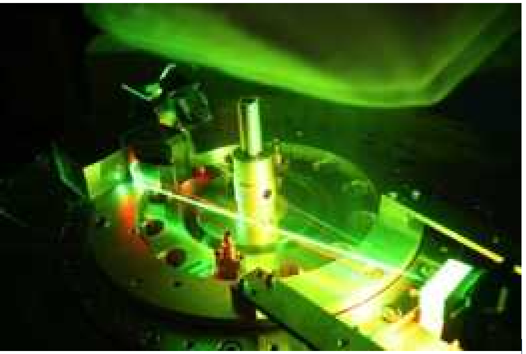

Sandia National Laboratories

Exceptional service in the national interest

SAND2016-0729PE

High Energy Density Physics at Sandia using Pulsed Power and Powerful Laser Pulses

Marius S. Schollmeier

Senior Research & Development Physicist

Sandia National Laboratories, Albuquerque, NM, USA

Institutsseminar, Helmholtz Institut Jena, Germany

February 3, 2016

U.S. DEPARTMENT OF ENERGY NNSA

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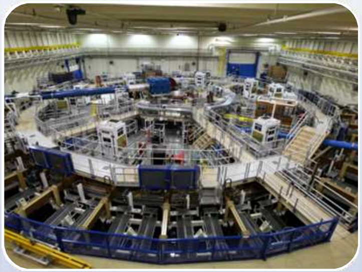
Outline

Sandia National Laboratories

- Overview & Research Framework



Z Pulsed Power Facility

- Overview & Capabilities, HED Science with Pulsed Power

Z Backlighter Facility

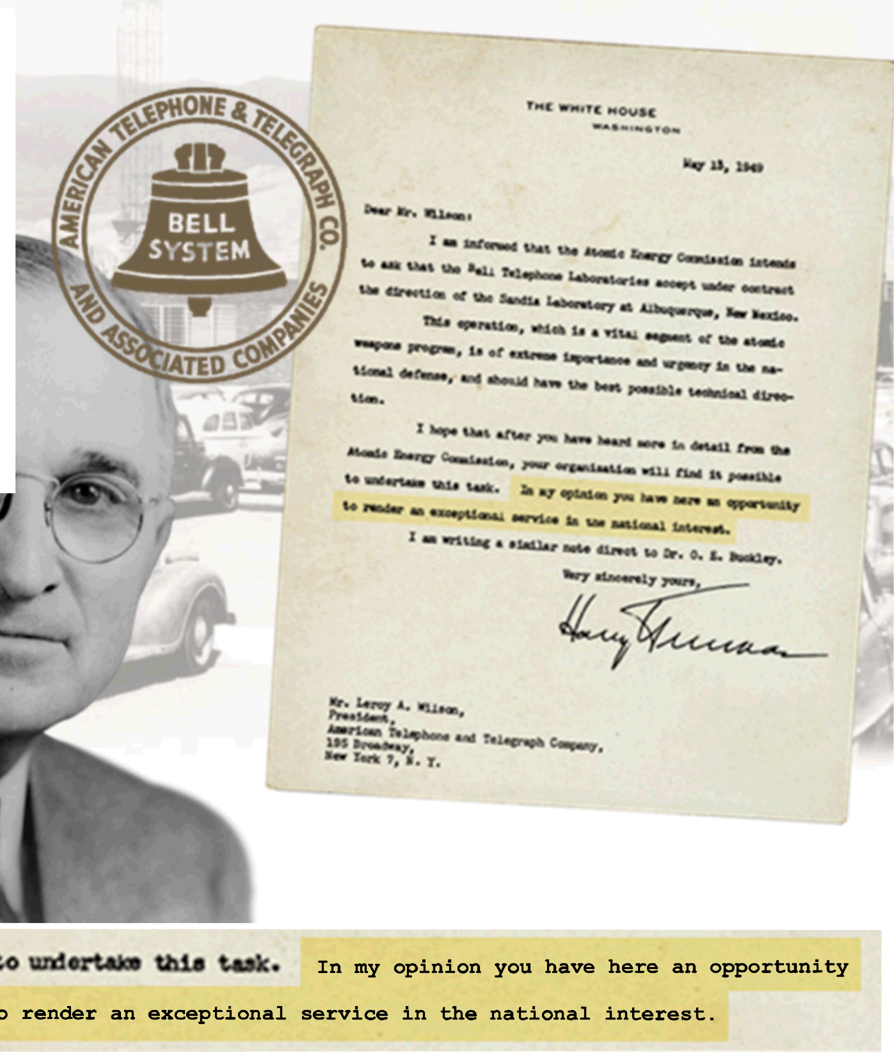
- Overview & Capabilities, Key Research Areas

Sandia's history dates back to the Manhattan Project

Exceptional service in the national interest

- **July 1945:** Los Alamos creates Z Division
- **November 1, 1949:** Sandia Laboratory established
- Government owned, contractor operated:
    - **1949–1993:** AT&T
    - **1993–1995:** Martin Marietta
    - **1995–Present:** Lockheed Martin Corporation

- Regular employees: 10,540
- Budget (FY14): $2.6B



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

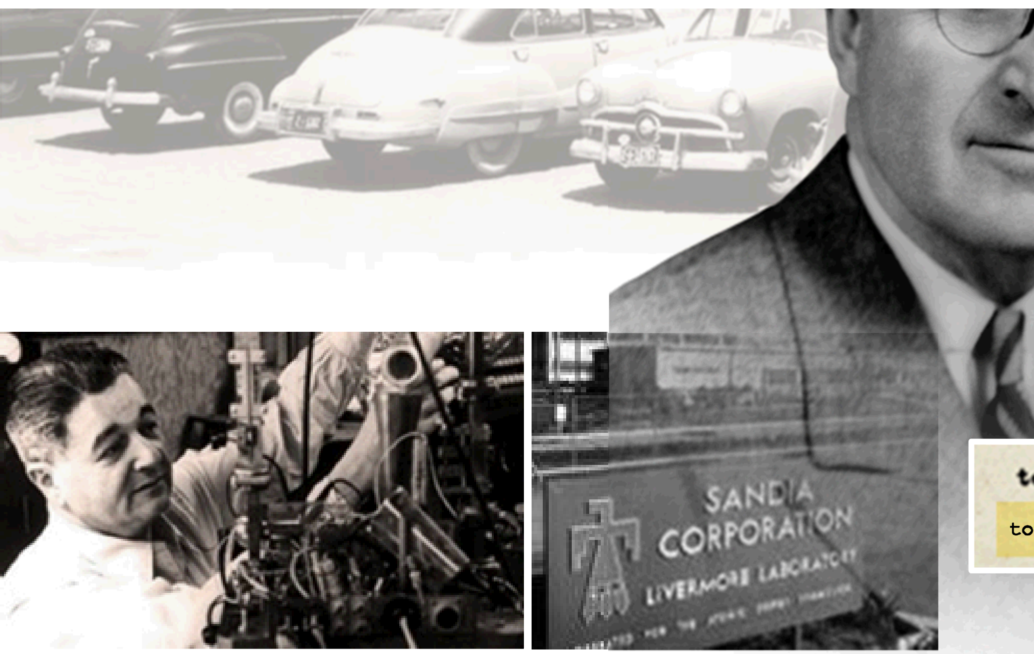
I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

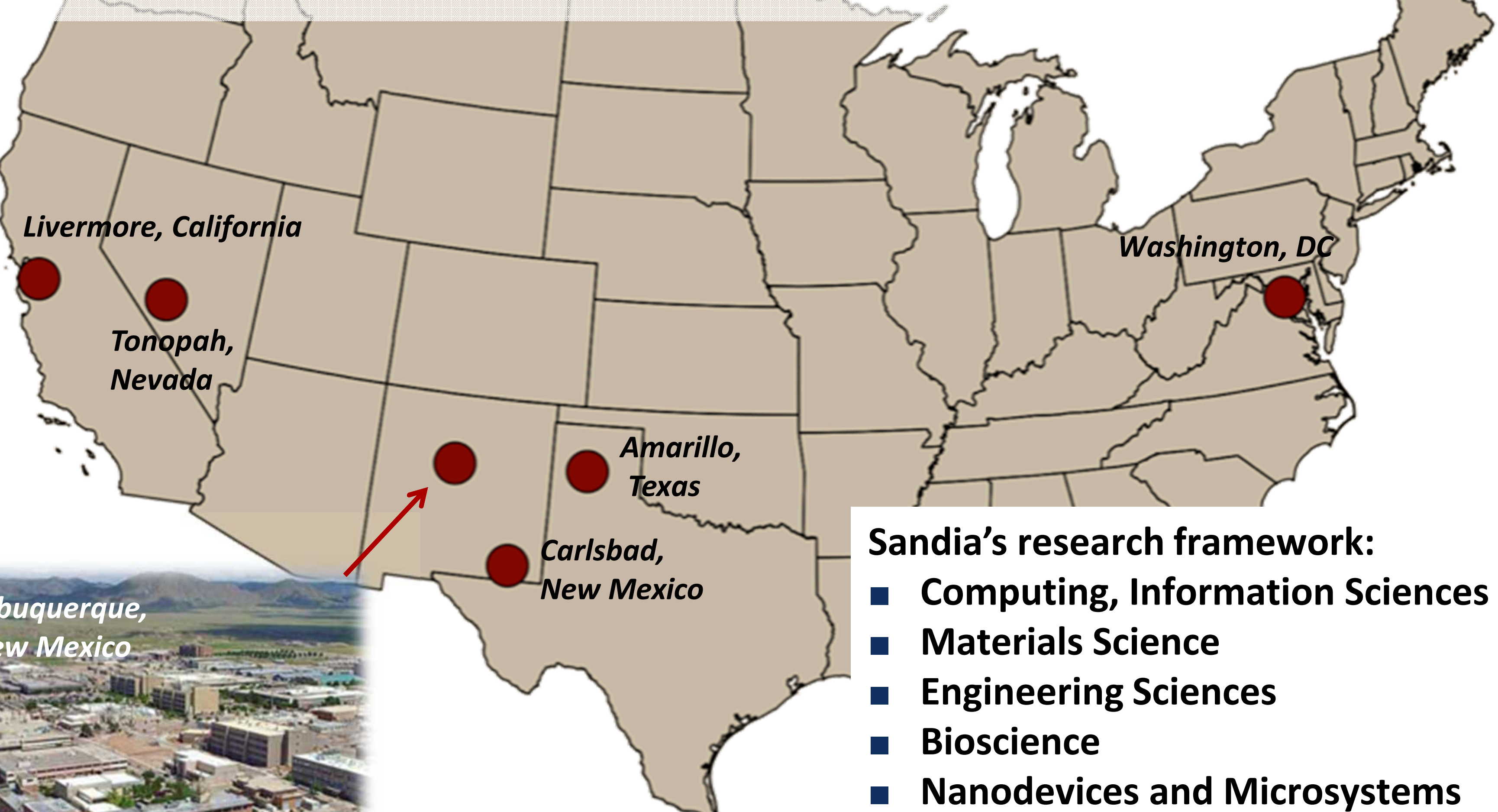
Very sincerely yours,

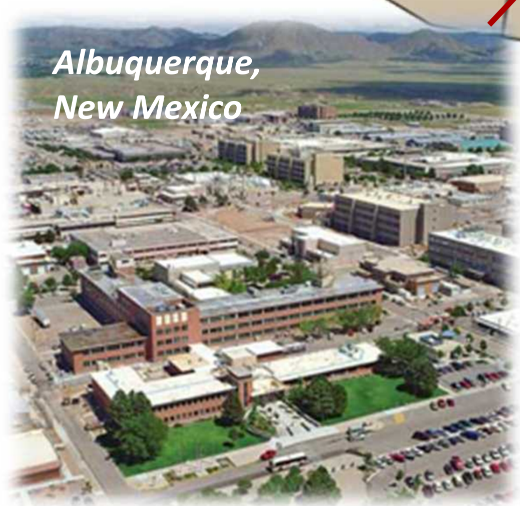
Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.



Sandia has sites across the United States, but the majority of its employees are in New Mexico





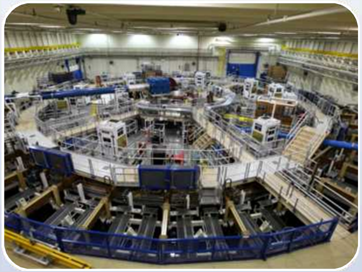
Sandia's research framework:

- Computing, Information Sciences
- Materials Science
- Engineering Sciences
- Bioscience
- Nanodevices and Microsystems
- Geoscience
- Radiation Effects and High Energy Density Science

Outline

Sandia National Laboratories

- Overview & Research Framework



Z Pulsed Power Facility

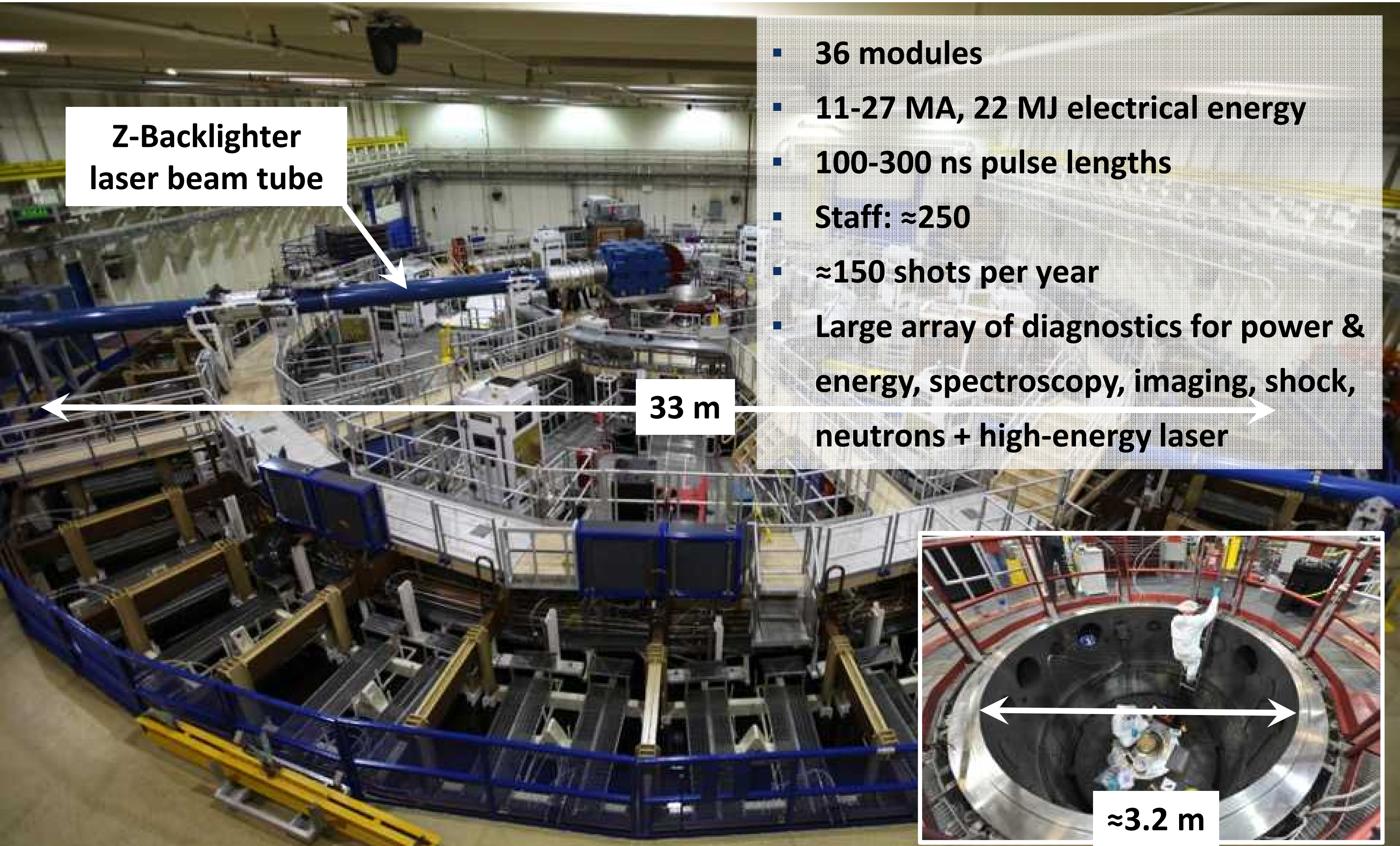
- Overview & Capabilities, HED Science with Pulsed Power

Z Backlighter Facility

- Overview & Capabilities, Key Research Areas

The Sandia Z Pulsed Power Facility uses electric current to efficiently couple MJs of energy to targets at its center*

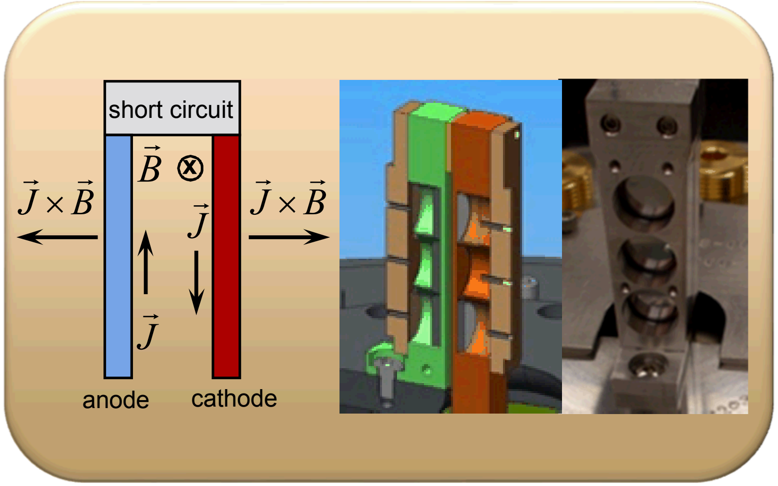
Sandia National Laboratories



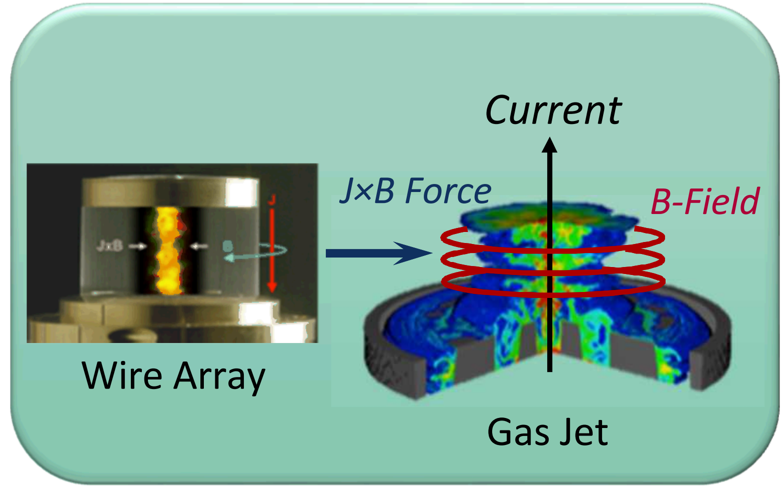
- 36 modules
- 11-27 MA, 22 MJ electrical energy
- 100-300 ns pulse lengths
- Staff: ≈250
- ≈150 shots per year
- Large array of diagnostics for power & energy, spectroscopy, imaging, shock, neutrons + high-energy laser

