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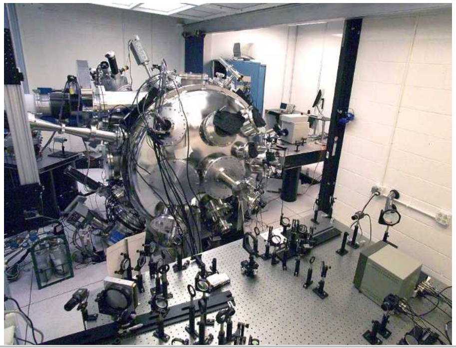

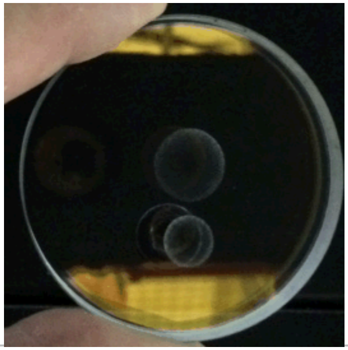

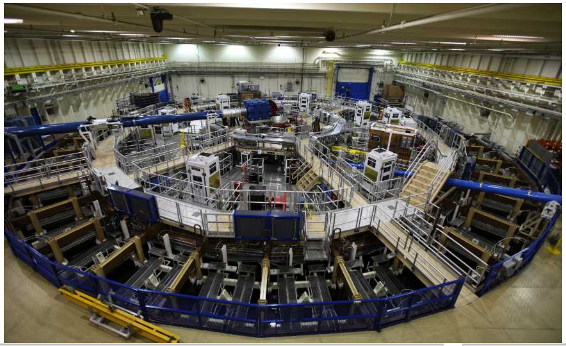

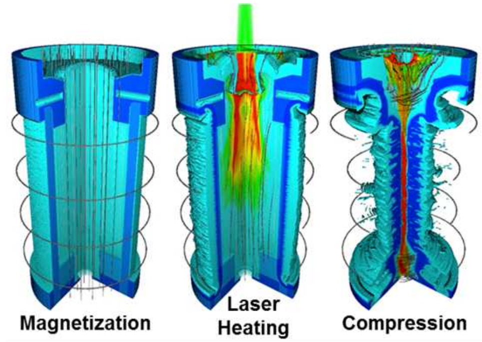

Recent Upgrades of Sandia's Z-Backlighter Facility based on New Requirements for Magnetized Liner Inertial Fusion on the Z-Machine

