
  - optical diagnostics for Te
  - computational advances in [time-dependent] density functional theory, extensions from EOS to transport

Fundamental science: Constituent models inform simulations



- Equation of state (EOS), conductivities, stopping powers, scattering signals, and even opacities are often parameterized by Z*, which is ill-defined

- Improving the internal consistency of theory could help constrain both simulations and diagnostics: future work on high-field & non-equilibrium effects



Hansen, Zylstra, Grabowski, Graziani, Murillo, Baczewski, Saunders, Gamboa

Radiation science: thermal and non-thermal emission

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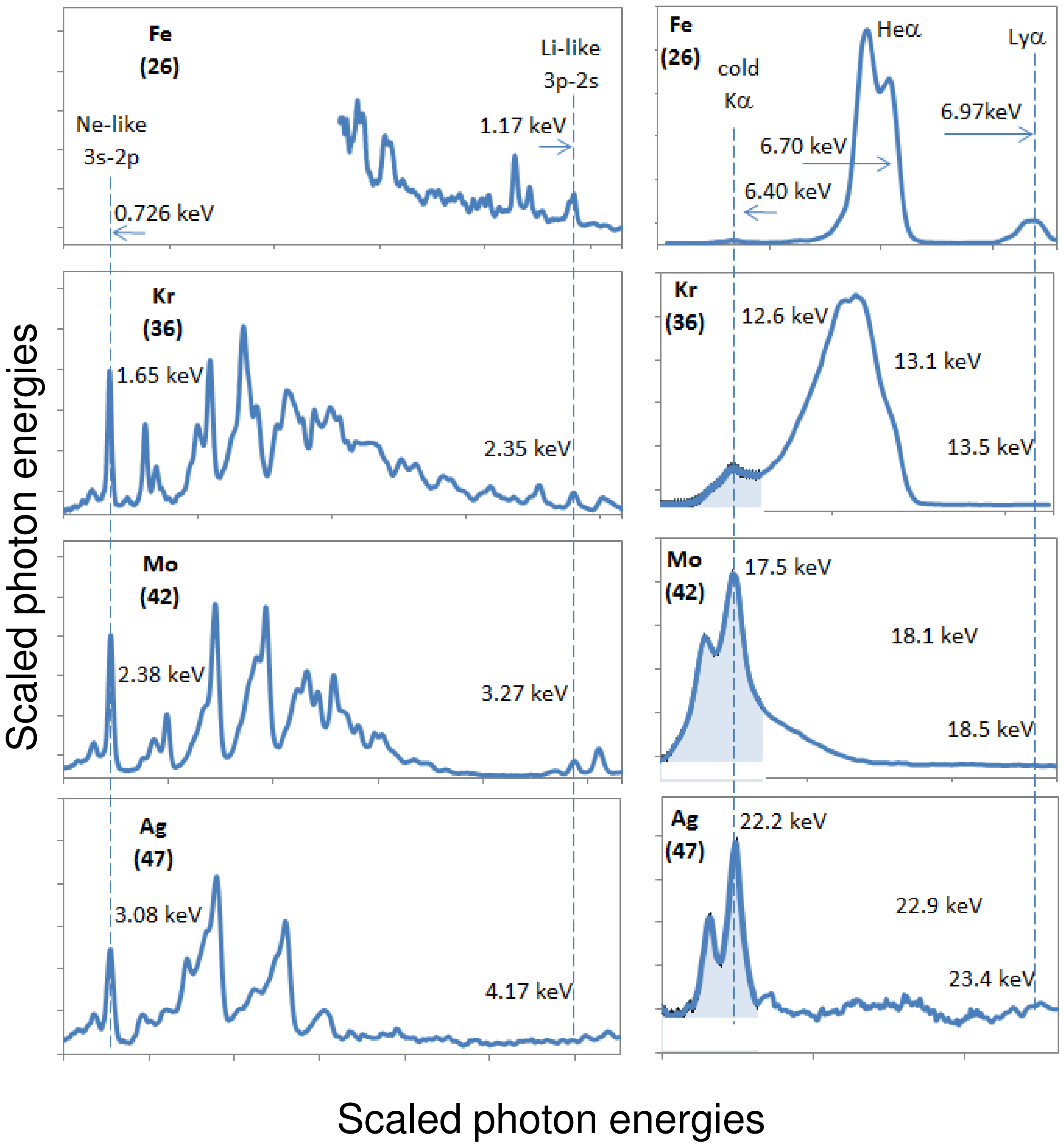
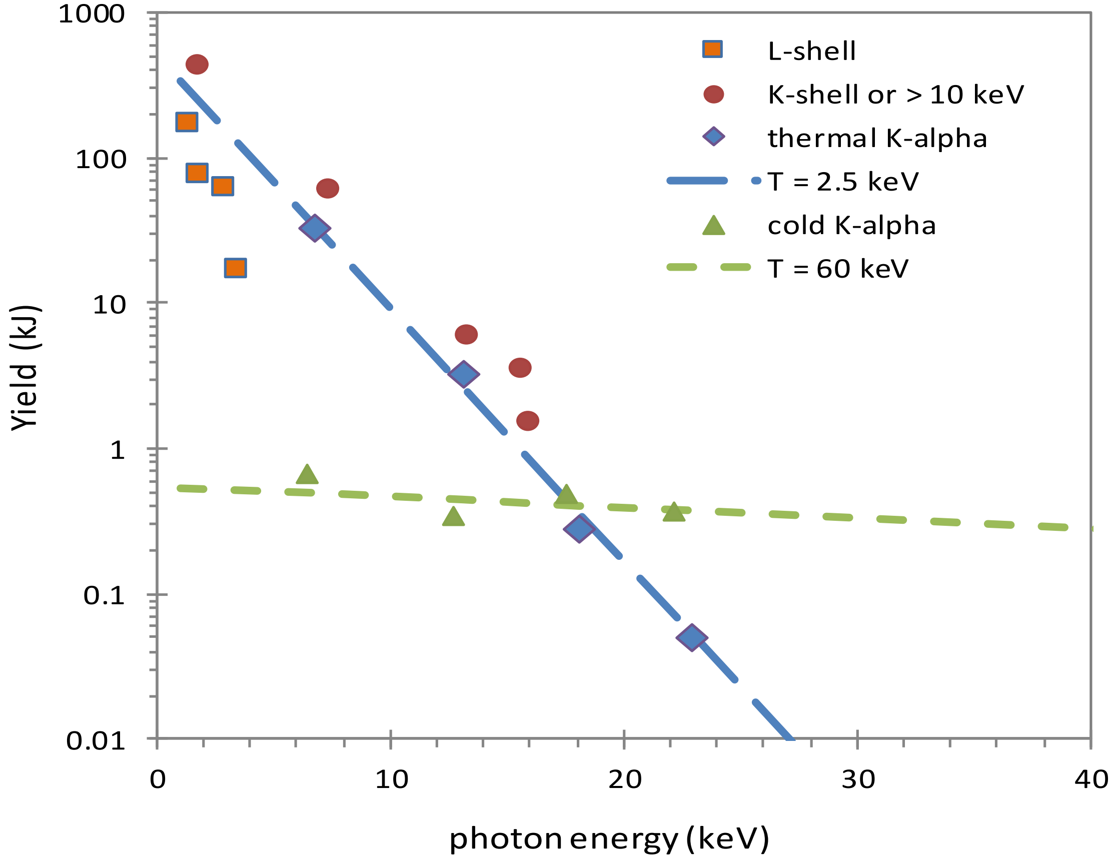
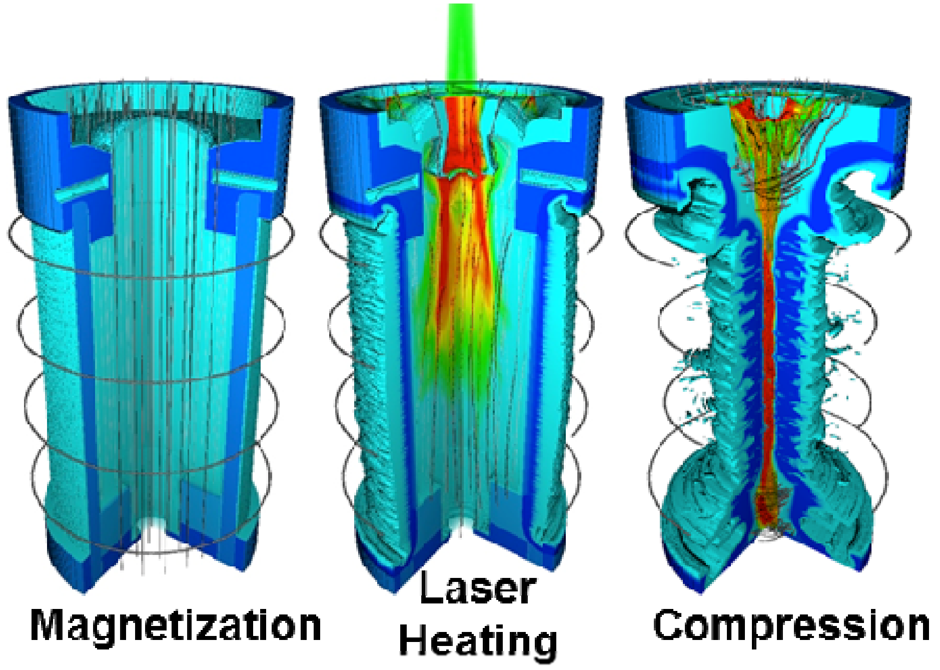


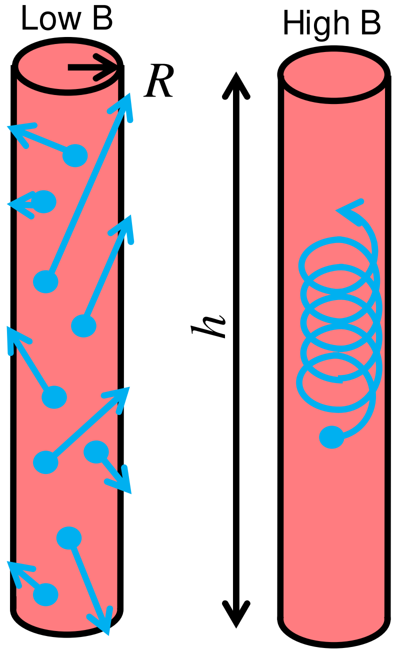
- Z can convert its 20 MJ stored energy to ~0.5 MJ of soft x-rays, but yields decrease as we push to higher photon energies
- Ongoing work on tailoring sources, enhancing non-thermal yields, and refining diagnostics

