September 2016

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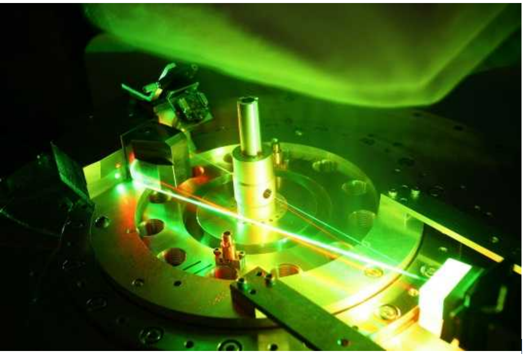

Sandia National Laboratories

Exceptional service in the national interest

Sandia's Z-Backlighter Laser Facility

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Boulder Damage Symposium
September 28, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- Overview
- Laser Facility
    - Lasers: Z-Beamlet, Z-Petawatt, Chaco
    - Optics Support Facility (OSF)
    - Target Bay
- Applications
- Conclusions

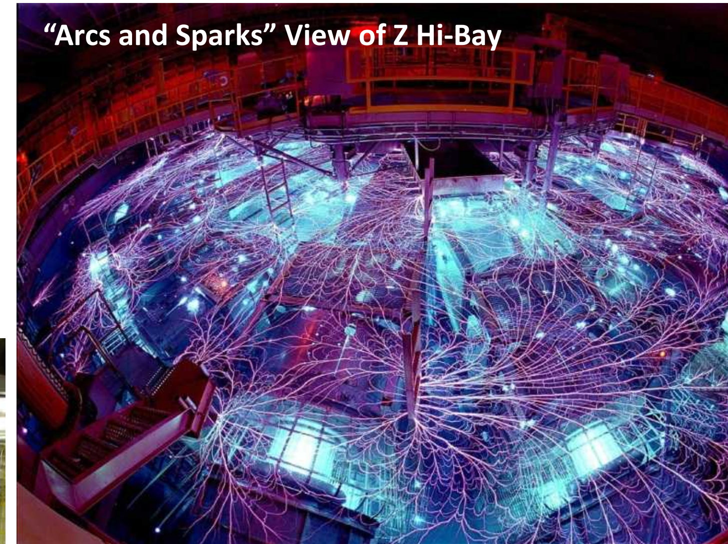
Overview

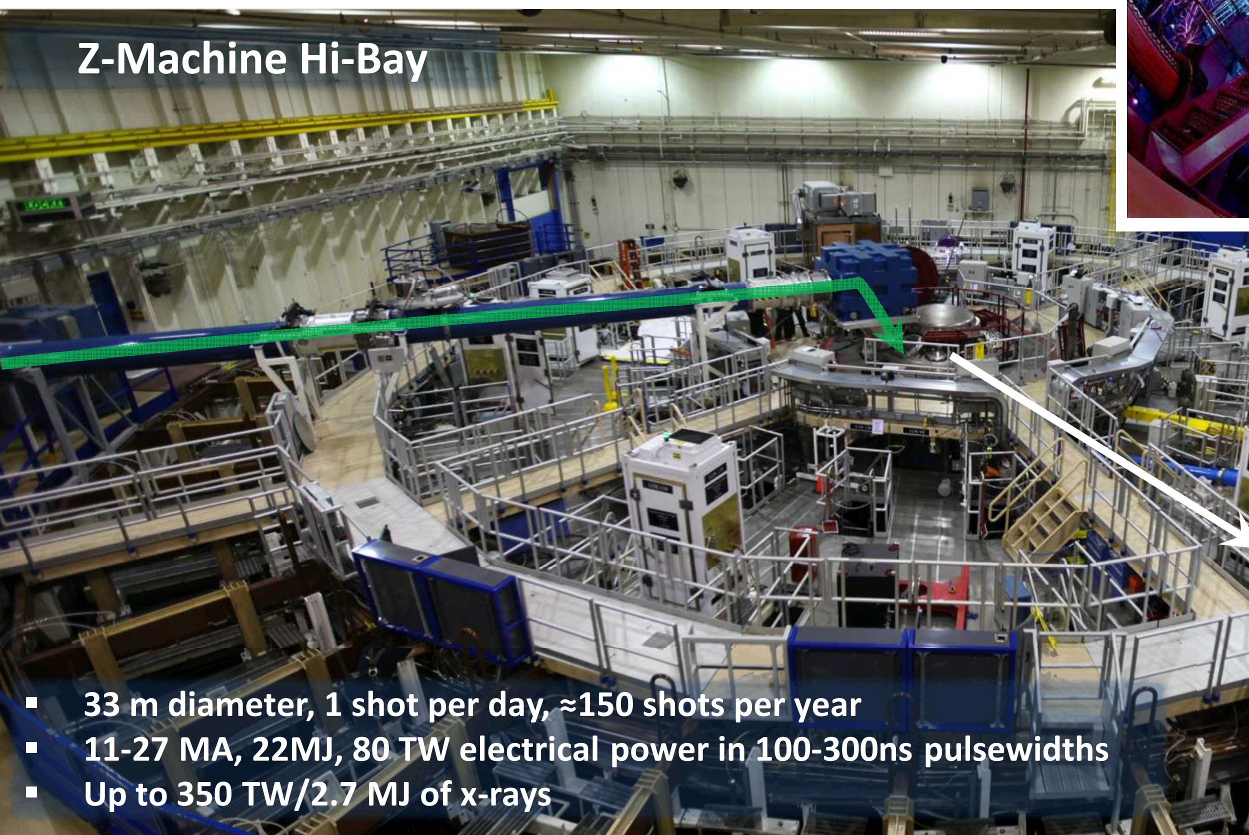
Sandia National Laboratories

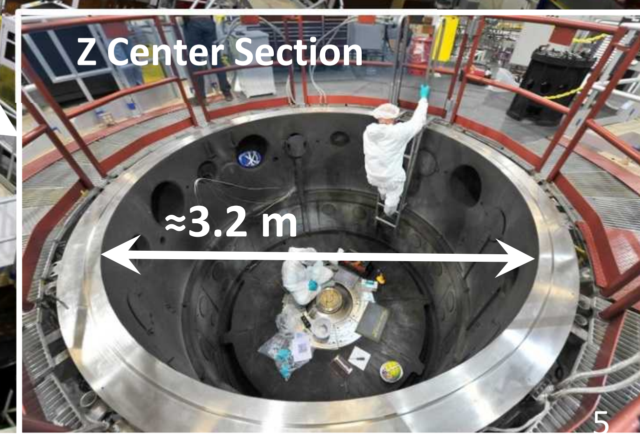
- **Federally funded research and development center (FFRDC)**
- **Government-owned, contractor operated (GOCO)**
- **Principal sites at Albuquerque, NM and Livermore, CA**
- **Regular employees: 10,540 (End of FY15)**
- **Total laboratory expenditures: $2.9B (FY15)**
- **Multi-disciplinary research, including:**
    - ***Radiation Effects and High Energy Density Science***

High Energy Density Science on Z

- The Z-Machine uses the Z-pinch principle for HED science:
  - Energy stored in capacitors is rapidly discharged through a "tube" (either a liner or wire array).
  - The high current generates enough B-field that the Lorentz force compresses (pinches) the "tube" to the central Z axis.
  - The resulting hot dense matter of the Z-pinch is a significant x-ray source.