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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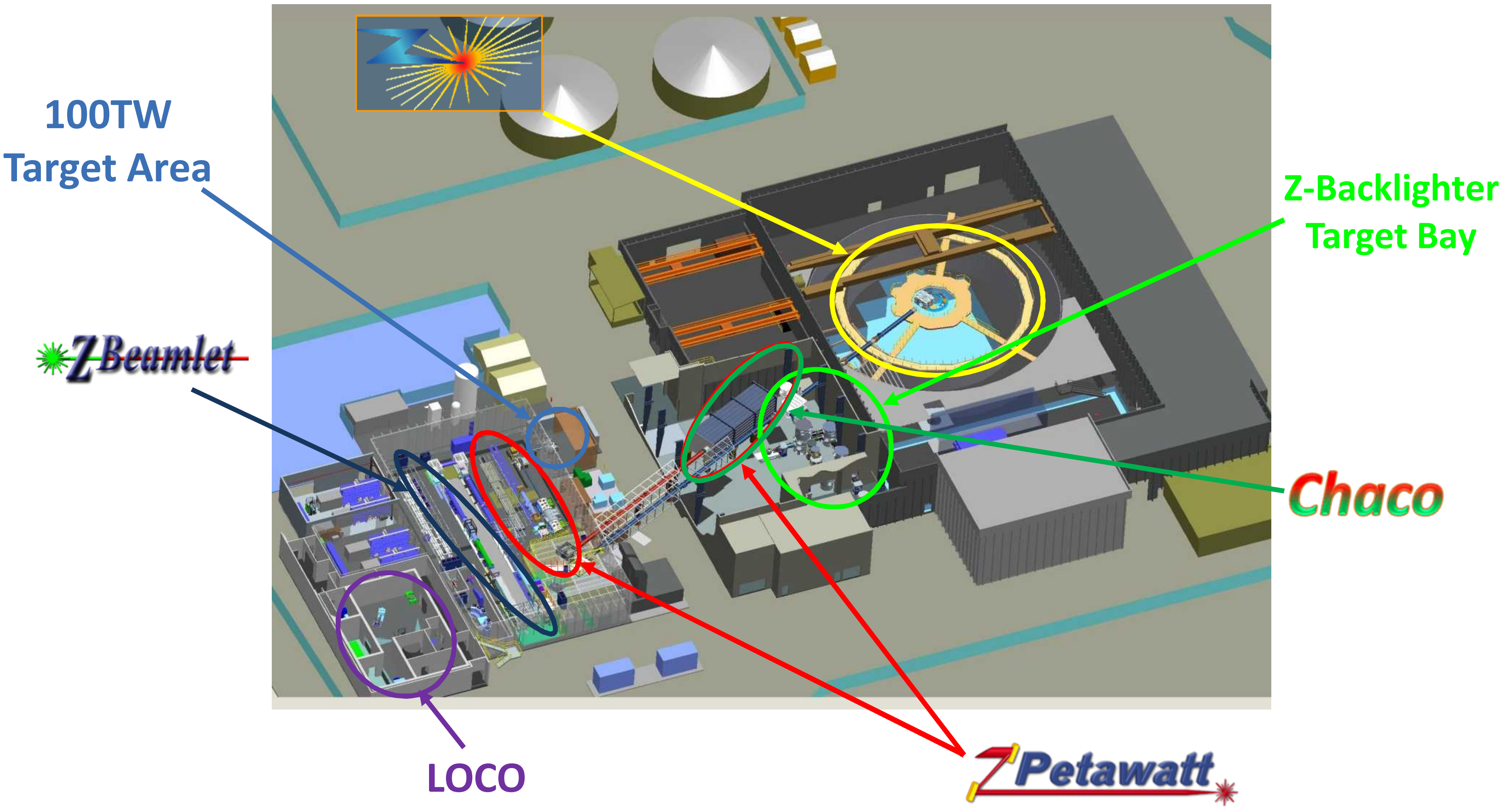
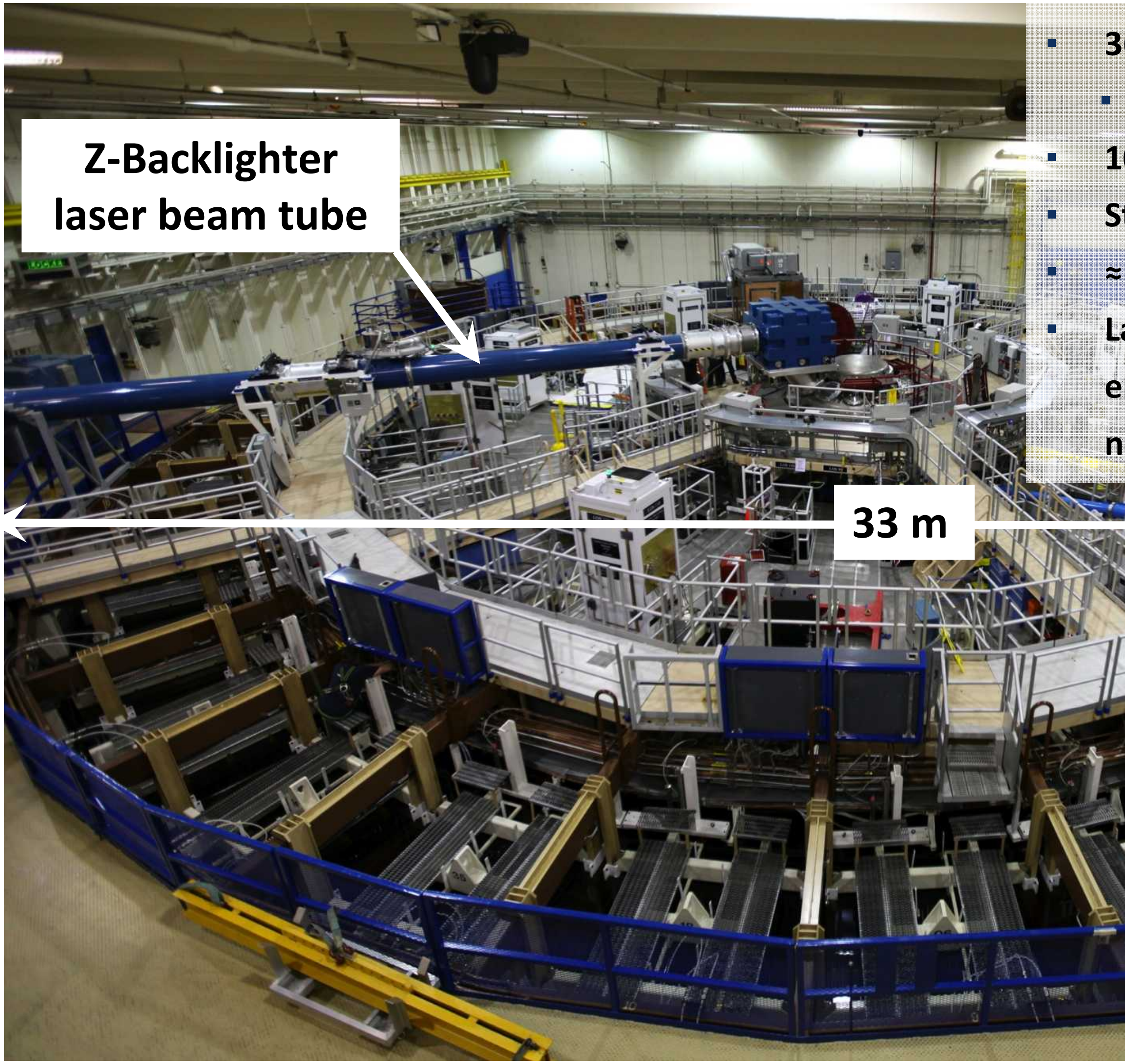
Outline