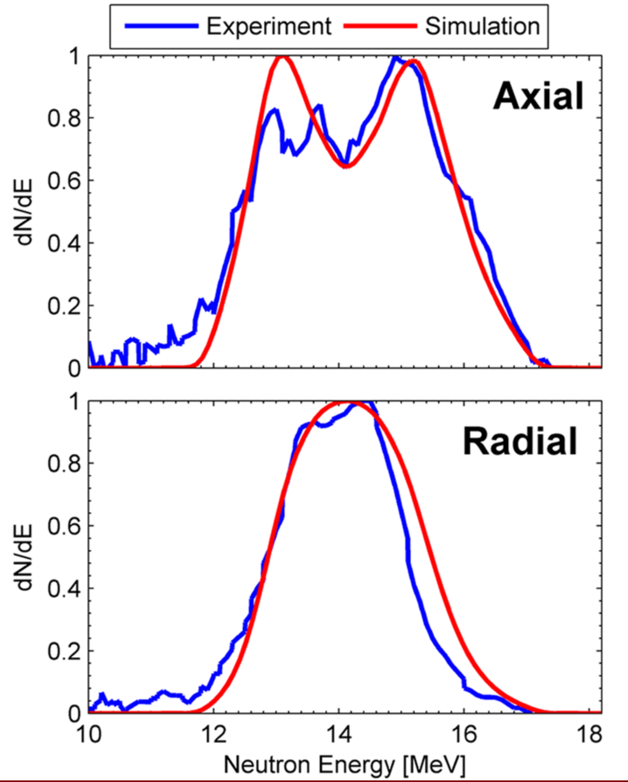


Ampleford, Jones, Vesey, Harvey-Thomson, Jennings

Fusion science: MagLIF







- With ~ 1 kJ laser preheat and 10-20T initial axial that inhibit radial thermal conduction, stabilize implosions, and trap charged particles, MagLIF experiments produce ~4×10^{12} DD neutrons (>10^{14} DT)

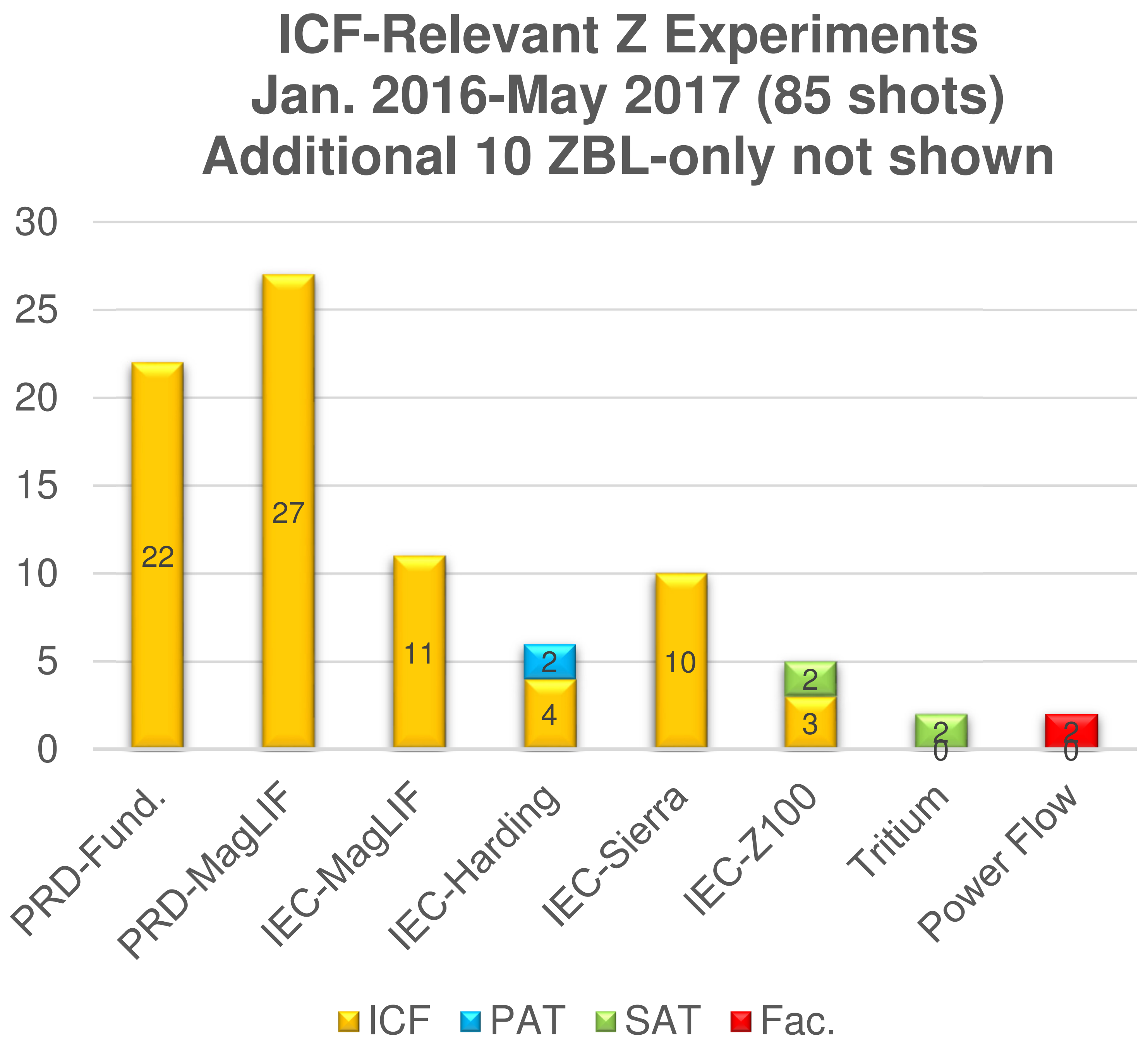
- X-ray spectra indicate T > 2 keV, ne >10^{23} e/cc and constrain liner/window mix; neutron data indicate that >40% of 1 MeV tritons (a good magnetic analog to DT alphas) thermalize in fuel before escaping confinement.

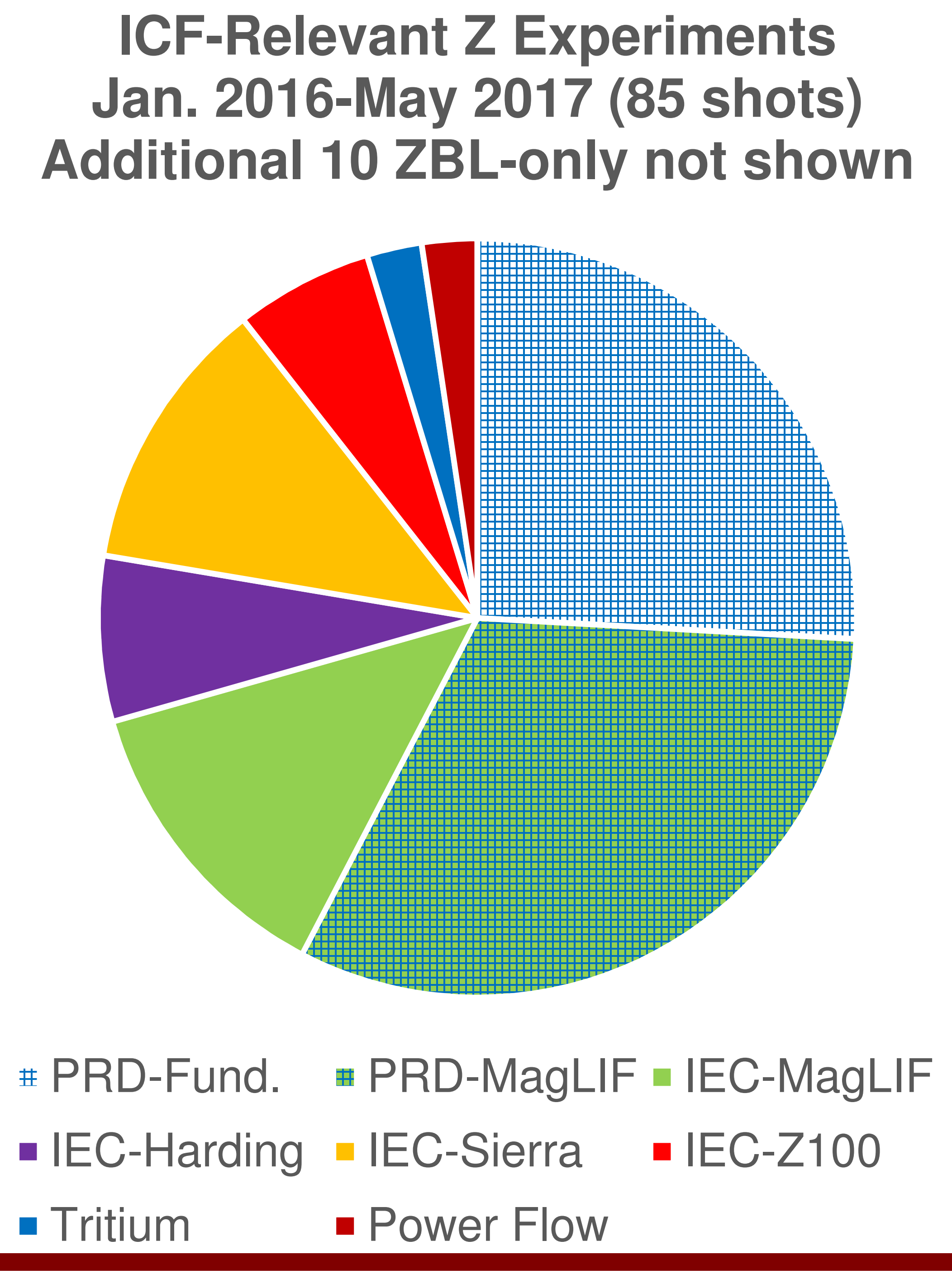
- Future work: understand fundamental physics of preheat, high-field transport, magnetohydrodynamics, implosions, instabilities, mix, stagnation, and magnetic confinement of fusion products; produce 100 kJ yields on Z

