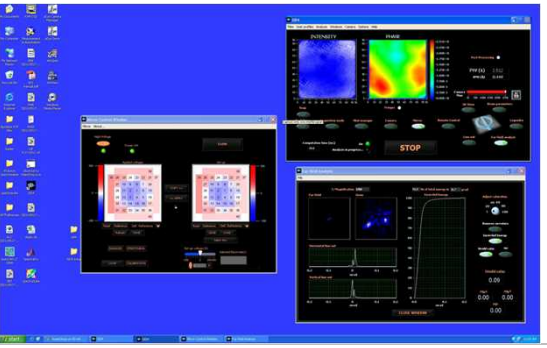
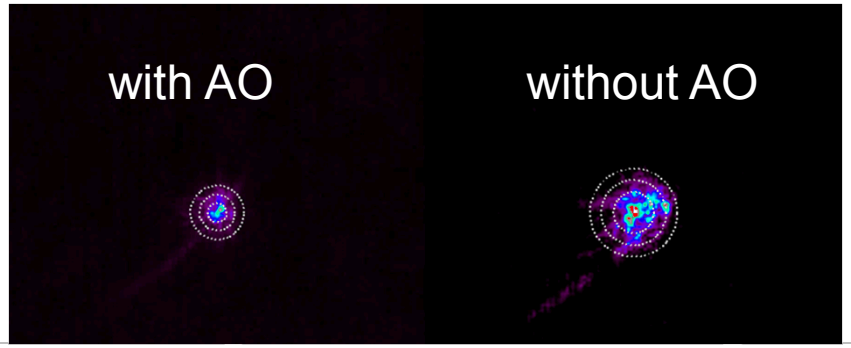
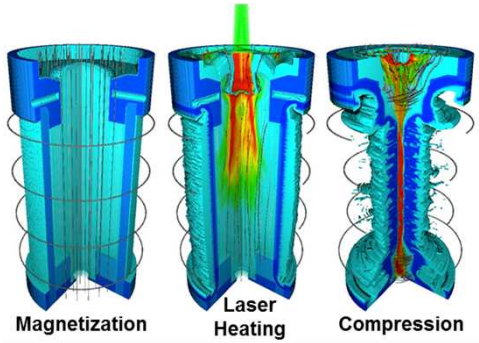
Exceptional service in the national interest

SAND2016-1889PE







Overview of Sandia's Z-Backlighter Facility and its Recent Upgrades in Order to Accommodate New Requirements for Magnetic Liner Inertial Fusion on the Z-Machine

Jens Schwarz

Shanghai Institute for Optics and Fine Mechanics

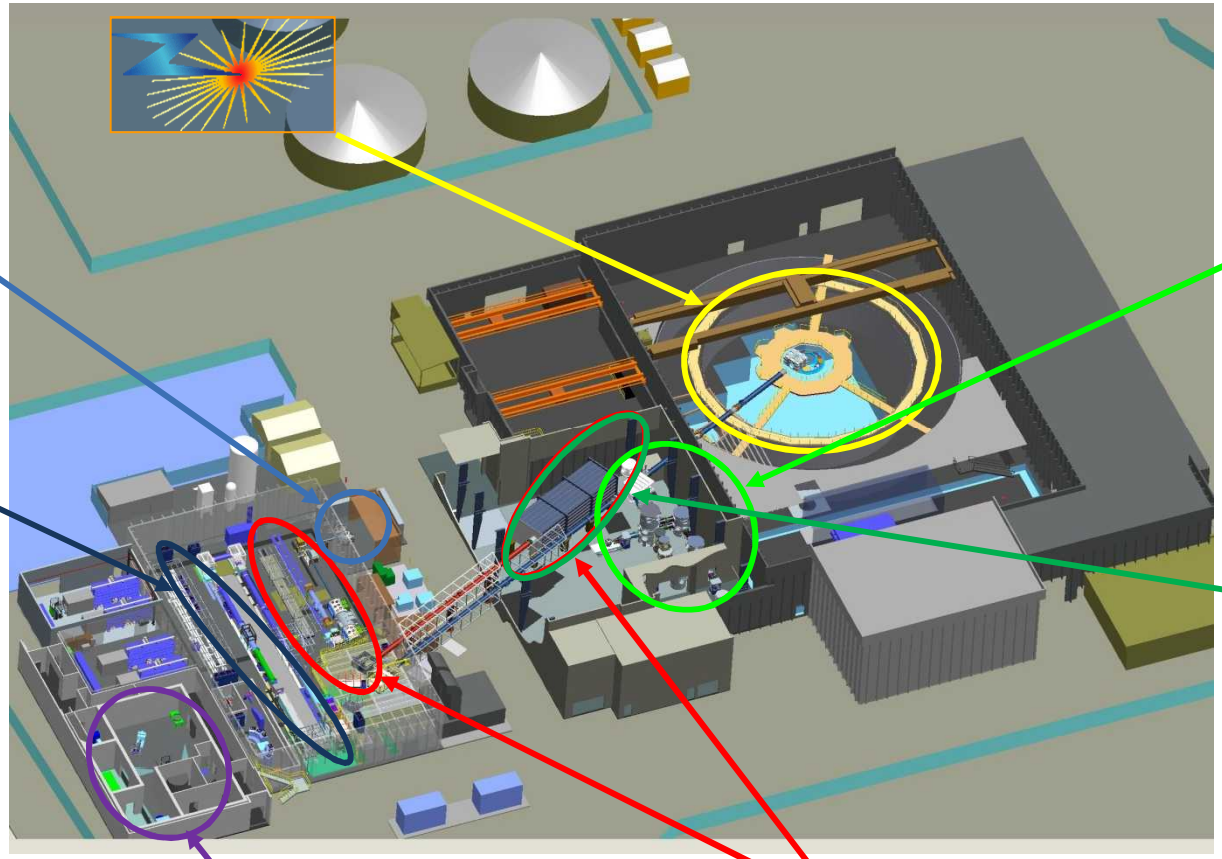
March 11th , 2016

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

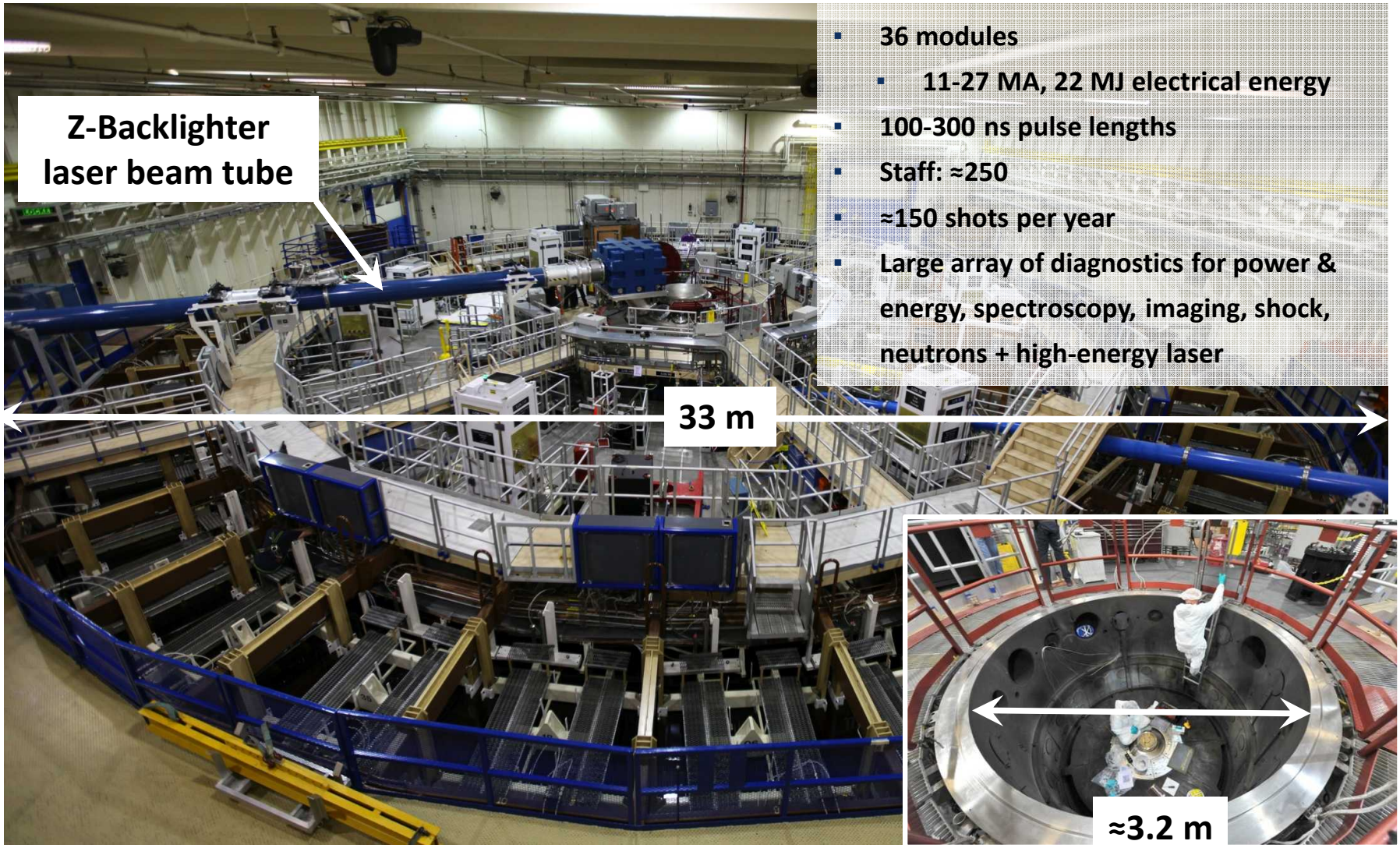
Outline

- Overview of Sandia's Pulsed Power Facility
  - The Z-Machine (very brief)
  - Z-Backlighter Facility
- The **M**agnetized **L**iner **I**nertial **F**usion (MagLIF) concept
- Recent Z-Beamlet and Z-Petawatt upgrades
  - Increase Z-Beamlet energy
  - Modify ZPW to operate in long pulse mode
- Optimize laser energy delivery MagLIF gas cell by:
    - Adding an appropriate pre-pulse
    - Employing beam smoothing via: phase-plates and adaptive optics
- Conclusion

Z-Pulsed Power Facility Overview



Z-Machine



- 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

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 – 10 ps	300 ps – 10 ns
typ. Spot size (µm FWHM)	75	6	20
E_{max} (J)	4000	100 (200TW) / 500 (ZPW)	50 (25)
I (W/cm^2)	~ 10^{17}	~10^{20}	~ 10^{16}
Shot Intervals (minutes)	180	180	20
'Special feature'	2 pulse MFB (two frame/2 color)	CPA probe beam (< 20 mJ)	8-10 ns option: 1ω and >100J (pending)

Z Beamlet

Z-Beamlet Laser (ZBL) Basics

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

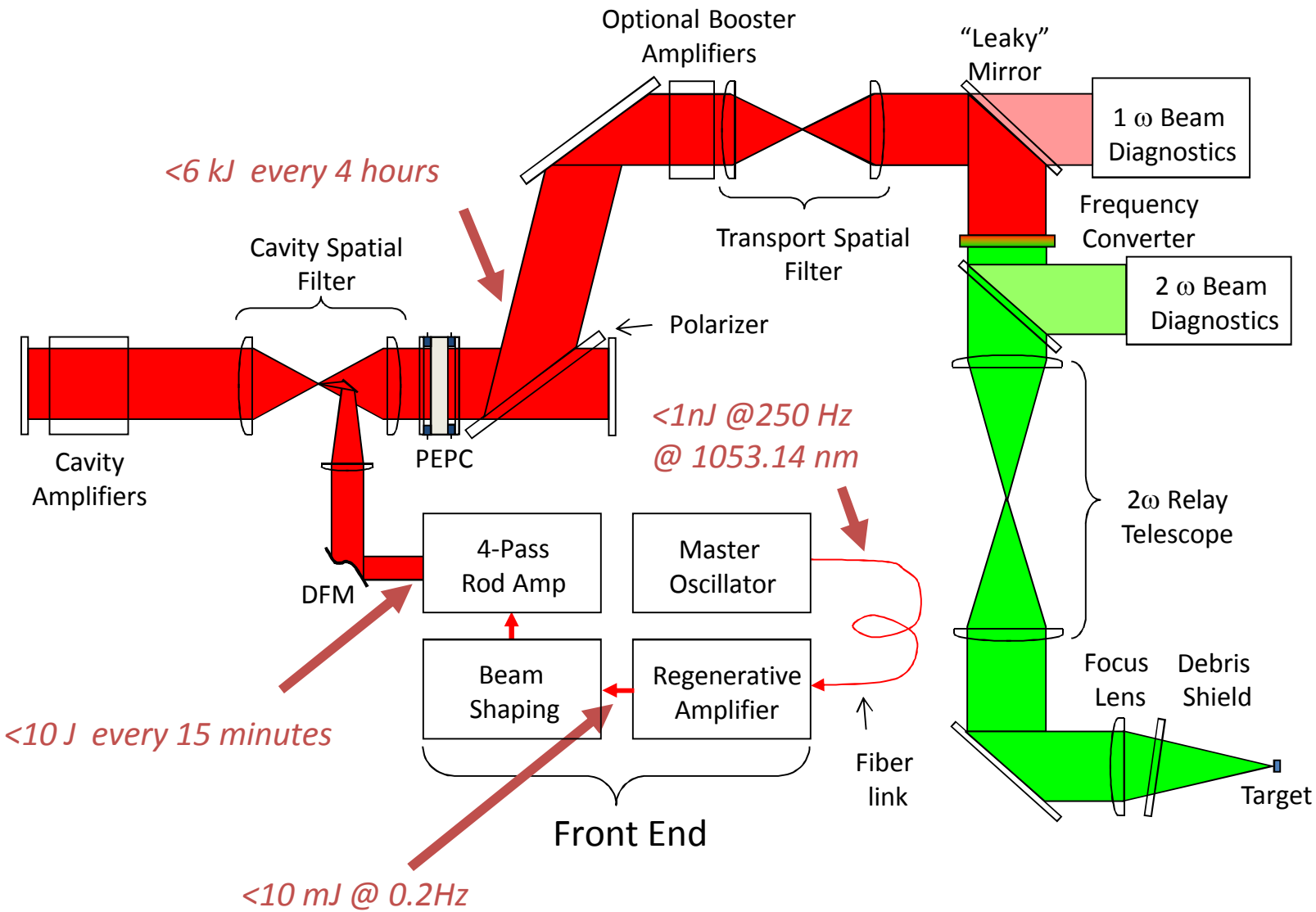
- Main uses:
  - Create x-ray source for backlighting
  - Preheat MagLIF fuel