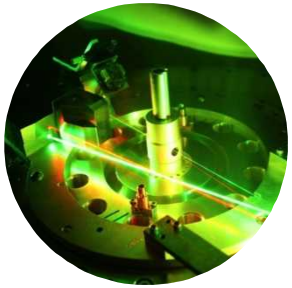




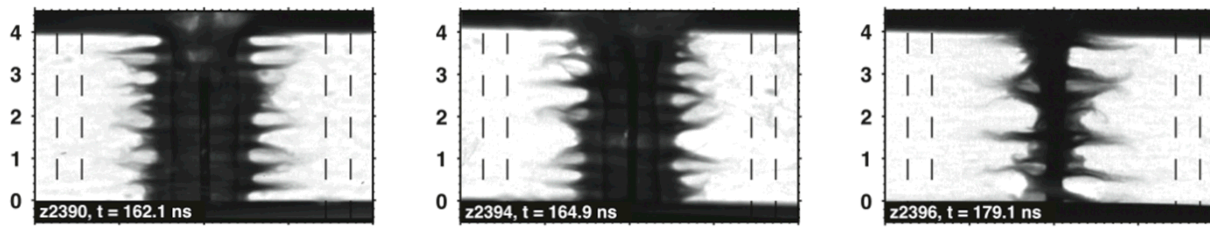


- 33 m diameter, 1 shot per day, ≈150 shots per year
- 11-27 MA, 22MJ, 80 TW electrical power in 100-300ns pulsewidths
- Up to 350 TW/2.7 MJ of x-rays

Z-Backlighter Research Support at Z

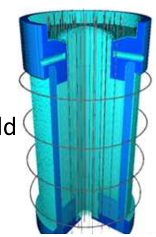


Drive 1.8, 6.2, and 7.2 keV x-ray backlighters for x-ray radiography of imploding liners or wire arrays (sub-ns synchronization)

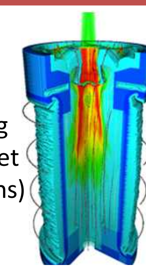


Preheat a Magnetized Liner Inertial Fusion (MagLIF) target

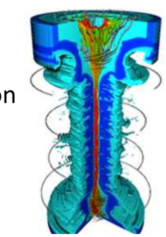
Magnetization with external B-Field (ABZ, 10-30 T)

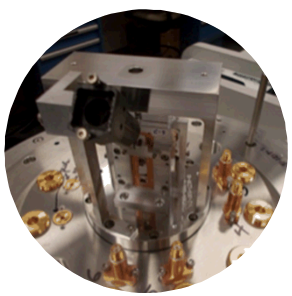


Laser heating with Z-Beamlet (2-6 kJ @ 2-6 ns)

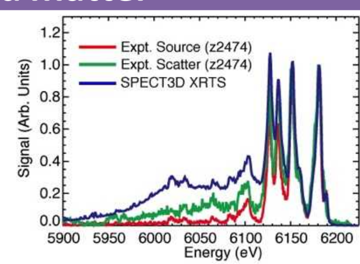


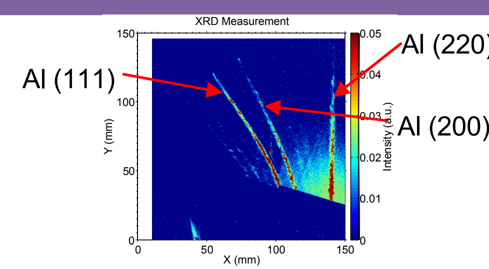
Compression with Z





Generate x-ray sources for x-ray scattering and diffraction on dynamically compressed matter





Laser Facility

Z-Backlighter Facility Overview

Z Backlighter

	Z Beamlet	Z Petawatt	Chaco
λ (nm)	527	1054	1064 (532)
τ	0.3-8 ns, typ. 2 ns	500 fs – 100 ps	100 ps – 10 ns
typ. Spot size (μm FWHM)	75	6	20
E_{max} (J)	4500	100 (200TW) / 500 (ZPW)	100 (50)
I (W/cm²)	~ 10^{17}	~10^{20}	~ 10^{17}
Shot Intervals (minutes)	180	180	20
'Special feature'	2 pulse MFB (two frame/2 color)	CPA probe beam (< 20 mJ)	Bursts; 8-10 ns option; 1ω and >100J (pending)

Optics Needs: 1ω/2ω coatings, both AR and HR, various AOI's, dry air/vacuum environments, peak LIDT's>10J/cm²