- 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
    - With optional co-injection into Z-Beamlet beamline
  - Employing beam smoothing via: phase-plates and adaptive optics
- Conclusion

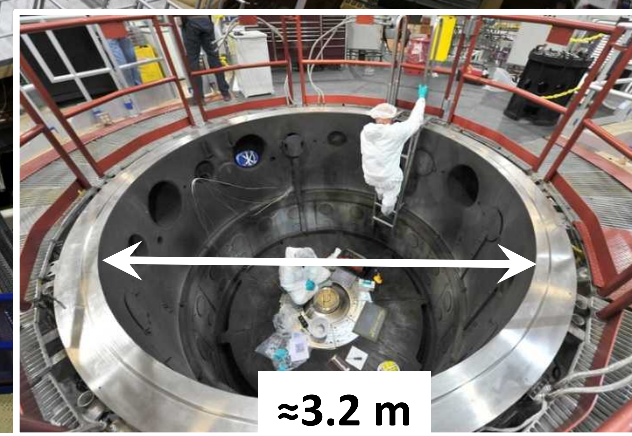
Z-Pulsed Power Facility Overview



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



Z-Backlighter Facility Overview

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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/cm²)	~ 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

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

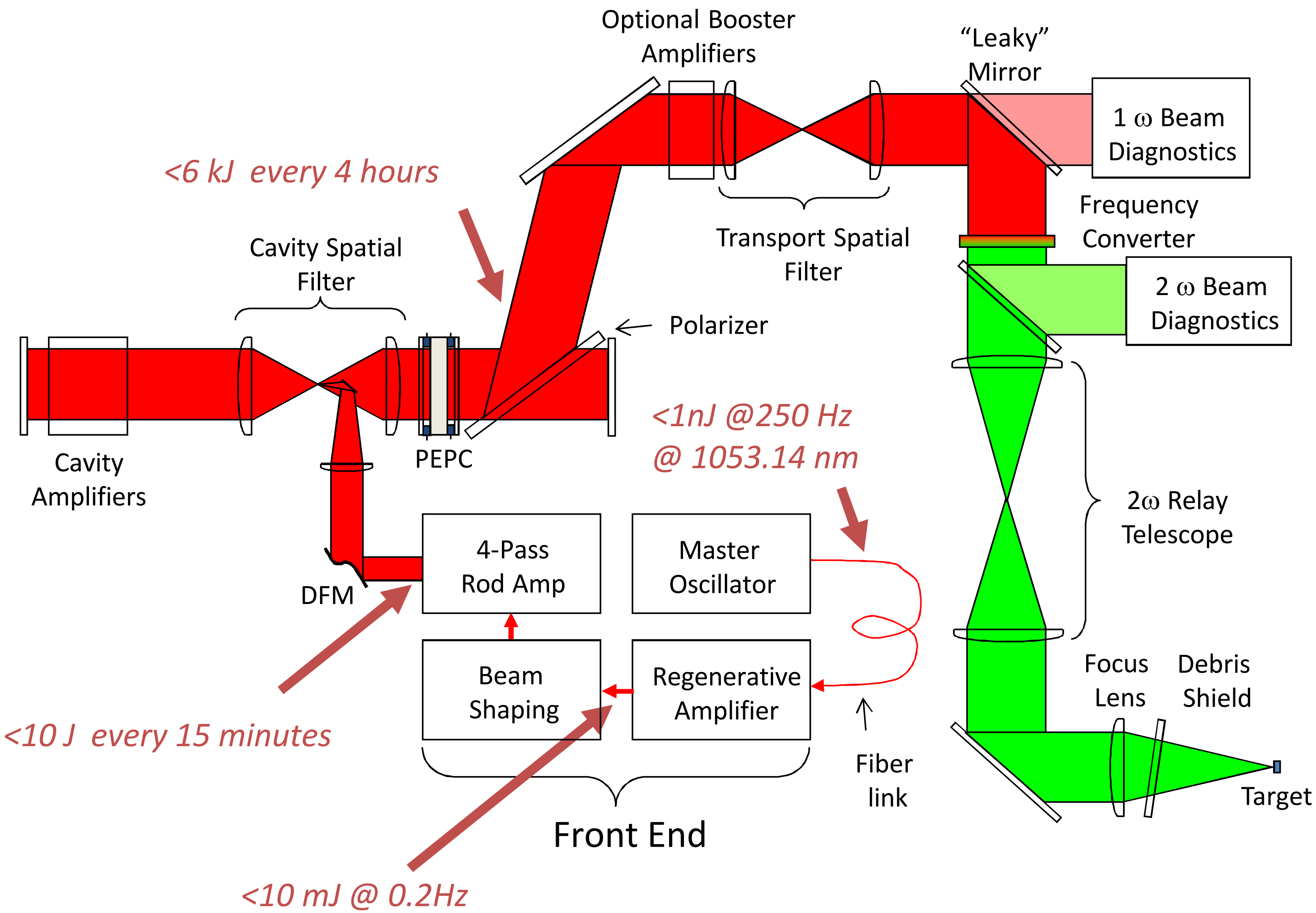
- Main uses:
  - Create x-ray source for backlighting
  - Preheat MagLIF fuel

- 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



Z Petawatt

Z-Petawatt Laser (ZPW) Basics

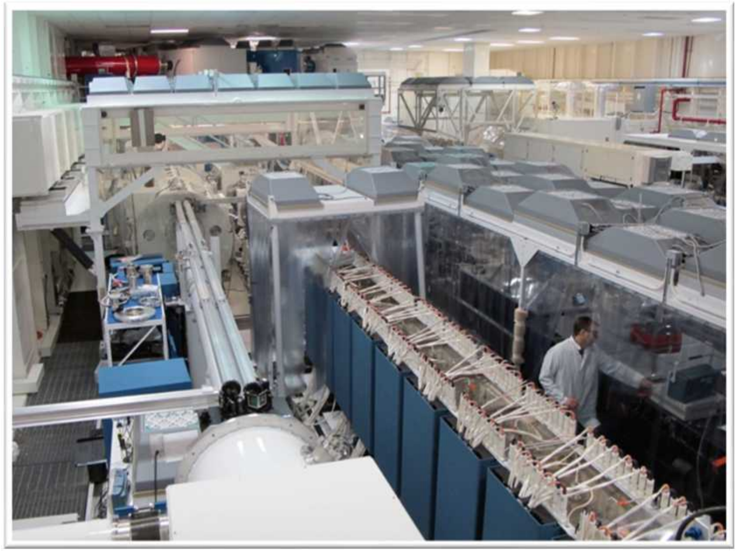
- Short-pulse, 1ω operation
  - High-field physics (particle acceleration/γ-rays)
  - Above-10 keV x-ray generation