- 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
  - $I \approx 10^{17}$ W/cm^2

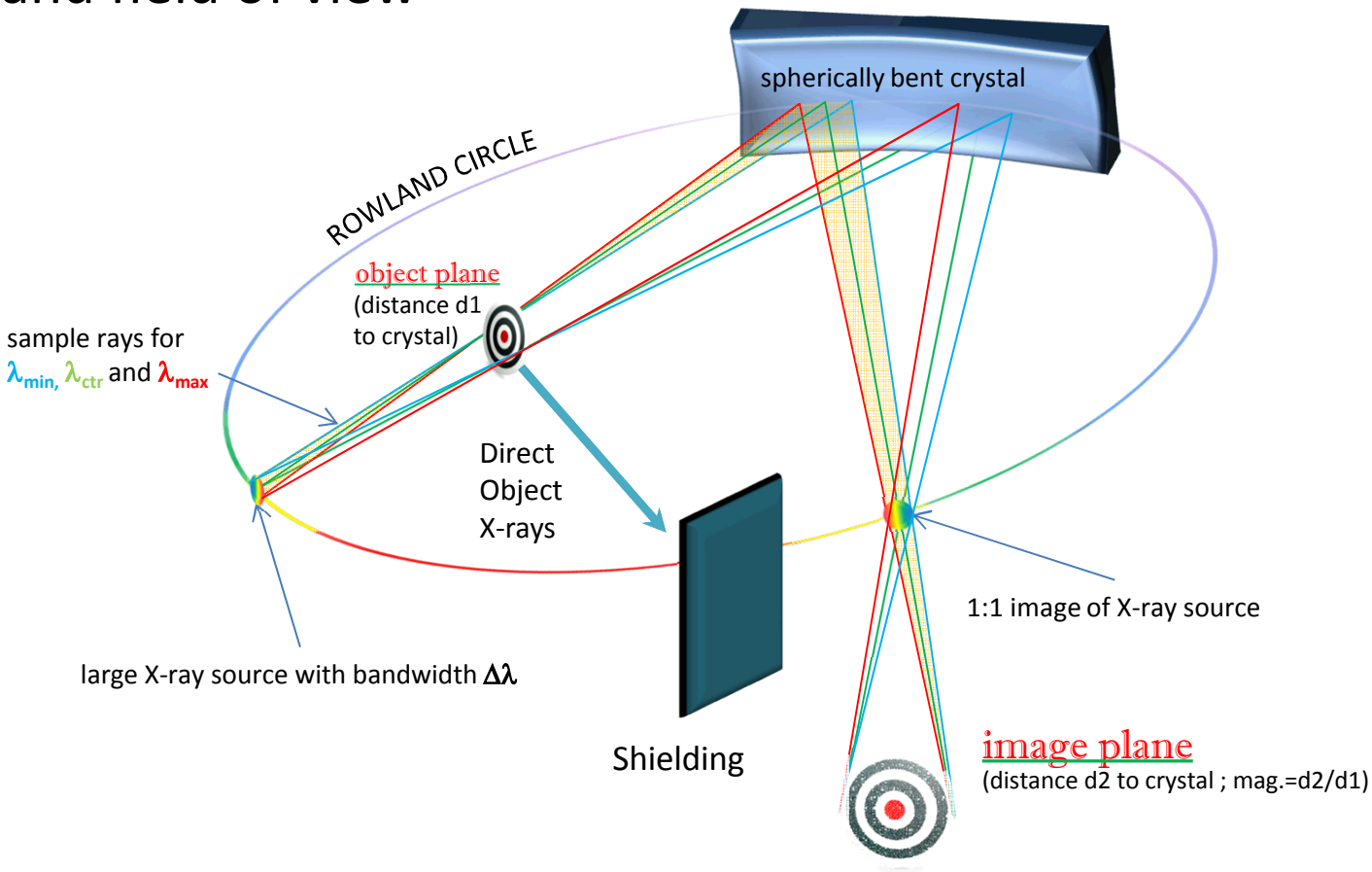
  - 4 target chambers + Z
  - Adaptive optics & phase modulation systems
  - Lens & phase plates for focusing
  - Arbitrary temporal shape, typ. 0.5 ns prepulse + 1-4 ns main

Z-Beamlet Laser Architecture

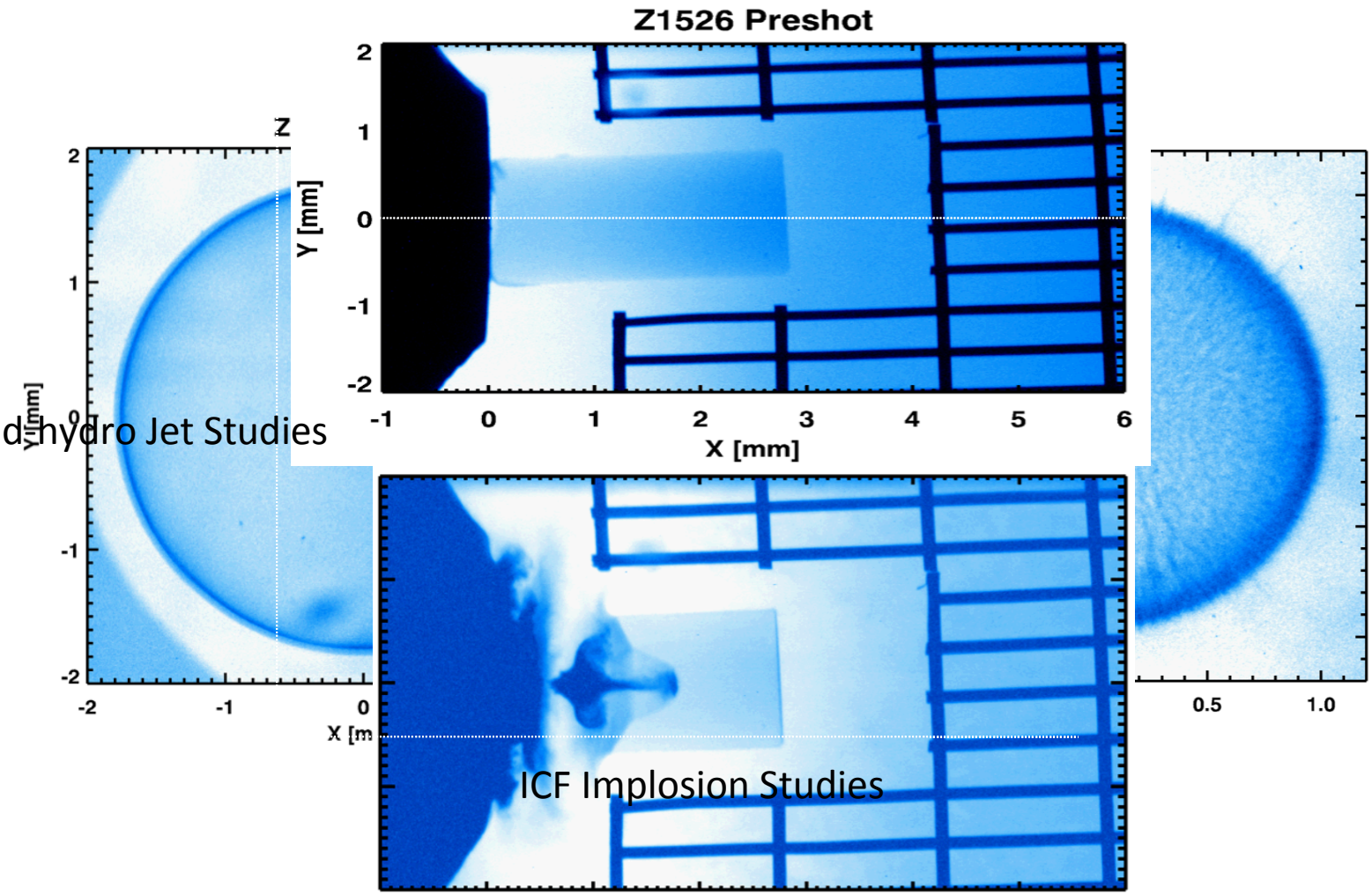


X-Ray Bent Crystal Imaging

- Bent crystal imaging improves monochromaticity, resolution, and field of view



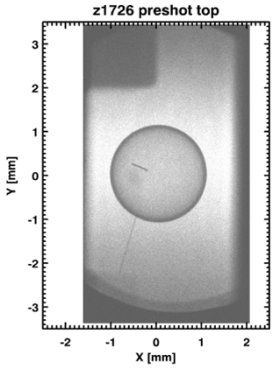
X-Ray Bent Crystal Imaging

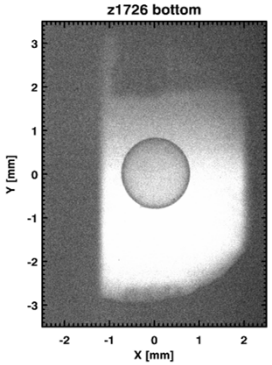


Radhydro Jet Studies

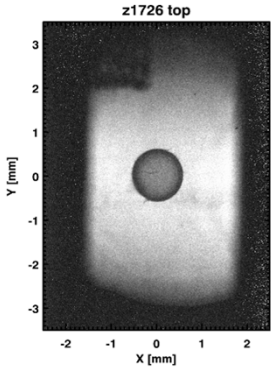
ICF Implosion Studies

2-Frame Imaging

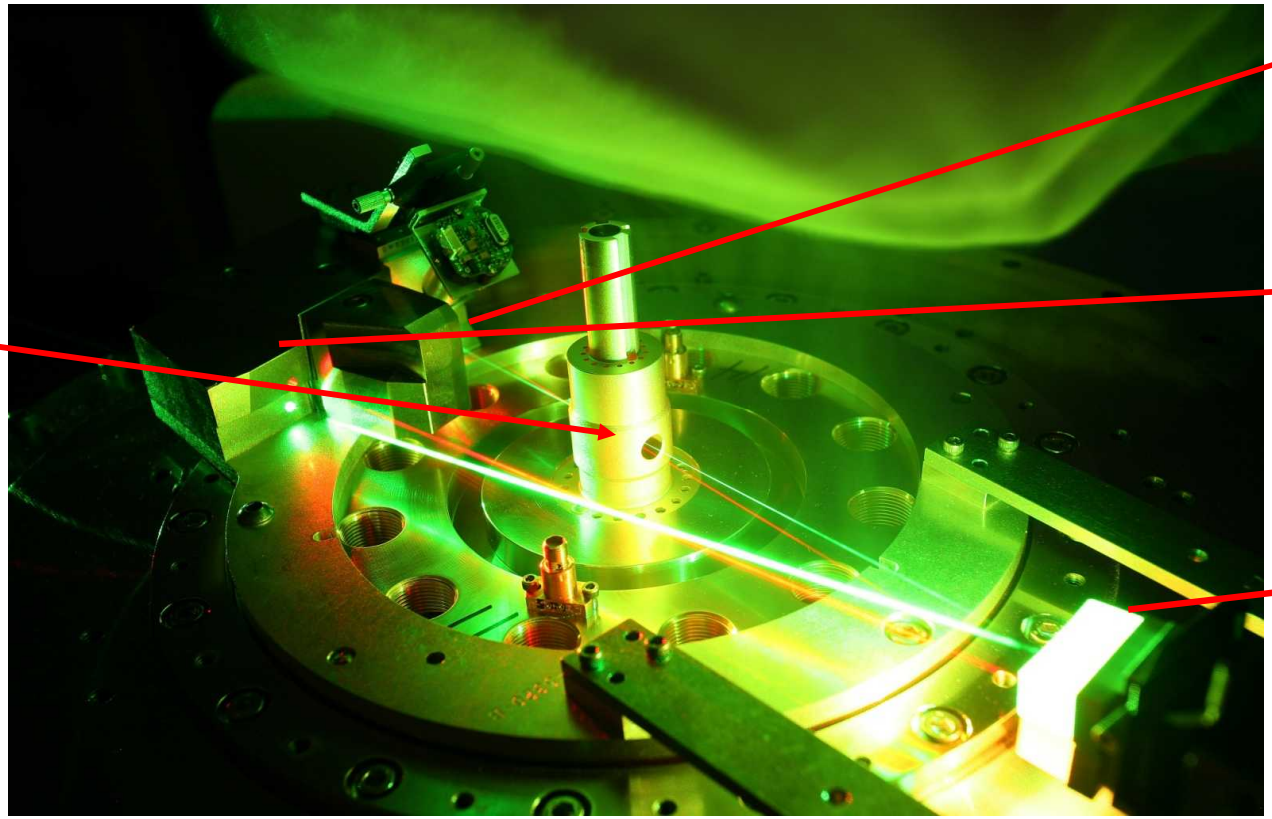




Δt=8ns



- **Using time delayed pulses and angular multiplexing, one can generate two radiographs for the same Z-shot with time delays up to 20ns.**