- Several additional Magneto-Inertial Fusion/ Magnetic Direct Drive concepts are being explored

Slutz, Gomez, Sinars, Rochau, Peterson, Ampleford, Harvey-Thomson, Jennings, Hahn, Sefkow…

Fusion efforts provide platforms for fundamental physics studies

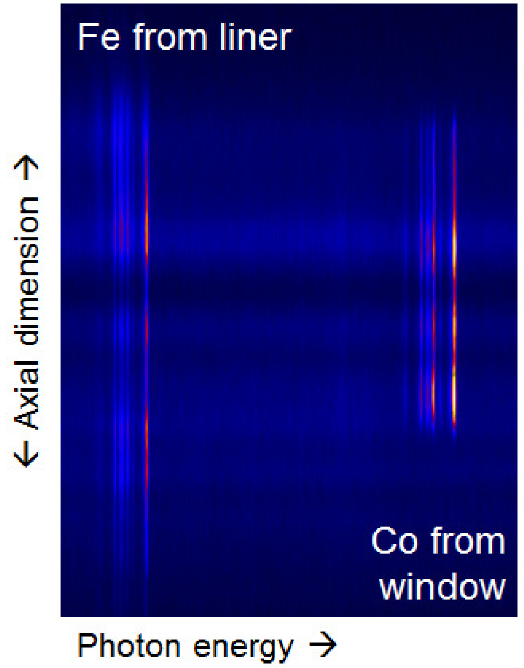




Slutz, Gomez, Sinars, Rochau, Peterson, Ampleford, Harvey-Thomson, Jennings, Hahn, Sefkow…

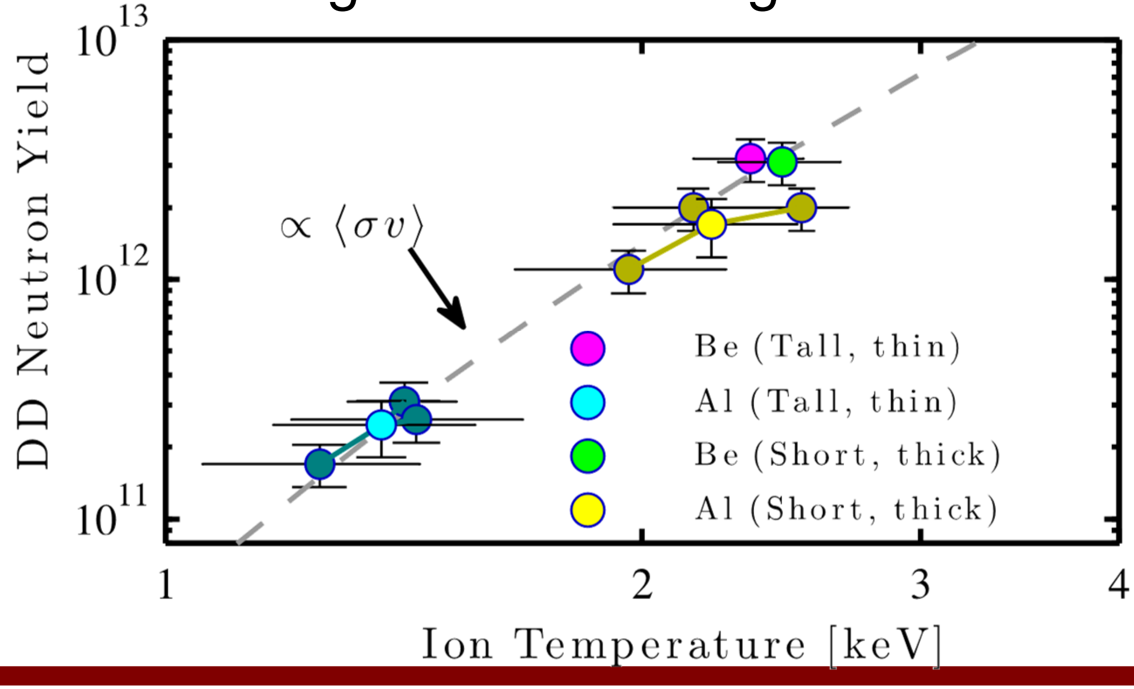
Fundamental science: laser-plasma interactions

Window dopants (here Co) help trace material transport (mix)

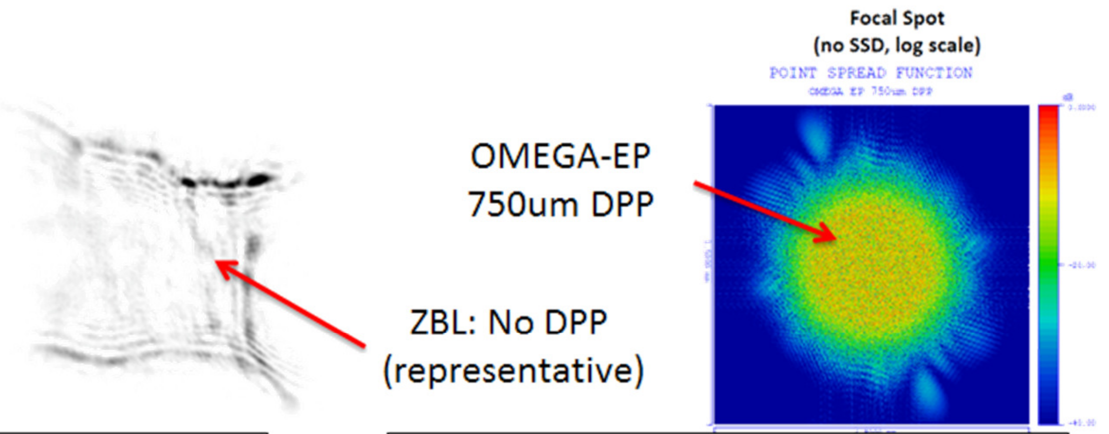


- Laser preheat in MagLIF is a critical factor in target performance; we are working to understand both energy and material transport through the LEH channel and window as a function of laser energy and target design

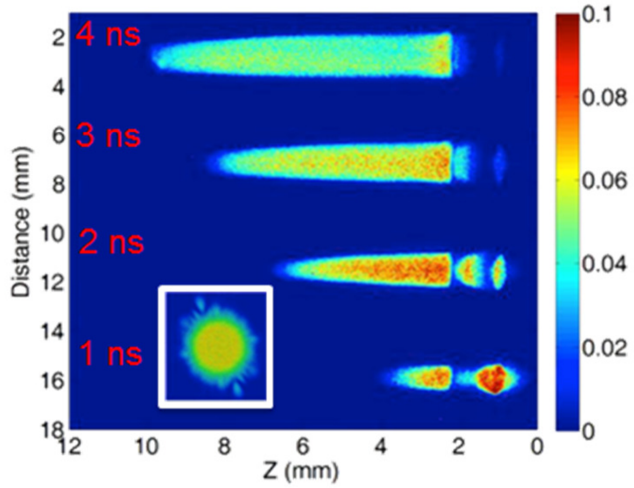
Yield degradation can signal low-Z mix



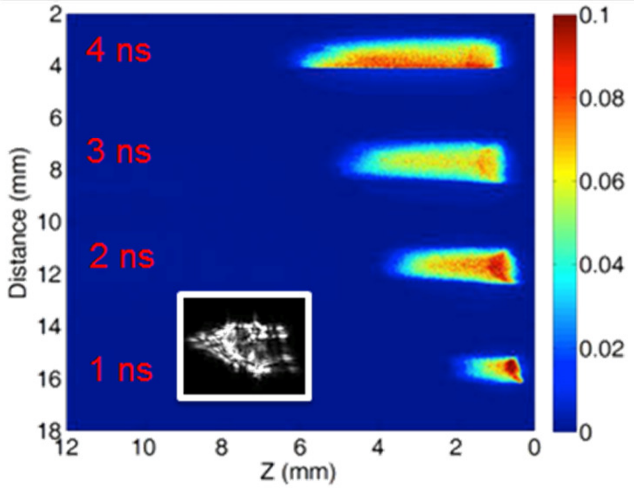
Z-Beamlet originally did not use any beam smoothing techniques adopted by the laser community



4 ns/3.1 kJ, 2 µm LEH, no prepulse with DPP (SNL Omega-EP data)

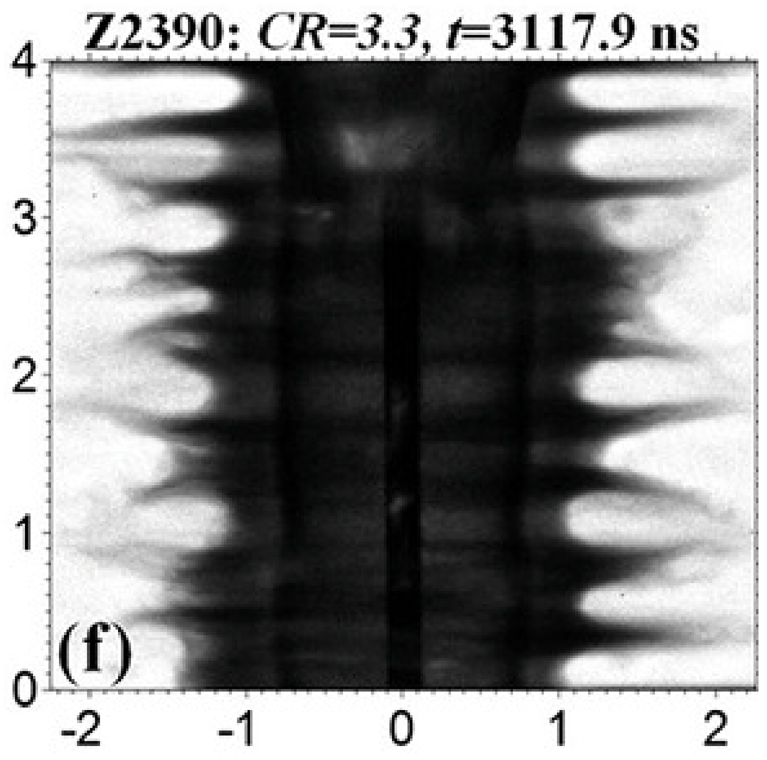


4 ns/2.93 kJ, 2 µm LEH, no prepulse without DPP (SNL Omega-EP data)