*http://www.sandia.gov/z-machine

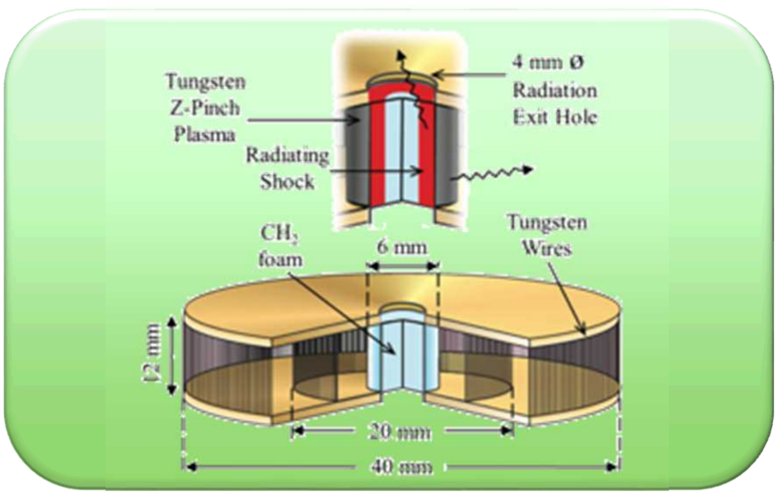
We use Z in several ways to create HED matter for various physics applications



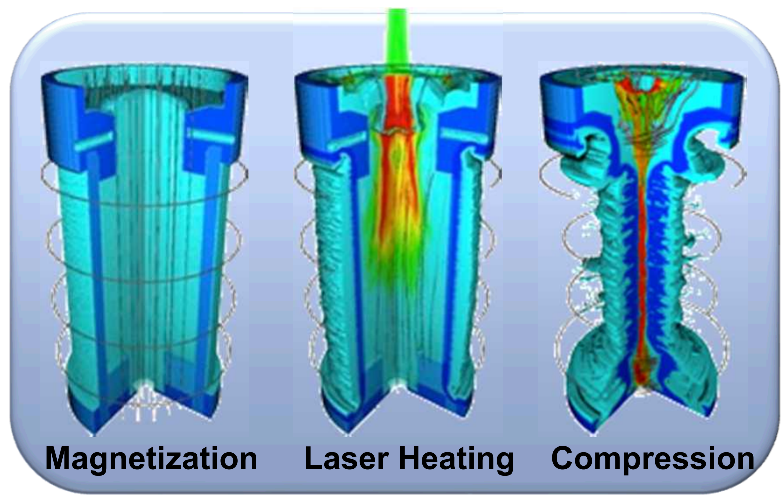
Dynamic Material Properties



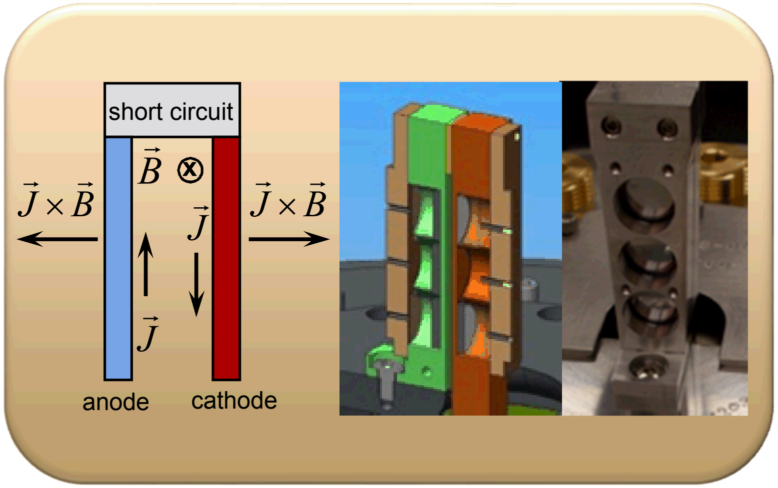
Z-Pinch X-Ray Sources



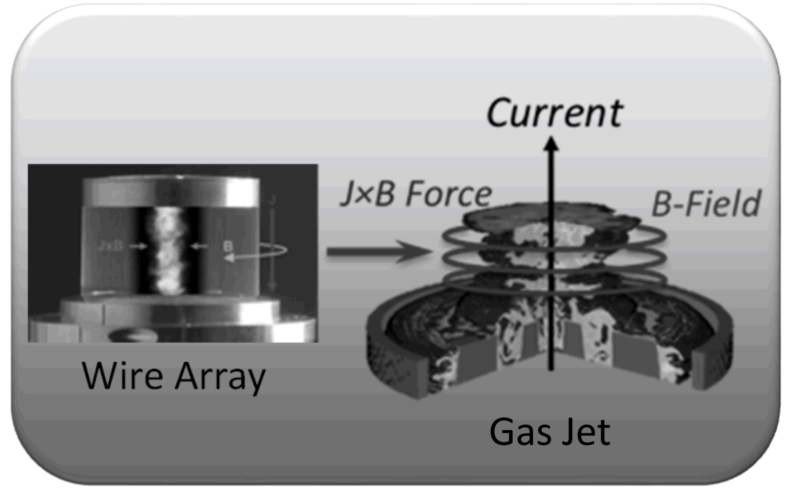
Astrophysical Plasmas



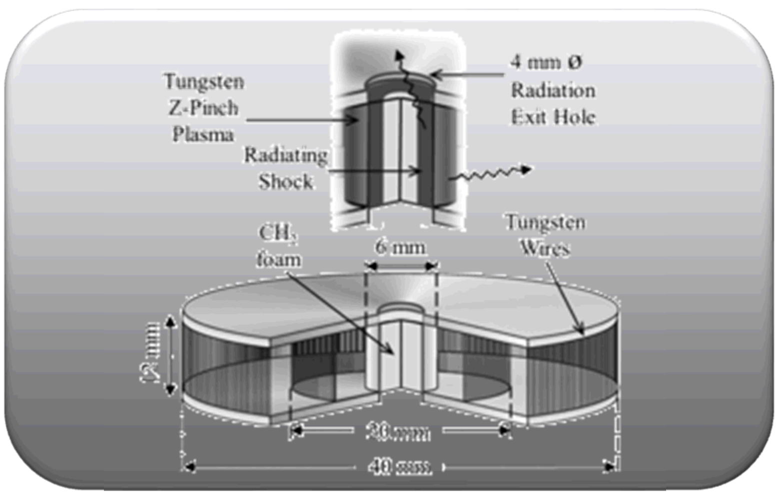
Inertial Confinement Fusion



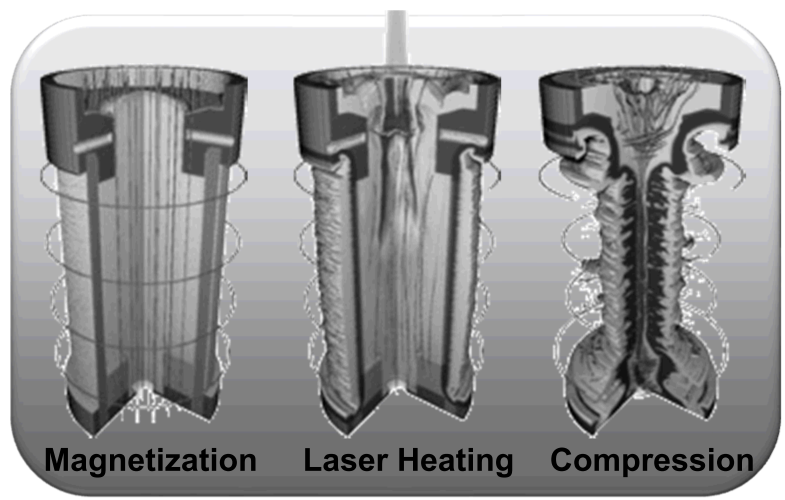
Dynamic Material Properties



Z-Pinch X-Ray Sources

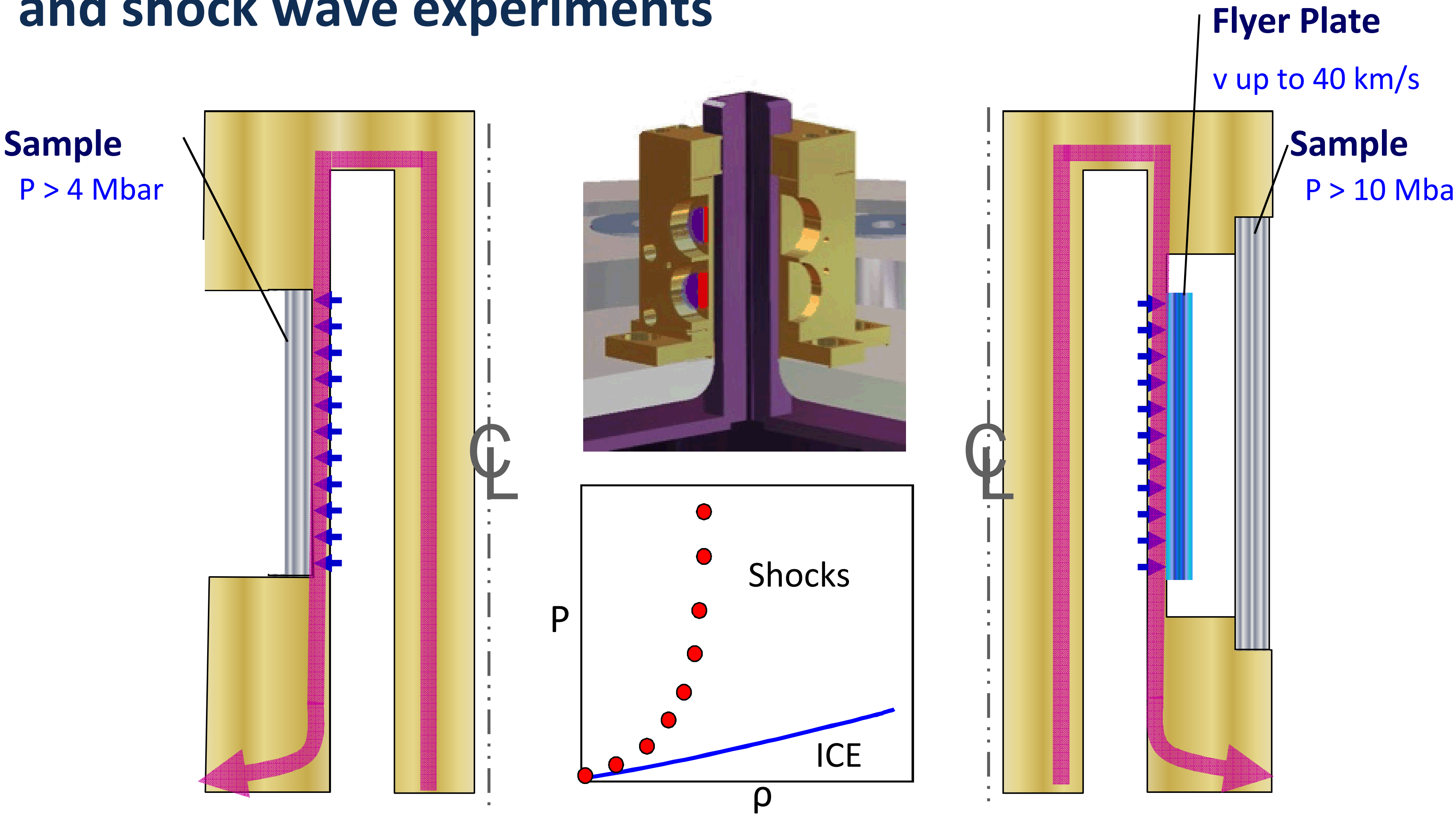


Astrophysical Plasmas



Inertial Confinement Fusion

Z can perform both shockless compression and shock wave experiments

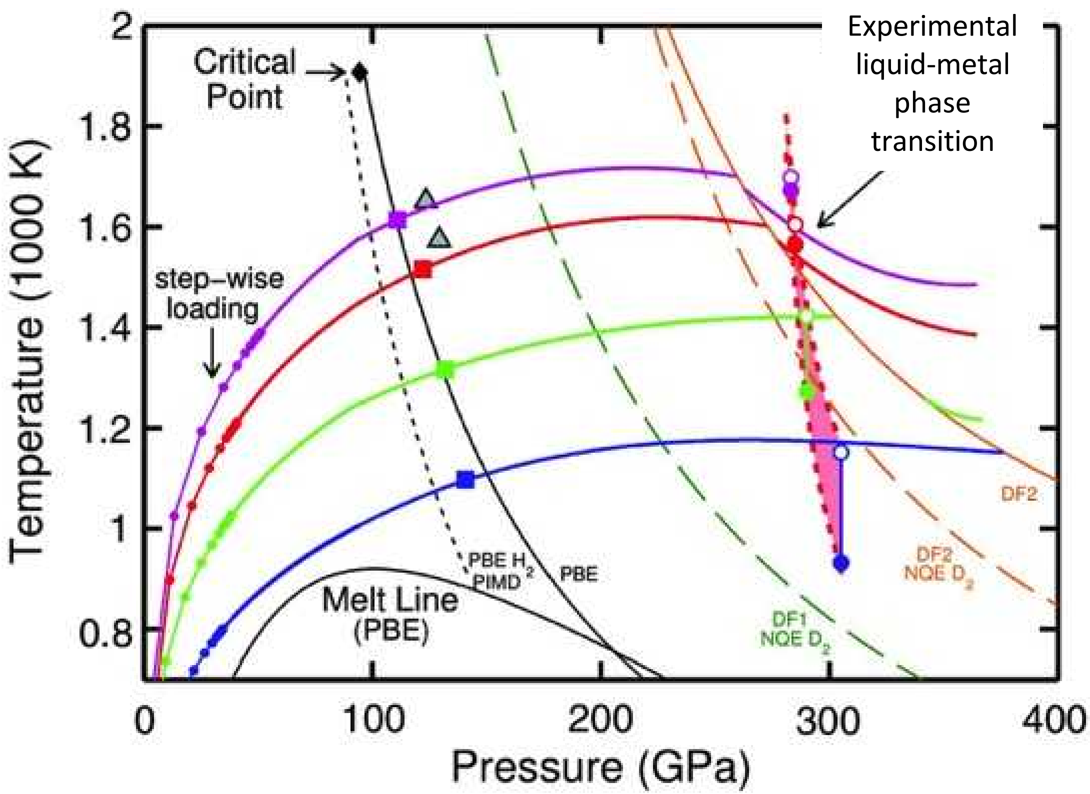


Shockless/Isentropic Compression Experiments (ICE): **gradual pressure rise in sample**

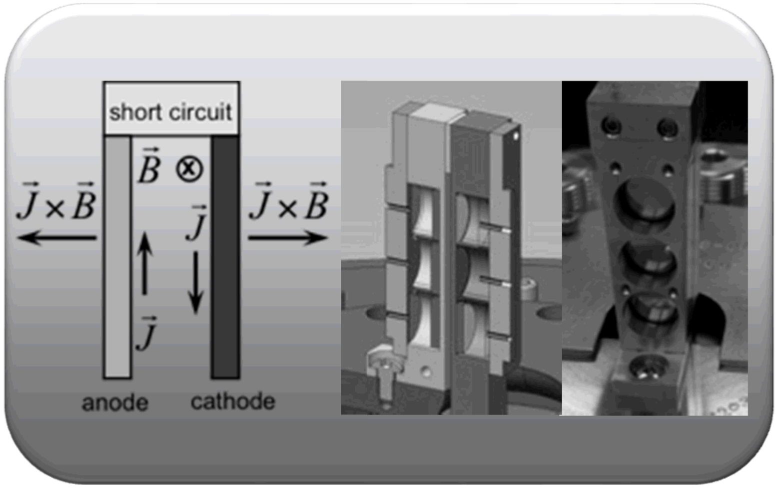
Shock Hugoniot Experiments: **shock wave in sample on impact**

Driving liquid deuterium into metal*

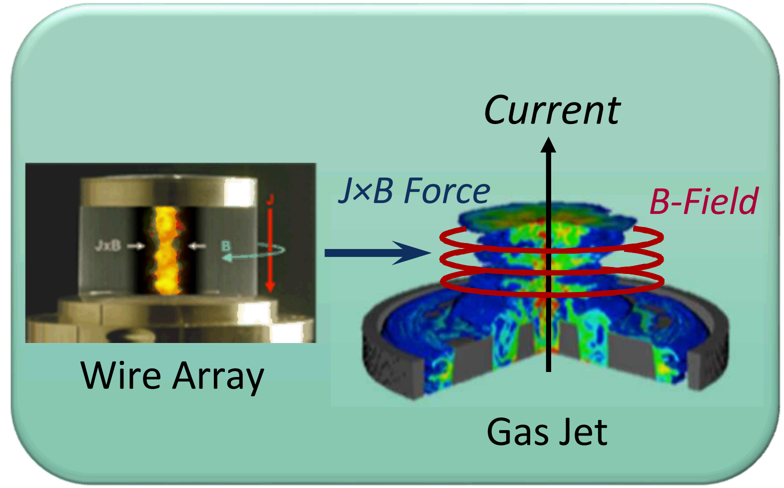
- Experiments used a new shock + ramp drive to scan this space
- Detection:
  - Reflection of visible light from the interface between the deuterium sample and its aluminum holder
  - Strong drop of signal at 120 GPa: bandgap is small enough that visible light is absorbed
  - Reflected light reappears between 280 to 300 GPa: shiny metal
- Insensitivity to T suggests transformation is primarily driven by compression rather than heating



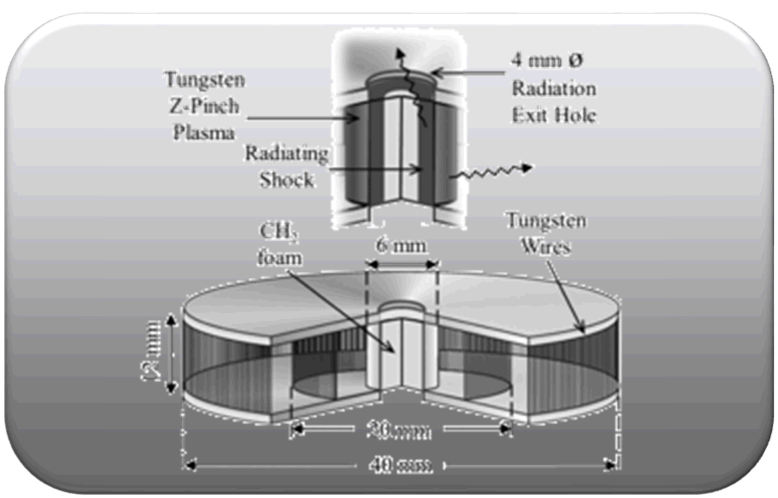
*M.D. Knudson, M.P. Desjarlais, A. Becker, R.W. Lemke, K.R. Cochrane, M.E. Savage, D.E. Bliss, T.R. Mattsson, and R. Redmer, Science **348,** 1455, (2015). Collaboration with Prof. Ronald Redmer's group at University of Rostock