Sandia National Laboratories

Z Petawatt

Z-Petawatt Laser (ZPW) Basics

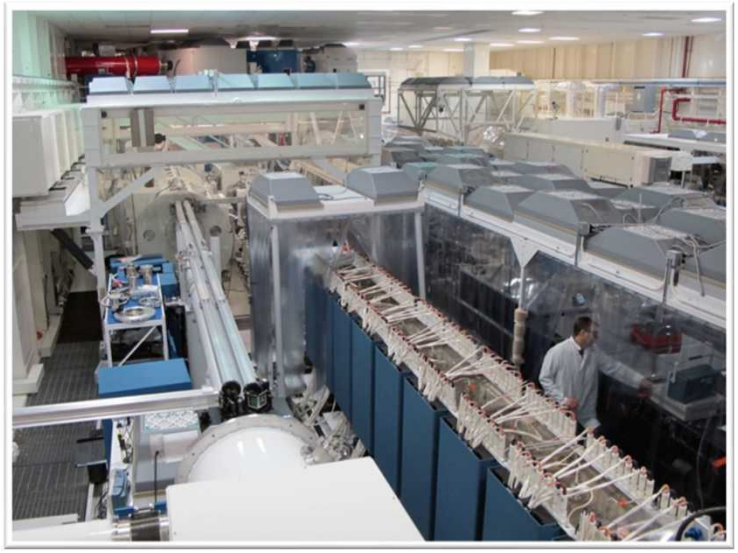
- Short-pulse, 1ω operation
  - High-field physics (particle acceleration/γ-rays)
  - Above-10 keV x-ray generation

- Long-pulse co-injection into ZBL and 2ω operation (pending)
  - Additional energy for ZBL pulse
  - Flexible prepulse for MagLIF/radiography

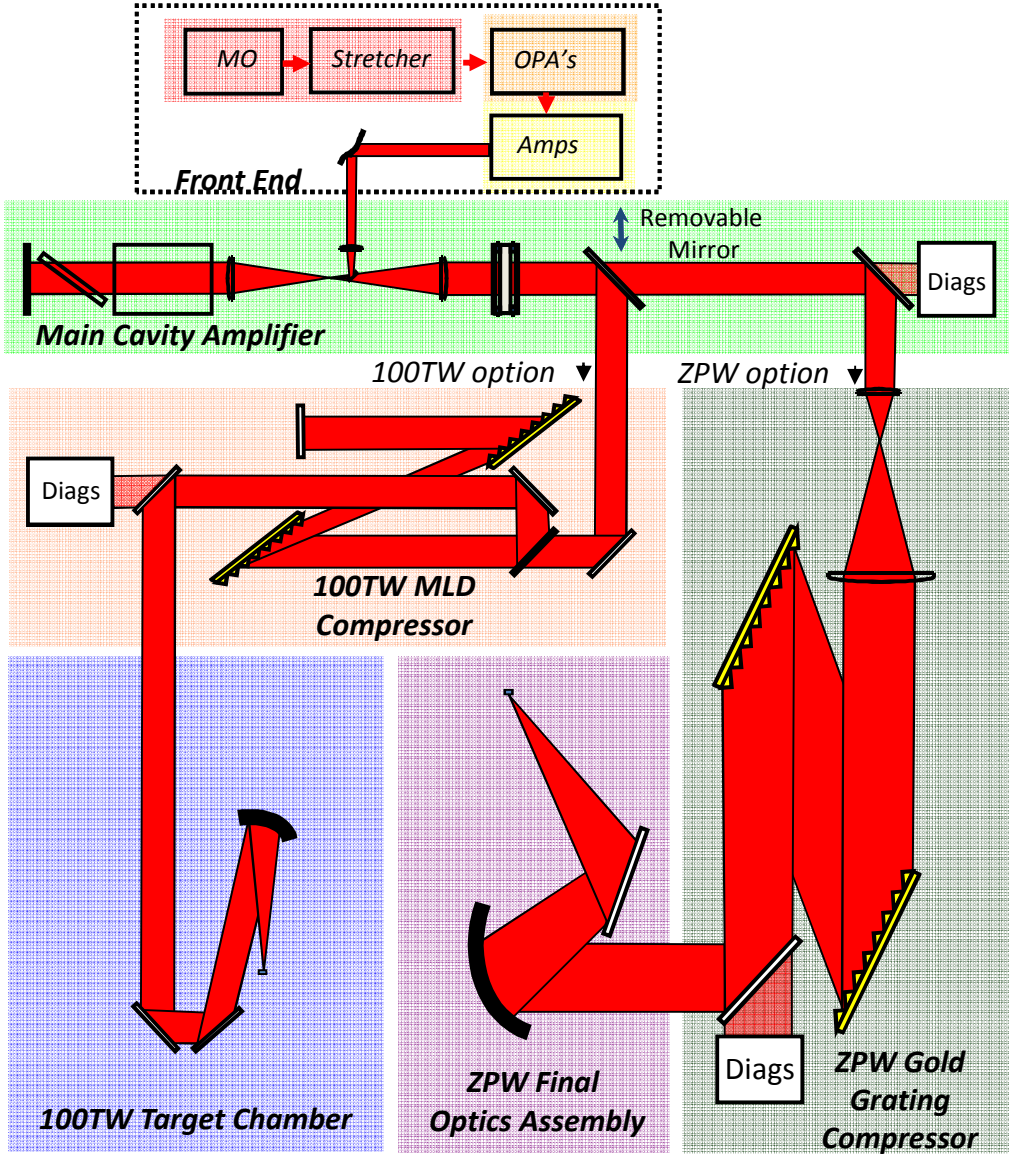
- Parameters:
  - Up to 500 J @ 1053nm, 500 fs, 43cm dia.
  - Up to 100 J @ 1053nm, 500 fs, 200 TW, 15cm dia.
  - Up to 400 J @ 527nm, 2 ns, 15cm dia.

  - 3 shots per day
  - Pulse length: 0.5 - 100 ps @ 1ω, 2 ns @ 2ω
  - $I = 2 \times 10^{20}$ W/cm^2 @ 1ω short pulse

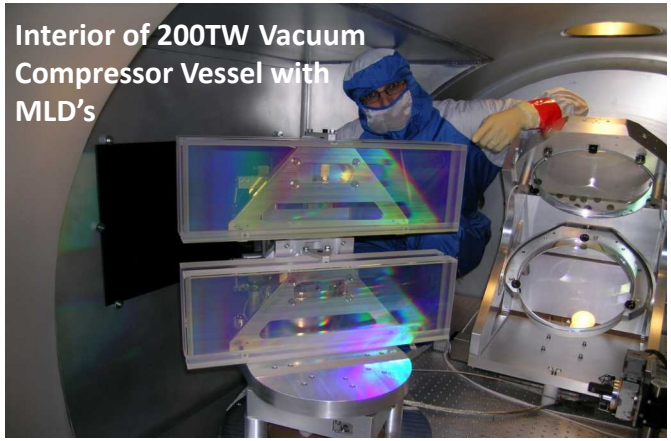
  - 2 target chambers + Z
  - Off-axis parabola or lens focusing
  - Full-aperture upgrade on-going: 2 kJ, 27 x 31 cm^2

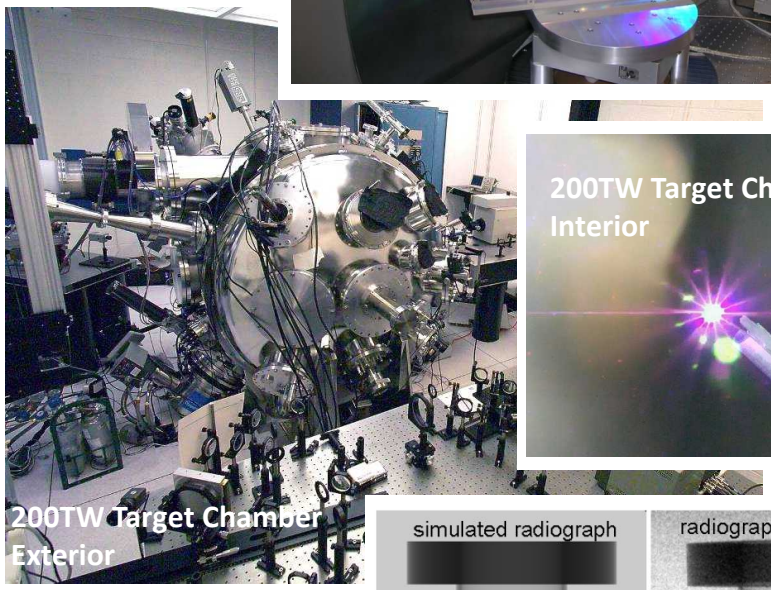


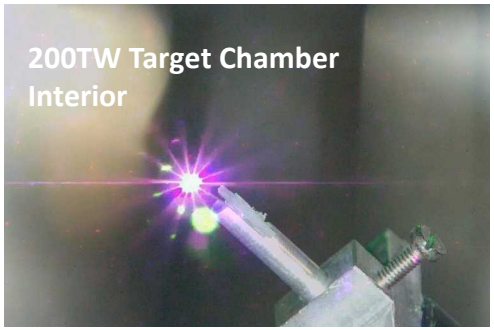
Z-Petawatt Basic Architecture

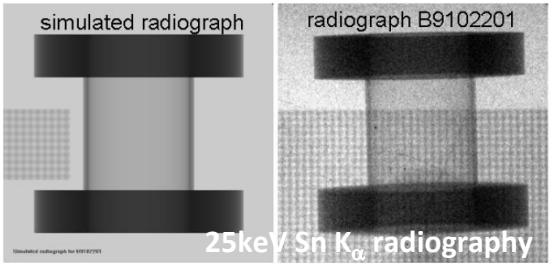


200TW Operation









- A smaller beam can be used to operate at the 200TW level using MLD gratings for temporal compression.
- A dedicated target chamber is used for stand alone experiments such as:
  - Proton beam generation
  - Bent crystal imaging development
  - Laser beam characterization
  - Novel high energy x-ray sources
- Diagnostics include:
  - X-ray pinhole camera
  - X-ray and optical streak camera
  - X-ray and optical spectrometers
  - Thomson parabola
  - Image Plate, RCF, and CR39 detectors
  - Single photon counting CCD's

Chaco

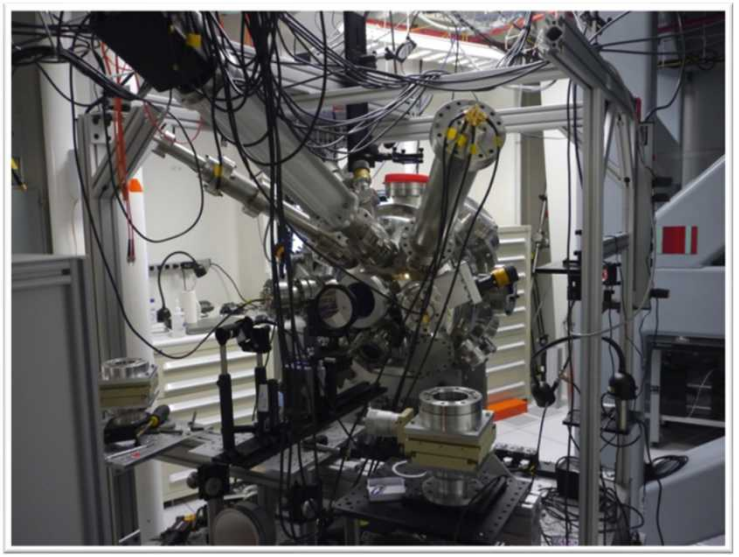
Chaco Laser Basics

- 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

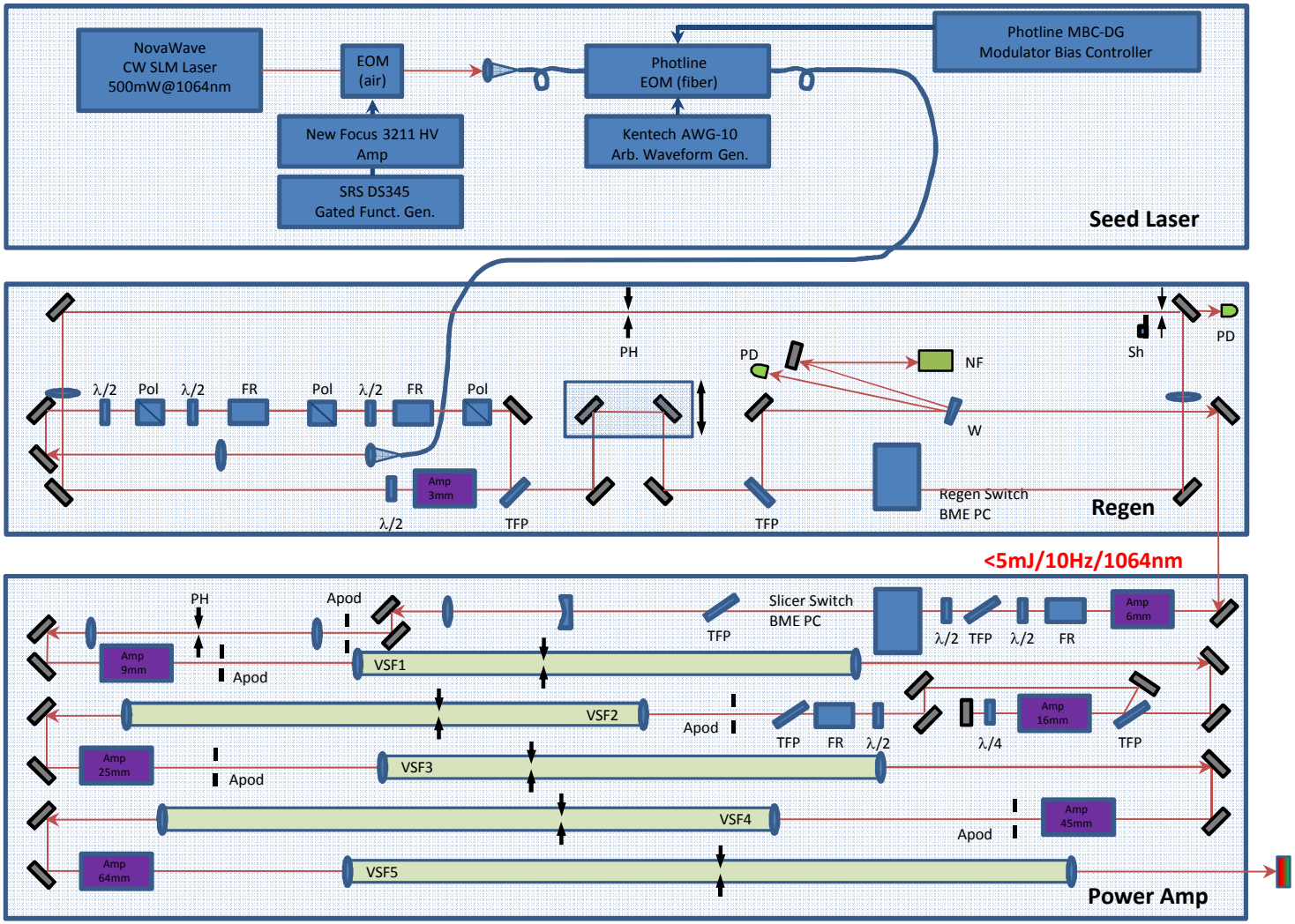
- Parameters:
  - Up to 100 J @ 1064nm, 10 ns, 50 mm diameter
  - Up to 10 J @ 532nm, 0.3 ns, 50 mm diameter