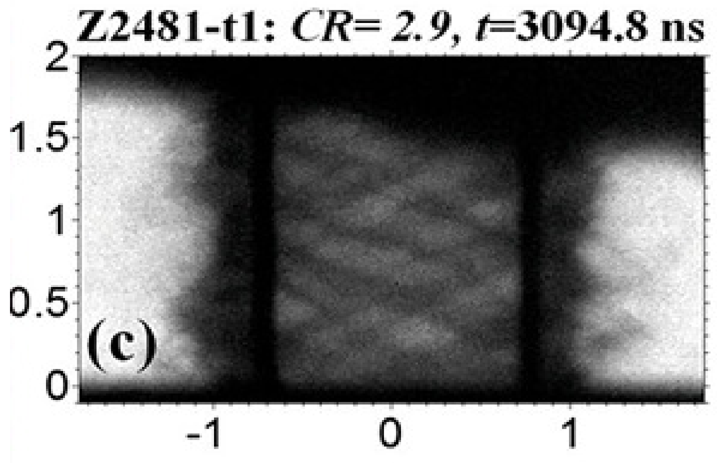


Giessel, Peterson, Harvey-Thomson, Jennings, Nagayama, Bliss…

Fundamental science: Magneto-Rayleigh Taylor (MRT) instabilities



$B_{Z0} = 0$

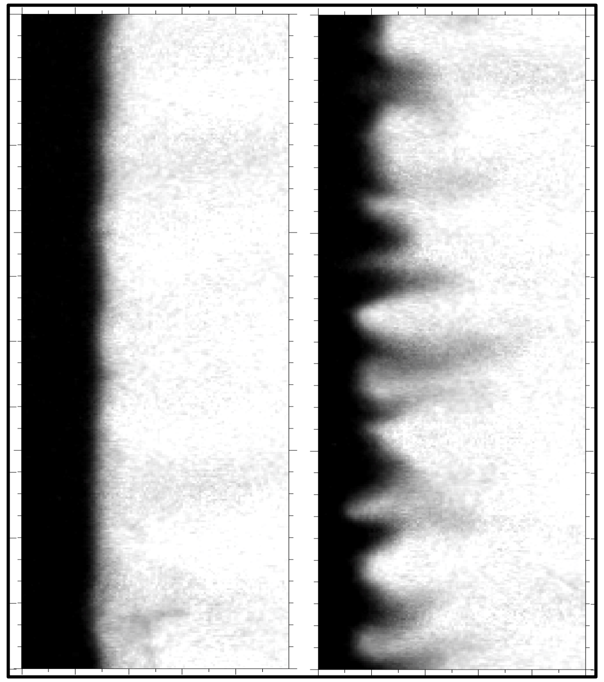


$B_{Z0} = 10$ T

TJ Awe et al PRL 111, 235005 (2013)

- Extensive radiographic studies have been done exploring the development of MRT instabilities, including their dependence on constitutive material properties
- Both axial magnetic fields and dielectric coatings appear to stabilize implosions, even to high convergence

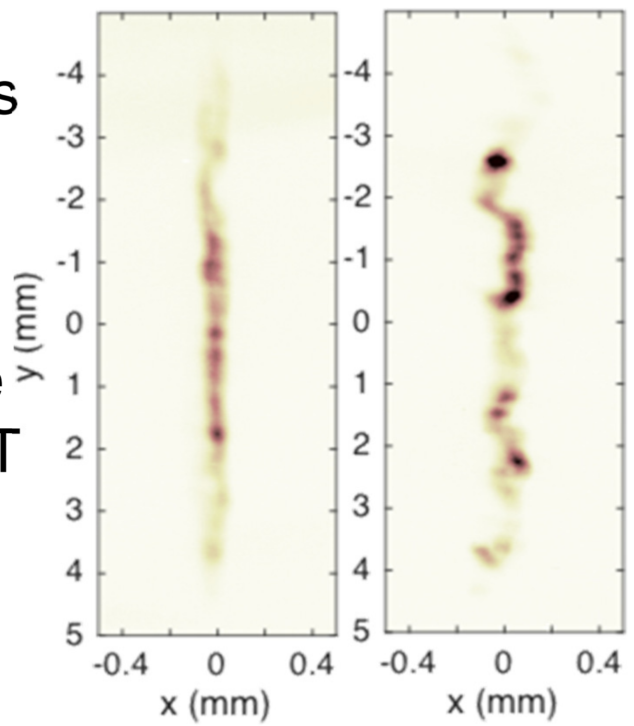
Coated Uncoated



KJ Peterson et al PRL (2015)

CH coatings on metal liners suppress the electro-thermal instability, the dominant MRT seed for MagLIF

Coated Uncoated



Awe, Peterson, Sinars, McBride, Ampleford, Harvey-Thomson, Jennings, Gomez

Fundamental science: deuterium compression

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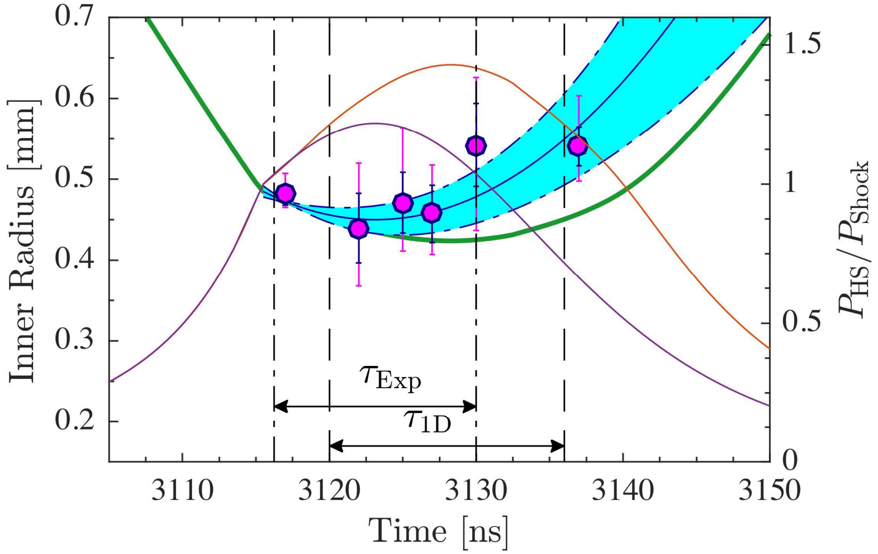
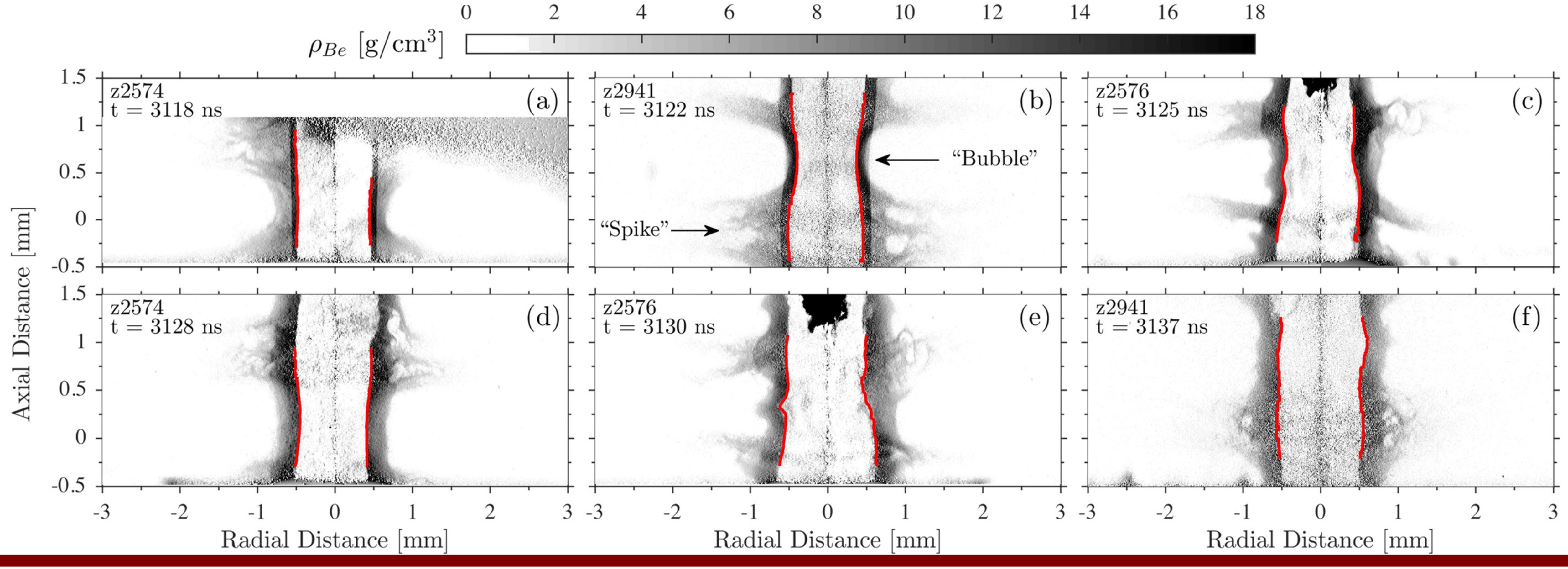
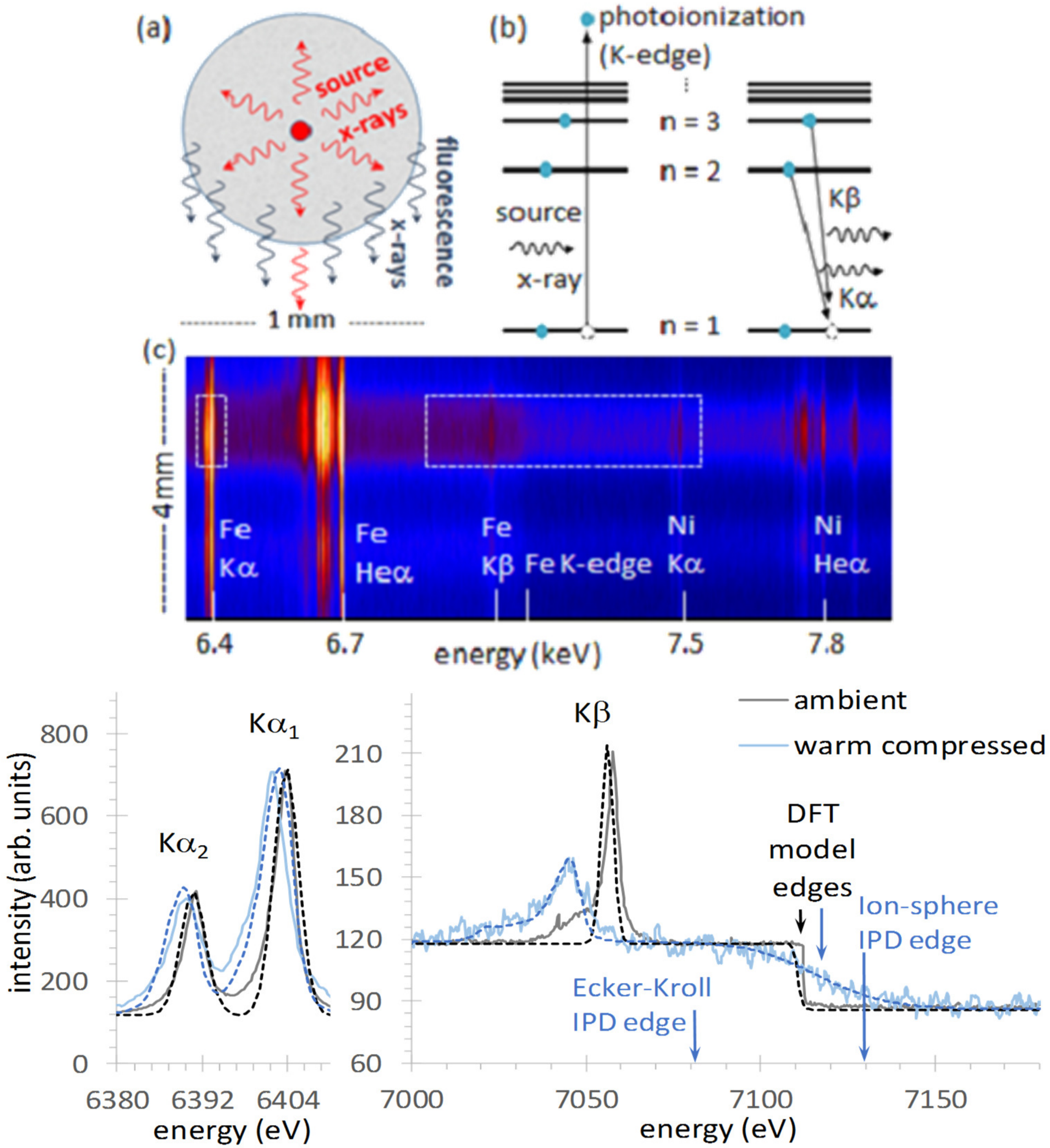