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

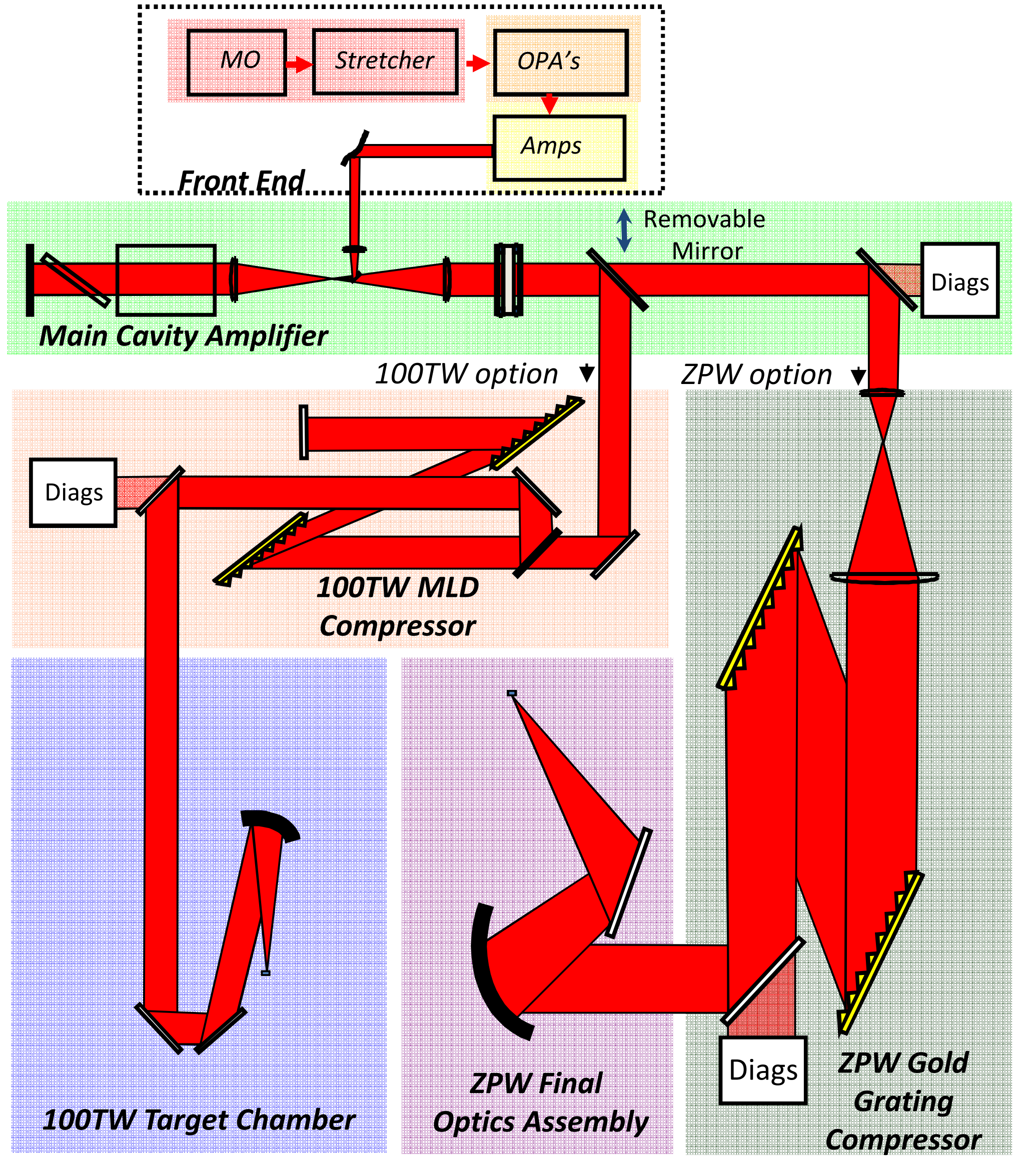
- Parameters:
  - Up to 500 J @ 1053nm, 500 fs, 43cm dia.
  - Up to 100 J @ 1053nm, 500 fs, 200 TW, 15cm dia.
  - Up to 400 J @ 527nm, 2 ns, 15cm dia.