  - 10-minute repetition rate
  - Pulse length: 0.3 - 10 ns
  - $I = 10^{16}$ W/cm^2

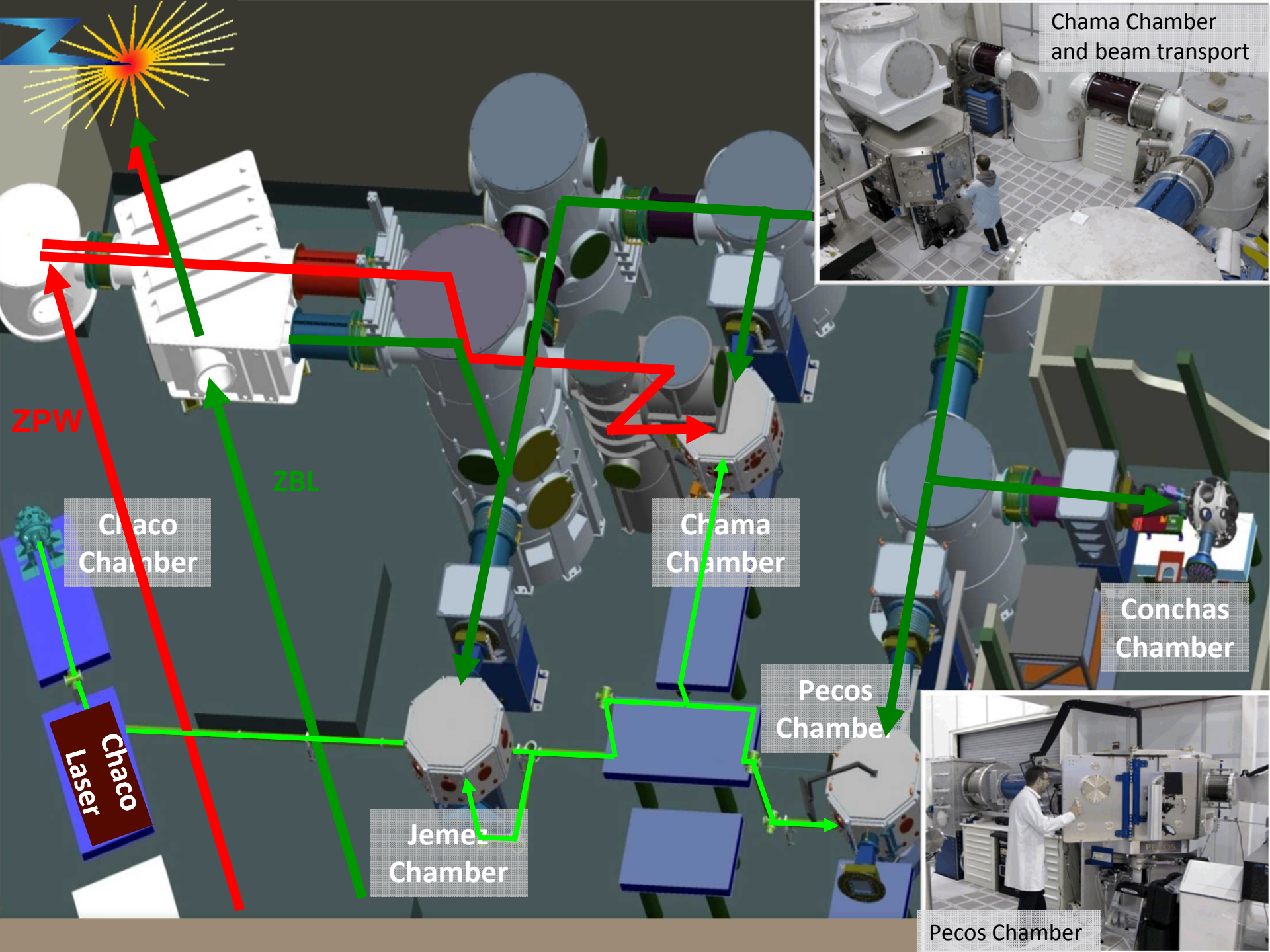
  - 3 target chambers + dedicated target chamber for development of ultrafast x-ray imager camera
  - Arbitrary temporal shape



Chaco Laser Architecture

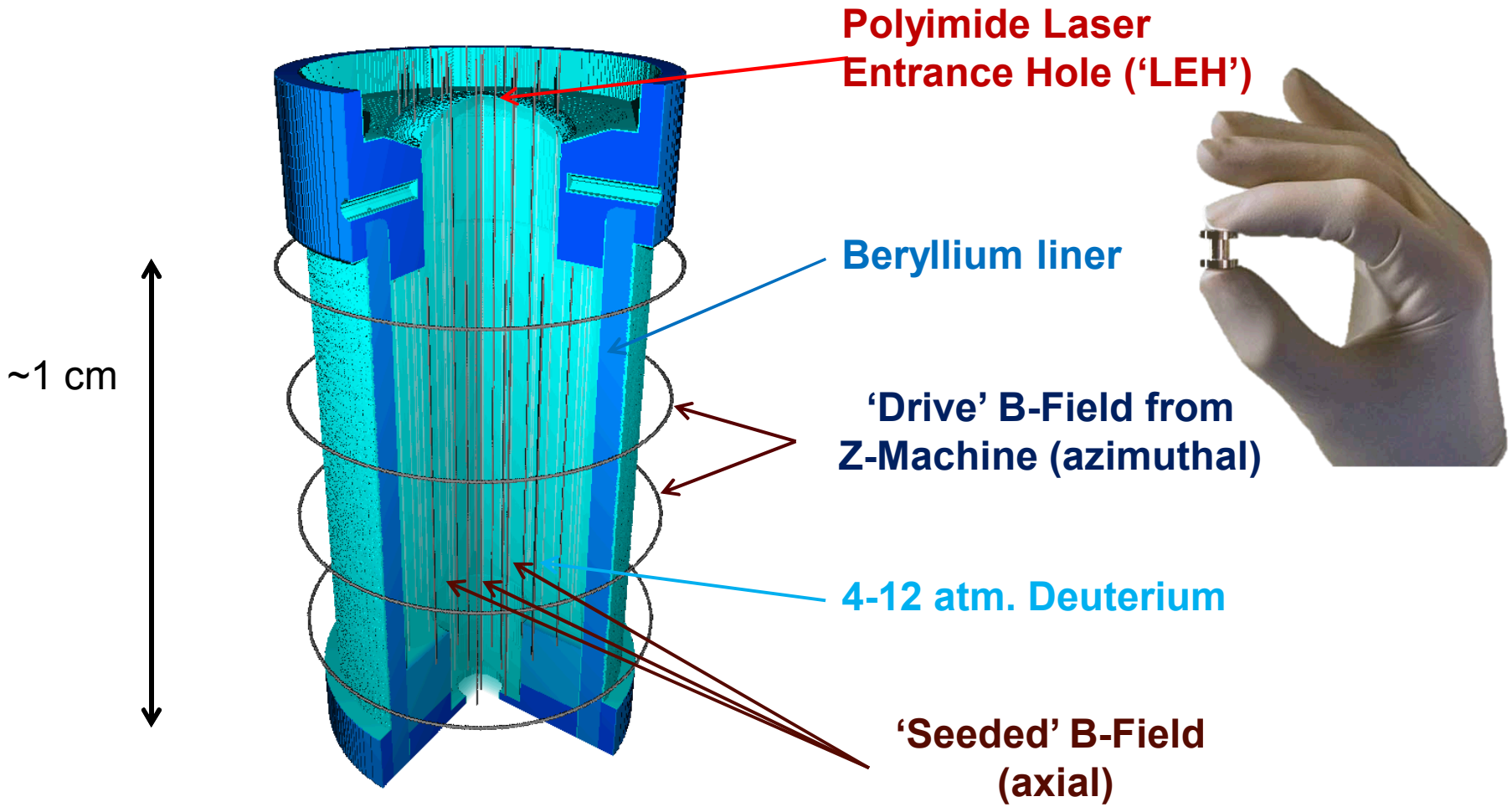


Target Bay

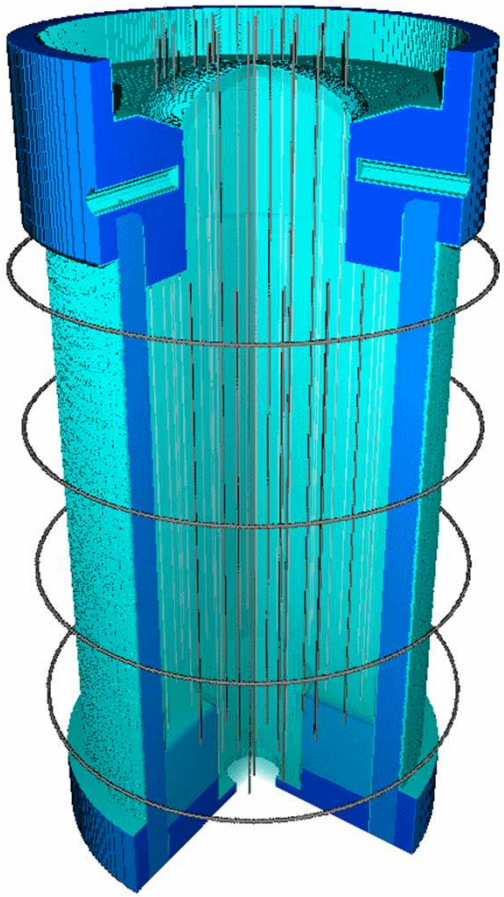

Chama Chamber
and beam transport
ZPW
ZBL
Chaco
Chamber
Chama
Chamber
Conchas
Chamber
Pecos
Chamber
Chaco
Laser
Jemez
Chamber
Pecos Chamber

MagLIF

Magnetized Liner Inertial Fusion

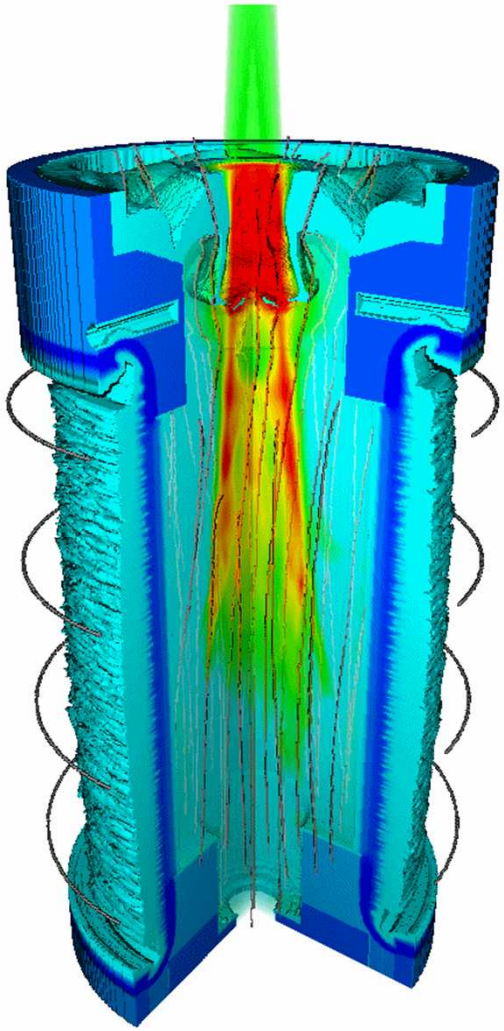


Magnetized Liner Inertial Fusion

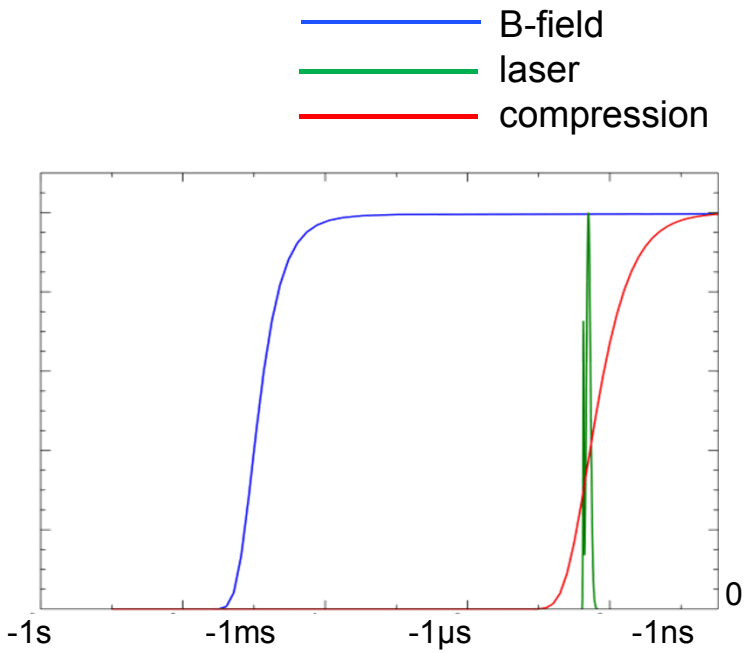


- B-Field from Z machine drive current starts to compress the Be lines and fuel
- Z-Beamlet injects several kJ of energy at 527nm into fuel
  - Magnetization of fuel
  - Minimizes heat conduction losses
  - B-Field compression
  - Stagnation temperature is proportional to initial temperature