- Cryogenic deuterium in a closed liner has been compressed to densities 10-60 g/cc and ρR ~ 0.5 g/cm²
- radiographs have observed a bounce at CR ~ 8, enabling rigorous tests of MHD simulations
- Future applications to hydrogen & magnetized EOS, + WDM



Knapp, Martin, Jennings, Peterson, Weiss…

Fundamental science: density effects on atomic structure



- MagLIF here acts as a self-backlighting plasma for warm dense matter studies, compressing a beryllium liner to ~10x ambient density and producing bright x-rays at stagnation.
- The x-rays are absorbed by the liner, leading to edge absorption and fluorescence emission from native iron impurities
- The thermal emission from the hot core tells us about fuel conditions and mix, while the absorption and fluorescence features help constrain atomic-scale models of dense plasma effects
- Future work: buried layers, monochromatic imaging of fluorescence for liner morphology…

Fundamental science: magnetic field effects on atomic structure

Sandia National Laboratories

REVIEW OF SCIENTIFIC INSTRUMENTS **85**, 11E609 (2014)

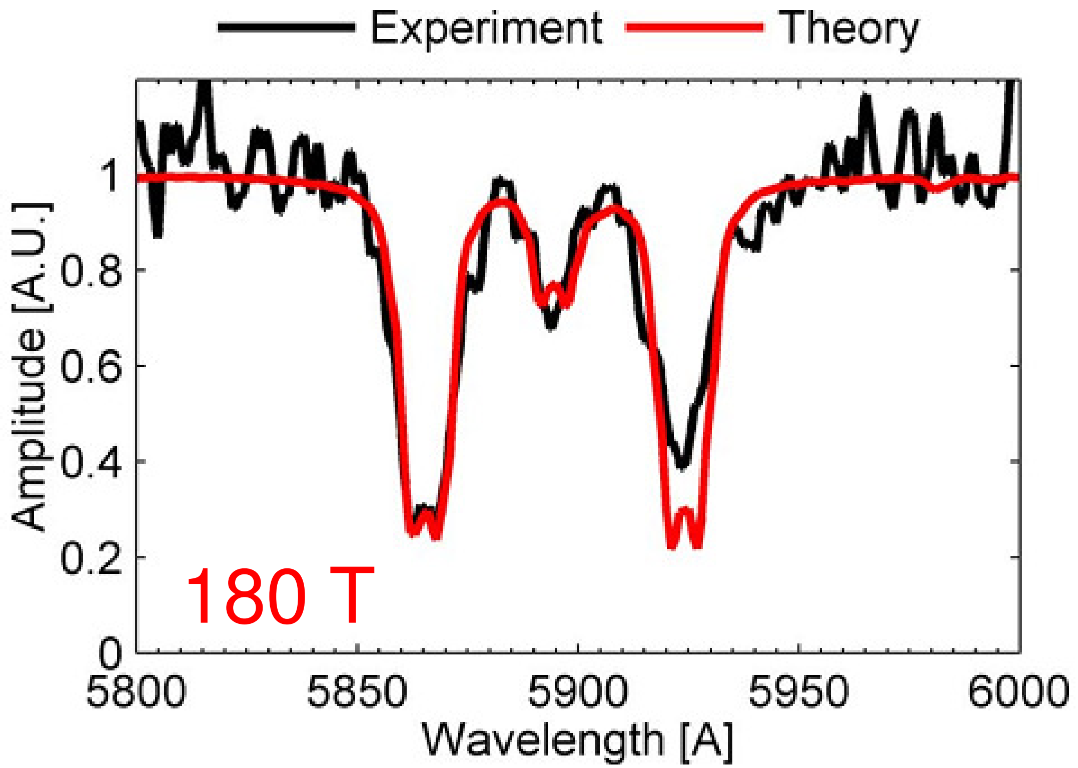
CrossMark

Magnetic field measurements via visible spectroscopy on the Z machine[a)]

M. R. Gomez,[1,b)] S. B. Hansen,[1] K. J. Peterson,[1] D. E. Bliss,[1] A. L. Carlson,[1]
D. C. Lamppa,[1] D. G. Schroen,[2] and G. A. Rochau[1]
[1]*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*
[2]*General Atomics, San Diego, California 92121, USA*

(Presented 4 June 2014; received 31 May 2014; accepted 14 July 2014; published online 1 August 2014)

Sandia's Z Machine uses its high current to magnetically implode targets relevant to inertial confinement fusion. Since target performance is highly dependent on the applied drive field, measuring magnetic field at the target is essential for accurate simulations. Recently, the magnetic field at the target was measured through splitting of the sodium 3s-3p doublet at 5890 and 5896 Å. Spectroscopic dopants were applied to the exterior of the target, and spectral lines were observed in absorption. Magnetic fields in excess of 200 T were measured, corresponding to drive currents of approximately 5 MA early in the pulse. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4891304]



- Zeeman splitting due to the azimuthal driving fields have been measured up to ~200 T, similar to fields around white dwarf stars

- In a MagLIF plasma, the axial field can be flux-compressed to >10 kT – similar to the fields surrounding neutron stars – and can potentially be measured through Zeeman splitting of x-ray lines

- Efforts on fundamental line shape theory (Zeeman, Stark, and collisional effects) which can enhance the utility of spectroscopic diagnostics are underway, along with efforts to extend B-field diagnostics

- Future work: increase collaborations with astrophysical community to study magnetized astrophysical systems

Gomez, Hansen, Lamppa, Patel, Banasek, Maron, Stambulchik

Fundamental science: solar-relevant opacities

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nature International weekly journal of science

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Archive > Volume 517 > Issue 7532 > Letters > Article

NATURE | LETTER

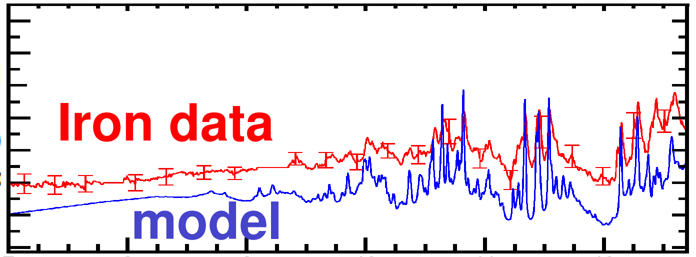
日本語要約

A higher-than-predicted measurement of iron opacity at solar interior temperatures

J. E. Bailey, T. Nagayama, G. P. Loisel, G. A. Rochau, C. Blancard, J. Colgan, Ph. Cosse, G. Faussurier, C. J. Fontes, F. Gilleron, I. Golovkin, S. B. Hansen, C. A. Iglesias, D. P. Kilcrease, J. J. MacFarlane, R. C. Mancini, S. N. Nahar, C. Orban, J.-C. Pain, A. K. Pradhan, M. Sherrill & B. G. Wilson