  - 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

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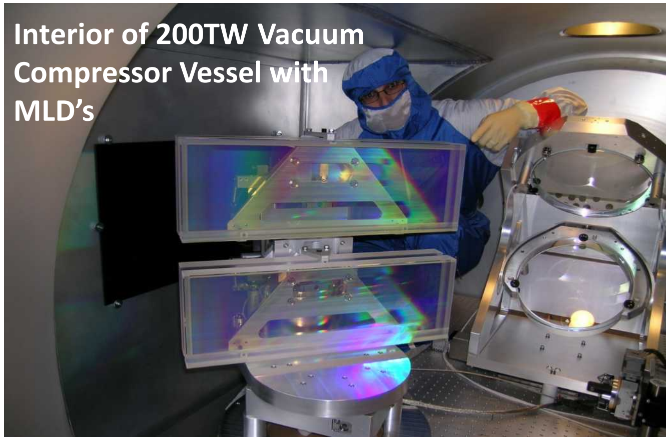
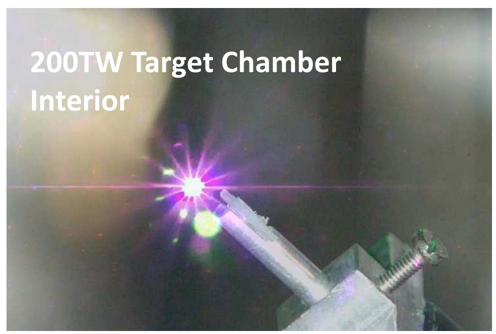
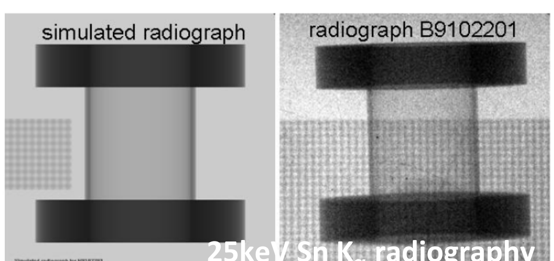




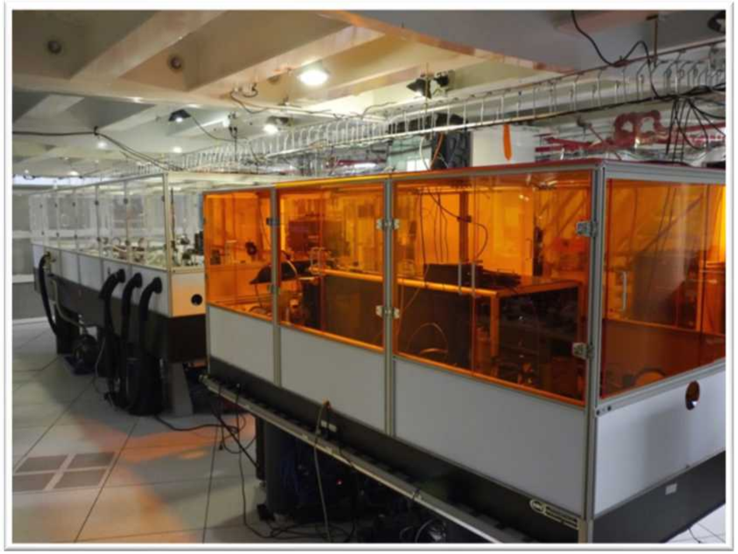


- **A smaller beam can be used to operate at the 200TW level using MLD gratings for temporal compression.**
- **A dedicated target chamber is used for stand alone experiments such as:**
  - **Proton beam generation**
  - **Bent crystal imaging development**
  - **Laser beam characterization**
  - **Novel 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**