Z-Backlighter Facility Map

Chaco

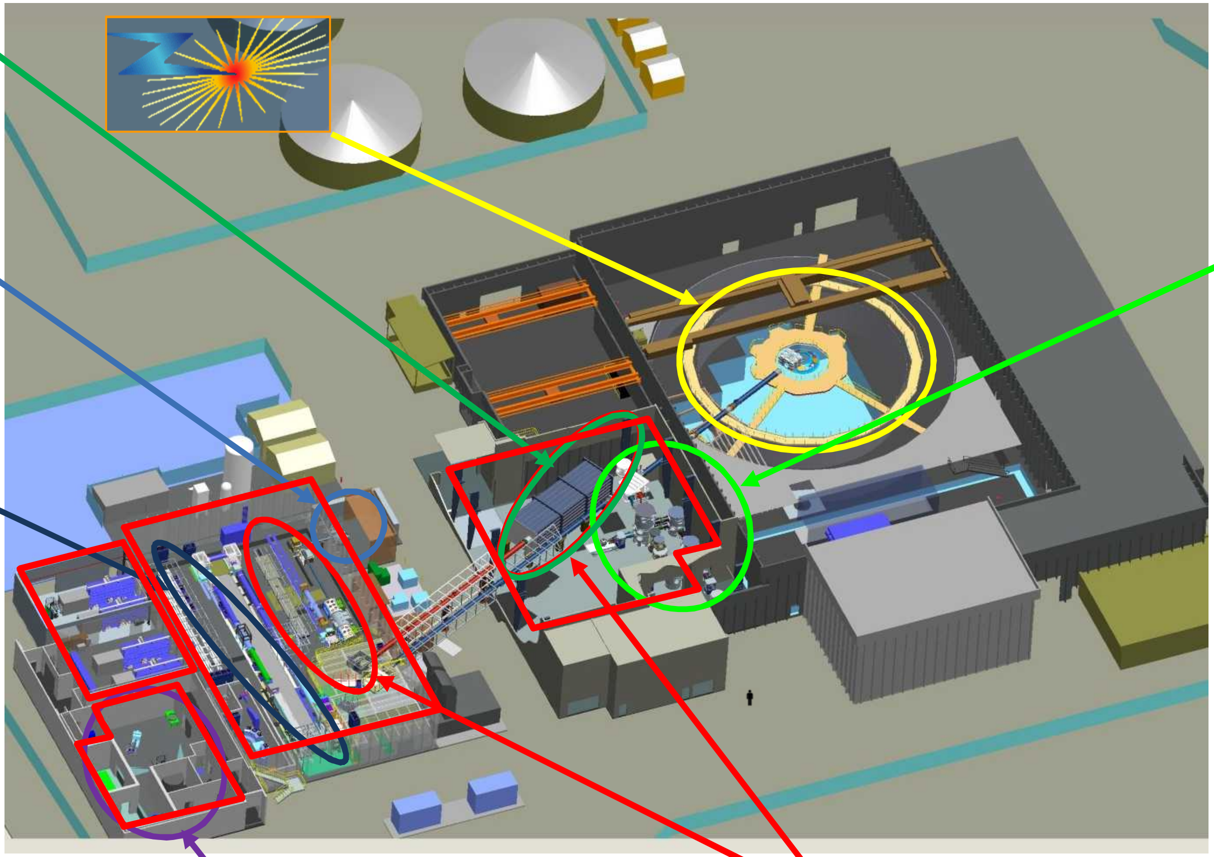
Total:
~19400ft^2 or ~1800m^2

→*Only 12 Permanent Staff*

200TW
Target Area

Z-Backlighter
Target Area

ZBeamlet



OSF

ZPetawatt

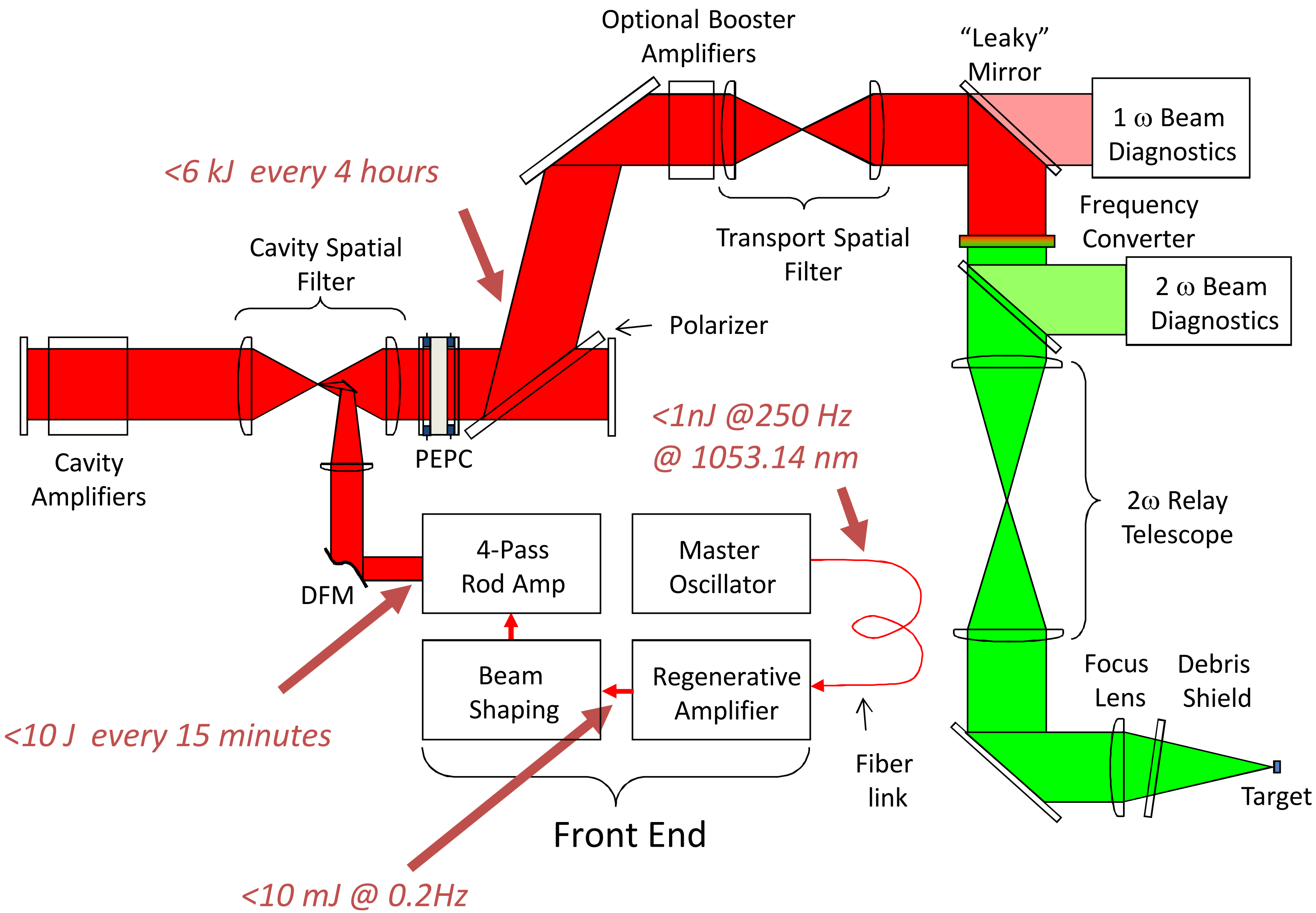
Z-Beamlet Laser Basics

- Background:
  - The Z-Beamlet Laser (ZBL) was the LLNL NIF prototype (1992-1998).
  - This Nd:Phosphate Glass laser now supports Z experiments at SNL.
    - 1st shots into Target Chamber: Mar 2001
    - 1st active Z radiographs: Jun 2001
- Laser Parameters:
  - Up to 6 kJ @ 1053 nm, , 31 x 31 cm^2 beam
  - Up to 4.5 kJ @ 527 nm, 31 x 31 cm^2 beam
  - 3 shots per day
  - $I \approx 10^{17}$ W/cm^2, 0.3 – 4 ns pulse length
  - Multi-frame option: 2 pulses (each at half energy) at 2-20ns delay with different pointing
- Application Comments:
  - <9 keV x-ray generation
  - 4 target chambers + Z
- Newer Efforts:
  - Adaptive optics (COTS)
  - Phase modulation systems for SBS suppression
  - Phase plates


View of Z-Backlighter Hi-Bay


View of Z-Beamlet

Z-Beamlet Laser Architecture

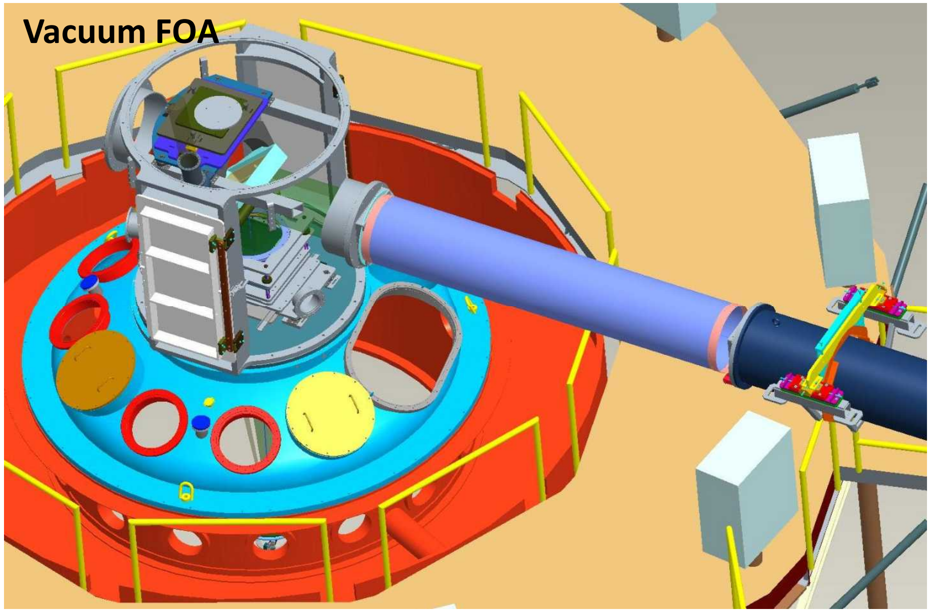


ZBL Beam Delivery to Z

- At the top of the accelerator, the beam enters a final optics assembly (FOA) consisting of:
  - 90° folding mirror
  - f =3.2 m aspheric lens
  - 3 cm thick Vacuum Window
  - 1 cm thick Debris Shield

- Backlighting pointing is slightly off axis WRT to Z.
  - This allows extras debris protection measures.
- MagLIF requires on-axis laser light at the Z pinch.
  - This exposes the window to direct axial debris.
  - A catastrophic window failure could:
    - Result in the rapid release of >5MJ of stored energy and
    - Generate large-scale dispersion of silica and Z powders.
- FOA evacuation avoids this issue. → No stored ΔE

- A sealed FOA also reduces exposure from the vapors of 2ML of transformer oil and 2.3ML of deionized water in Z.



Debris Shields and Vacuum Windows constitute unique optics supply needs.