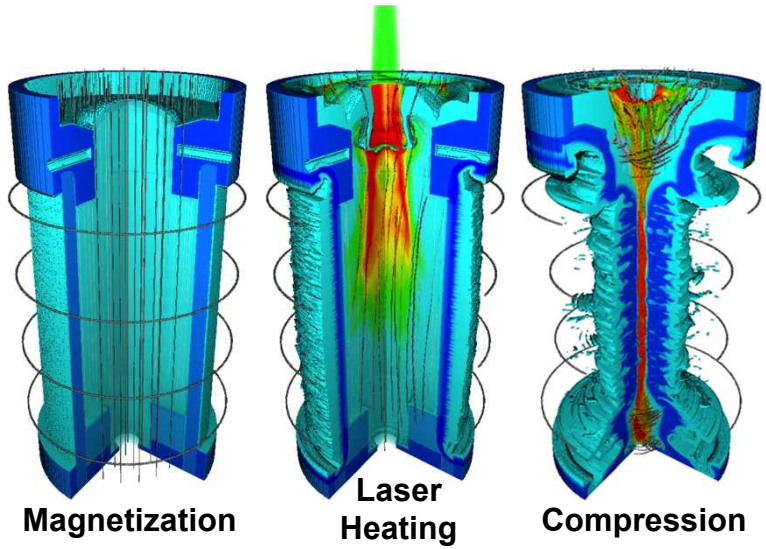
Magnetized Liner Inertial Fusion

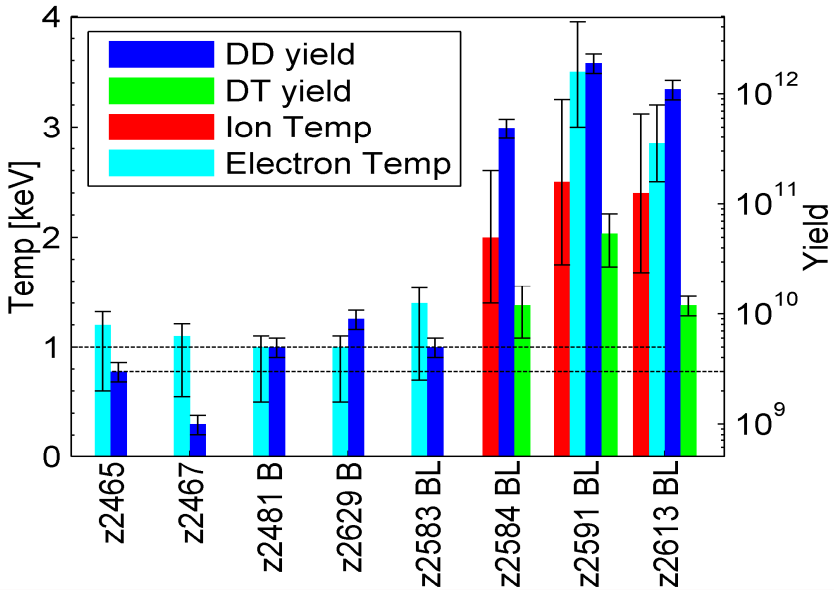


- Fuel compresses to densities and temperatures enabling thermonuclear fusion



Magnetized Liner Inertial Fusion





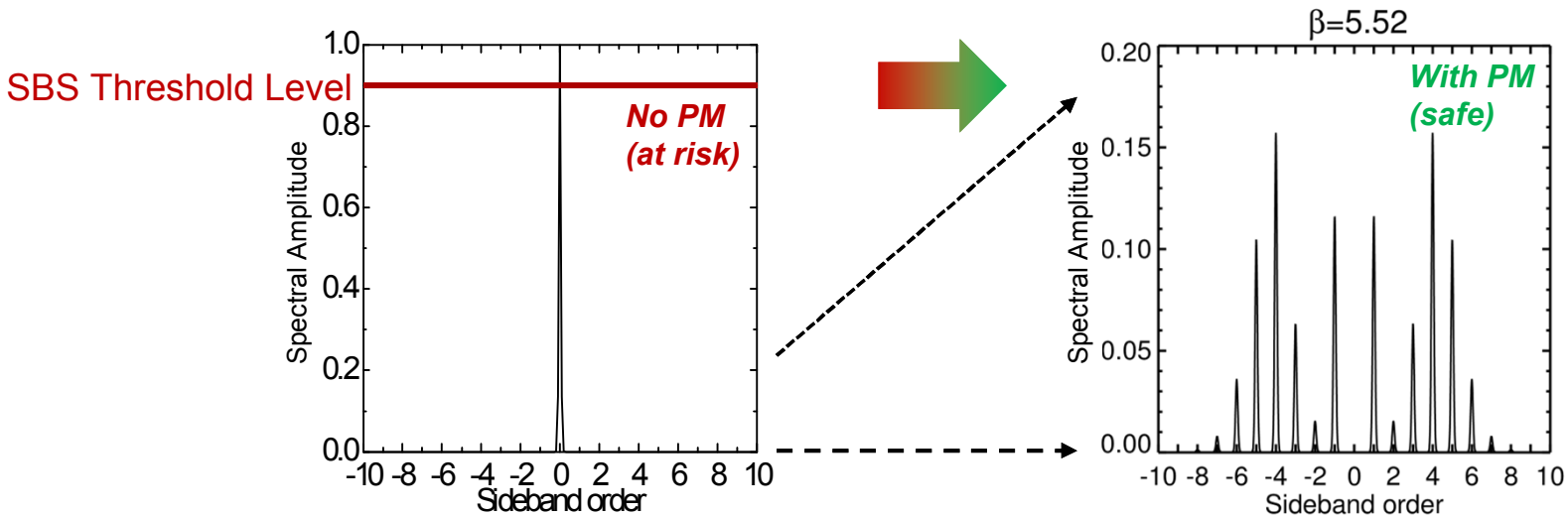
- Point Design:
  - 30 Tesla initial magnetic field
  - Laser heating of ~3 mg/cm^3 D_2 fuel produces ~250 eV plasma
  - Thick (AR=6) Be liner with R_0=2.7 mm, peak velocity ~100 km/s for a 27 MA peak current drive
  - At stagnation the fuel absorbs 120 kJ, reaches 8 keV and ~0.5 g/cm^3, and is highly magnetized at 13500 Tesla
  - Yields >100 kJ predicted in 2D

S. Slutz et al.: Physics of Plasmas **17**, 056303 (2010)

Upgrades Prompted by MagLIF

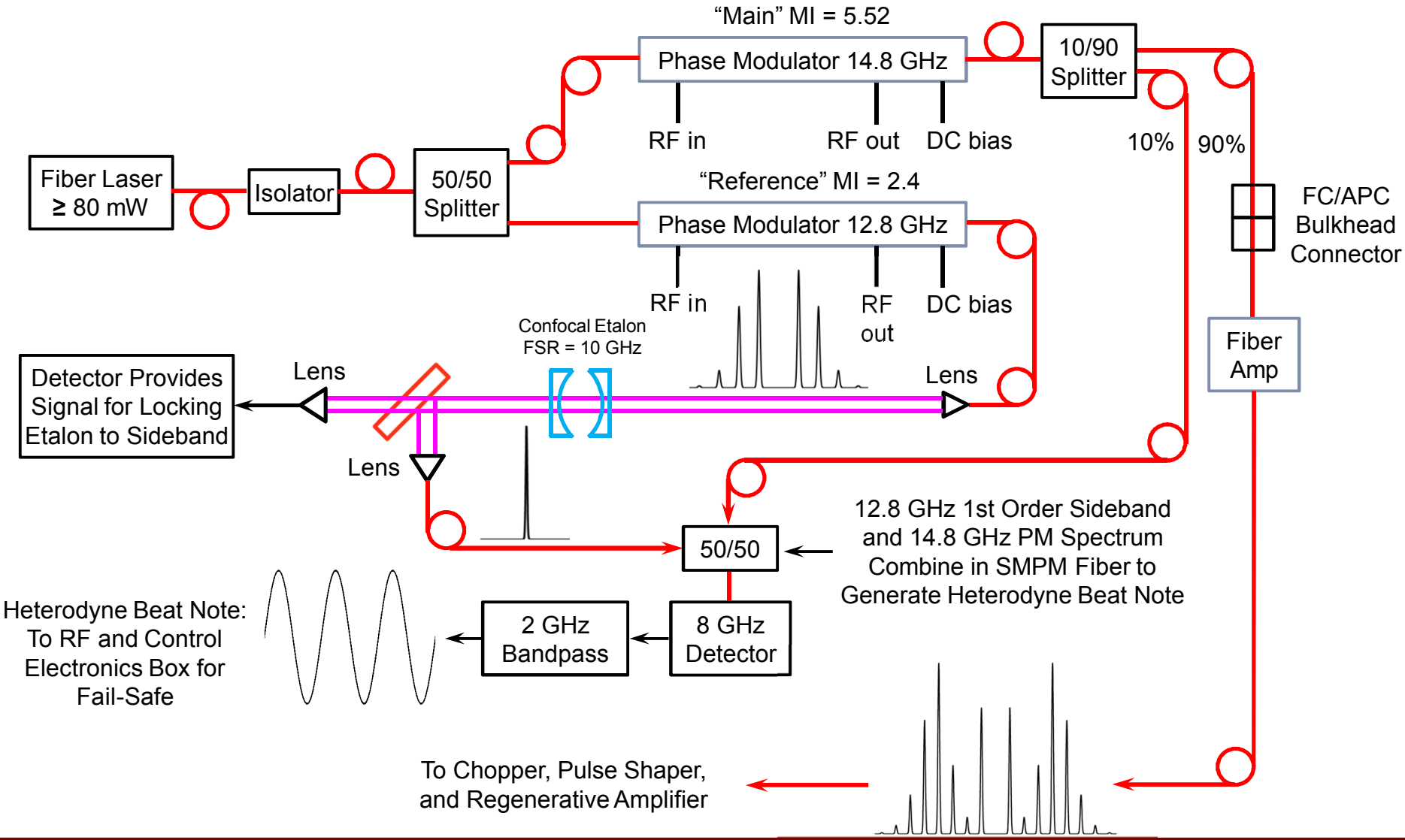
Backlighter Driver: SBS suppression

- High intensity laser beams generate acoustic waves in a large aperture medium so that the waves can amplify, leading to optical scattering, energy instability, and optical damage.
  - Estimated SBS threshold for a desired 4ns FWHM pulse: 5.2kJ
- Adding spectral sidebands is needed for SBS suppression



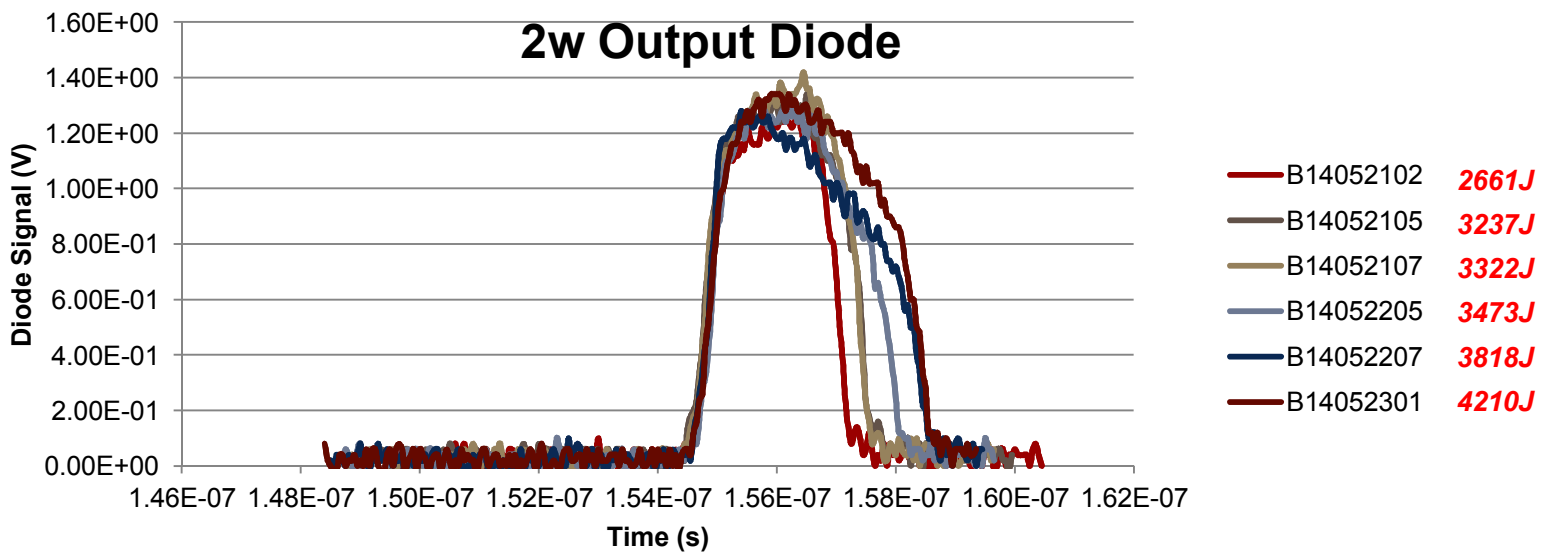
J. Murray *et.al*, J. Opt. Soc. Am. B **6**, 2402-2411 (1989)

Design for PM and Heterodyne



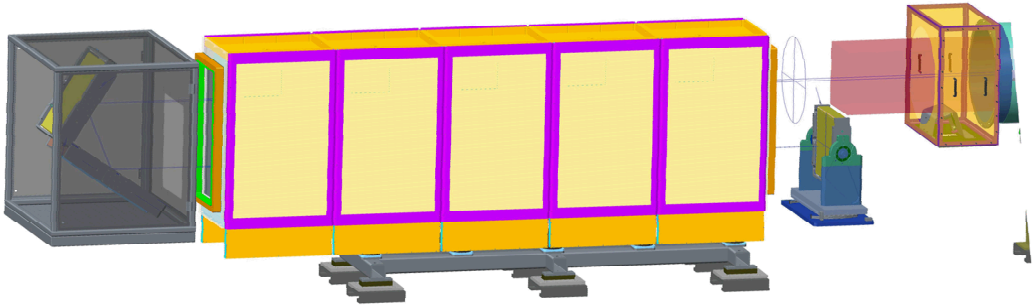
SBS suppression: Results

- Achieved FM->AM compensation in fiber transport and regen by installing a grating compressor and a BRF
- Tested PM failsafe system
- Demonstrated 5.6/4.2kJ at 1ω/2ω with 3.6ns pulsewidth



Adding Boosters for Z-Beamlet

- SBS suppression allows up to 5 booster amplifiers, each adding about 500J of stored energy (11+5)*500J=8kJ at 1054nm
  - Maximum extractable energy: 6 kJ at 527nm
- One booster was activated this last year using spare circuits
- Further booster activation would require a modification of the PW amplifiers in order to free up pulsed power circuits.