Affiliations | Contributions | Corres

Nature **517**, 56–59 (01 January 2015)
Received 17 September 2014 | Accep
2014



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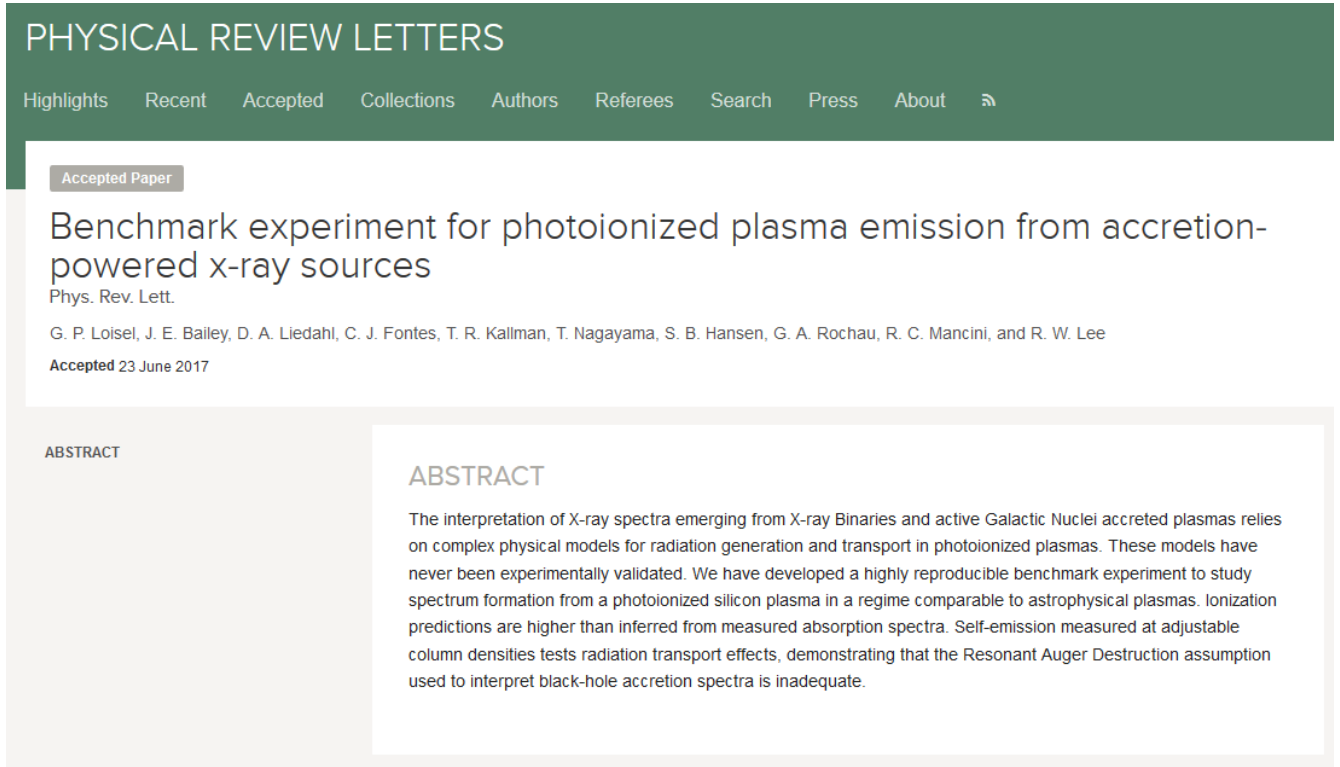
Nearly a century ago it was recognized[1] that radiation absorption by stellar matter controls the internal temperature profiles within stars. Laboratory opacity measurements, however, have never been performed at stellar interior conditions, introducing uncertainties in stellar models[2, 3, 4, 5]. A particular problem arose[2, 3, 6, 7, 8] when refined photosphere spectral analysis[9, 10] led to reductions of 30–50 per cent in the inferred amounts of carbon, nitrogen and oxygen in the Sun. Standard solar models[11] using the revised element abundances disagree with helioseismic observations that determine the internal solar structure using acoustic oscillations. This could be resolved if the true mean opacity for the solar interior matter were roughly 15 per cent higher than predicted[2, 3, 6, 7, 8], because increased opacity compensates for the decreased element abundances. Iron accounts for a quarter of the total opacity[2, 12] at the solar radiation/convection zone boundary. Here we report measurements of wavelength-

- A decade ago, new elemental abundances led to inconsistency between helioseismology measurements and solar models
- A decadal effort by Bailey *et al.* to measure opacities on Z found higher-than-predicted absorption for iron, a key contributor to solar opacity
- Ongoing work to identify trends with material and conditions, improve & extend experiments, and investigate possible model extensions to resolve disagreement between experiment and theory
- Upcoming experiments on NIF will provide alternate platform opinion on iron opacity; efforts at LCLS are underway to test line broadening models

Fundamental science: photoionized plasmas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Benchmark experiment for photoionized plasma emission from accretion-powered x-ray sources

Phys. Rev. Lett.

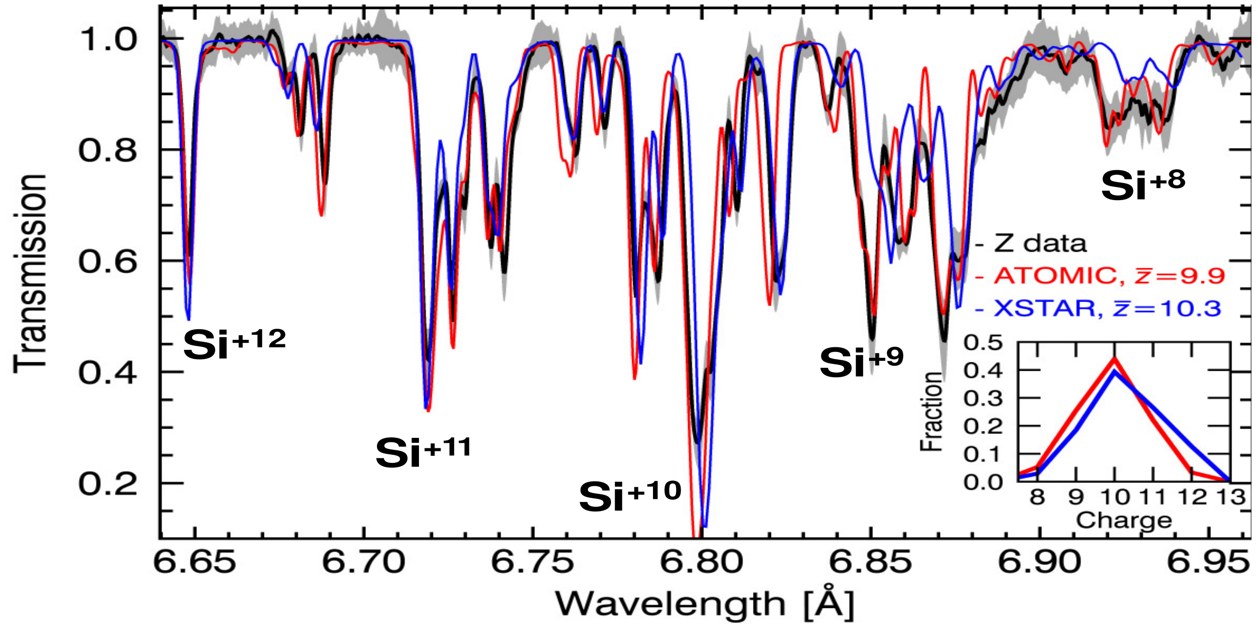
G. P. Loisel, J. E. Bailey, D. A. Liedahl, C. J. Fontes, T. R. Kallman, T. Nagayama, S. B. Hansen, G. A. Rochau, R. C. Mancini, and R. W. Lee

Accepted 23 June 2017

ABSTRACT

ABSTRACT

The interpretation of X-ray spectra emerging from X-ray Binaries and active Galactic Nuclei accreted plasmas relies on complex physical models for radiation generation and transport in photoionized plasmas. These models have never been experimentally validated. We have developed a highly reproducible benchmark experiment to study spectrum formation from a photoionized silicon plasma in a regime comparable to astrophysical plasmas. Ionization predictions are higher than inferred from measured absorption spectra. Self-emission measured at adjustable column densities tests radiation transport effects, demonstrating that the Resonant Auger Destruction assumption used to interpret black-hole accretion spectra is inadequate.

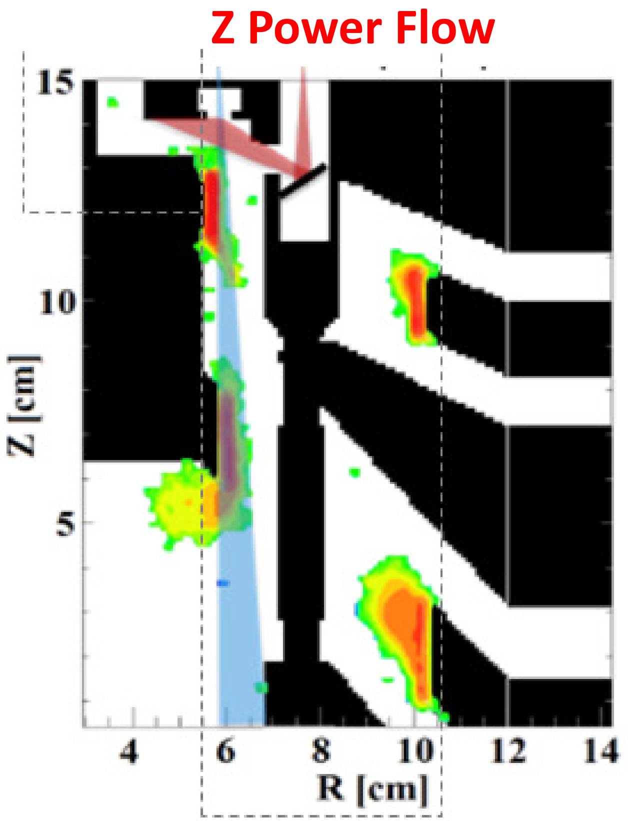


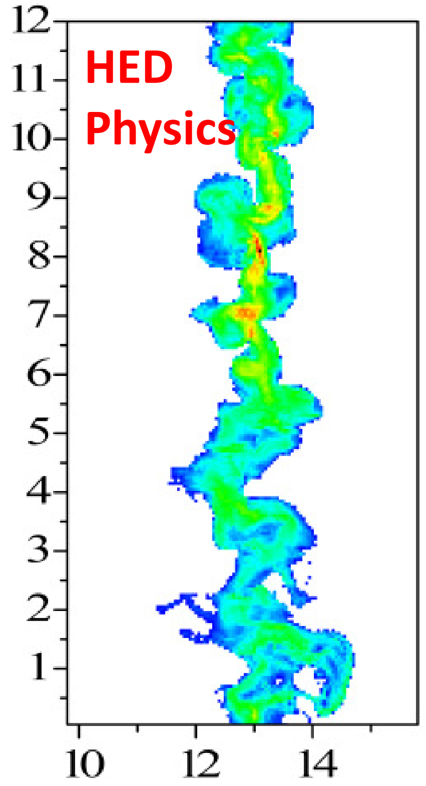
- Iron K-shell lines emitted from outside black holes are gravitationally redshifted and transported through low-density gas, but expected emission from L-shell ions is not observed.
  Hypothesis: Resonant Auger Destruction (RAD)