Large Optics Coatings


Handling of a truncated 94cm fold mirror


Coating of a truncated 94cm fold mirror


Final product for a 75cm HR (200lb weight)

- A steady supply of AR-coated debris shields and vacuum windows is needed.
  - ~50/year of each
- To this end, the Z-Backlighter facility installed a 90” coating chamber into a Class 100 cleanroom area with optical metrology capabilities.
  - We refer to this as the Optics Support Facility (OSF).

- Coatings:
  - Materials: Typically HfO_2/SiO_2
    - Other oxides (Al_2O_3, TiO_2, Nb_2O_5, Ta_2O_5) also used
  - Deposition methods: e-beam, ion-assisted deposition e-beam
  - Single-run size capability: 3 optics at 94 cm, 1 at 1.5 m option
- Metrology: Spectrophotometer, Large-area reflectometer, Interferometer

- Coating Examples (both air and vacuum use environment designs):
  - AR’s at 1054nm/1064nm and 527nm/532nm (1045-1064nm option)
  - HR’s at 1054nm/1064nm and 527nm/532nm (1045-1064nm option)
  - Other: MLD gratings, Thin Film Polarizers, OAP’s (all at 1ω)

- Independent ns-laser damage testing (SPICA) shows good damage thresholds:
  - In the range of 17-25 J/cm^2 for AR coatings
  - In the range of 75-85 J/cm^2 for HR coatings
- In-house small-area 1ω/2ω testing at Sandia with ns sources corroborates this.
- >0.5ps source testing at 1ω/2ω is also optional.

Z-Petawatt Laser Basics

- **Background:**
  - **Using the same infrastructure as ZBL, the ZPW system has been constructed for higher energy x-ray radiography.**

- **Laser Parameters:**
  - **ZPW** **Up to 500 J @ 1053nm, 0.5-200ps, 41 x 41 cm^2**
  - **200TW** **Up to 100 J @ 1053nm, 0.5ps, 15cm round**
  - **Co-Injection** **Up to 500 J @ 527nm, 2ns , 15cm round**
  - **3 shots per day**
  - **$I \approx 10^{20}$ W/cm^2 @ 1ω**

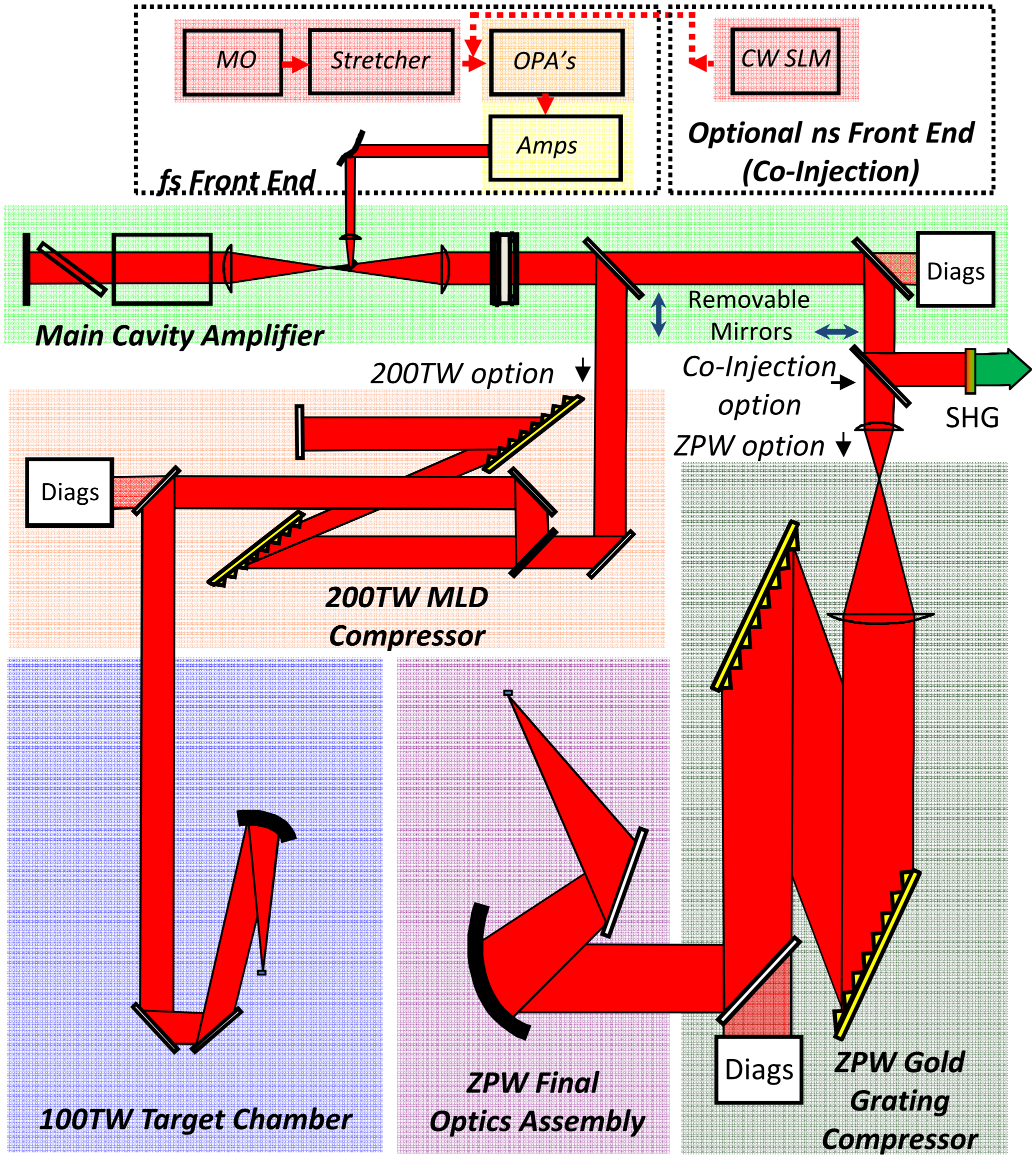
- **Application Comments:**
  - **>8keV x-ray generation**
  - **High-field physics (particle acceleration/γ-rays)**
  - **2 target chambers + Z**

- **Newer Efforts:**
  - **Co-injection into ZBL: ns, 2ω operation**
    - **Additional energy for ZBL pulse**
    - **Flexible prepulse for MagLIF/radiography**
  - **Lens-based focusing (chirped 0.1-0.2ns)**
  - **2 kJ full-aperture upgrade**

View of ZPW System

Interior of 200TW Vacuum Compressor Vessel with 21cm X 60cm MLD gratings

Z-Petawatt Basic Architecture



- **ZPW uses chirped pulse amplification (CPA) to reach the petawatt level.**
- **Spare parts from ZBL were use to build a 2-pass main amplifier cavity with a sub-apertured 15cm round beam.**
- **After temporal re-compression, propagation occurs in vacuum.**
  - **The smaller beam can be turned down to 100J in 500fs using MLD gratings ("200TW" option)**
  - **The beam can be expanded and run up to 500J in 500fs using gold gratings (Petawatt option)**
- **Focusing requires off-axis parabolic reflectors (i.e. no transmissive optics) unless at longer pulsewidths.**
- **With a narrow-band seed, the compressors can be by-passed and SHG performed for ns 2ω applications.**