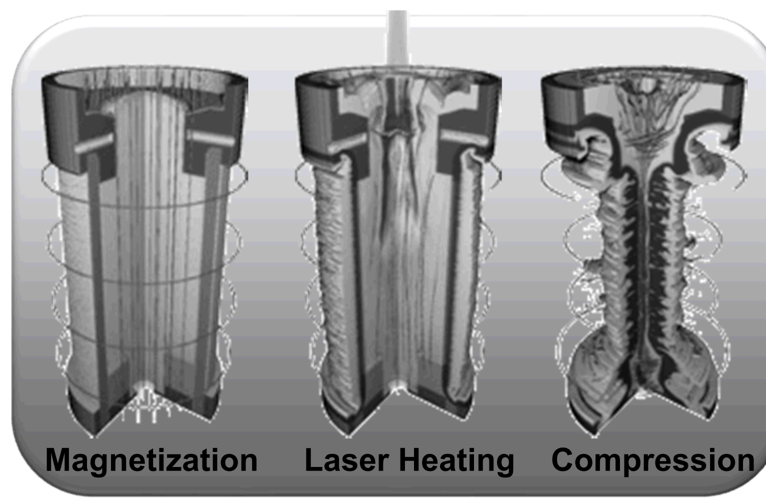
Dynamic Material Properties



Z-Pinch X-Ray Sources



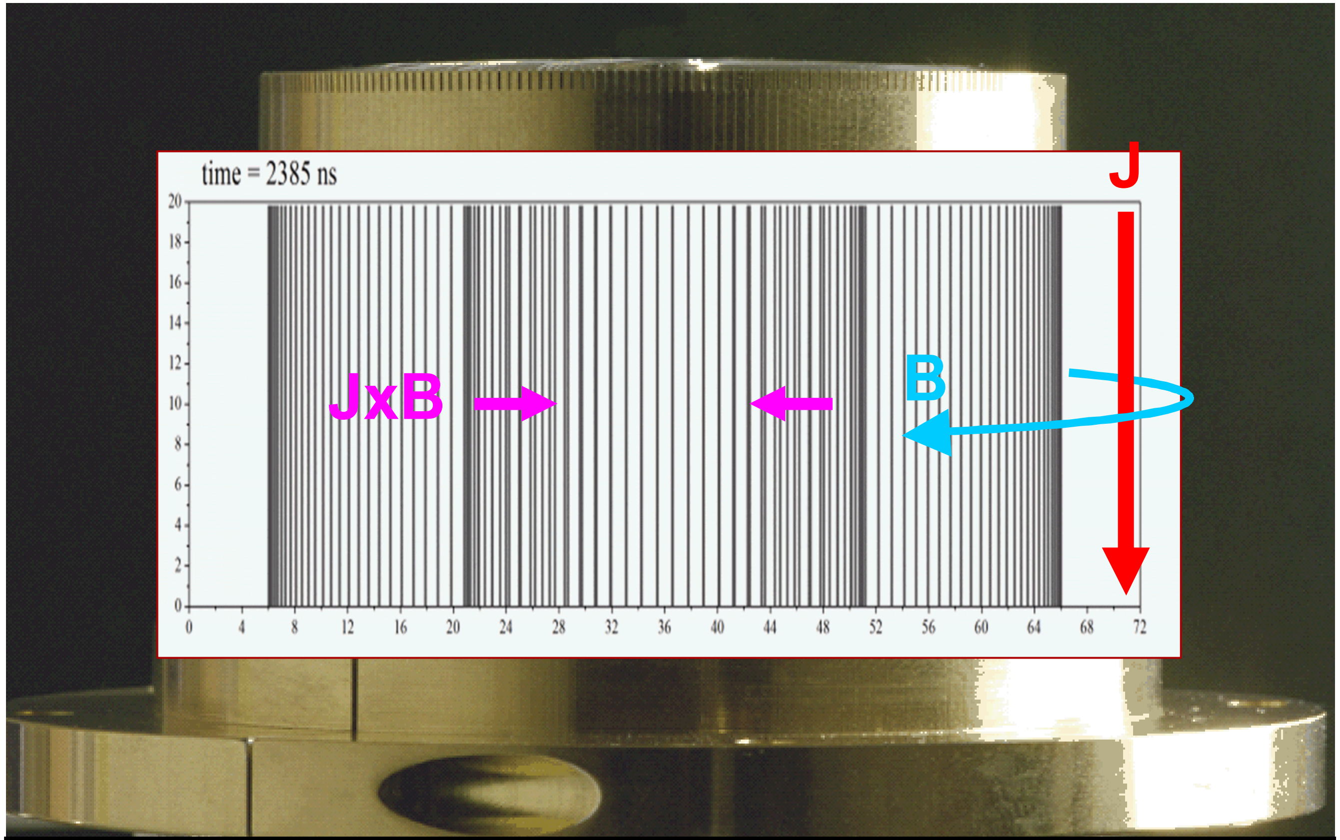
Astrophysical Plasmas



Inertial Confinement Fusion

(Nested) wire array Z pinches

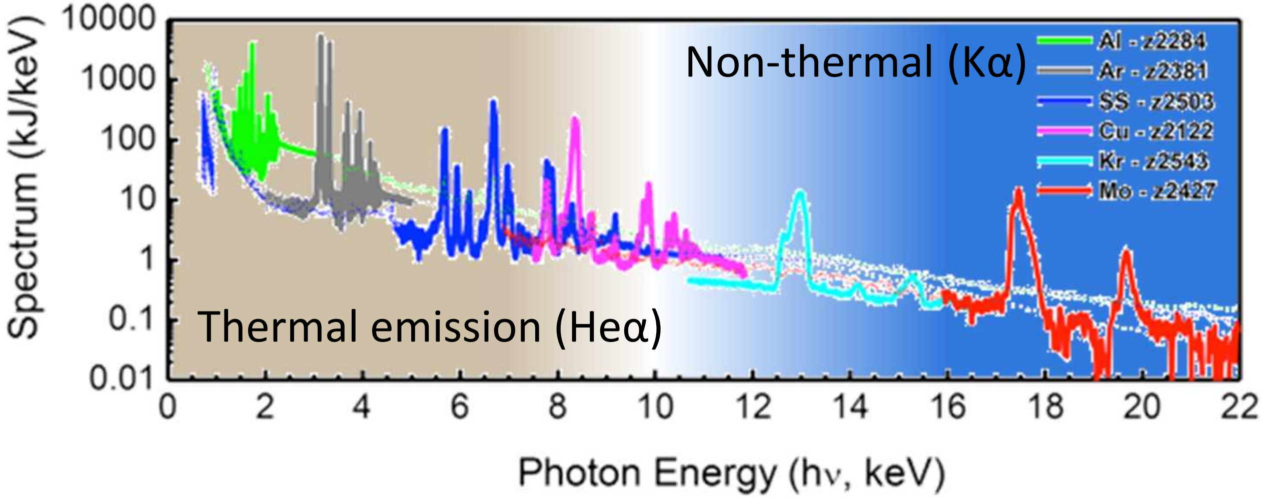
≈50 mm



$P_{rad} \approx 400$ TW, $Y_{rad} \approx 2.5$ MJ (total)

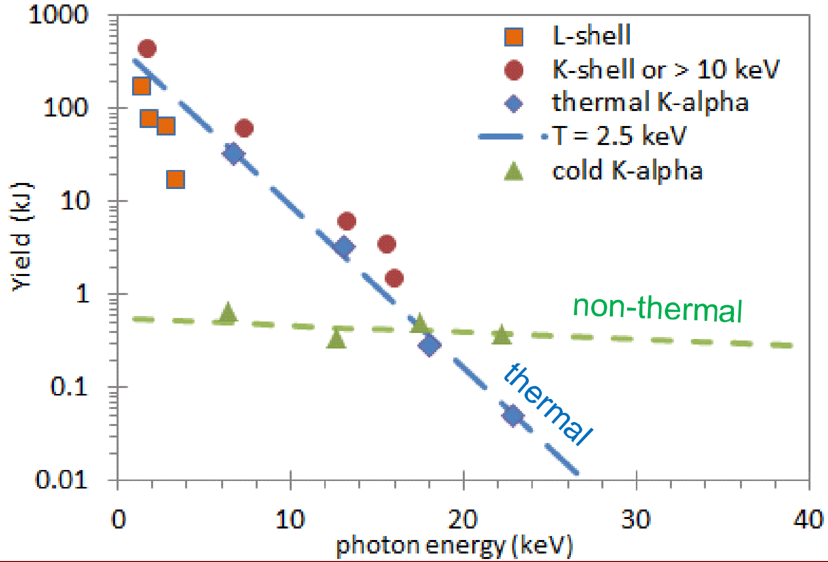
≈ 10-15% efficiency

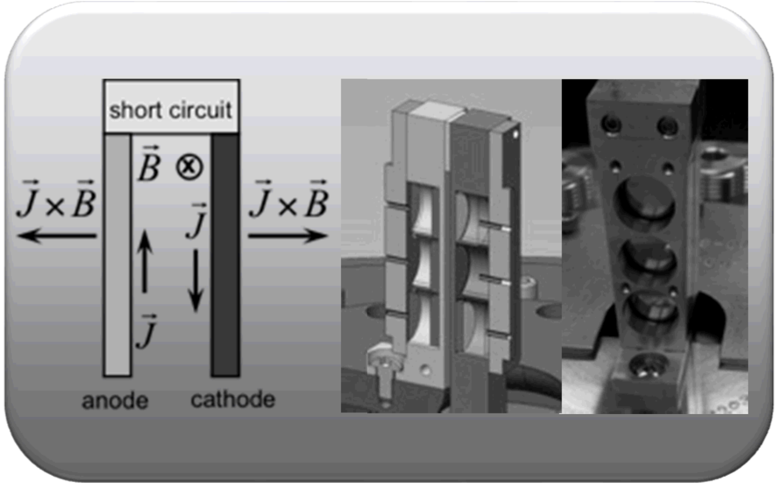
Imploding z pinches produce intense few-keV x-ray emission



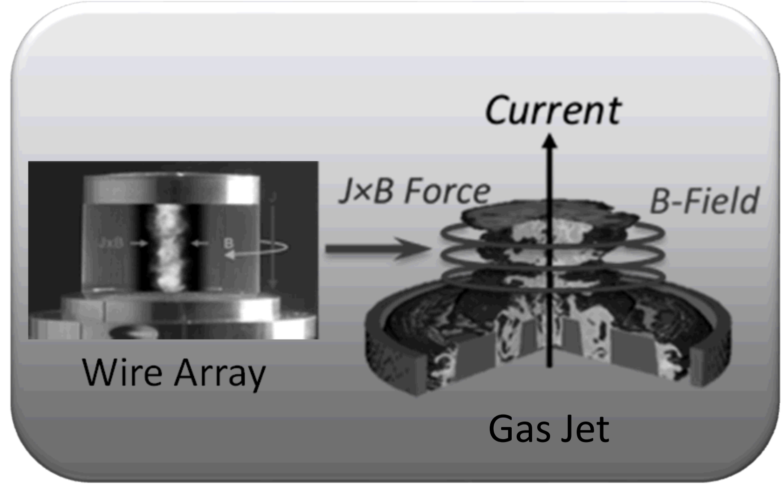
- ≈375 kJ of Al K-shell (hν ≈ 1-2 keV)
- ≈80 kJ of stainless steel K-shell (hν ≈ 5-9 keV)
- Few-kJ of Mo K-shell (hν ≈ 17 keV)

- X-ray sources for radiation effects studies, testing of atomic models, complex 3D MHD

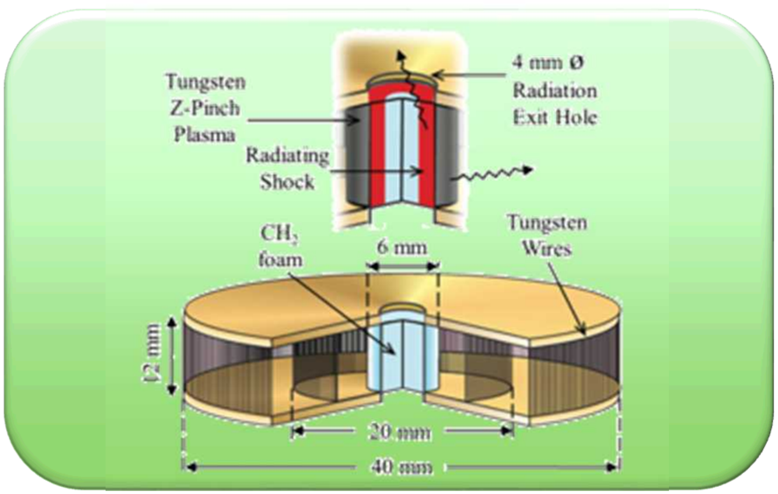




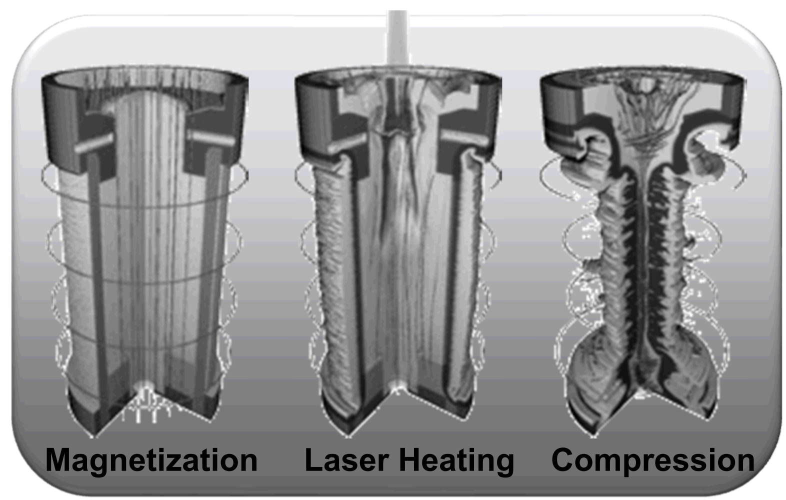
Dynamic Material Properties



Z-Pinch X-Ray Sources

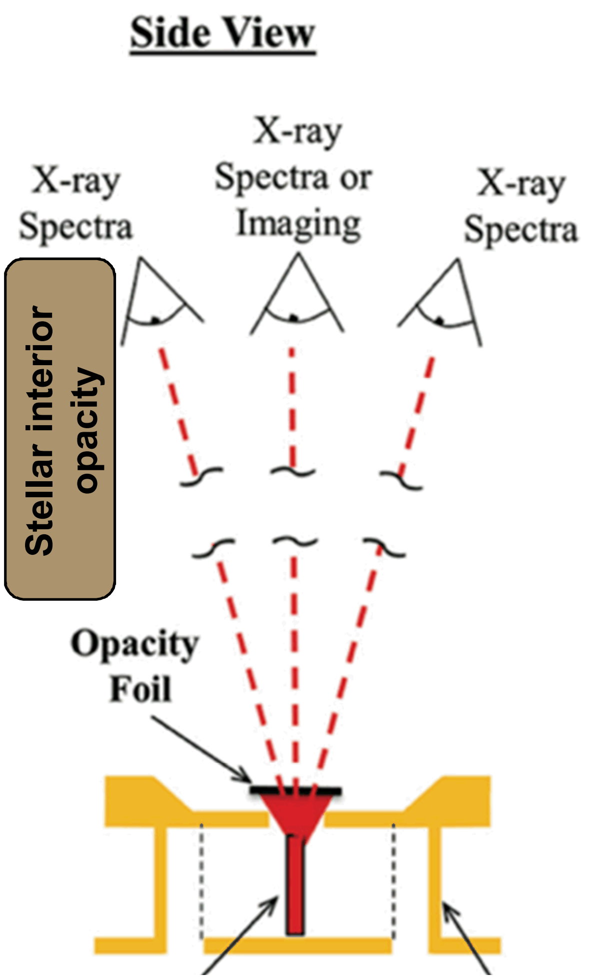


Astrophysical Plasmas



Inertial Confinement Fusion

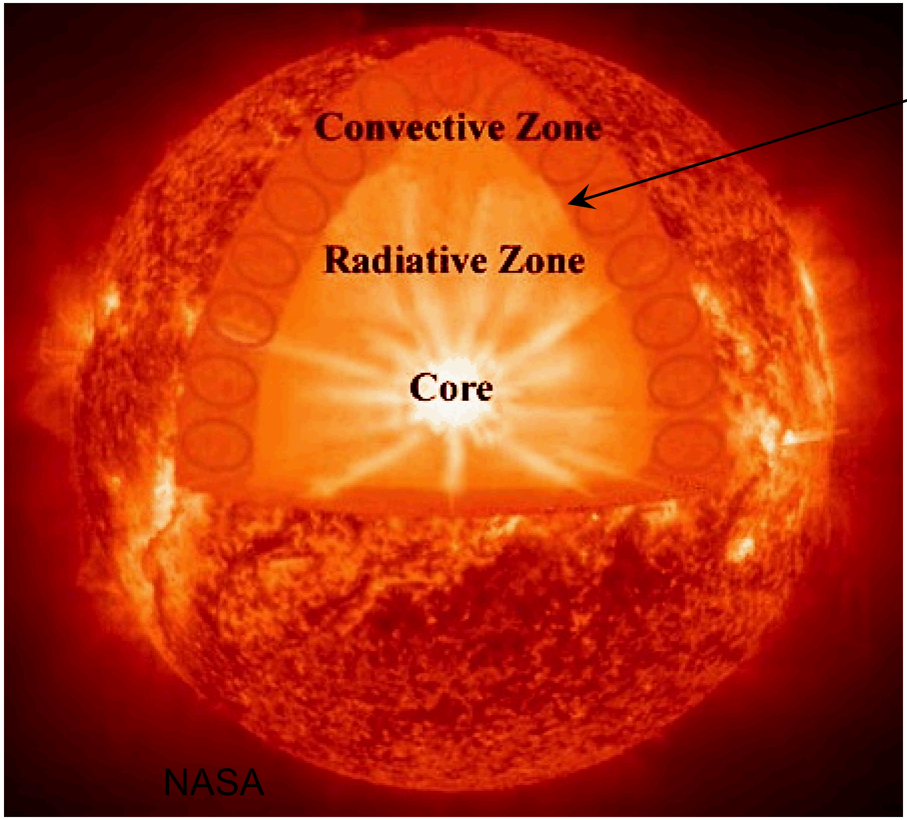
Z Astrophysical Plasma Properties (ZAPP) collaboration uses the same x-ray source to simultaneously address 4 separate astrophysics topics*



Z dynamic hohlraum x-ray source:
1-2 MJ, $2 \cdot 10^{14}$ W

*G.A. Rochau et al., Phys. Plasmas 21, 056308 (2014)

Does opacity uncertainty cause the disagreement between solar interior models and helioseismology?