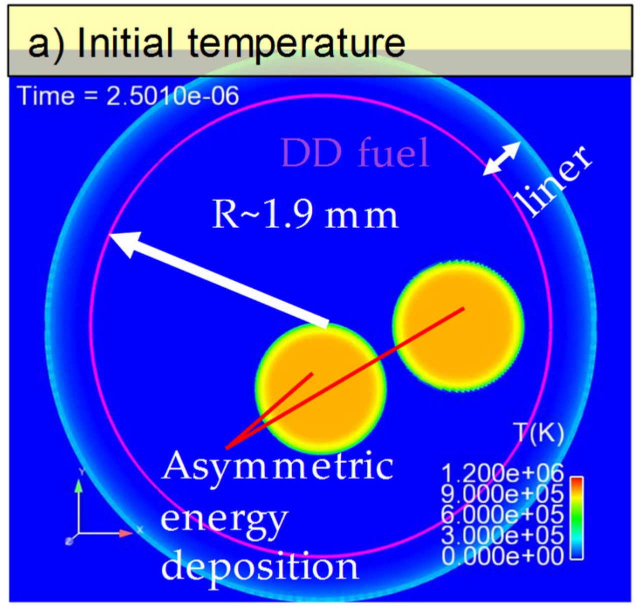
- Samples irradiated with Z' copious x-rays were measured in transmission and absorption, ruling out complete RAD as an explanation for x-ray observations

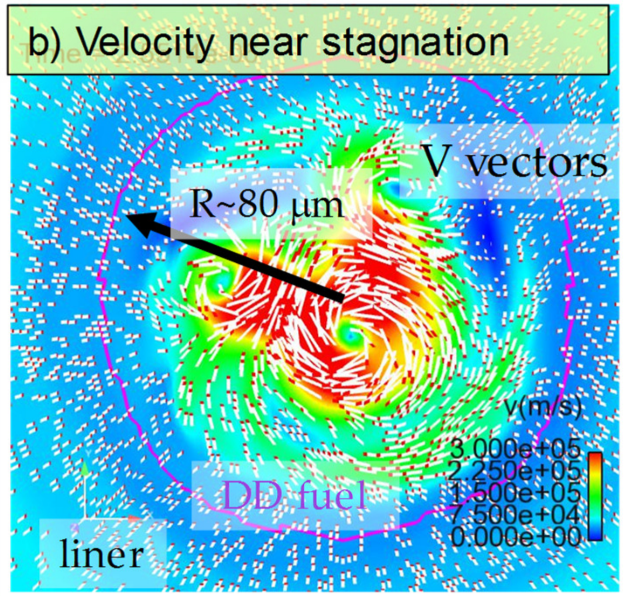
- Ongoing work on atomic kinetics in both Si and Ne samples, density effects on H and He lineshapes and continuum, increasing precision of measurements, and extended applications to astrophysical plasmas (including magnetized astro)

Computational science: simulations and data analysis









- Multi-Scale Algorithms and models aim to couple power flow and target physics capabilities to help enable Z-next design: hydro + PIC on enormous scale range
- Continued development of Magneto-radiation-hydrodynamics models that account for extended MHD, improved constitutive models, and high-order effects (Nernst, Eddington); predictions for simulated data
- Bayesian analysis tools that extract high-level information on the plasma state which incorporates myriad data
- Future connects to astrophysical community

Laity, Cuneo, Martin, Knapp, Glinsky, Jennings, Seyler, Yu…

Outlook and opportunities

- Science case and risk analysis for scaling ICF, Radiation, and Dynamic Materials experiments to Z-Next will benefit from community input: *NISP, HEDSA, RENEW,…*

- ICF platforms offer rich opportunities to study fundamental HED science: imaging + optical, X-ray, and neutron spectroscopy reveal details of implosion, stagnation, and atomic-scale properties of material at extreme conditions. *opportunities for collaboration in platform development, diagnostics, analysis…*

- Increasing diagnostic capabilities (enhanced space, time, and energy resolution) will provide ever-finer data requiring sophisticated analysis *opportunities for data mining, Bayesian analysis, error analysis, constitutive modeling, forward simulation*

- The high efficiency of pulsed power and the attendant strong magnetic fields enable studies of regimes relevant to Mangeto-Inertial Fusion, atomic-scale physics in extreme environments, stockpile stewardship, and astrophysics

Visions emerging from the PPS&T planning process; In 20 years we would like to:

- **Dynamic Material Properties**
  - Have impacted NCT assessments and pit production decisions, which will require about 150 high-hazard materials experiments at moderate pressures with large sample sizes and time scales (highest impact if within 10-12 years)
  - Have the capability to validate key material model predictions at very high pressures in a small number of experiments per year
- **Radiation Effects Science**
  - Have revitalized key existing nuclear survivability facilities to ensure the continued qualification of our stockpile
  - Establish new capabilities for warm x-rays, 14 MeV neutrons, and combined hostile environments for qualification and model validation
- **Inertial Confinement Fusion:** Be able to produce tens of MJ yields in the laboratory on a path to >250 MJ yields in the future for weapons and effects testing
- **Codes:** Have validated, integrated code capabilities sufficient to design and engineer the power-flow, target physics, and containment systems needed to achieve these visions
- **Academia & Industry:** Have the U.S. national laboratories recognized as world leaders in pulsed power science and technology, underpinned by strong integration with academia and industry, and thoughtful engagement with international partners

High-speed hCMOS cameras continue evolving to meet the needs of the ICF and HED science programs

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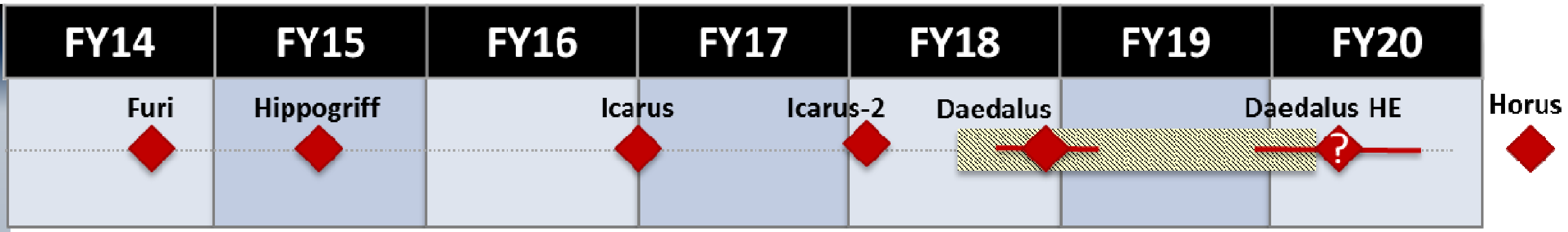
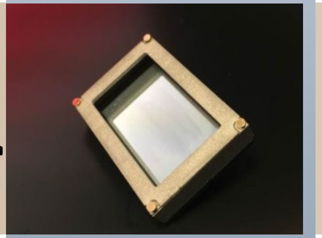
Timeline



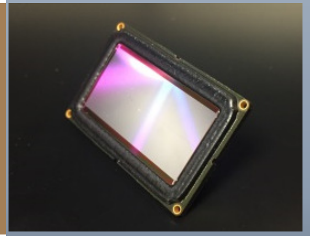
Furi / Hippogr



- 1st full-scale multi-frame sensors
- 1.5-2ns minimum shutter
- Optimized for 1-10 keV x-ray detection

DOE Secretary's Award
NNSA Award of Excellence
R&D100 Award

Icarus



- 1st cameras compatible with pulse-dilation
- 1 ns min. shutter with 2 or 4 (Icarus-2) frames per hemisphere
- Optimized for soft x-ray, visible, and e- detection

Daedalu

- 3 frames per hemisphere (≥6 frames with interlacing)
- 1-side abuttment for spectroscopy and z-pinch imaging applications
- Large well for high energy x-rays while maintaining low end sensitivity