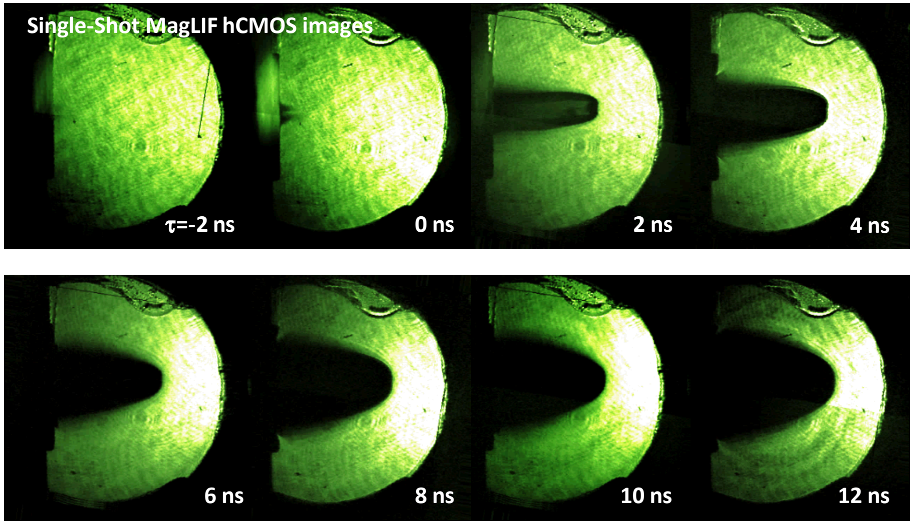
Chaco Laser Basics

- Background:
  - Chaco is a Nd:YAG/Nd:Silicate Glass system used as for soft x-ray generation and probing.
  - Spectral separation from ZBL/ZPW aids in discrimination in certain applications.

- Laser Parameters:
  - Up to 100 J @ 1064nm, 8ns, 5cm round
  - Up to 50 J @ 532nm, 8ns, 5cm round
  - 20 minute between shots
  - $I = 1 \times 10^{17}$ W/cm^2 @ 2ω
  - Probe Beam Multi-Pulse Options
    - Up 8 pulses in a sequence
    - Multiple pulse separation options:
      - From sub-ns to >50ns spacing

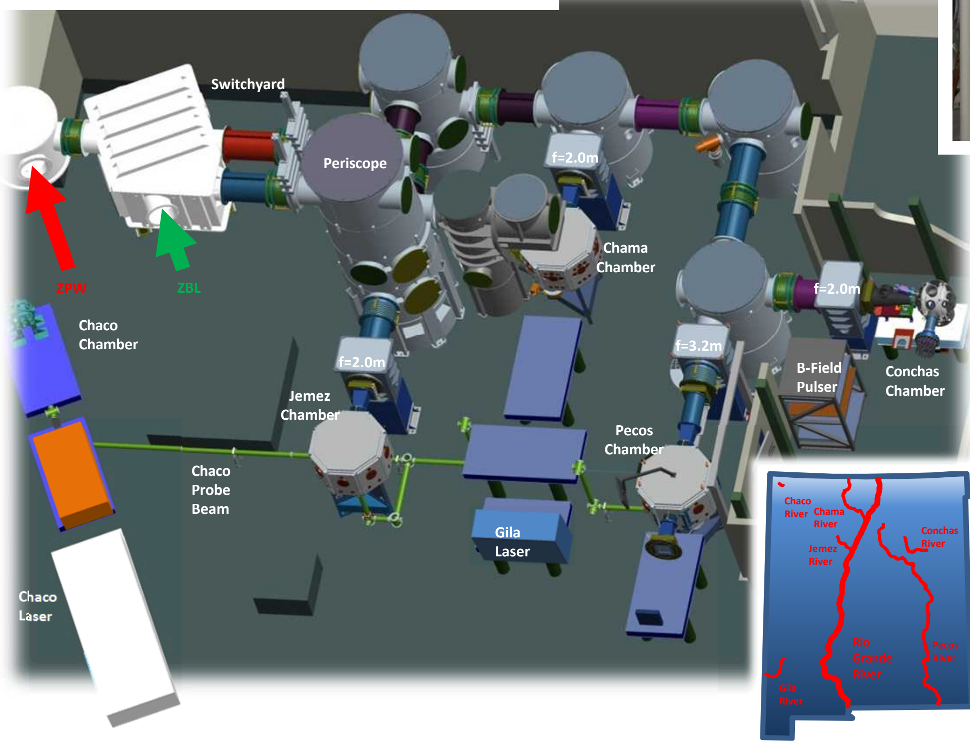
- Application Comments:
  - Probe beam
  - <5 keV x-ray generation
  - 4 target chambers

- New Efforts:
  - Shock driver for dynamic x-ray diffraction



- The probe beam/hCMOS camera development facilitates MagLIF studies of the laser-driven (2kJ/527nm) evolution of thin plastics (1μm) over a laser entrance hole, with a 300 Torr backfill of Ne behind.

The Target Bay

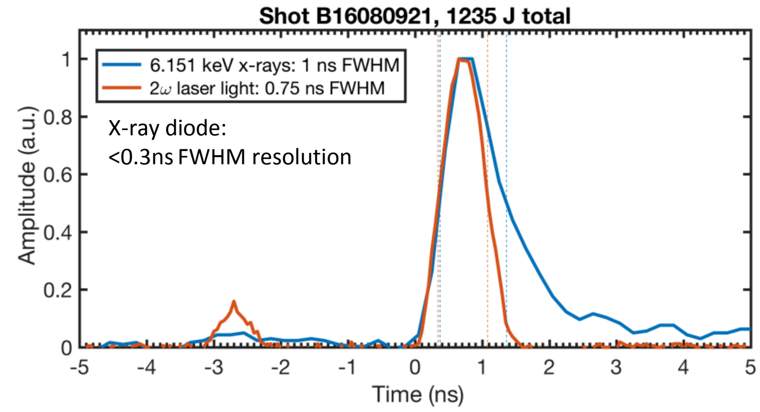


- 5 laser target chambers (named for New Mexico rivers) for HEDP interactions exist with various applications:
  - Jemez: ~ 1.5m Octagonal chamber used for ZBL /Chaco Laser
  - Pecos: ~ 1.5m Octagonal chamber used for ZBL /Chaco Laser
  - Chaco: 60cm spherical chamber used for Chaco Laser
  - Chama: ~ 1.5m Octagonal chamber (incorporating local shielding) used for ZPW/ZBL /Chaco Laser
  - Conchas: 80cm spherical chamber used for ZBL only
- Conchas has an optional B-field pulser:
  - Built under a collaboration with the University of Texas
  - Specs: 100kA per cap, 5 caps, ~1µs pulse, >10T at load
  - Availability: Conchas chamber in 10-30T range currently.

Applications

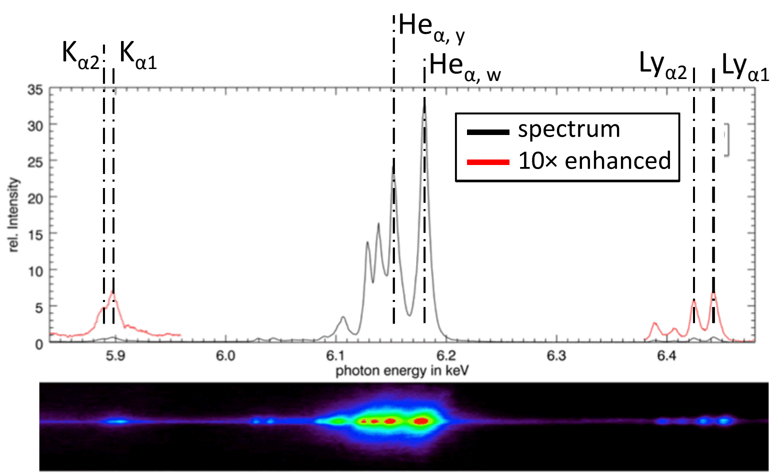
Laser-driven X-ray Sources: <10keV

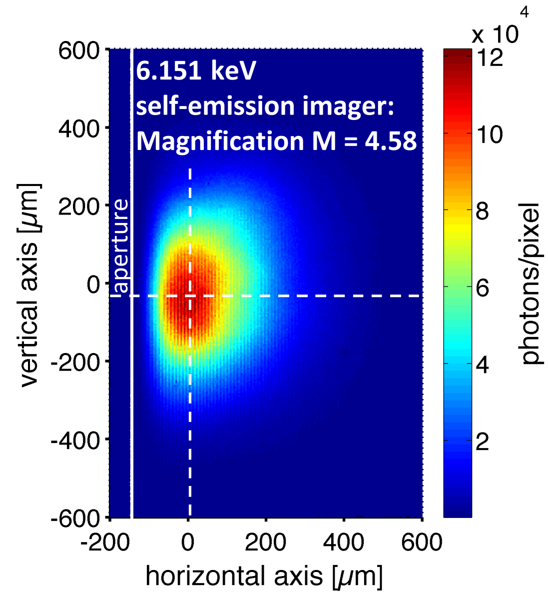
- **Lasers focused onto metallic foils generate x-ray line sources for backlighting and x-ray scatter/diffraction studies.**