Discrepancies in CZ boundary location: Standard solar models disagree with internal solar structure using acoustic oscillations

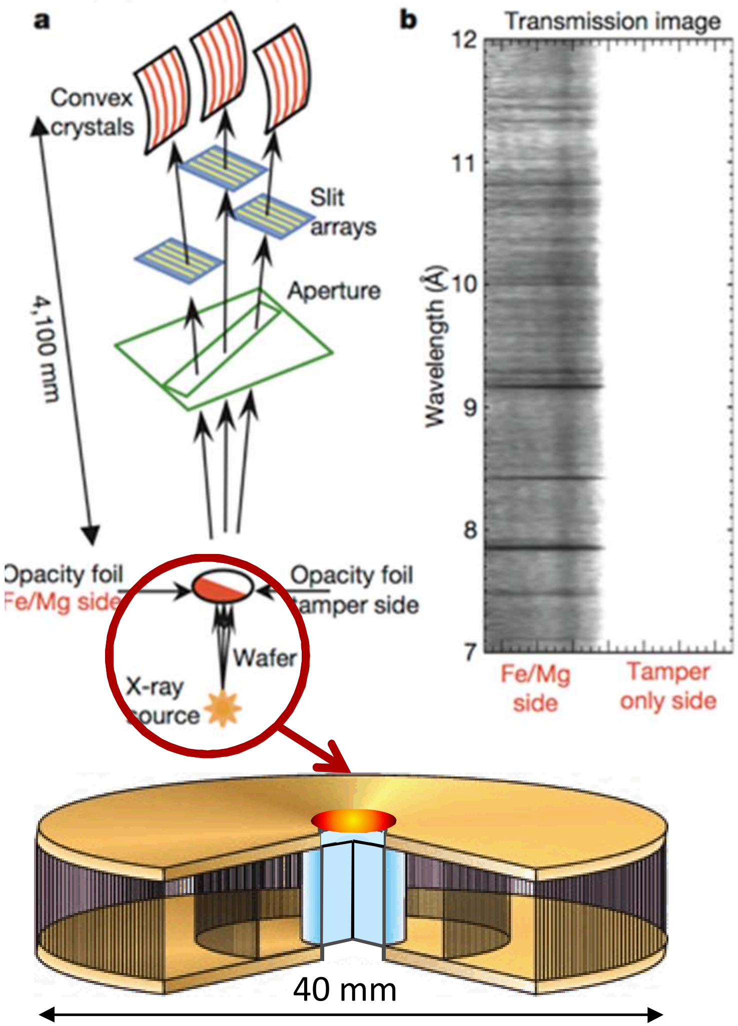
Models depend on:

- **element abundances**
- **EOS**
- **opacity**

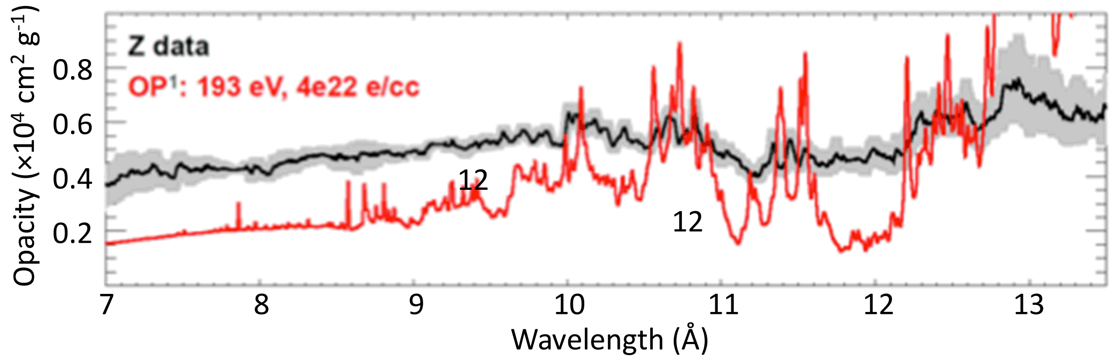
Disagreement could be resolved if the true mean opacity for the solar interior matter were roughly 15 per cent higher than predicted*

*S. Basu *et al*, Phys. Rep. 457, 217 (2008); Space Sci. Rev. 196, 49 (2015).

Z experiments have measured iron plasma opacity at nearly solar convection zone base conditions*

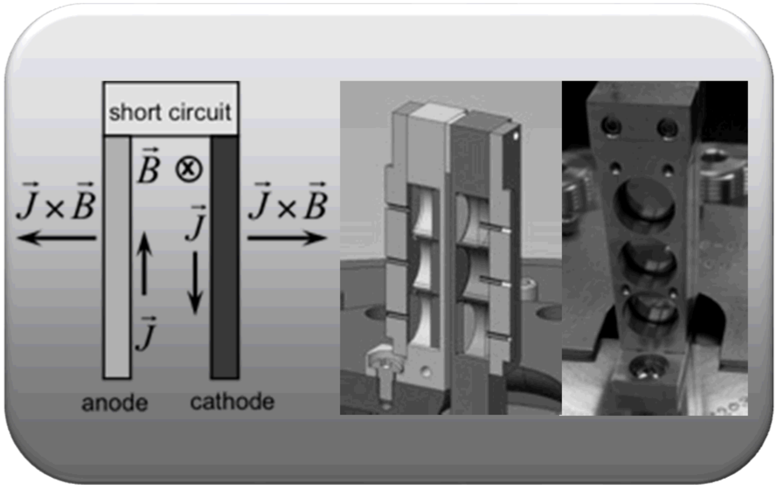


Z dynamic hohlraum x-ray source: 1-2 MJ, $2\cdot10^{14}$ W

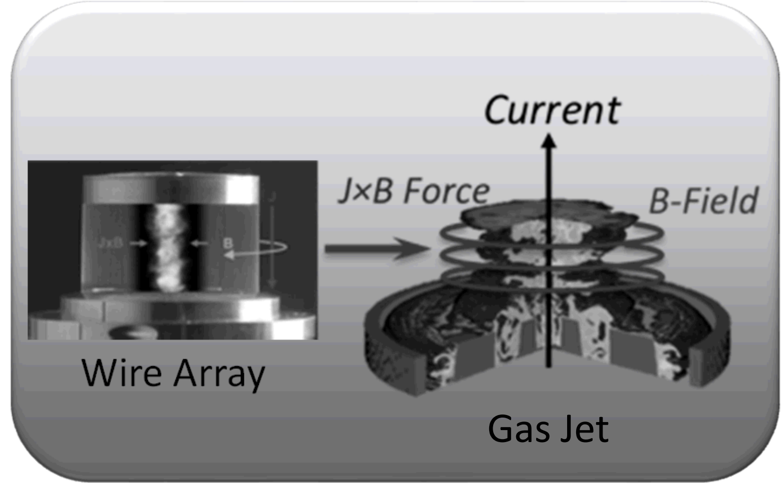


- **Experiment temperature is the same as in sun, density within a factor of 2**
- **Z iron opacity is ≈7% higher than calculated**
- **Hundreds of spectra measured and analyzed to support reliability and reproducibility**
- **Measurements imply that some of the disagreement between modeling and measurements may indeed be due to incorrect opacity models**

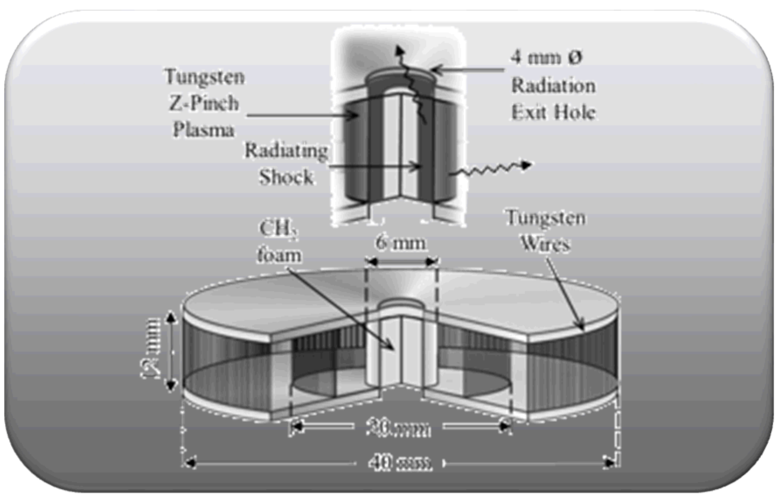
*J. Bailey et al., *Nature* 517, 56 (2015)



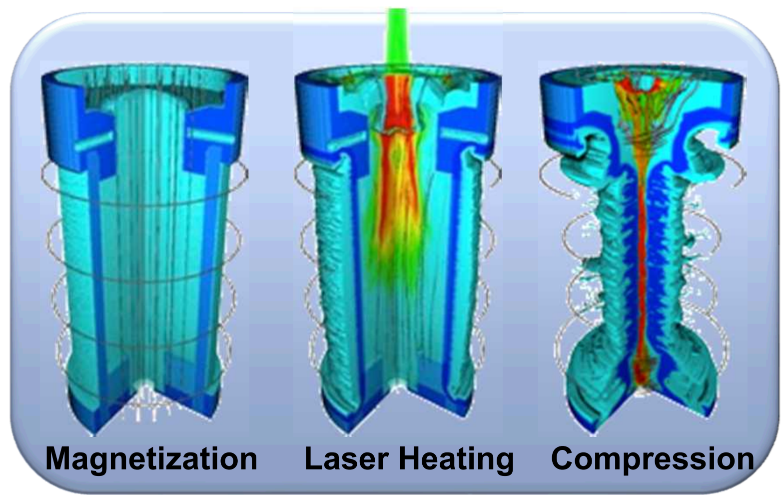
Dynamic Material Properties



Z-Pinch X-Ray Sources



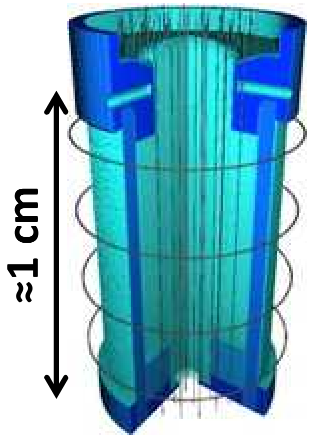
Astrophysical Plasmas



Inertial Confinement Fusion

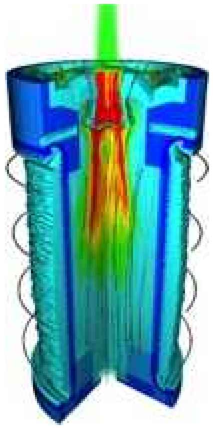
Magnetized Liner Inertial Fusion (MagLIF)

Sandia National Laboratories



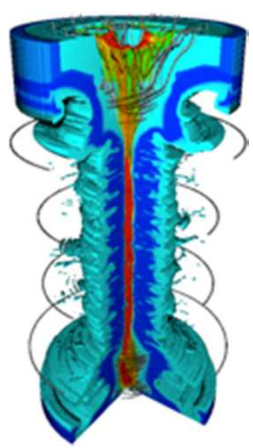
Initialize axial magnetic field (B_0 = 10-30 T)

- Inhibits thermal losses from fuel to liner
- May help stabilize liner during compression
- Flux compression increases field to kT
- Fusion products magnetized → α particles become trapped in field



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

- Initial average fuel temperature 150-200 eV → 10 keV at compression
- Reduces compression requirements (final size and velocity)
- Coupling of laser to plasma is an important science issue

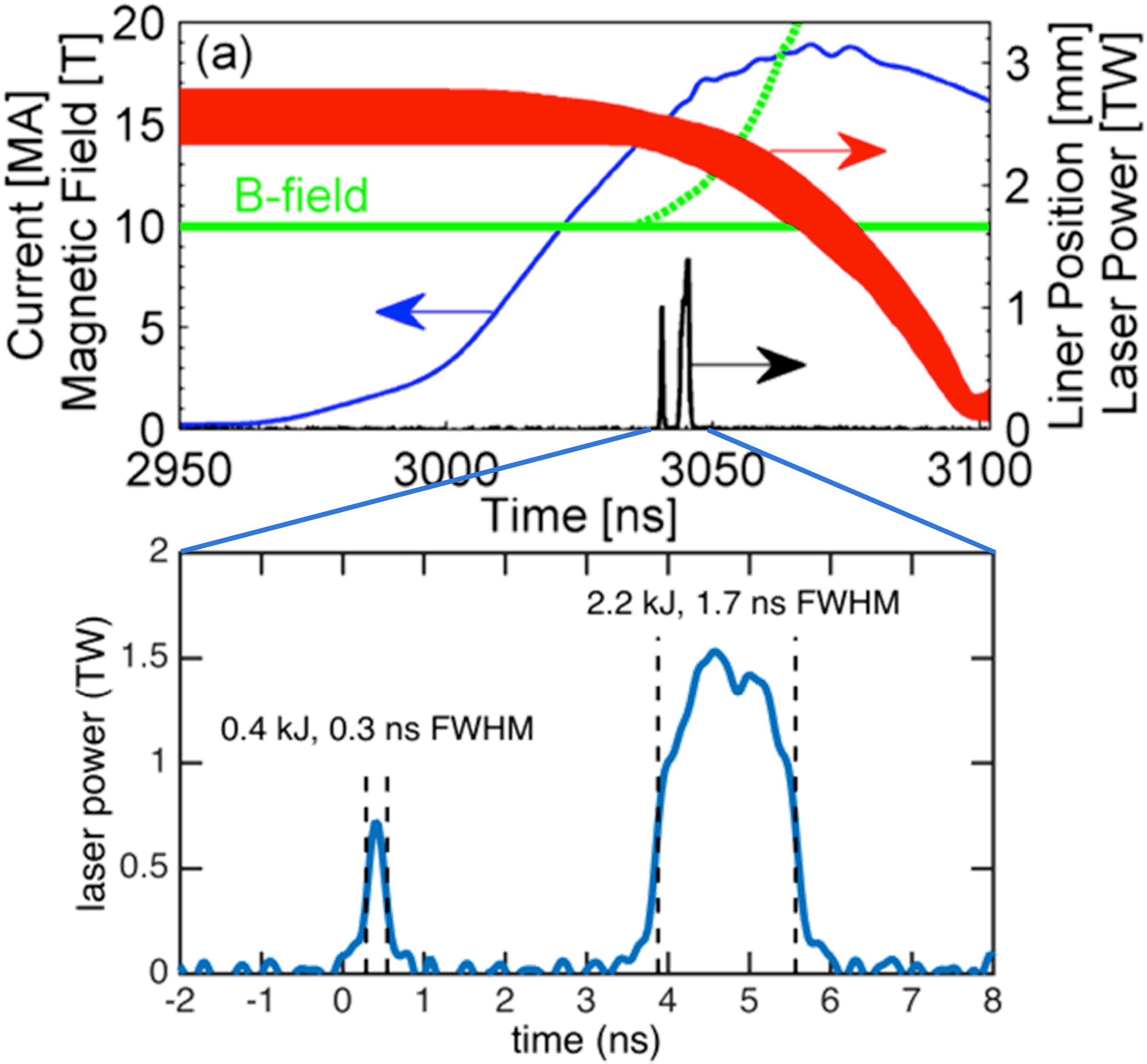


Magnetic compression of fuel

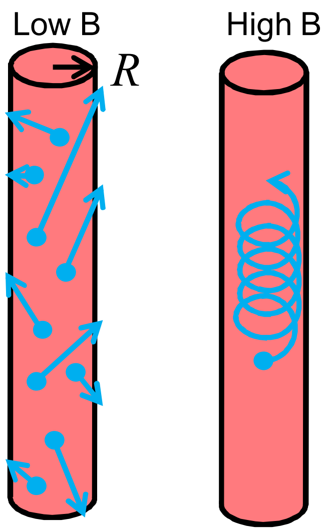
- 70-100 km/s, quasi-adiabatic fuel compression
- Low Aspect liners ($r/\Delta r \approx 6$) are robust to hydrodynamic instabilities
- Significantly lower pressure/density than NIF ICF

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)

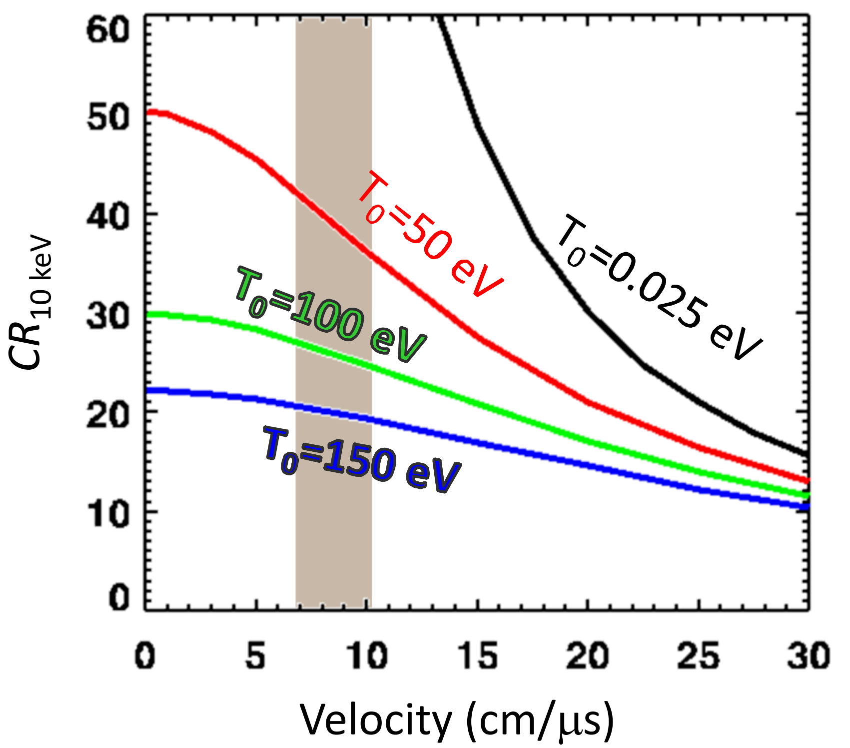
MagLIF time scales



MagLIF employs a slow implosion (70-100 km/s) so preheat and magnetization are required to achieve thermonuclear conditions