Horus

- Potentially 1st 130 nm sensor

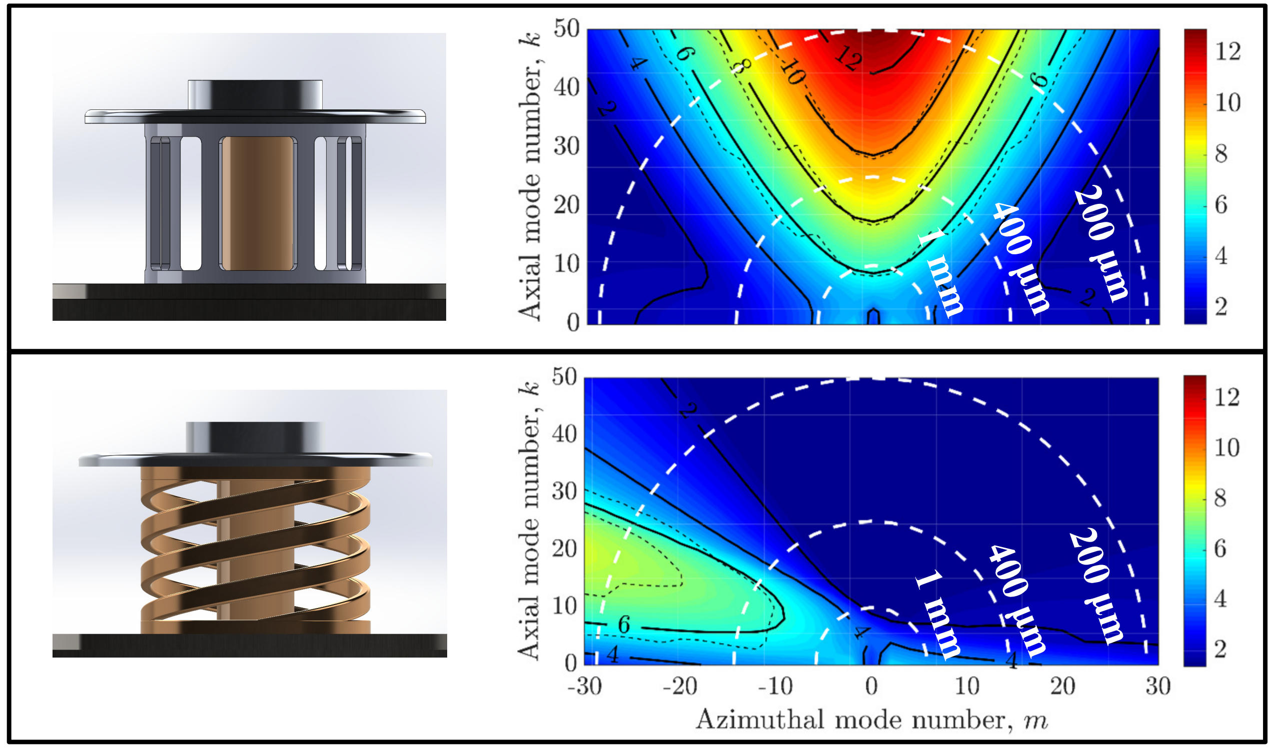
Design goals may include

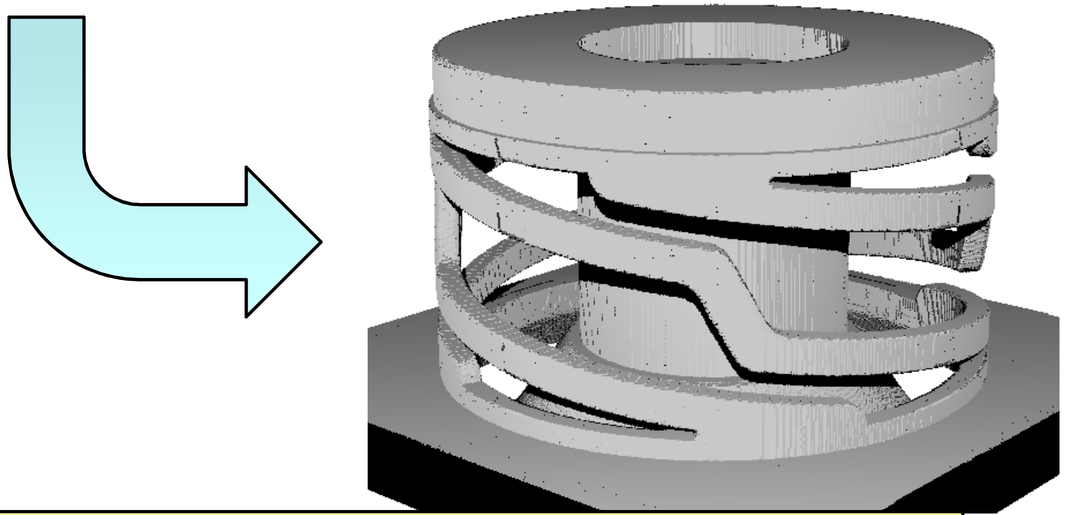
- 6 frames per quadrant (≥12 frames with interlacing)
- 0.25 ns minimum shutter

UXI Sensors

Novel MRT instability stabilization mechanism described, with supporting numerical design calculations underway

- **Motivation**: Magneto-Rayleigh-Taylor (MRT) instability limits performance of magnetic direct drive ICF platforms, like MagLIF. There is immense value in finding ways to curb its growth.
- **Approach**: Normally, magnetic fields in z-pinches accelerate the growth of the most unstable MRT modes. Yet, by generating a magnetic field whose orientation rotates as the liner implodes (e.g., by twisting the return current can), MRT growth can be reduced dramatically.
- **Outcome**: Initial theoretical study published in PRL [1], suggesting growth of most detrimental MRT modes could be reduced by several e-foldings. 3D design calculations underway using ANSYS Maxwell and GORGON

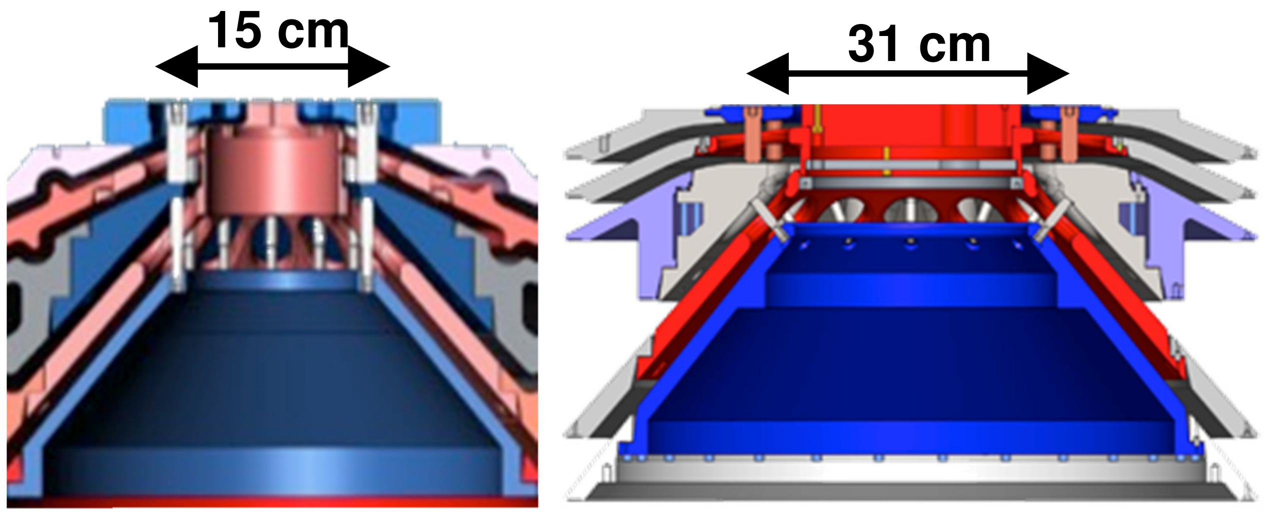


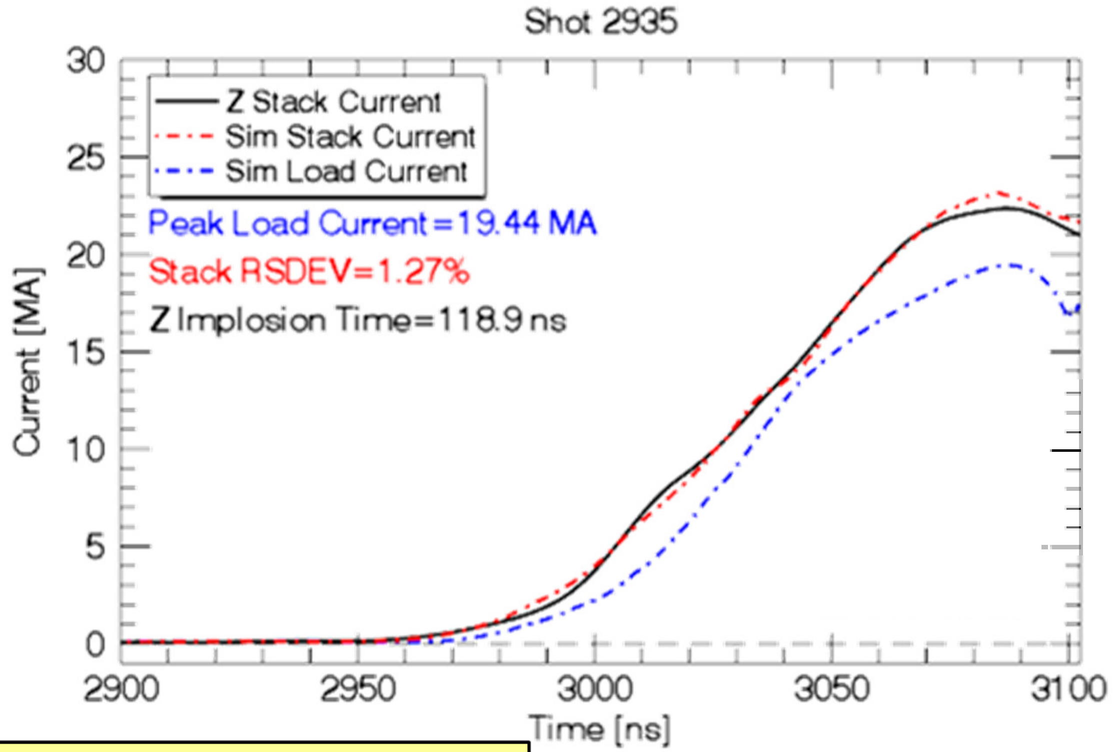


Top: MRT e-folding spectra and representative MagLIF hardware

Driver Target Coupling PRD: We have demonstrated improved current coupling using a new Z convolute

- **Motivation**: Can we improve current delivery to MagLIF targets by reducing current loss in the Z convolute?
- **Approach**: The MagLIF load structure was adapted for the 31-cm ("large") convolute, which utilizes wide A-K gaps to delay plasma gap closure.
- **Outcome**: The peak load current into the standard MagLIF target was increased by +1.25MA using the 31-cm convolute, and efforts are underway to improve the facility utilization of the platform.





Circuit Model Evaluation of 31-cm Convolute MagLIF (Z2935)

(Opportunity to be pursued)

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Challenge (WHY?)

• What's the problem/roadblock to be tackled
• What are the 2-3 bullets that elaborate the scope?

Approaches (HOW?)

• What's the tool (synthesis/characterization/simulation)?
• What's the resolution (spatial, temporal, ...)/sensitivity
•

Timeliness (WHY NOW?)

Why now and not earlier?
• Where's the state of the art (and where could it go)
• . . .

Impact (SO WHAT?)

• if the new opportunity is pursued and the challenge is addressed, then what?
• What coupled needs exist?
• . . .

Transformational Opportunity Candidate

Opportunity

• What's the short question that captures the spirit of the opportunity (e.g., How do we control material processes at the level of electrons?)
• What are the 2-3 bullets that elaborate the scope?

Approaches

• Characterization tools
• Computational tools
• Synthesis tools
• Intellectual tools
• . . .

Timeliness

Why now and not earlier?
• New tools are now available (e.g, nanoscience, ultrafast, computation)
• Supporting grand challenges have been advanced (e.g., mapping genome → gene therapy)
• . . .

Impact

• Enables understanding new classes of behavior (e.g., solving far from equilibrium → weather, fracture, traffic jams . . .)
• Enables new control of phenomena (e.g., principles of self-assembly → new classes of functional materials)
• . . .