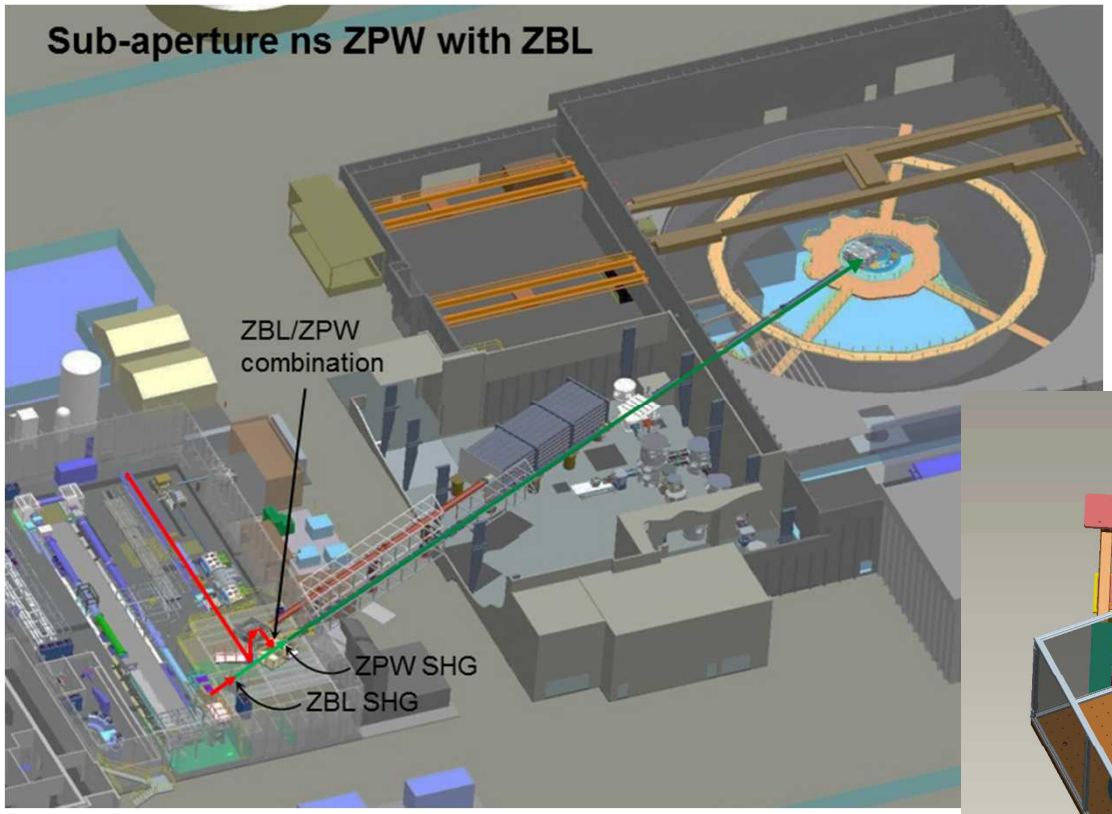


Z-Petawatt in long pulse mode

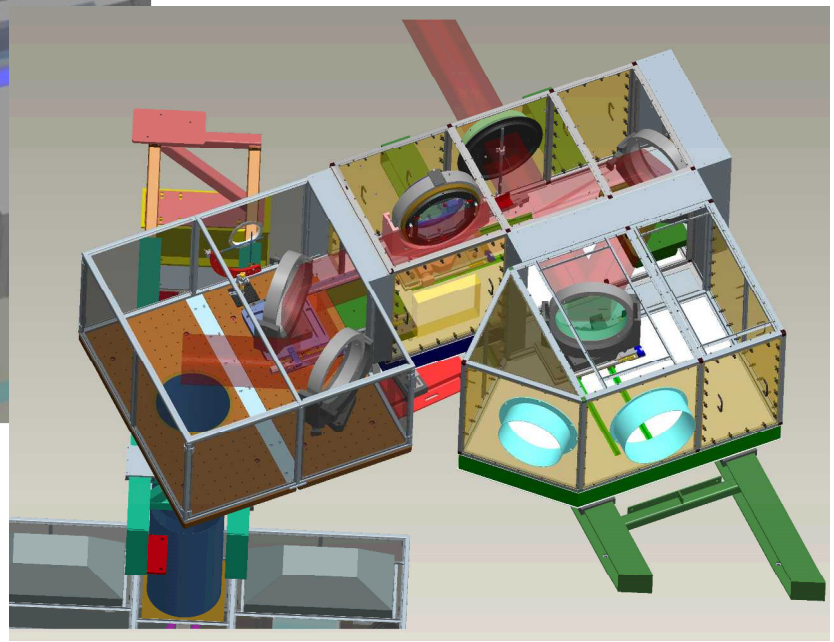
- Co-injecting and co-boring ZPW with ZBL is motivated by:
  - The need for more energy for MagLIF experiments, either for:
    - Overall energy increase for target pre-heating,
    - Removal of the laser entry hole (LEH) window, or
    - Possibly backlighting of MagLIF experiments.

- For LEH removal, ZPW would operate in long pulse mode and act as a ZBL pre-pulse with arbitrary time delays.
  - This will allow enough time for hydrodynamic evolution in the ablated LEH window so that the ZBL main beam:
    - “Sees” a low density beam and hence less beam distortion, and
    - Transmits a larger fraction of the main pulse as a result.

ZPW-ZBL co-injection scheme



- Projected 2ω energy:
  - 500 J at sub-aperture this CY
  - 3 kJ at Full aperture (years)

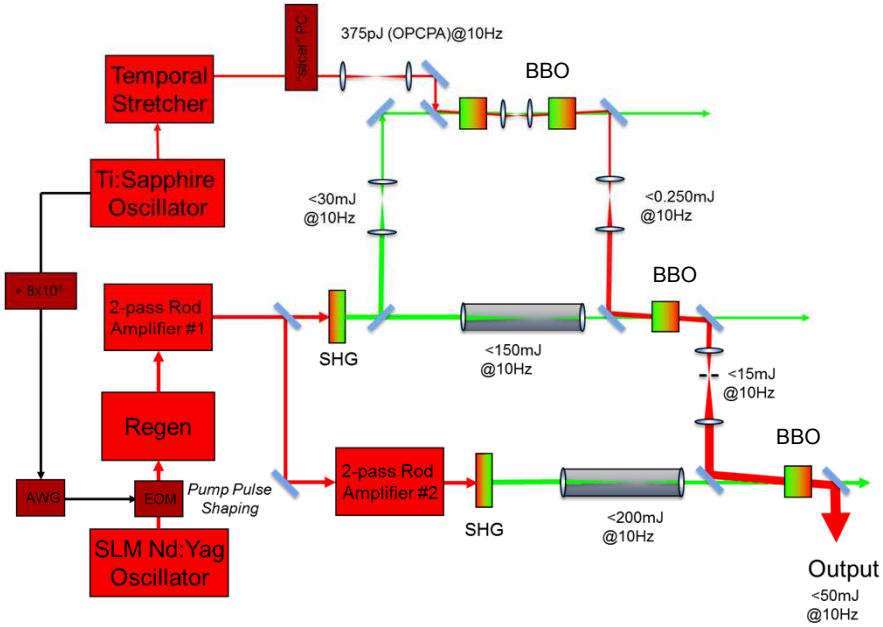


- Requires SLM laser due to gain narrowing constraints
- Additional rod amplifiers are needed for full aperture, kJ operation.

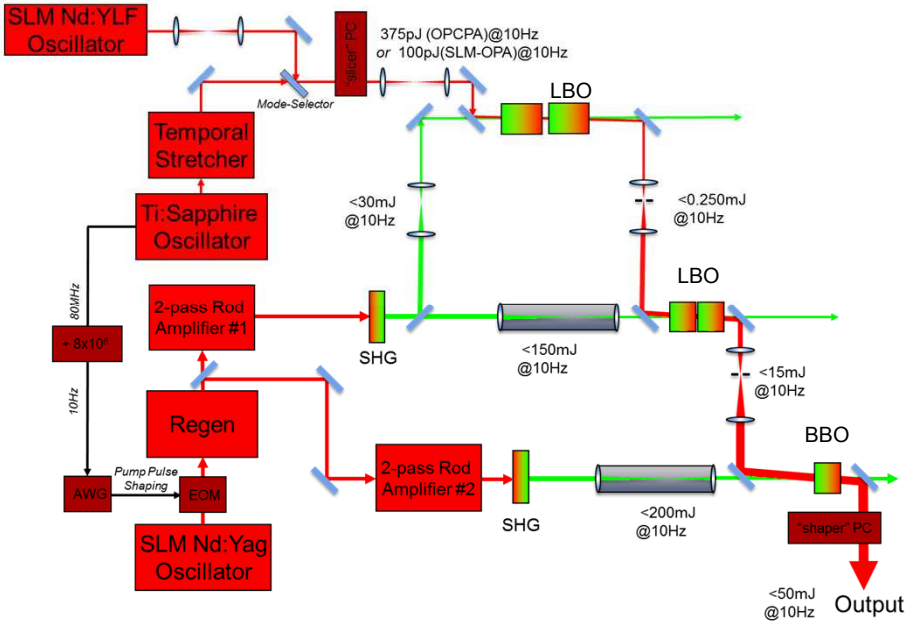
OPCPA changes required

- Old/New schematic for CPA operation
  - Improved spectral bandwidth, energy and pointing stability
  - Less laser damage, higher temporal/spectral control

Old

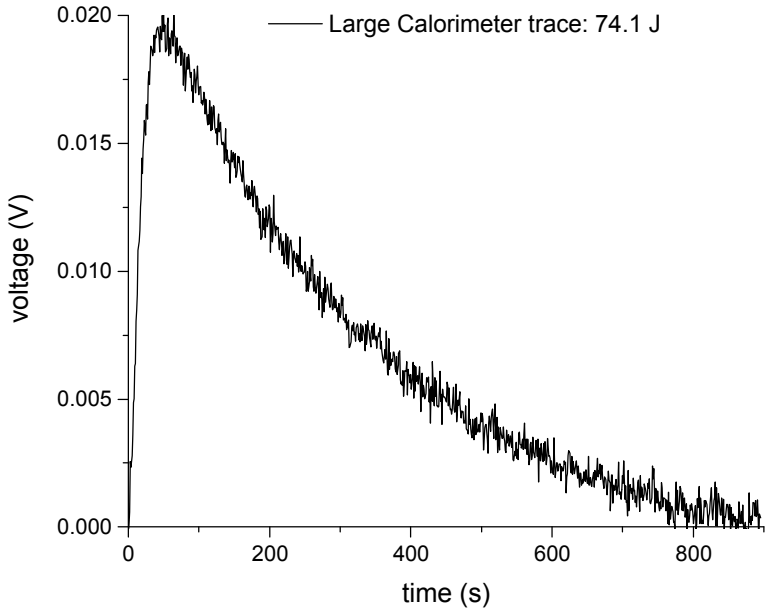


New



First long-pulse results

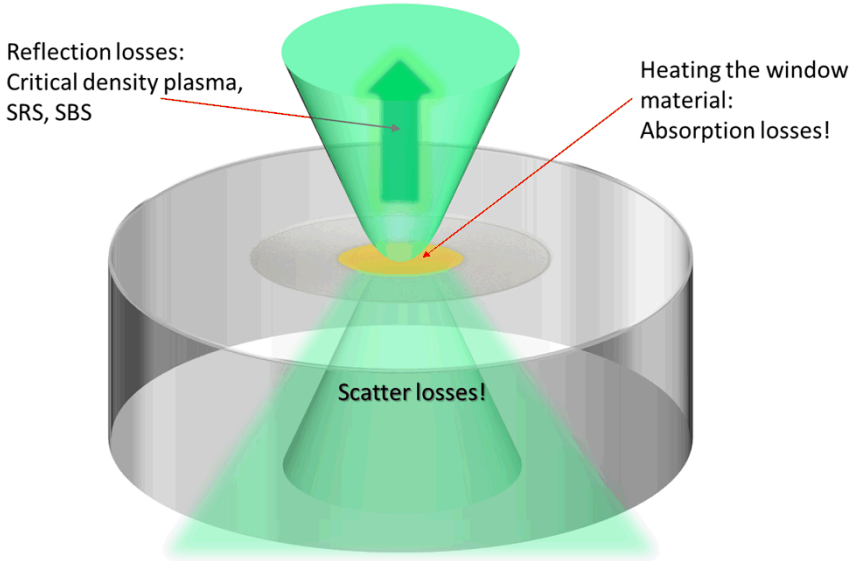
- Using the new SLM seed source, early gain tests show a double pass main amplifier gain of 120x.
- Still working on spatio/temporal pulse shaping to pre-compensate gain-distortions (see other talk).
  - Spatial pre-compensation with laser machined apodizers
  - Temporal pre-compensation with Pockels cells



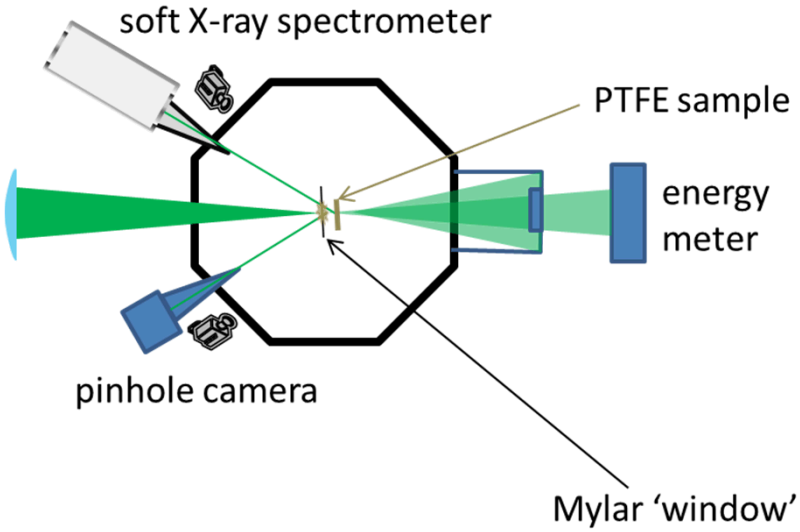
Beam Quality Improvements

Optimizing energy into gas cell

- High gas fill pressures require 'very thick' windows (e.g. >3 µm for 180 psig). How can we facilitate burning through the foil?
- LPI such as SRS, SBS, TPD… are very complex and are heavily dependent on beam quality at the window.