Simulated CR necessary to achieve T = 10 keV



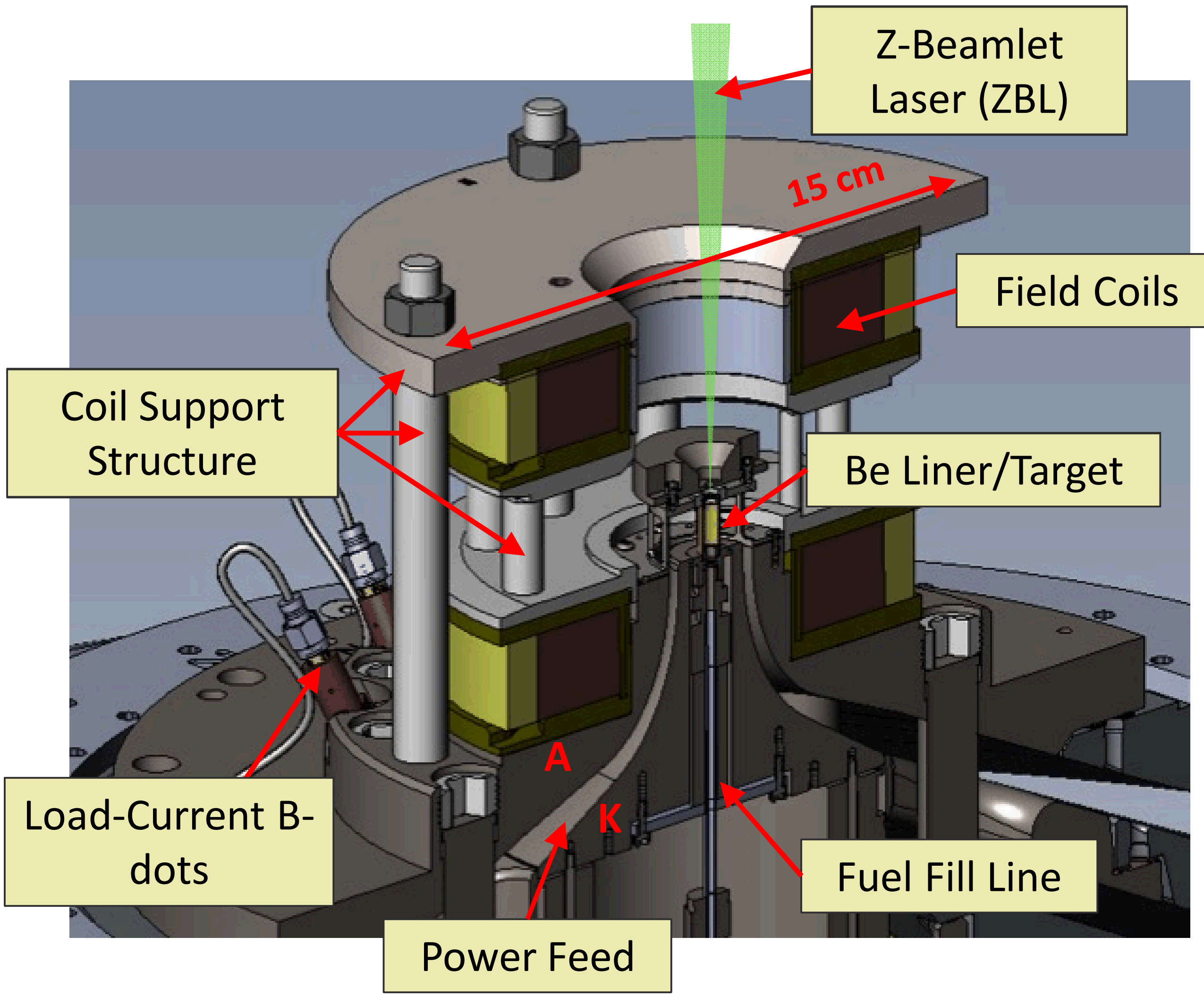
- **Initial 10-30 T field greatly amplified during the implosion through flux compression**
- **Magnetization (“BR”) reduces ρR requirements for α deposition and minimizes electron heat losses***

To realize the benefits of preheat, losses must be mitigated during the implosion

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

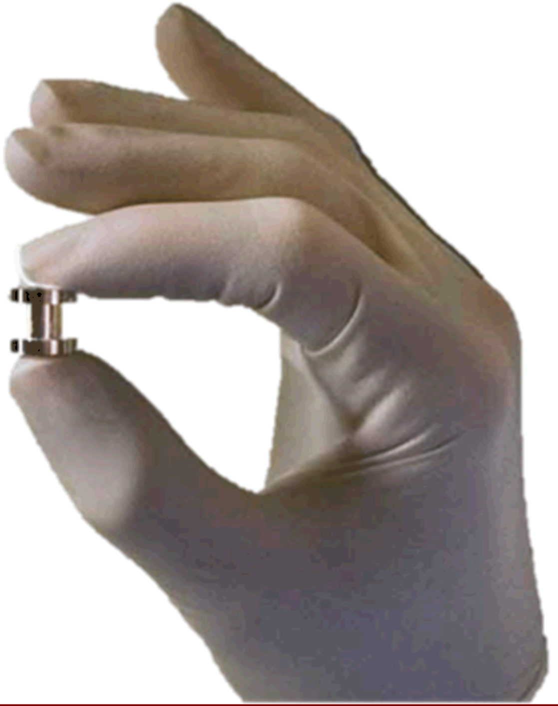
Anatomy of a MagLIF Experiment

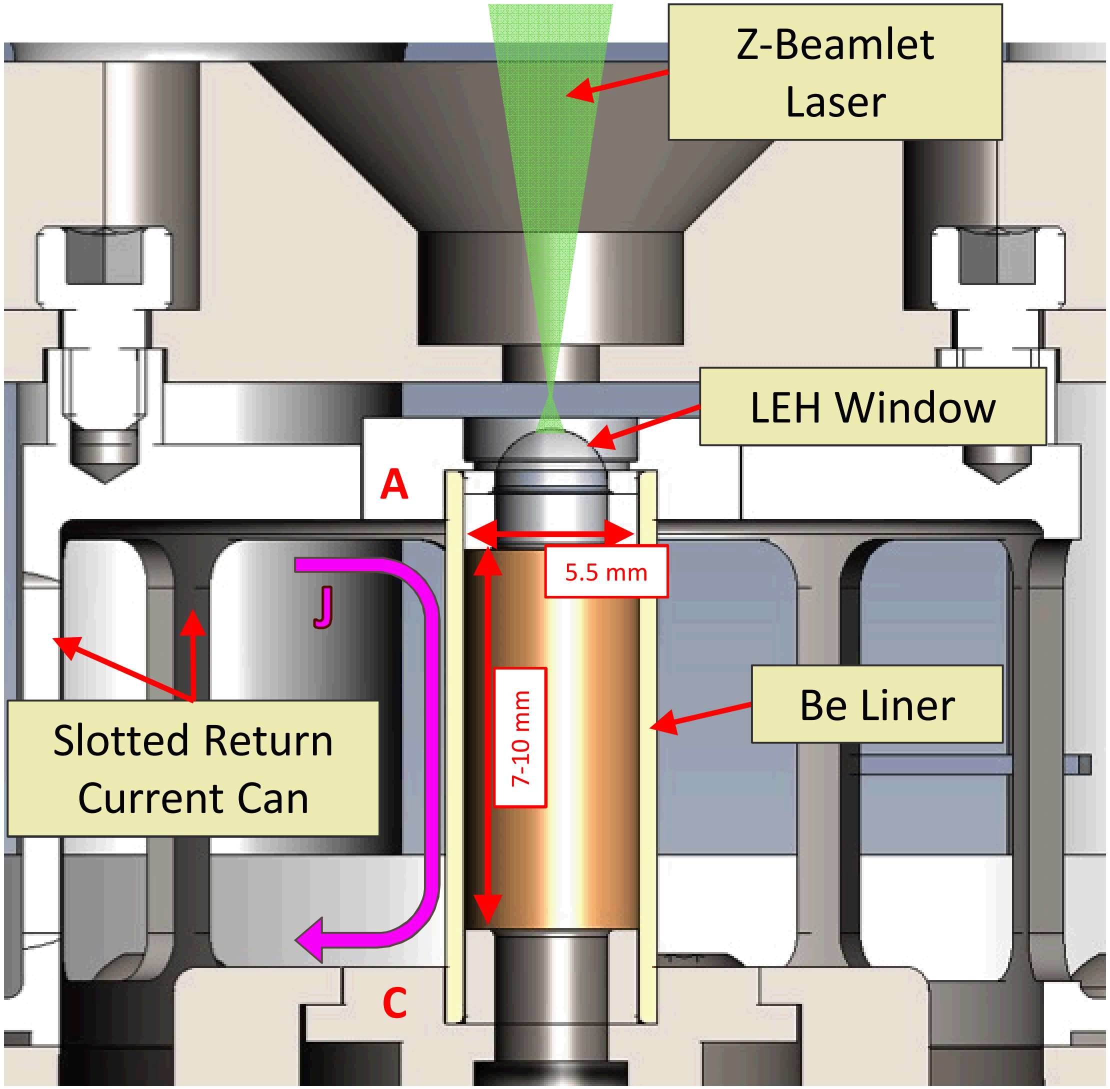
- **Field Coils**: Helmholtz-like coil pair, 10-30 T axial field w/ ≈3 ms rise time
- **ZBL**: 1-4 kJ green laser, 1-4 ns square pulse w/ adjustable prepulse
- **Power Feed**: Up to 24 MA (typical ≈18 MA) in 120 ns



Anatomy of a MagLIF Target

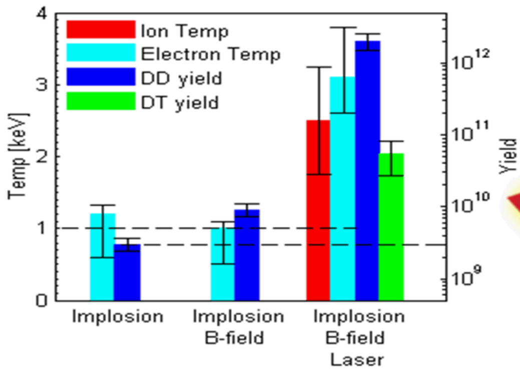
- **Be Liner**: OD = 5.63 mm, ID = 4.65 mm, h = 5–10 mm
- **LEH Window**: 1-3 µm thick plastic window. Supports 60 PSI pure D_2 gas fill.
- **Return Can:** Slotted for diagnostic access



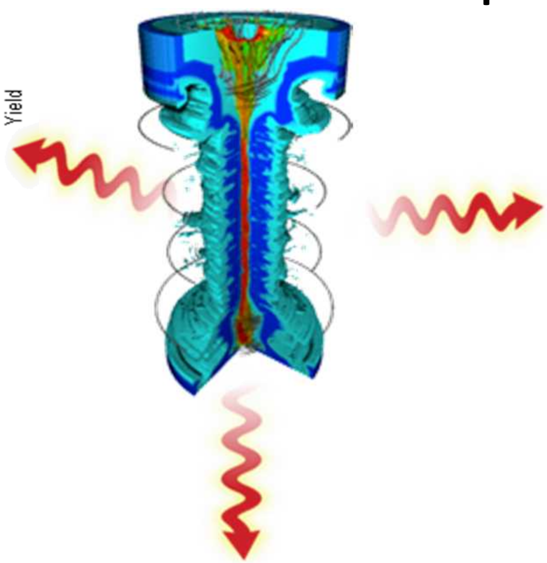


An ensemble of measurements from our first MagLIF experiments are consistent with a magnetized, thermonuclear plasma!

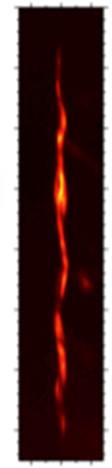
Nuclear Activation (yield)



MagLIF Z pinch

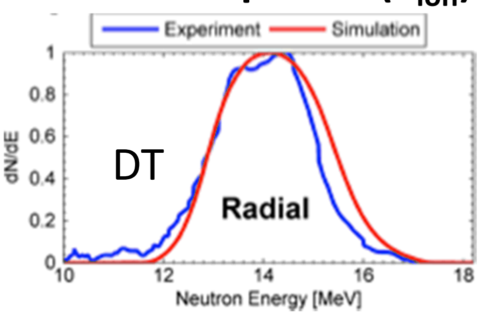


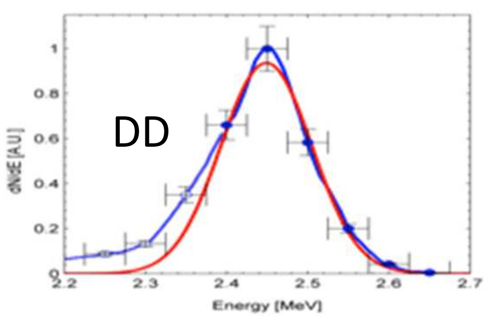
X-ray Imaging (hot plasma shape)



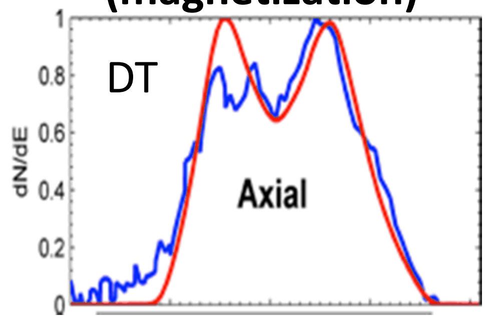
M.R. Gomez *et al.* PRL (2014).
P.F. Schmit *et al.*, PRL (2014).
P.F. Knapp *et al.*, PoP (2015).
M.R. Gomez *et al.*, PoP (2015).
S.B. Hansen *et al.*, PoP (2015).

Neutron spectra (T_{ion})

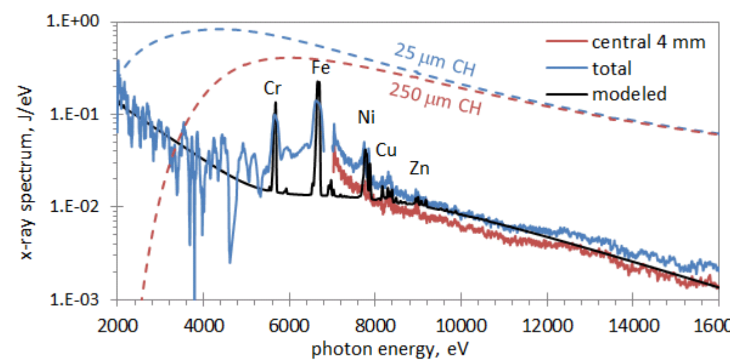




DT Neutron spectra (magnetization)



X-ray Spectra (T_e, mix)



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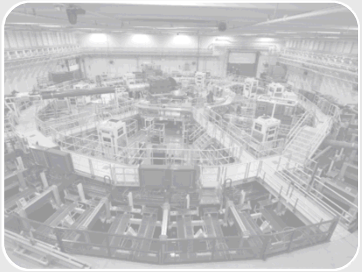


Z Pulsed Power Facility

- Overview & Capabilities, HED Science with Pulsed Power

Z Backlighter Facility

- Overview & Capabilities, Key Research Areas

Z-Backlighter Facility Overview

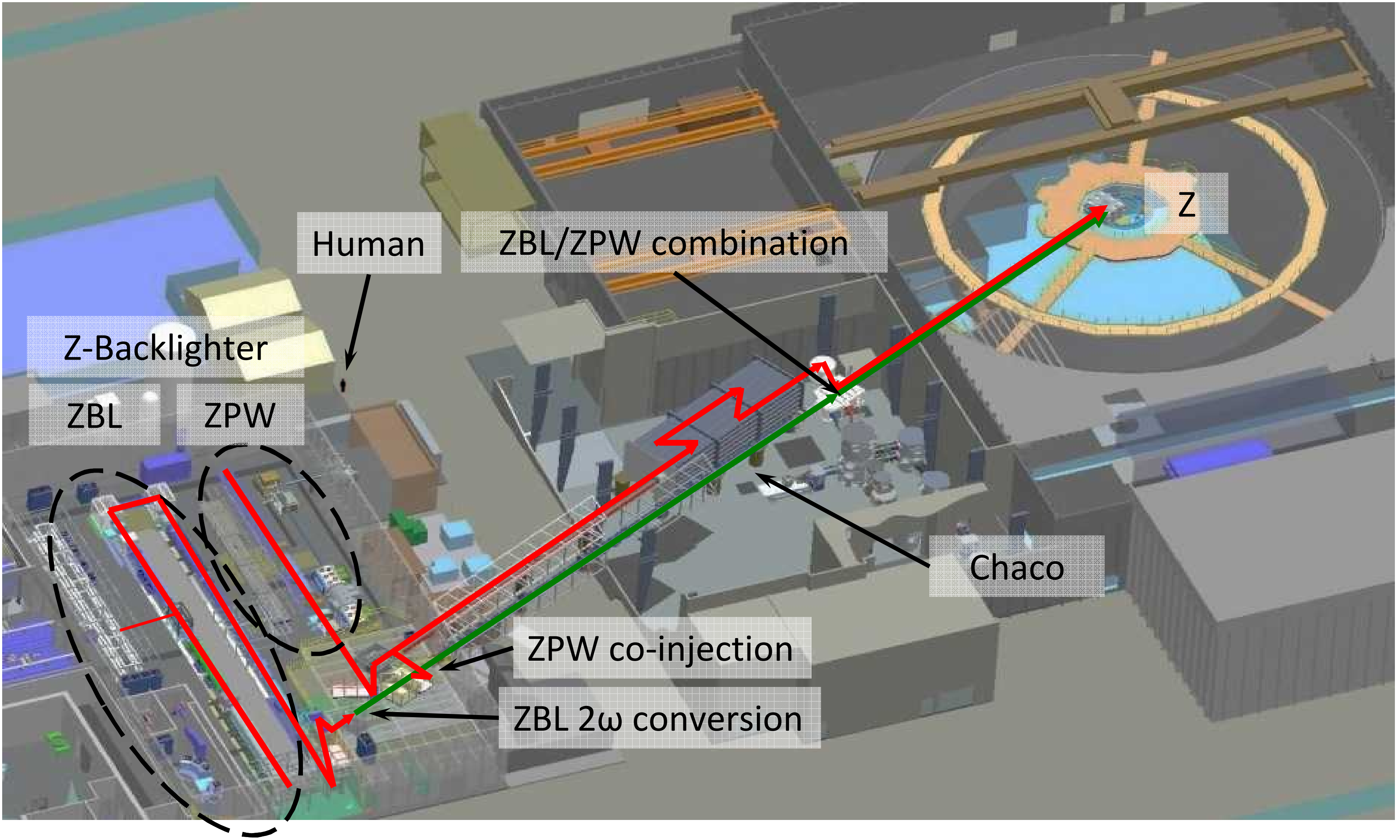
Sandia National Laboratories

Z Backlighter

	Z Beamlet	Z Petawatt	Chaco
λ (nm)	527	1054 / 527 (2 ns)	1064 (532)
pulse duration	1-6 ns	sub-ps / 2 ns	300 ps – 10 ns
E_{max}	4.5 kJ	400 (ZPW) / 800 (2 ns)	100 (50)
'Special feature'	2 pulse Multi-Frame-Backlighter or single pulse	1ω, sub-ps operation or 2ω, ns co-injection into ZBL	0.3-10 ns option or picket-fence pulses

Staff: 14 full-time employees & 3 grad students to support 3 laser systems, Z shots, 5 target chambers and new diagnostics!