Key parameters:

- **Up to 9 keV x-rays with <u>Z-Beamlet</u>:**
  - **He_{α} line emission from ions in hot plasma**
  - **≈10^{16} photons in 1-4 ns pulse**
  - **Laser spot size: ~200μm**
  - **X-ray spot size: 340μm X 227μm (FWHM)**



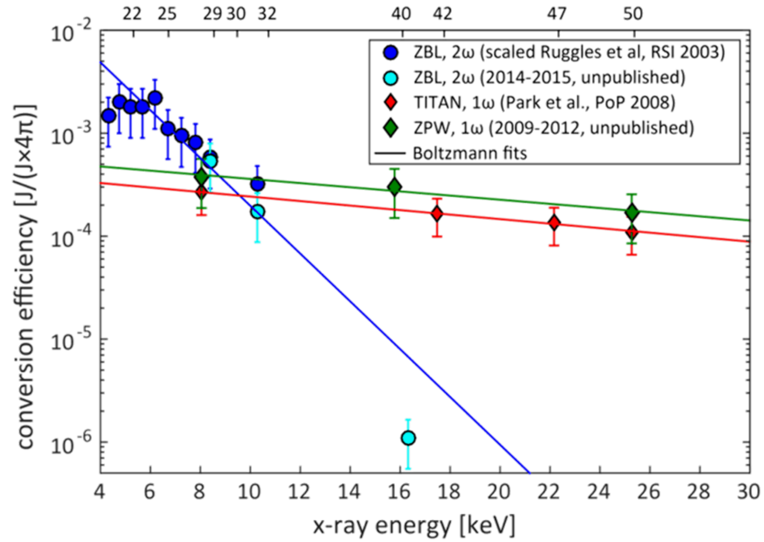


Laser-driven X-ray Sources: >10keV

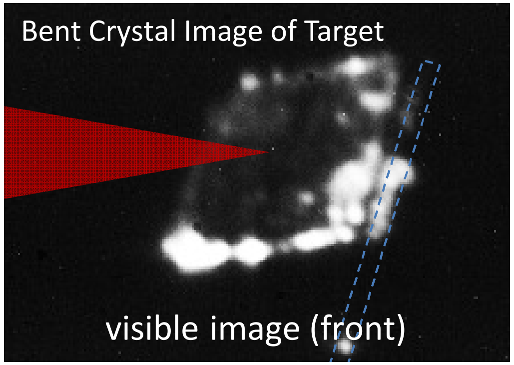
- **Lasers focused onto metallic foils generate x-ray line sources for backlighting and x-ray scatter/diffraction studies.**

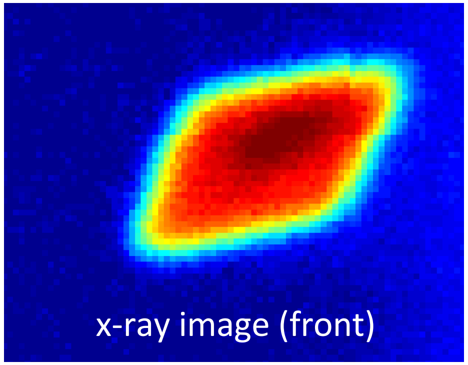
- **Up to 25 keV x-rays with <u>Z-Petawatt:</u>**
  - **K_α line emission from cold atoms in dense matter**
  - **≈10^{14} photons in 0.5-100 ps pulse**
  - **Laser spot size: ~ 10μm**
  - **X-ray spot size: Mass-limited target size**

X-ray source efficiency

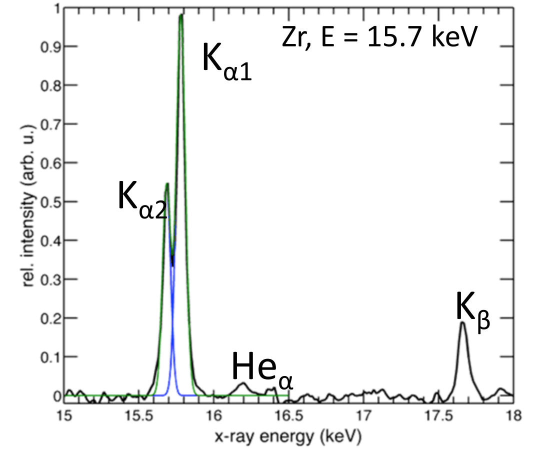


ZPW laser





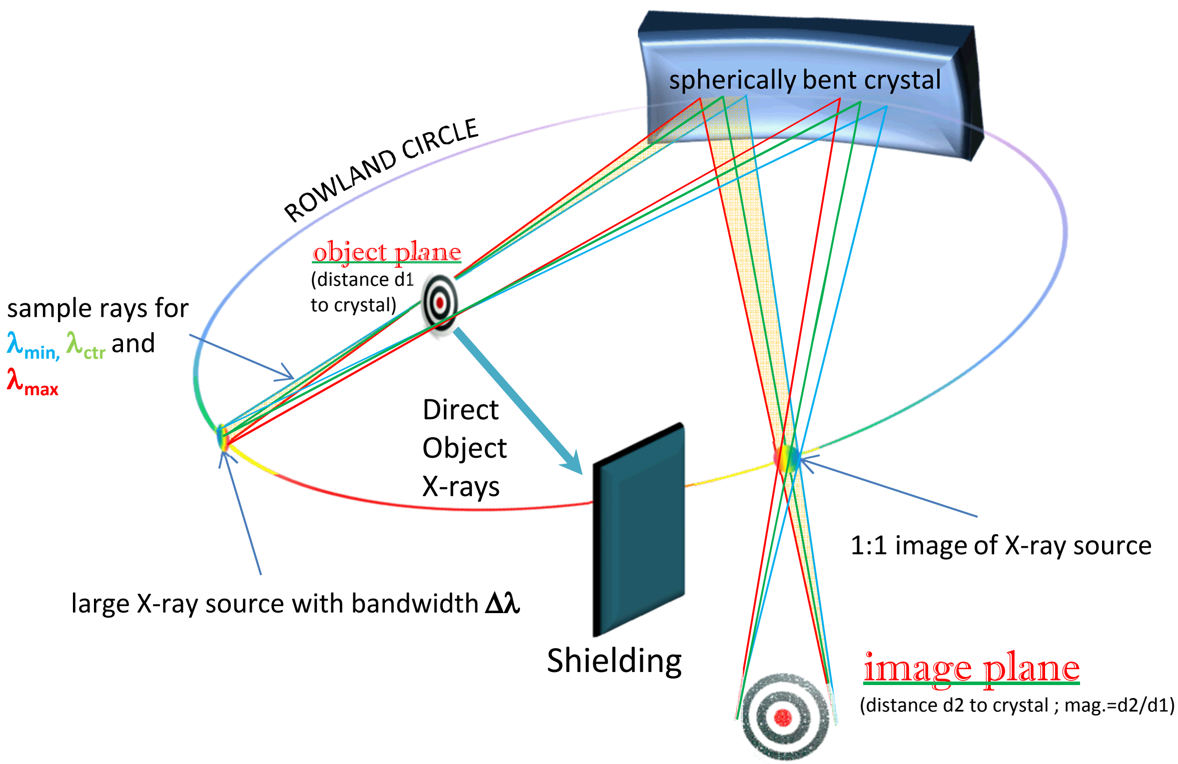
Target: Cu, 250 × 250 × 25 μm³ MLT foil, 8keV
ZPW Laser: 100 J, 0.5 ps, >10^{20} W/cm²