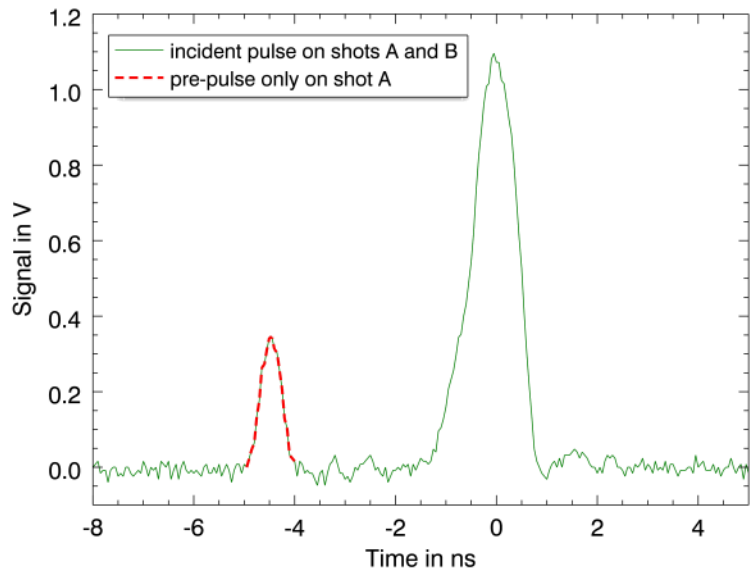
Schematic of basic LPI at capsule window

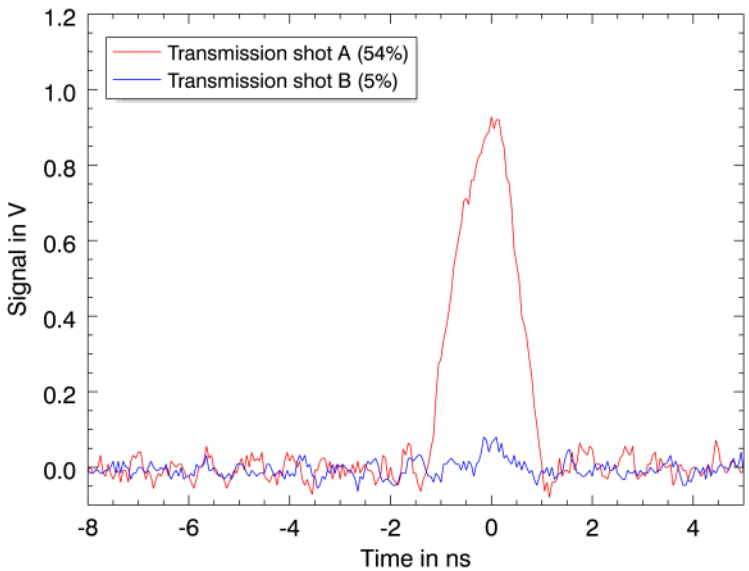


Experiment to study LPI at capsule window

LEH transmission vs. pre-pulse

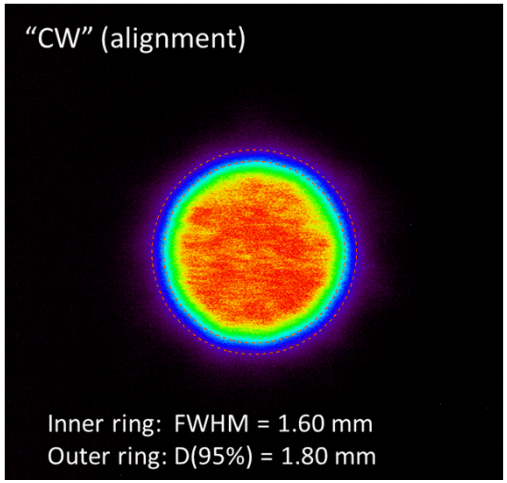
- Laser: 1.5kJ main pulse, 300J pre-pulse
  - Best results for pre-pulse>200J; minimal improvement >500J
- Pre-pulse delay limited by AWG, regen round-trip and pinhole closure time to < 5ns
- Co-injected Petawatt beam will allow for arbitrary delay!

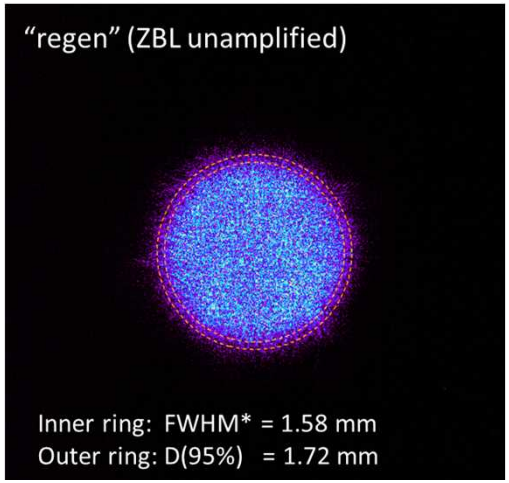


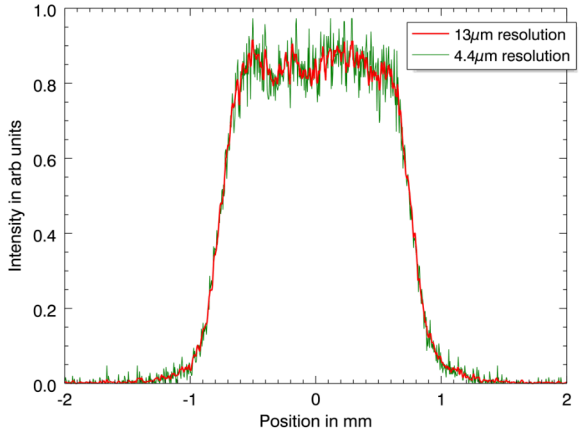


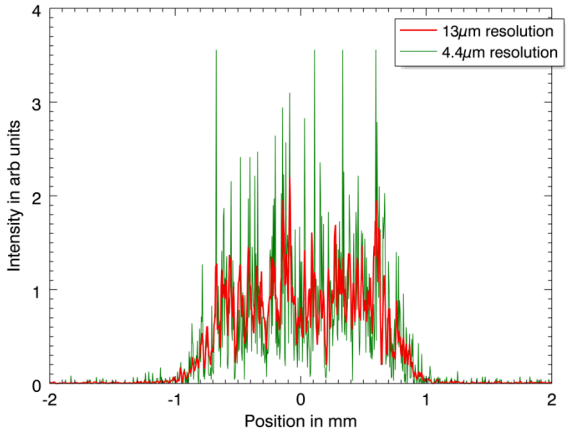
Beam smoothing: Phase-plate

- LLE phase-plate loaner optimized for 1.8mm diameter focus



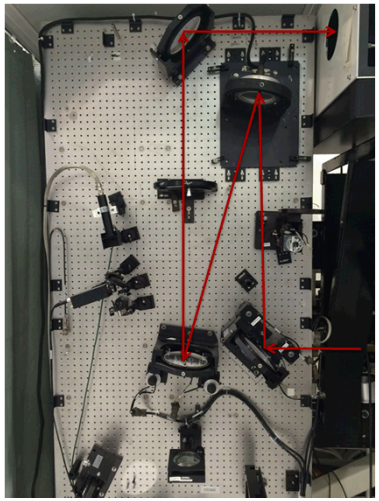






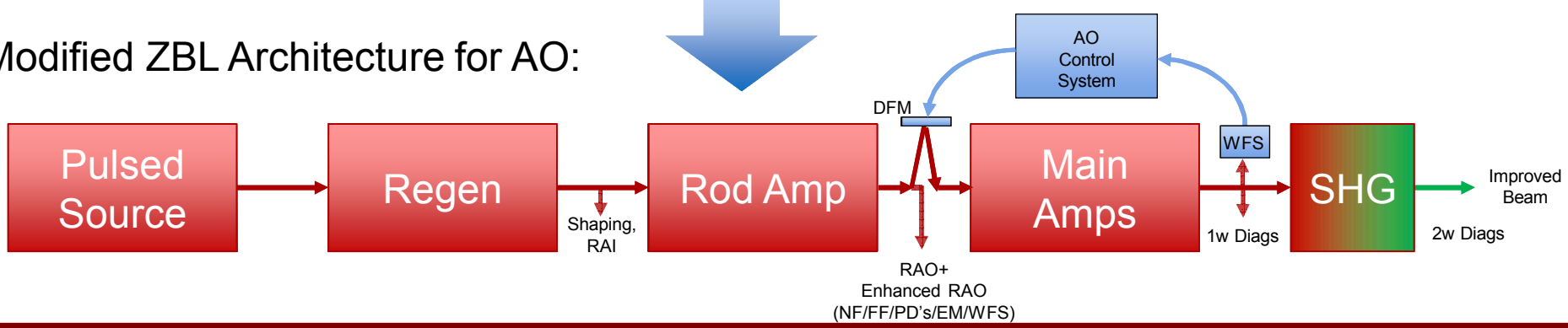
Adaptive Optics (AO) on Z-Beamlet

- We use a commercial adaptive optics package
  - SID4 wavefront sensor from Phasics in conjunction with NightN bi-morph mirror



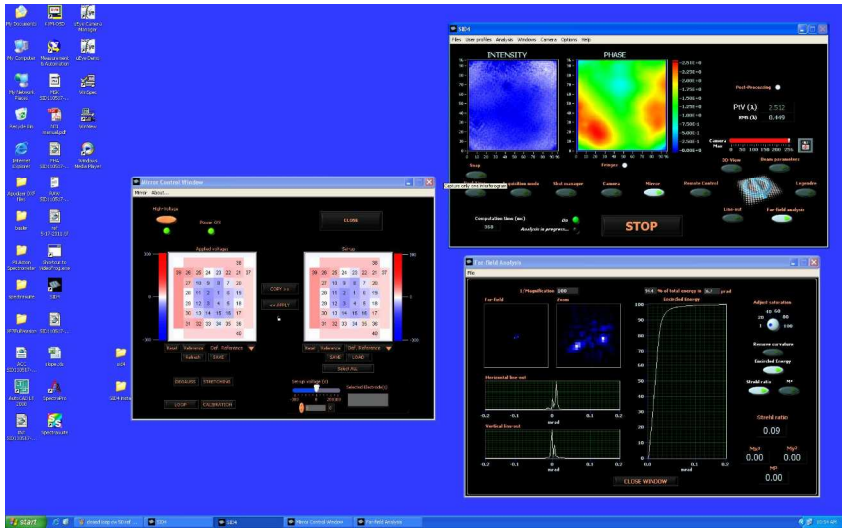
Existing ZBL Architecture:

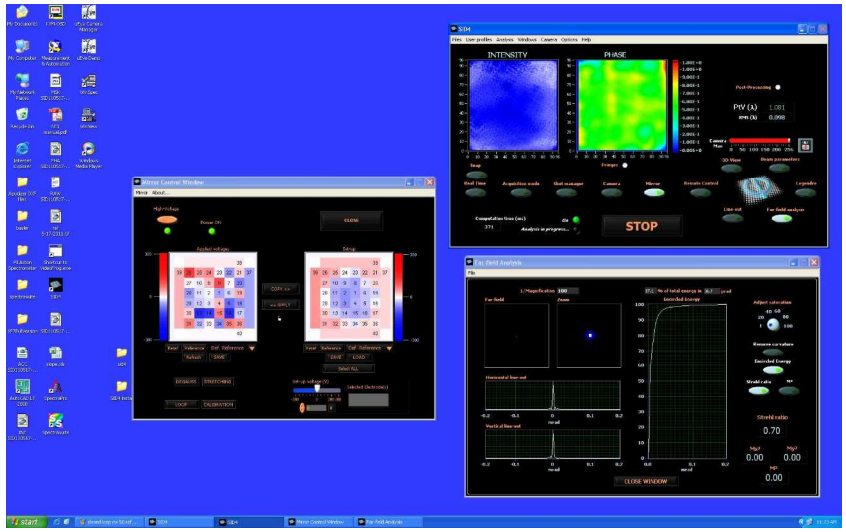
Modified ZBL Architecture for AO:



AO: Correcting static aberrations

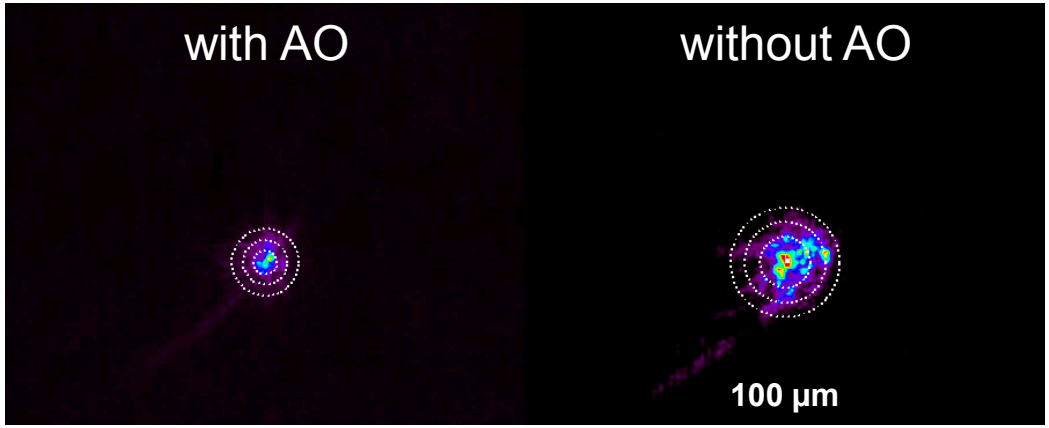
- Static aberrations were previously significant due to a faulty large waveplate (since replaced):
  - PV: 2.5 waves, RMS: 0.45 waves, Strehl: 0.09
- When closing the loop with a cw alignment beam, we achieve:
  - PV: 1.1 wave, RMS: 0.1 wave, Strehl: 0.70

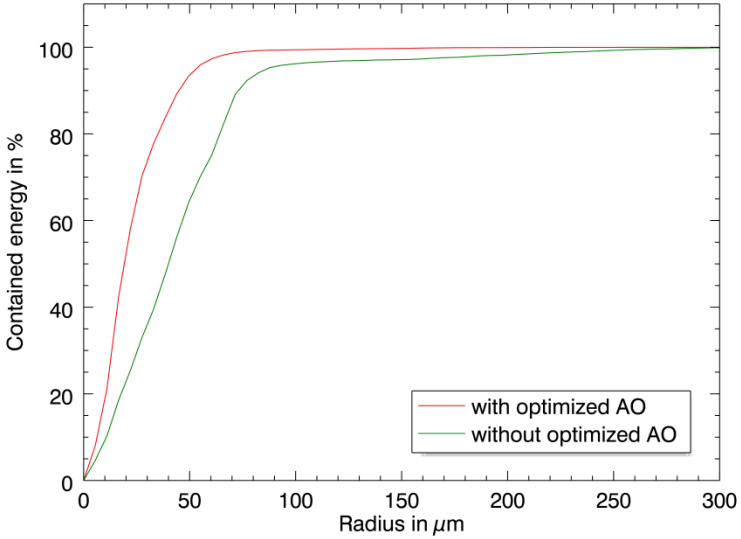




AO correction of regen beam

- Using the same static correction from the previous slide, but looking at the target chamber focus, one can see a dramatic improvement of encircled energy.
- However, the highest order aberrations are not compensated yet as can be been in the log scale images below.



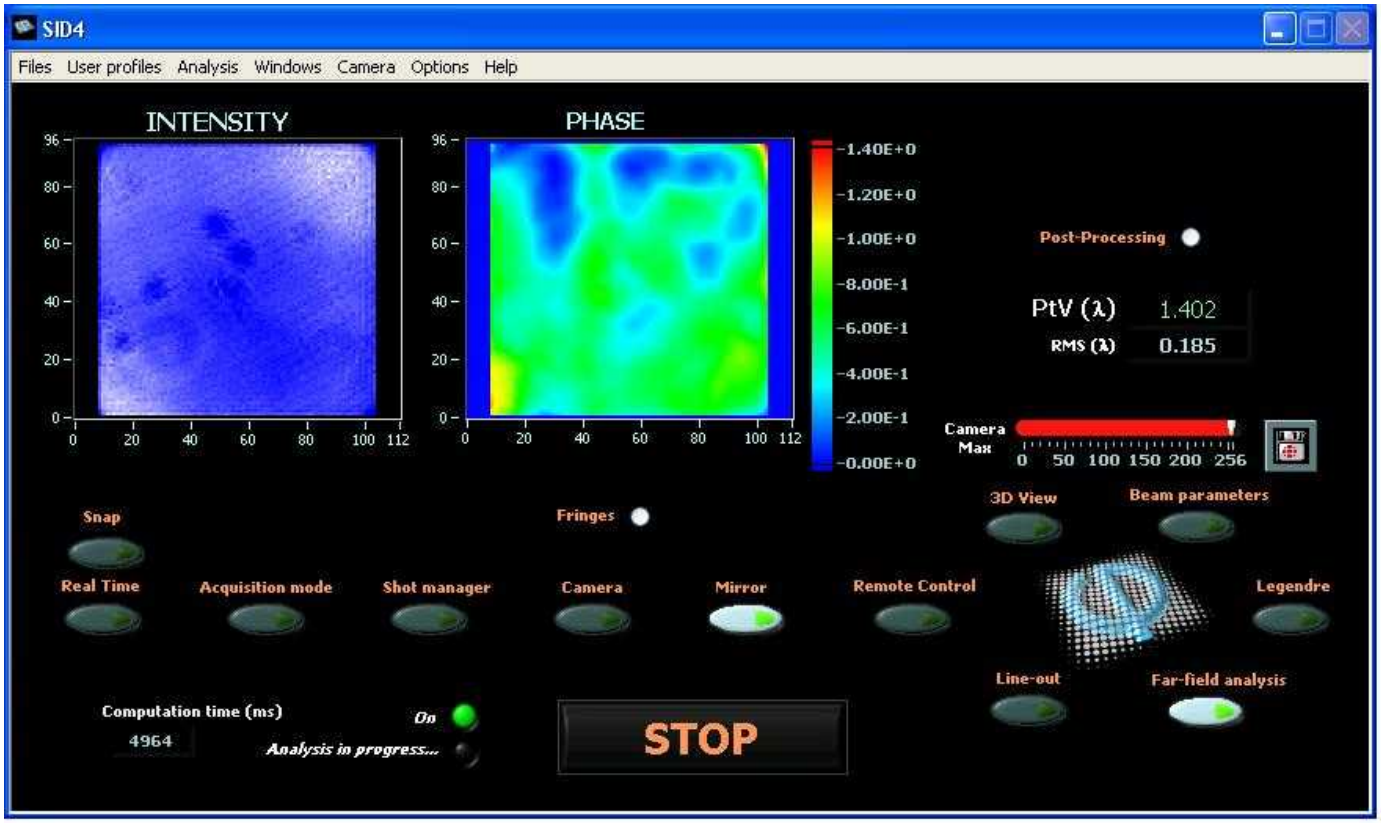


Radii for 50%, 80%, 95% contained energy:

19 µm	40 µm
35 µm	64 µm
53 µm	87 µm

AO on full system shot

- First attempt to correct full system shot.



Full system shot with AO

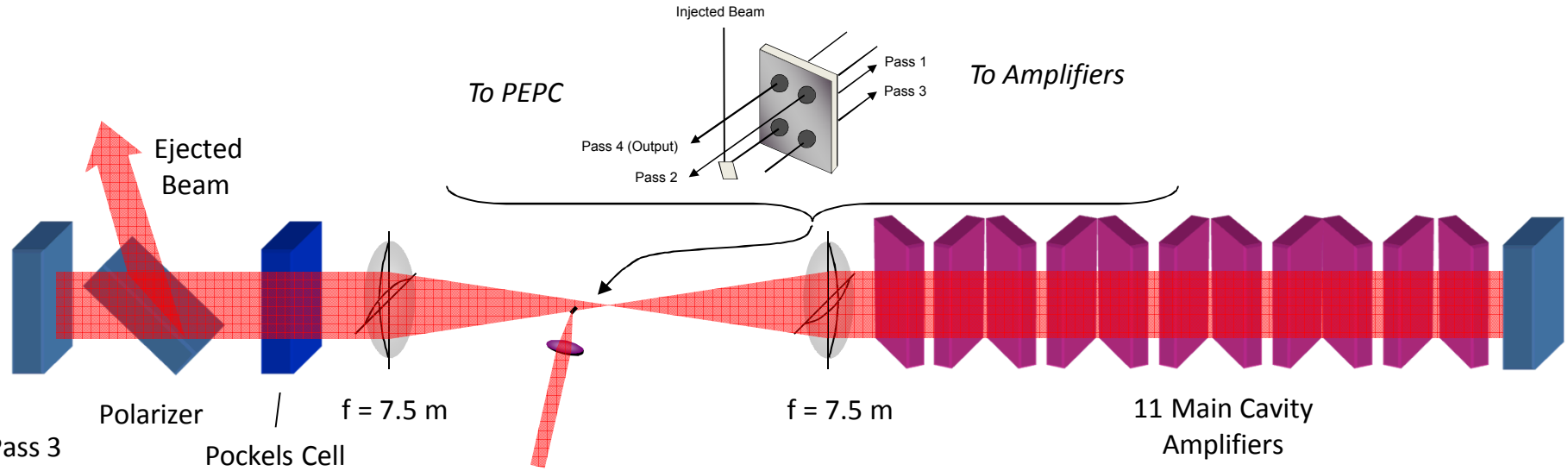
Full system shot with AO

Conclusion

- An overview of the current Z-Backlighter facility and its capabilities has been given
- The new MagLIF mission has prompted a variety of substantial upgrades to Z-Beamlet and Z-Petawatt.
- Z-Beamlet's 2ω energy has been doubled and it's focal spot quality was greatly improved.
- Z-Petawatt can now operate in short- and long-pulse mode, making it a versatile tool for MagLIF, backlighting, and high intensity laser plasma interactions.

Backup Slides

Z-Beamlet Main Cavity

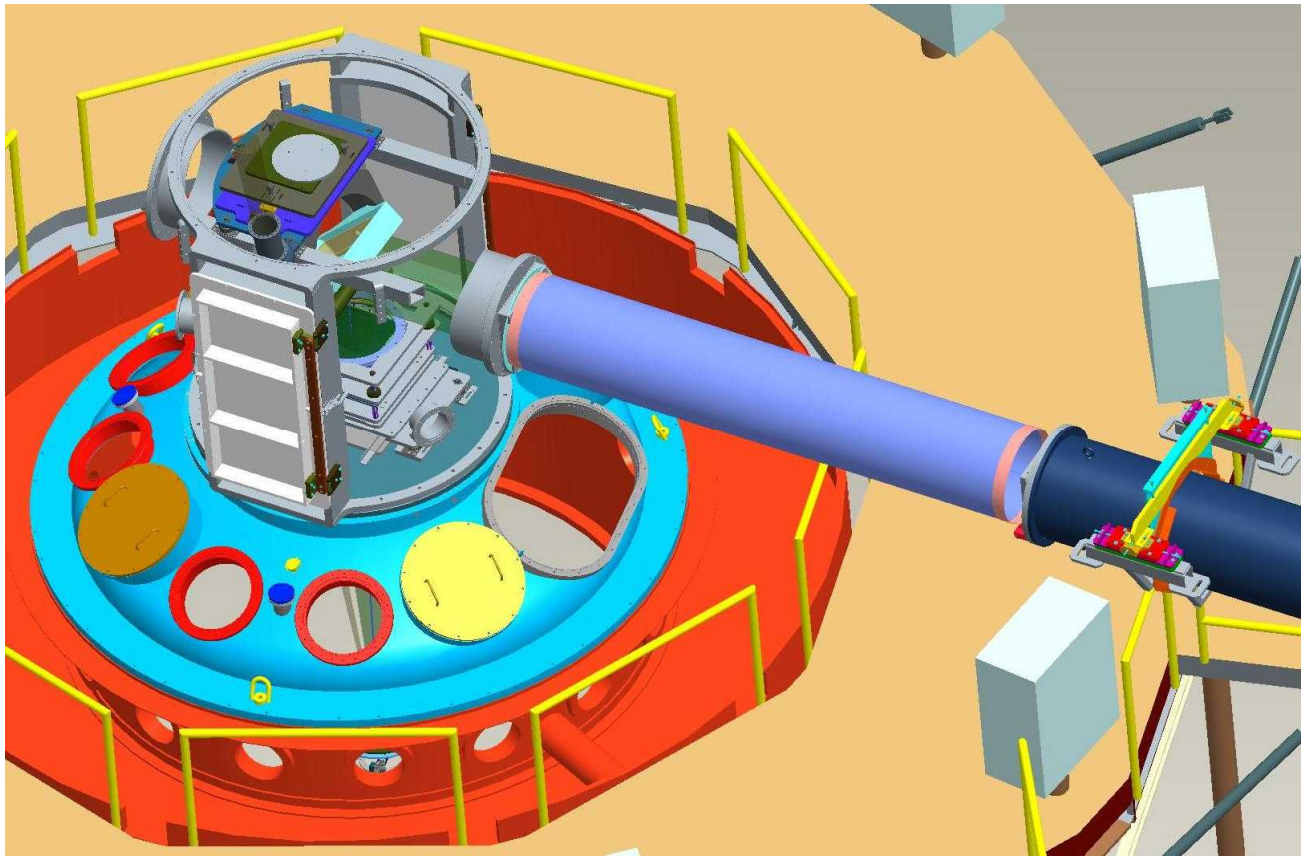


- 4-pass angled design (like the rod amplifier)

- PEPC/ polarizer combination "locks" the beam in the cavity.

- *Net single-pass gain:* ~11 X for the 11 BAU's
- *Net four-pass gain:* ~16,000 X

- *Extractable optical energy:* < 6 kJ

Final Optics Assembly (FOA)

- The original On-axis FOA operates at atmospheric pressure and uses a 32 cm square vacuum window at the Center Section interface.
  - The laser is point slightly off axis WRT to Z, allowing a few extras debris protection measures.
- Certain experiments require on-axis laser light at the Z pinch, potentially exposing the vacuum window to high-energy axial debris.
  - A catastrophic window failure could result from high-energy debris penetration, resulting in the rapid release of >5MJ of stored energy along with the large-scale dispersion of silica and post-shot dust.
- A newer FOA has been constructed and is in use on certain experiments.
  - The new system is a pressure vessel which is evacuated to avoid the stored energy risk.