Z-Backlighter Facility Overview



Z-Beamlet Laser (ZBL) Basics

- 1992 – 1998: LLNL NIF prototype (Beamlet)
- Since 2001: Z-Beamlet at Sandia

- Main uses:
  - Create x-ray source for backlighting
  - Preheat MagLIF fuel

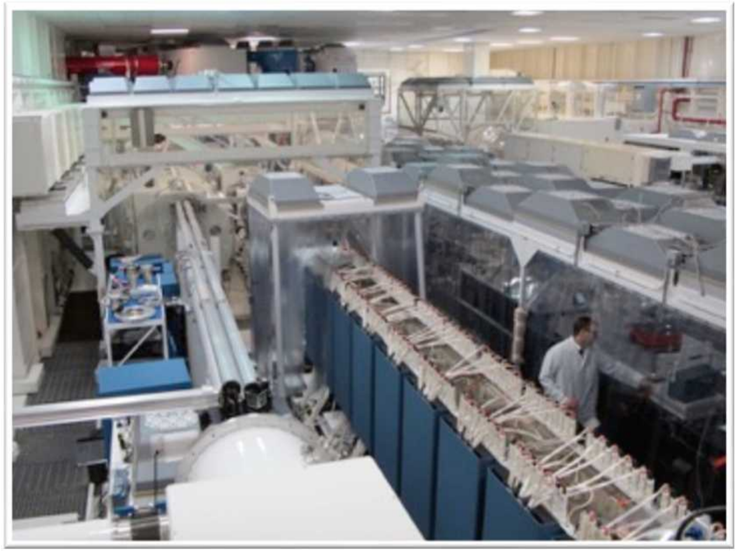
- Parameters:
  - Up to 6 kJ @ 1053 nm, , 30 x 30 cm^2 beam
  - Up to 4 kJ @ 527 nm, 30 x 30 cm^2 beam

  - 3 shots per day
  - I ≈ 10^{17} W/cm^2

  - 4 target chambers + Z
  - Adaptive optics & phase modulation systems
  - Lens & phase plates for focusing
  - Arbitrary temporal shape, typ. 0.5 ns prepulse + 1-4 ns main

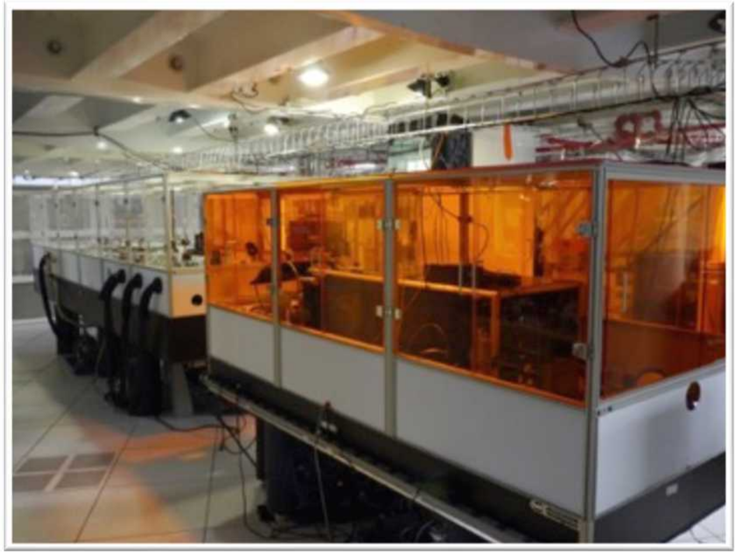
Z-Petawatt (ZPW) Laser Basics

- Shortpulse, 1ω operation
  - High-field physics (particle acceleration/γ-rays)
  - Above-10 keV x-ray generation
- Co-injection into ZBL and 2ω operation
  - Additional energy for ZBL pulse
  - Flexible prepulse for MagLIF/radiography
- Parameters:
  - Up to 500 J @ 1053nm, 500 fs, sub-aperture
  - Up to 100 J @ 1053nm, 500 fs, 100 TW, 6” round
  - Up to 500 J @ 527nm, 2 ns, sub-aperture
  - 3 shots per day
  - Pulse length: 0.5 - 100 ps @ 1ω, 2 ns @ 2ω
  - $I = 2 \times 10^{20}$ W/cm^2 @ 1ω
  - 2 target chambers + Z
  - Off-axis parabola or lens focusing
  - Full-aperture upgrade on-going: 2 kJ, 27 x 31 cm^2

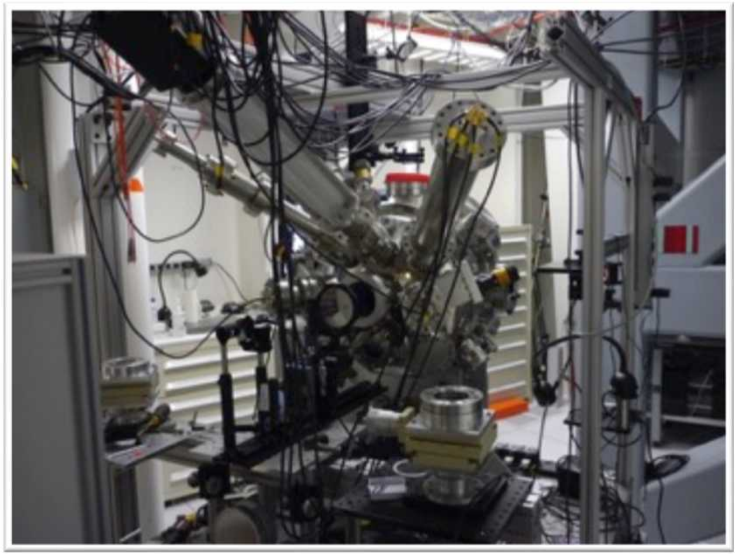


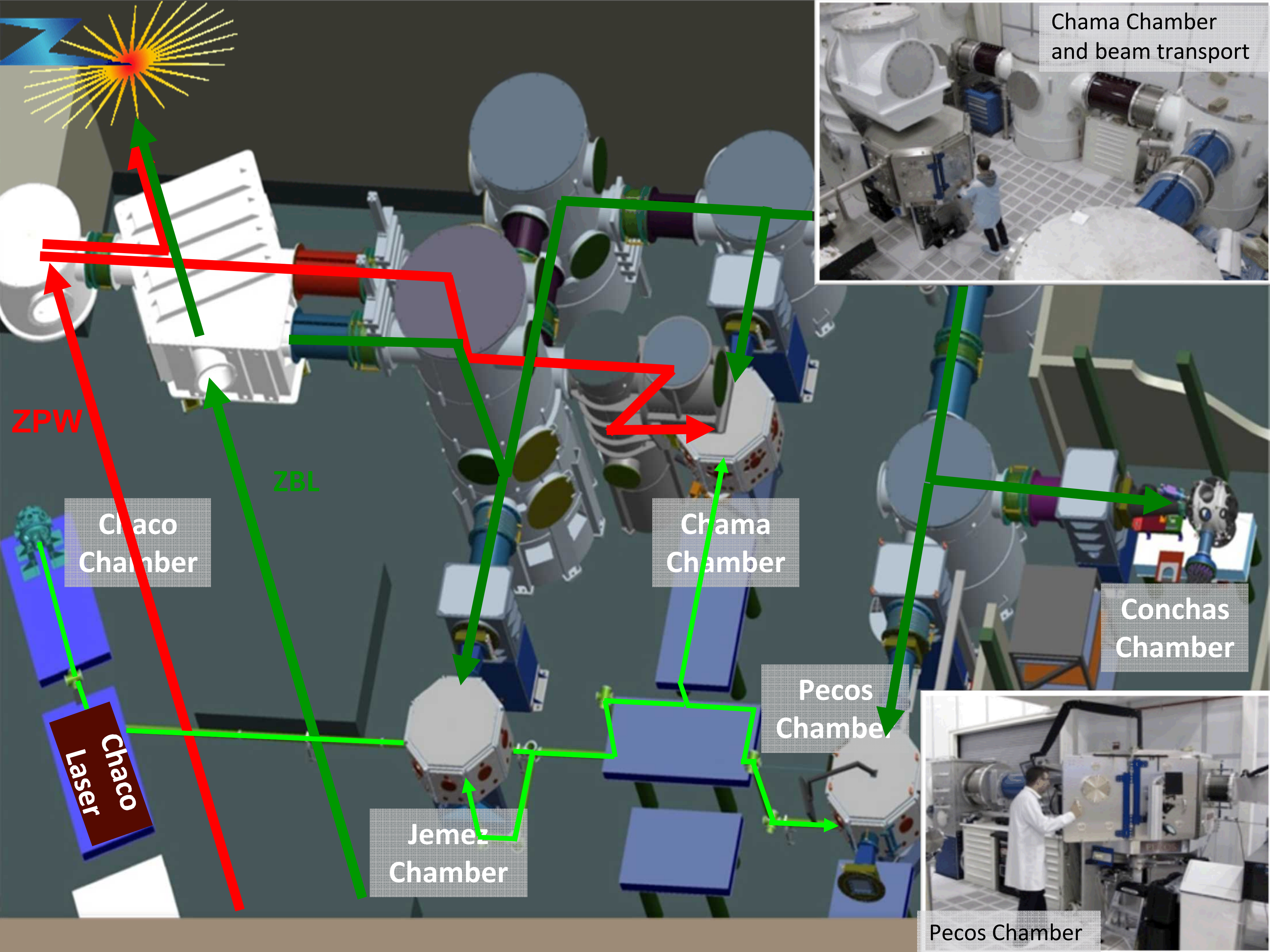
Chaco Laser Basics

- Versatile, nanosecond laser system:
  - Synchronized to ZBL and ZPW
  - Laser compression of samples
  - Multi-frame probe for shadowgraphy, interferometry
  - 8-pulse capability with 1 ns inter-pulse intervals



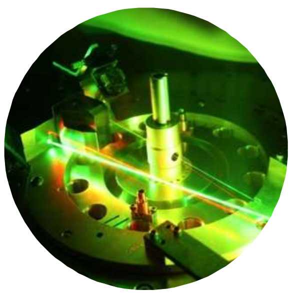
- Parameters:
  - Up to 100 J @ 1064nm, 10 ns, 50 mm diameter
  - Up to 10 J @ 532nm, 0.3 ns, 50 mm diameter
  - 10-minute repetition rate
  - Pulse length: 0.3 - 10 ns
  - I = 10^{16} W/cm^2
  - 3 target chambers + dedicated target chamber for development of ultrafast x-ray imager camera
  - Arbitrary temporal shape

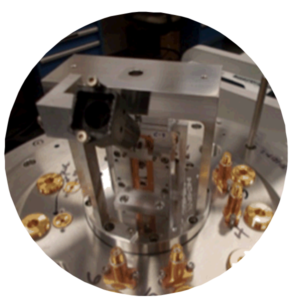




Chama Chamber
and beam transport
ZPW
ZBL
Chaco
Chamber
Chama
Chamber
Conchas
Chamber
Pecos
Chamber
Chaco
Laser
Jemez
Chamber
Pecos Chamber

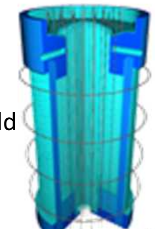
Key research areas at the Z-Backlighter Facility



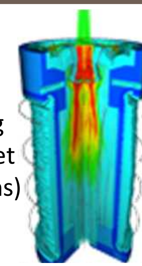


Investigate preheating of MagLIF targets

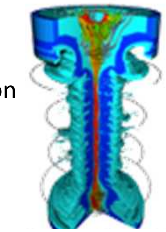
Magnetization with external B-Field (ABZ, 10-30 T)



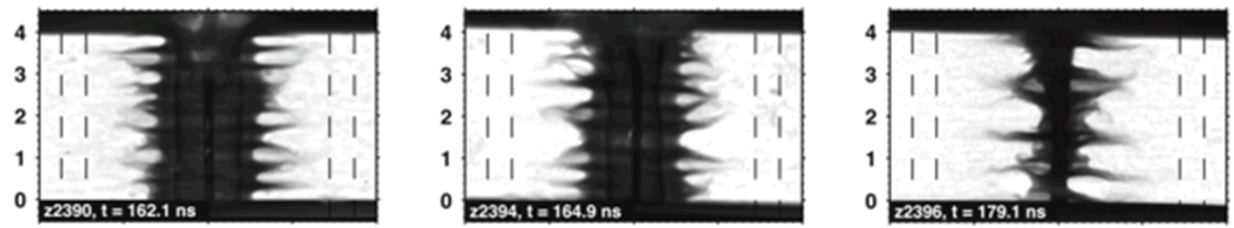
Laser heating with Z-Beamlet (2-6 kJ @ 2-6 ns)



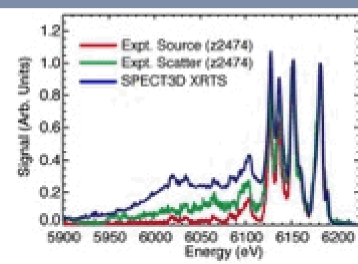
Compression with Z

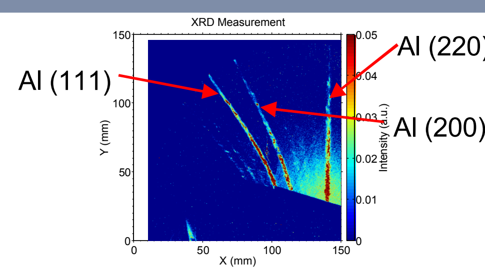


Improve x-ray backlighting for radiography of imploding liners or wire arrays



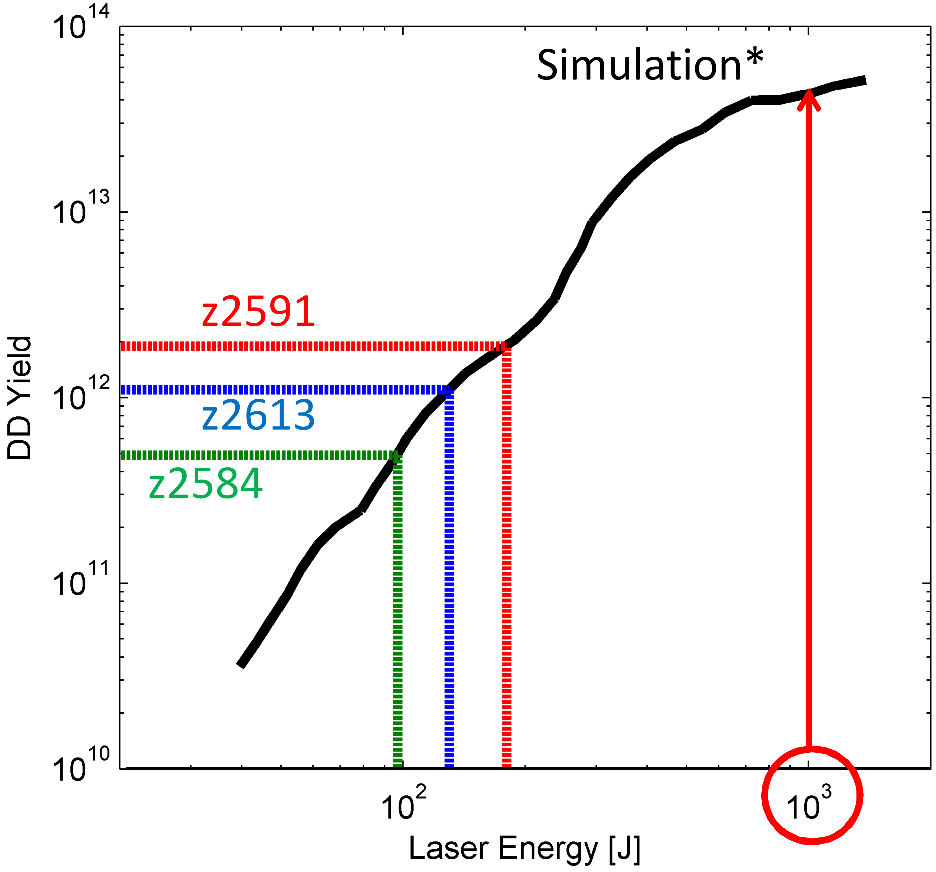
Develop sources for x-ray scattering and diffraction on compressed matter





Laser energy coupling is the biggest lever on MagLIF target performance

- **Simulations can match the measured Z shot data (DD yield, radial blastwave, inferred temperature, etc.)**
- **However, only under the assumption that ≈100-300 J out of 2.5 kJ are deposited in the fuel!**
- **Where does the remaining laser energy go?**



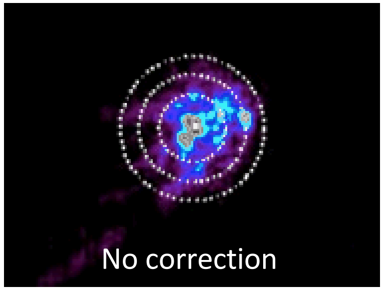
*Simulations performed by A.B. Sefkow

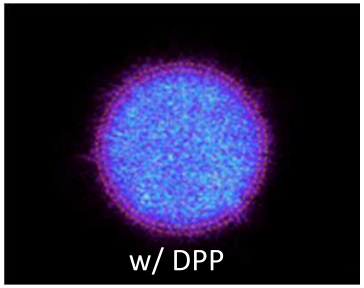
The problem with having windows in a MagLIF target

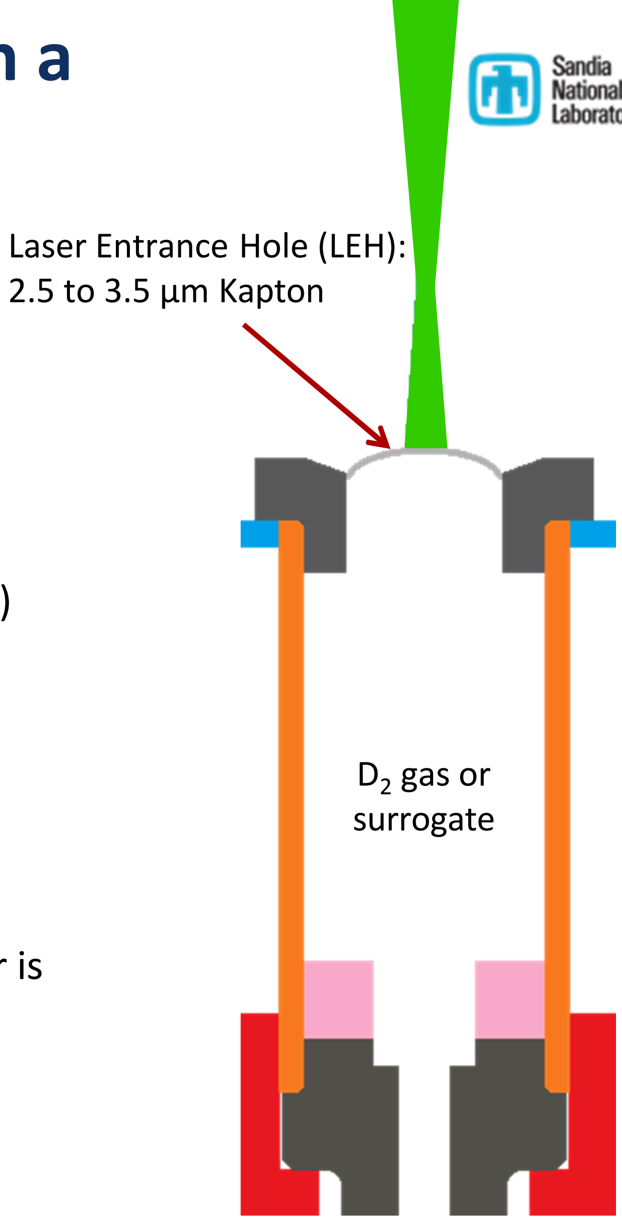
- **High energy density requires high gas density**
  - Thick window: 3.5 µm Kapton across 3 mm
  - Very high laser absorption and backscatter in the window
  - How much absorption? Mitigation strategies?