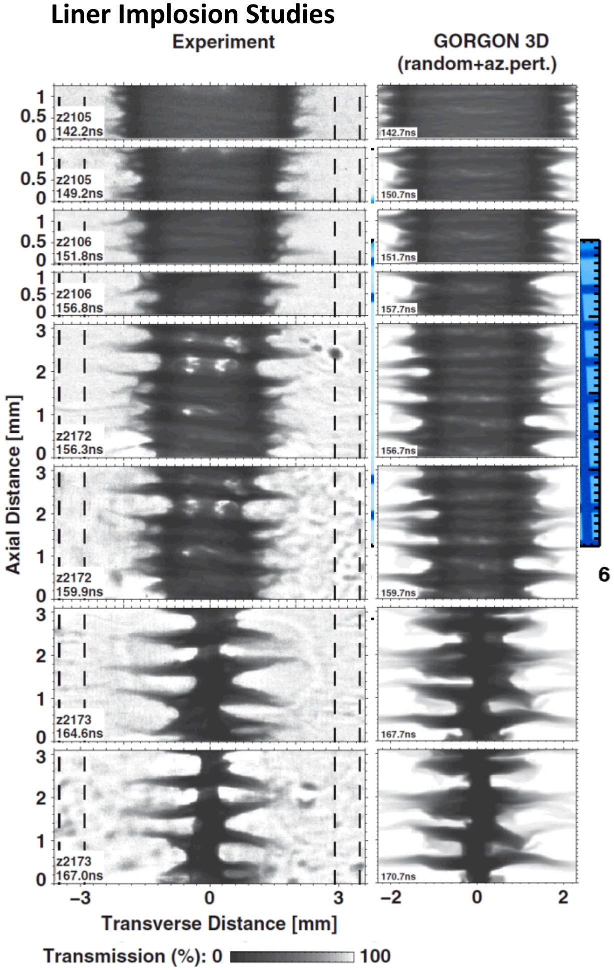


ZPWLaser: 1 ps, 100 J, I = 10^{20} W/cm²

X-Ray Backlighting: Bent Crystal Imaging

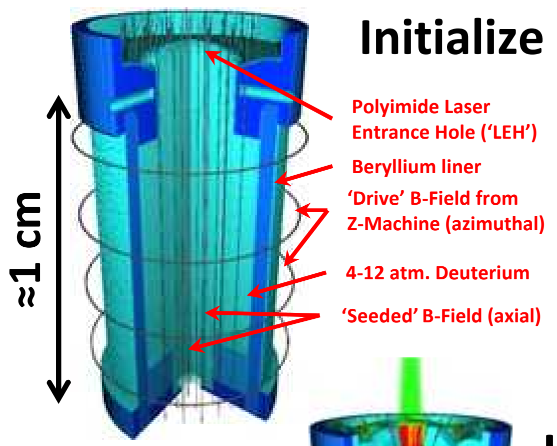
- The laser-generated x-ray source can be used with an x-ray imaging system.
- Bent crystal x-ray imaging improves monochromaticity, resolution, and field of view.





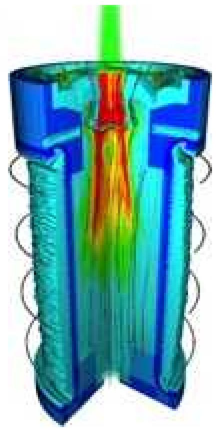
*R.McBride *et al.*, PRL 109, 135004 (2012)

Magnetized Liner Inertial Fusion (MagLIF)*



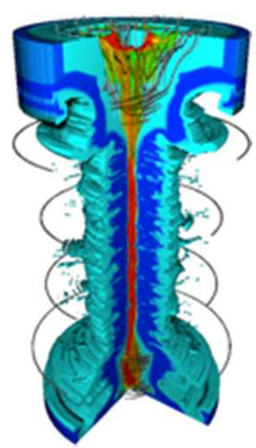
Initialize axial magnetic field (B_0 = 10-30 T)

- Inhibits thermal losses from fuel to liner
- May help stabilize liner during compression
- Flux compression increases B 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/Δr* ≈ 6) are robust to hydrodynamic instabilities
- Significantly lower pressure/density than non-magnetized ICF

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*S.A. Slutz et al.: Physics of Plasmas **17**, 056303 (2010); S.A. Slutz & R.A. Vesey, Phys. Rev. Lett (2012); A.B. Sefkow *et al.*, Phys. Plasmas (2014)

Conclusions

Conclusions

- The Z-Backlighter Facility houses several high energy lasers:
  - Z-Beamlet: nanosecond regime for 1-9keV line backlighting and MagLIF heating
  - Z-Petawatt: sub-picosecond/picosecond regime for 8-25keV line backlighting/diffraction
  - Chaco: picosecond/nanosecond for <5keV line backlighting, probing, and shock driver

- Target Bay operations have a variety of target chambers and options.
  - 5 Chambers with multiple x-ray and visible diagnostics (including probe beams)
  - >10T B-field capability.

- OSF coating infrastructure allows support of large optics needs (AR/HR coatings at high LIDT) as well as consumables (debris shields/Vacuum windows).

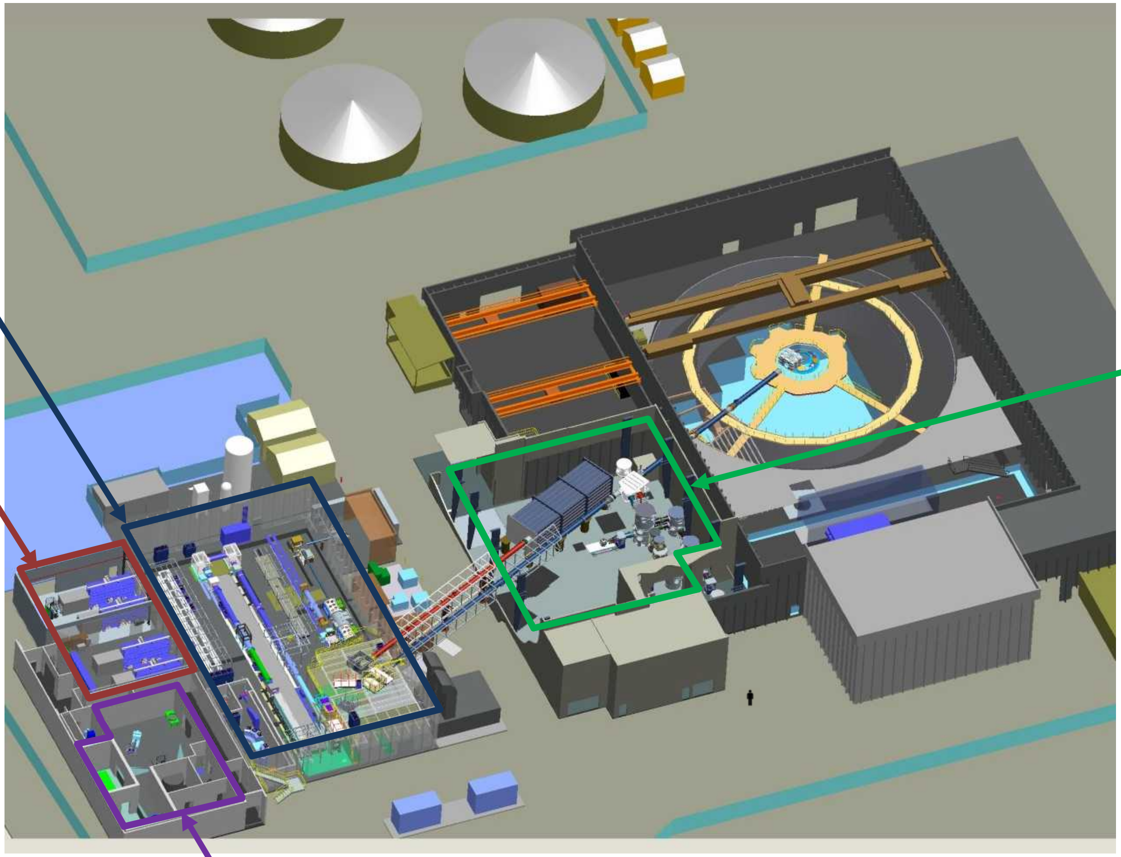
- Future activities include:
  - Full-aperture ZPW with meter-class MLD gratings
  - Development of Chaco as a shock driver
  - Optimization of ZBL in MagLIF applications