- **Laser spot size is always a compromise**
  - Small spots burn easily through LEH (and possibly all the gas)
  - Large spots are more efficient in fuel heating
  - Laser must not hit bottom of fuel container

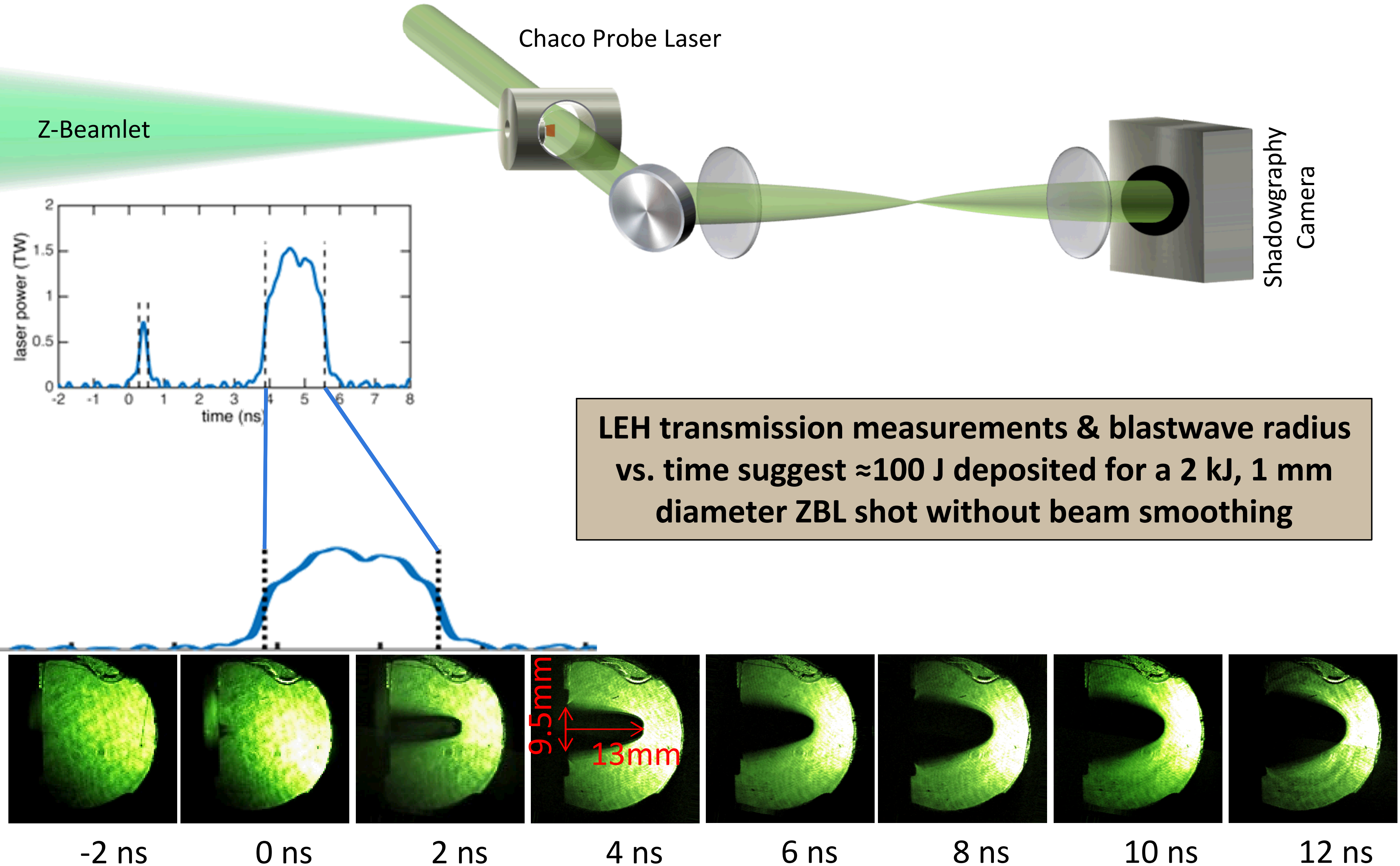
- **Ideal laser profiles cannot be 'dialed in' by defocusing**
  - Unconditioned laser spots have detrimental modulations
  - Unconditioned laser are hard or impossible to model
  - Distributed phase plates smooth beams, but which diameter is best?





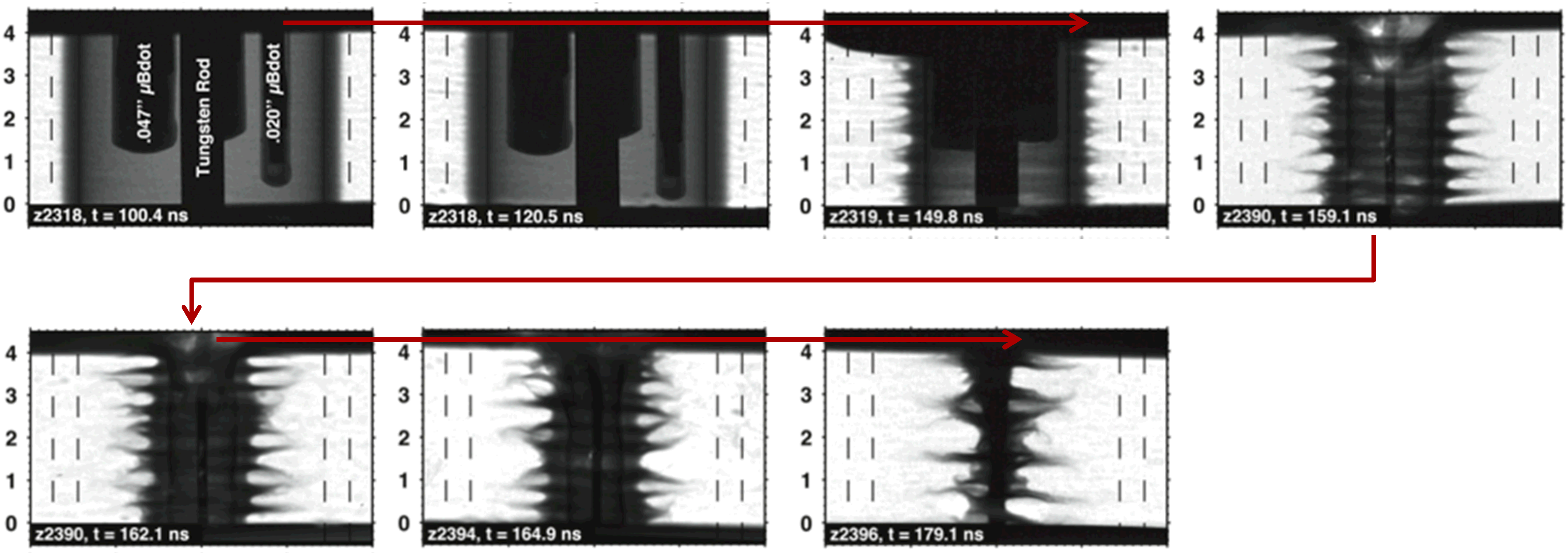


Window transmission and energy deposition in a gas



LEH transmission measurements & blastwave radius vs. time suggest ≈100 J deposited for a 2 kJ, 1 mm diameter ZBL shot without beam smoothing

X-ray backlighting probes magneto-Rayleigh-Taylor instability in imploding liners



1 frame: ≈1 cm field-of-view, ≈10 μm features ⟶ Which diagnostics can support that?

≈100 ns long implosion but fast moving towards end ⟶ Need 1 ns, multi-pulse x-rays

Liner becomes opaque for CR > 15 ⟶ Need high-energy x-rays

Images from R.D. McBride, Phys. Plasmas **20**, 056309 (2013)

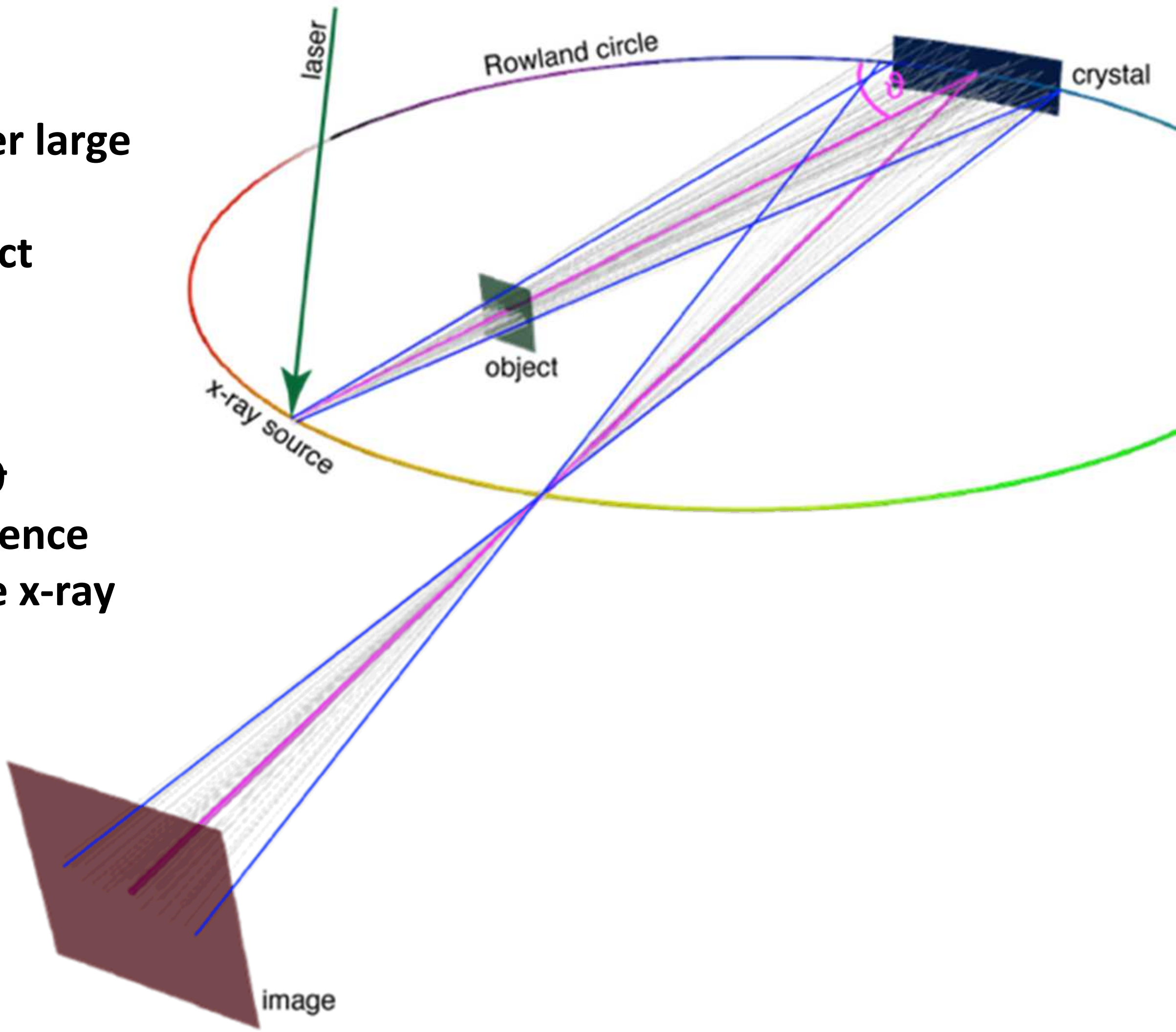
X-ray backlighting with spherical crystals

Advantages:

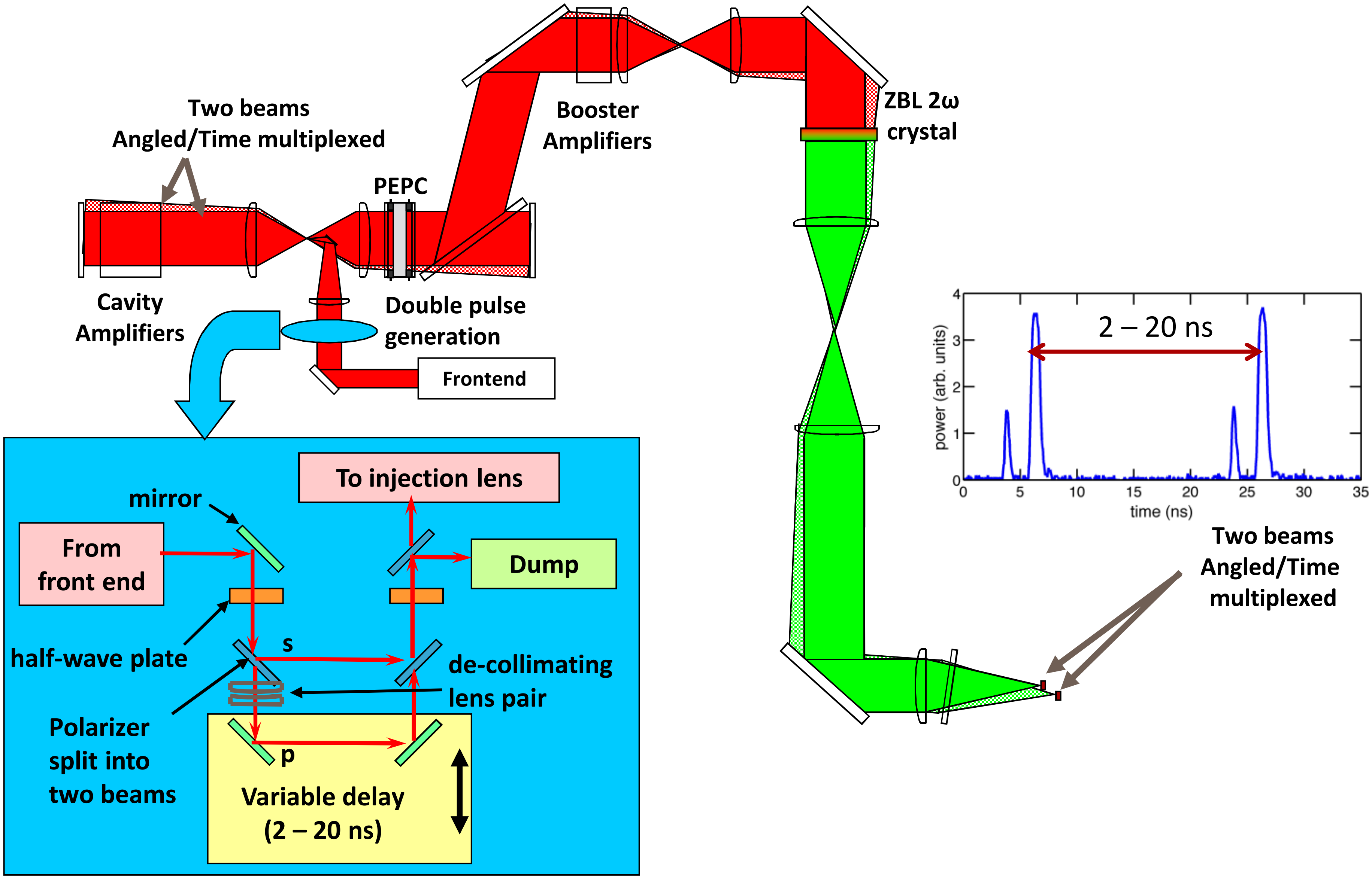
- high sensitivity
- monochromatic
- <20 µm spatial resolution over large field-of-view (>1 cm)
- no direct line-of-sight to object (debris/noise)

Limitations:

- Bragg condition: $m\lambda = 2d \sin \vartheta$
- Astigmatism: off-normal incidence
- Source: needs to emit suitable x-ray spectral line



ZBL 2-frame backlighter configuration



Two-color, two-frame x-ray backlighter at Z

X-ray sources:

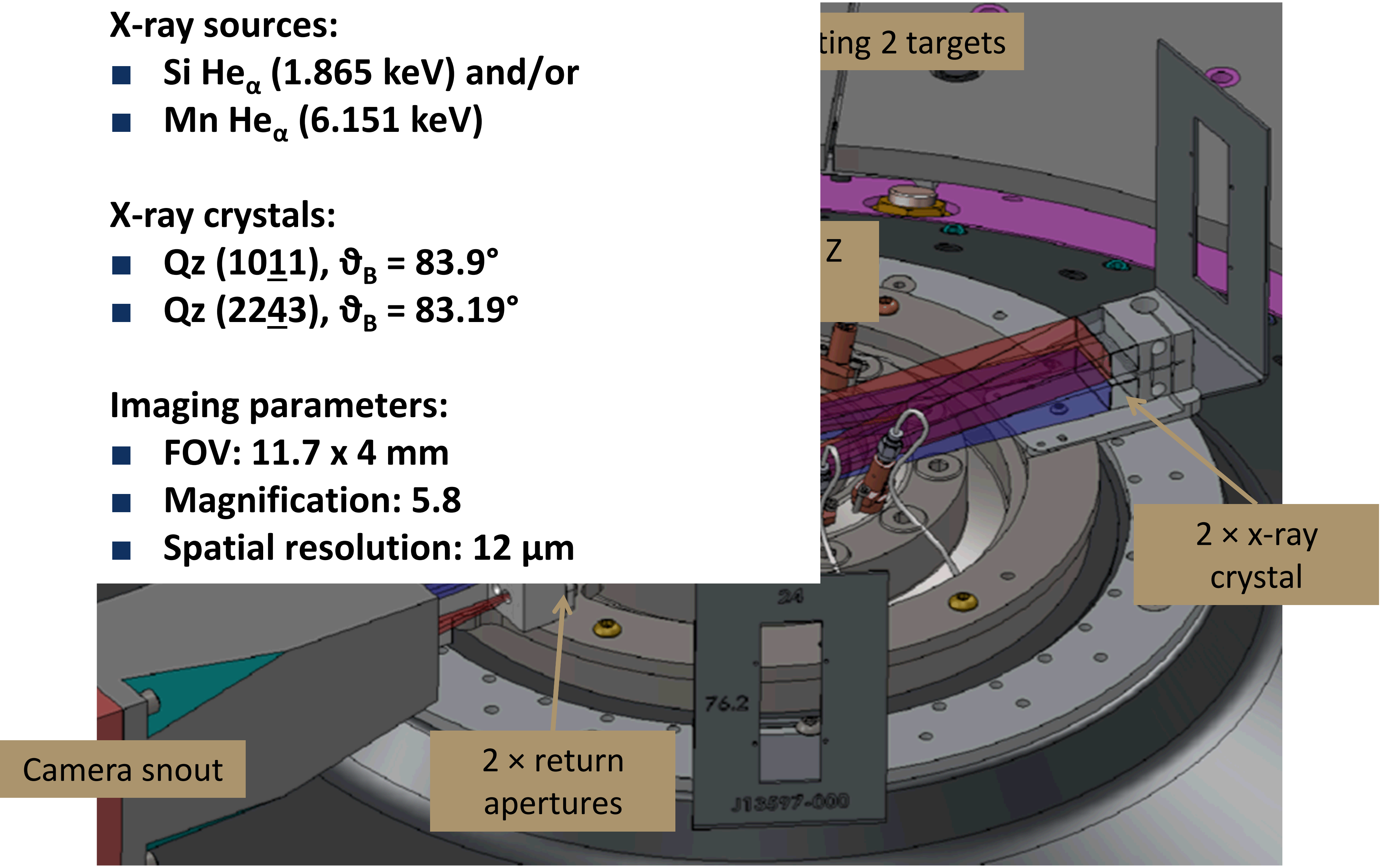
- Si He_{α} (1.865 keV) and/or
- Mn He_{α} (6.151 keV)

X-ray crystals:

- Qz $(10\underline{1}1)$, $\vartheta_B = 83.9°$
- Qz $(22\underline{4}3)$, $\vartheta_B = 83.19°$

Imaging parameters:

- FOV: 11.7 x 4 mm
- Magnification: 5.8
- Spatial resolution: 12 µm



Z couples several MJ of energy to the load hardware*

Pre-shot photo of MagLIF coils & target hardware

Post-shot photo

2 × spherical crystals

2 × laser targets + cameras

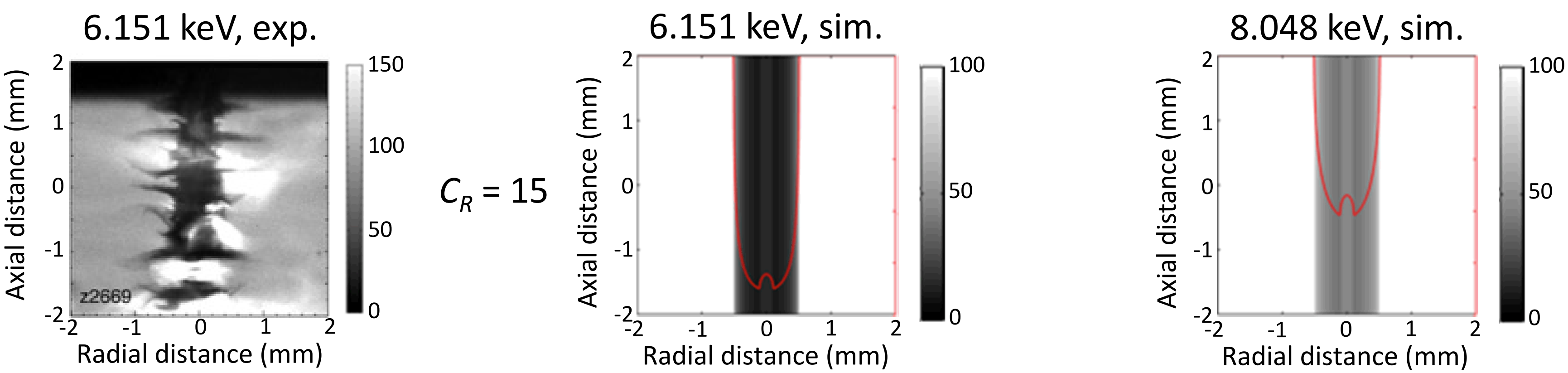
2 × return aperture towards image plate detector

*several MJ energy release is equivalent to a few sticks of dynamite

Developing a higher-energy backlighter

- Literature survey [1,2] reveals only few spherical crystal systems:
  - Si Heα (1.865 keV) and Quartz $(10\underline{1}1)$
  - Mn Heα (6.151 keV) and Quartz $(22\underline{4}3)$
  - Cu Kα (8.048 keV) and Quartz $(21\underline{3}1)$
  - Ti Kα (4.511 keV) and Quartz $(20\underline{2}3)$
  - Zr Kα (15.775 keV) and Quartz $(23\underline{5}4)$
  - Ru Heα (19.693 keV) and Ge (15 7 7)

- What limits the use of crystal imagers at Z and ZBL?
- How to find all possible combinations and rank them?
- Is above-6-keV backlighting at Z feasible, and if so, at which energy?