Backups

Z-Backlighter Scale

Z-Backlighter Laser Bay (~8520ft^2 or ~792m^2)

Z-Backlighter Capacitor Rooms (~2230ft^2 or ~207m^2)



Z-Backlighter Target Bay (~6280ft^2 or ~583m^2)

LOCO (OSF) (~2330ft^2 or ~216m^2)

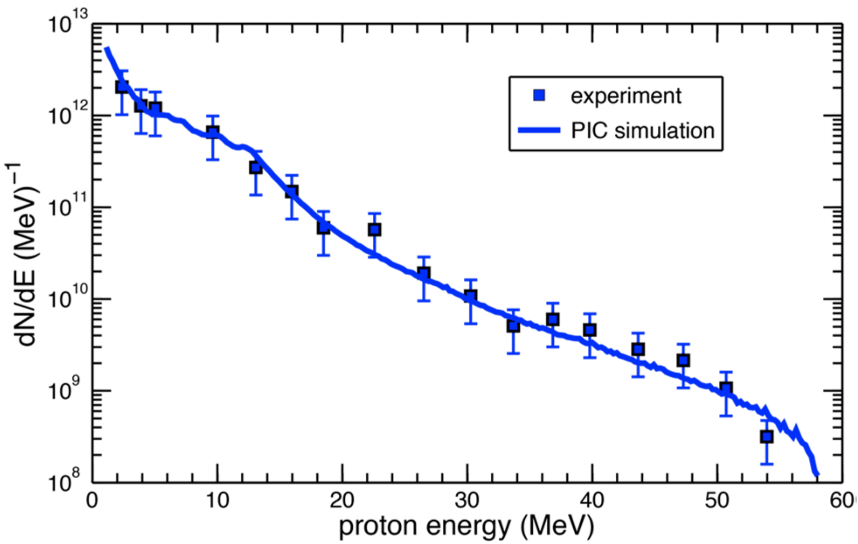
Total: ~19400ft^2 or ~1800m^2

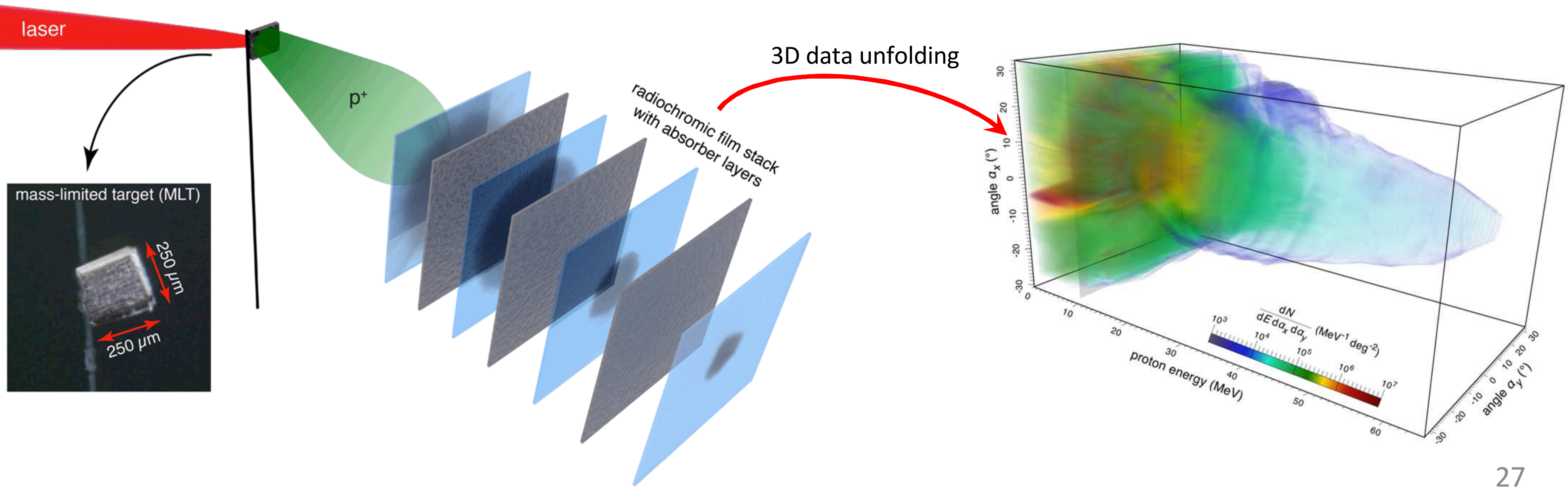
(Only 12 Permanent Staff)

Laser-driven Radiation Sources: Protons

Key parameters *:

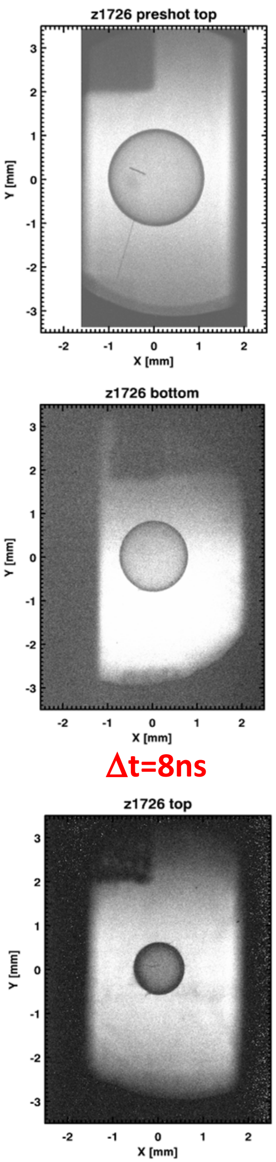
- **High-intensity irradiation (with 200TW laser) of metallic foils leads to energetic proton emission**
- **Thermal spectrum**
- **Sharp cutoff, up to 65 MeV**
- **≈10^{13} protons total**
- **Divergent beam up to ±30°**
- **Beam parameters depend on temporal laser pulse profile**





*M.Schollmeier *et al.,* Phys. Plasmas 22, 043116 (2015)

Two-Frame Radiography



- Modifications to ZBL allow two separately timed pulses at slightly different angles.
- This allows the crystal imaging technique to take two radiographs on the same Z shot.
  - Delays from 2ns to 20ns between frames
  - Possible use of different x-ray sources and matched crystals