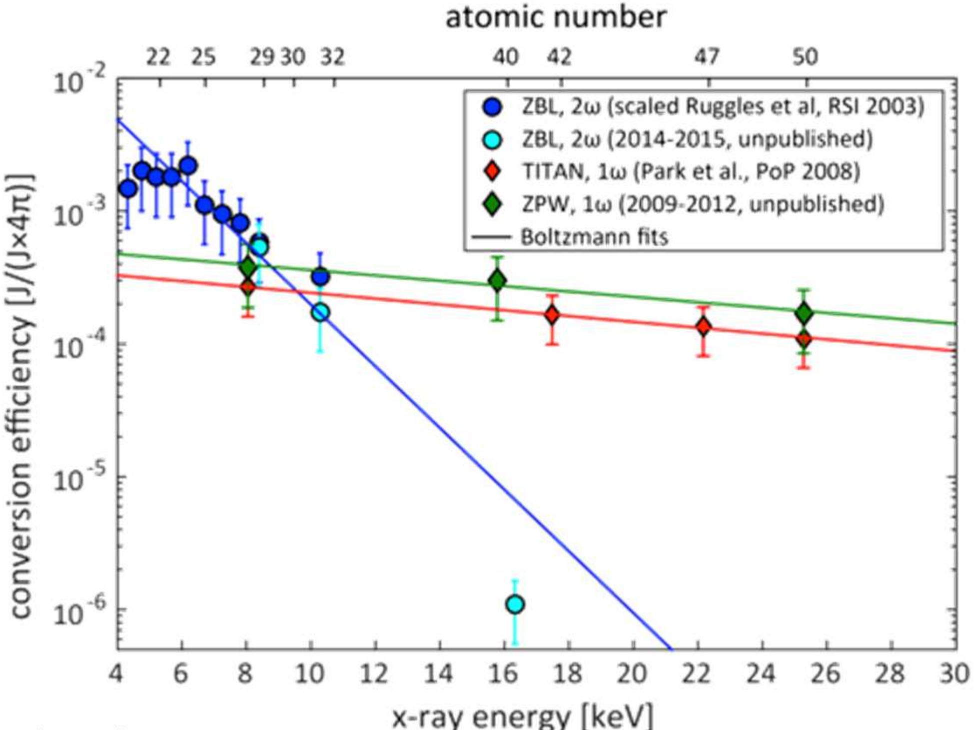


[1] M.S. Schollmeier et al., Appl. Opt. 54, 5147 (2015) [2] J.A. Koch, et al., Appl. Opt. 54, 10227 (2015)

Source efficiency and crystal reflectivity limit the image brightness

- Image brightness $I_d = \eta \dfrac{N_{\mathrm{phot}}\Omega}{4\pi A_{\mathrm{obj}} M^2}$ [1]
- **η depends on integrated reflectivity, spectral linewidth and source size:**
  - **use XOP [2] to calculate integrated reflectivity R_{int}**
  - **use linewidth and source size from experiments**

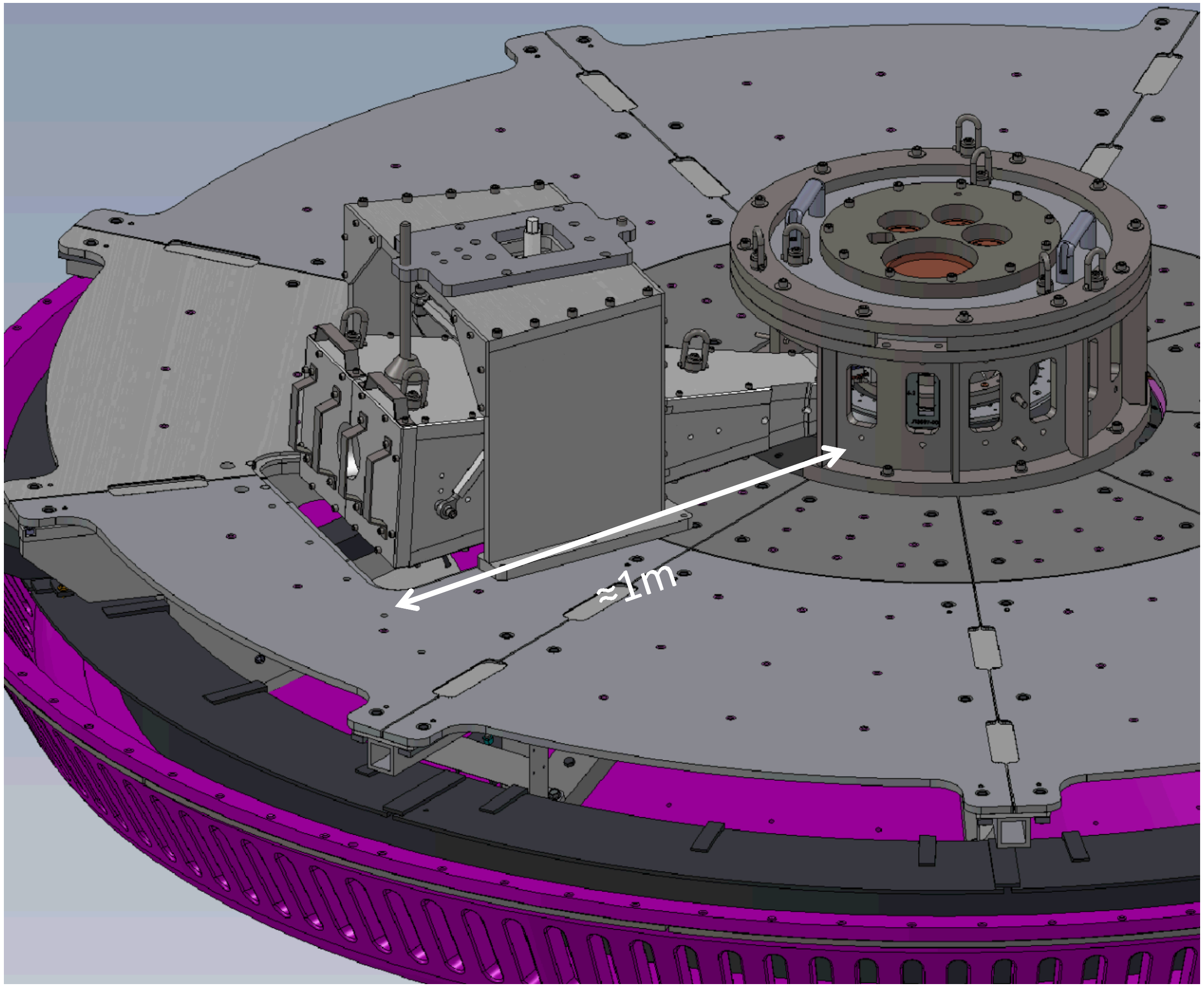
- **Source yield N_{phot} depends on laser-to-x-ray energy conversion:**
  - **Measure conversion efficiency**
  - **Fit Boltzmann distributions to measured data:**
    $$CE = P_1 \times \exp(-E/P_2)$$
  - **Use those fits to interpolate N_{phot} in estimates for I_d**



[1] M.S. Schollmeier et al., Applied Optics 54, 5147 (2015)
[2] M. Sanchez del Rio and R.J. Dejus, AIP Conf. Proc. 705, 784 (2004)

Existing hardware limits Bragg angles to $\vartheta_B = (83.5 \pm 1)^\circ$

- Detector shielding: 2.54 cm tungsten everywhere
- Weight: 400 kg
- Costs: ≈$250k just in materials
- Position fixed due to cut-out in base plate and interference with other diagnostics



Systematic search for spectral line/crystal combinations

Description	Quantity
Elements	Si – Ag, without P, S, Tc, Ru, Rh
Spectral lines	He-like resonance and intercombination, $K_{\alpha1}$, $K_{\alpha2}$
Energy range (*E*)	1.74 – 22.85 keV
Crystals	α-Quartz, Ge, Si, Mica, GaAs, InAs
Miller index ranges (*h, k, l*)	0 – 18 each
Possible combinations tested	4,609,248
Total number of matches with R_{int} > 0	**18,484**

General search and down-selection process:

- **Use Python script to iterate through all combinations**
- **call XOP to calculate R_{int} for matches, then calculate N_{phot} and I_d**
- **Find highest reflectivity crystals for each element & x-ray energy**

Requirements for Z:

- **6 < E < 10 keV to ensure good contrast and good penetration**
- **Bragg angle within (83.5 ± 1)°**
- **High reflectivity for good signal-to-noise ratio**

Finding a higher-energy backlighter for Z

index	element	x-ray energy [eV]	crystal	Miller indices (h k l)	ϑ_B [°]	R_{int} [µrad]	PSL* per 25 µm px
1	Si	1865	Quartz	(0 1 1)	83.9	421.17	143
2	**Si**	**1865**	**Quartz**	**(1 0 1)**	**83.9**	**185.40**	**63**
3	Cl	2789.8	Quartz	(1 1 1)	83.5	64.93	9.5
4	**Ar**	**3124**	**Ge**	**(2 2 0)**	**82.8**	**843.15**	**145**
5	Ca	3883	Quartz	(1 2 0)	83.1	11.25	1
6	Sc	4295	Quartz	(1 1 3)	83.5	52.98	3.2
7	**Mn**	**6151**	**Quartz**	**(2 2 3)**	**83.2**	**85.98**	**1.4**
8	**Co**	**7242**	**Ge**	**(3 3 5)**	**82.8**	**118.60**	**0.7**
9	**Ni**	**7766**	**Quartz**	**(2 4 0)**	**83.1**	**63.32**	**0.4**
10	Zn	8999	InAs	(1 5 7)	83.6	69.50	0.2
11	Zn	8950	Quartz	(2 1 7)	84.4	20.34	0.07
12	Ga	9628	Quartz	(1 6 0)	82.9	26.48	0.03
13	Ga	9575	Quartz	(4 3 3)	83.2	16.93	0.03
14	Ge	10280	Si	(8 4 0)	83.3	62.12	0.05
15	Ge	10221	Quartz	(3 0 8)	83.9	46.81	0.05

Astigmatism: 5-8 µm, w/ IP resolution: 12-14 µm

red = already used combinations
blue = interesting combinations

*PSL = PhotoStimulated Luminescence

7.2 keV backlighting: Laser-only tests demonstrate feasibility

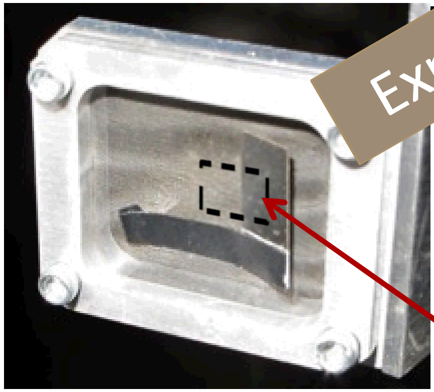
Measurements:

- **Meridional ESF = (12.5 ± 0.5) µm**
- **Sagittal ESF = (16 ± 0.5) µm**
- **Brightness: 1500 phot./px**

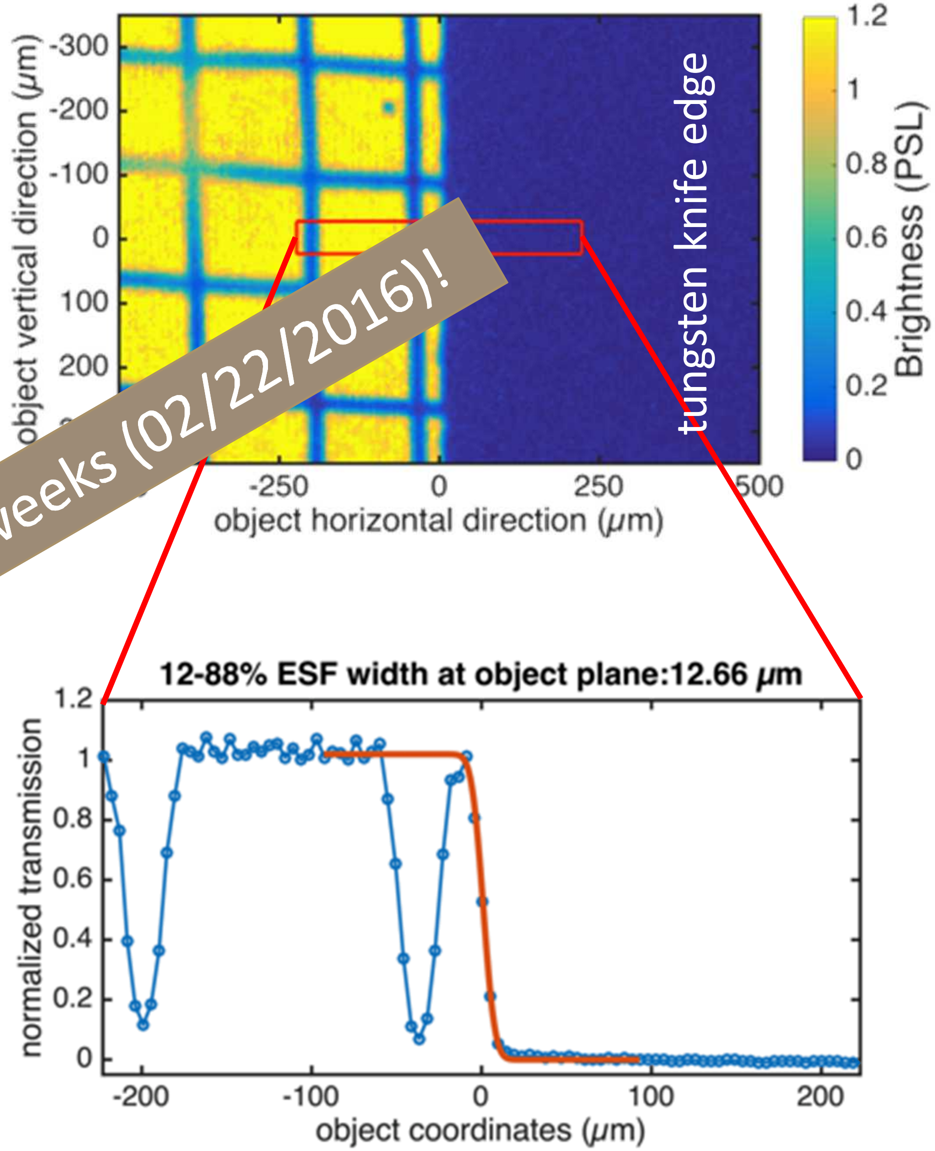
Ray-tracing model:

- **Using 65 µm Gaussian PSF for detector [1]**
- **Meridional ESF: (12 ± 1)**
- **Sagittal ESF: (15 ±**
- **/px**

Experiments at Z in ≈2 weeks (02/22/2016)!



0.5 mm thick tungsten knife edge on 150 lpi mesh



[1] T. Ao et al., JQSRT 144, 92-107 (2014)

Summary: HED Science at the Z-Facility

Sandia National Laboratories

4 key research areas at Z

- Dynamic Material Properties: Dynamic compression experiments for EOS studies
- Astrophysical Plasmas: Stellar interior opacity, Photoionized plasmas, white dwarf photospheres
- Z-Pinch X-Ray Sources: High x-ray yield for radiation effects studies
- Magnetized Liner Inertial Fusion: Nuclear fusion in the lab

3 laser systems at the Z-Backlighter Facility

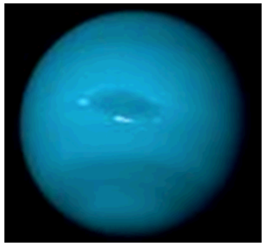
- Z-Beamlet: kJ, ns, 2ω, $\approx 10^{17}$ W/cm^2
- Z-Petawatt: sub-kJ, ps, 1ω, 10^{20} W/cm^2 or sub-kJ, ns, 2ω
- Chaco: <100 J, ns, 2ω, $\approx 10^{16}$ W/cm^2

3 key research areas at ZBL

- Investigate preheating of MagLIF targets
- Improve x-ray backlighting for radiography of imploding liners or wire arrays
- Develop sources for x-ray scattering and diffraction on dynamically compressed matter

Dynamic compression achieves HED material conditions relevant from planetary science to fusion

- **Planetary science – Jupiter, Saturn, Uranus, Neptune, and exoplanets [e.g., hot Neptunes]**
    - Metallization of hydrogen/deuterium: M. Knudsen, Science 2015



- **Planetary science – earths and super-earths**
    - Determining the vaporization threshold for iron – and implications for planetary formation: Kraus, Nature Geoscience 2015

- **Materials for Stockpile Stewardship, HED and inertial confinement fusion (ICF)**
    - Investigating the periodic table from **A**luminum to **Z**irconium: a broad range of materials are of interest - a talk in itself
    - The programmatic work drives precision – *we rely on the data!*

We turn planetary science *quantitative* by high fidelity modeling and high-precision experiments!