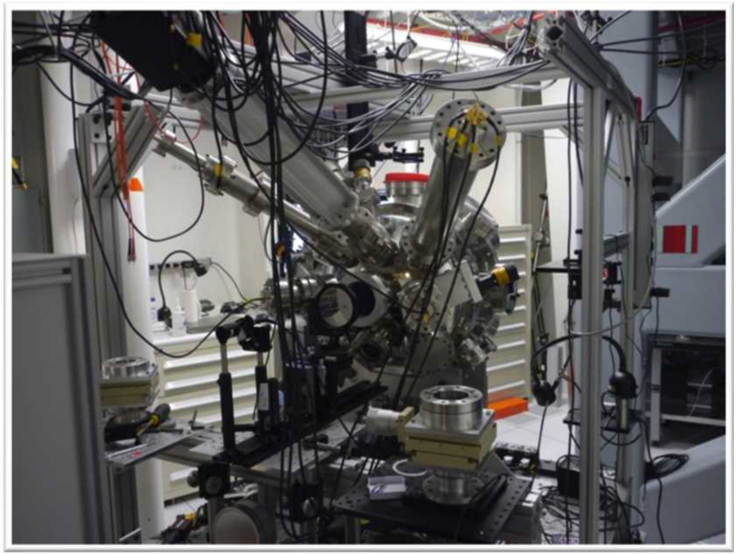
Chaco

Chaco Laser Basics

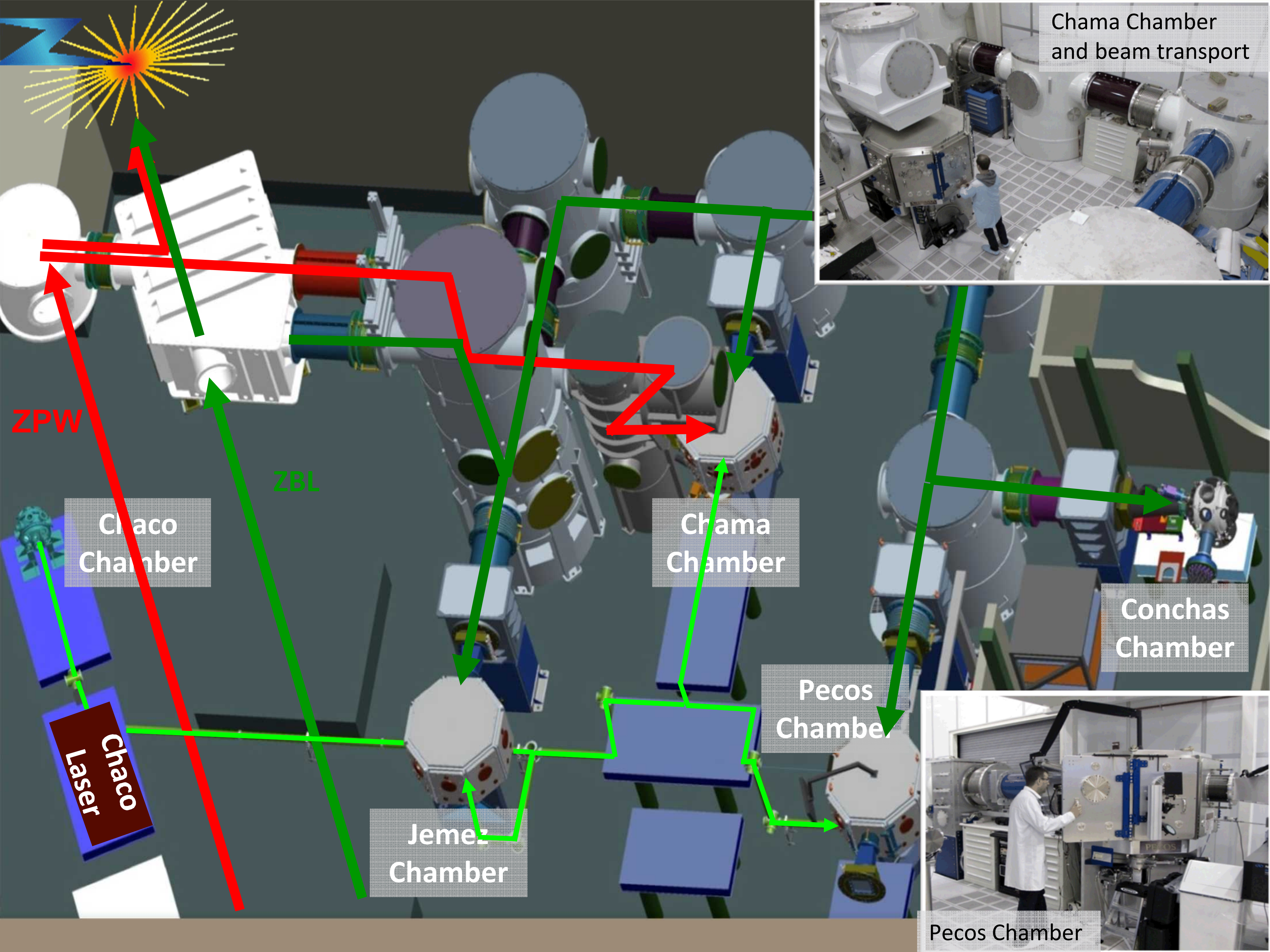
- Versatile, nanosecond laser system:
  - Synchronized to ZBL and ZPW
  - Laser compression of samples
  - Multi-frame probe for shadowgraphy, interferometry
  - 8-pulse capability with 1 ns inter-pulse intervals



- 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



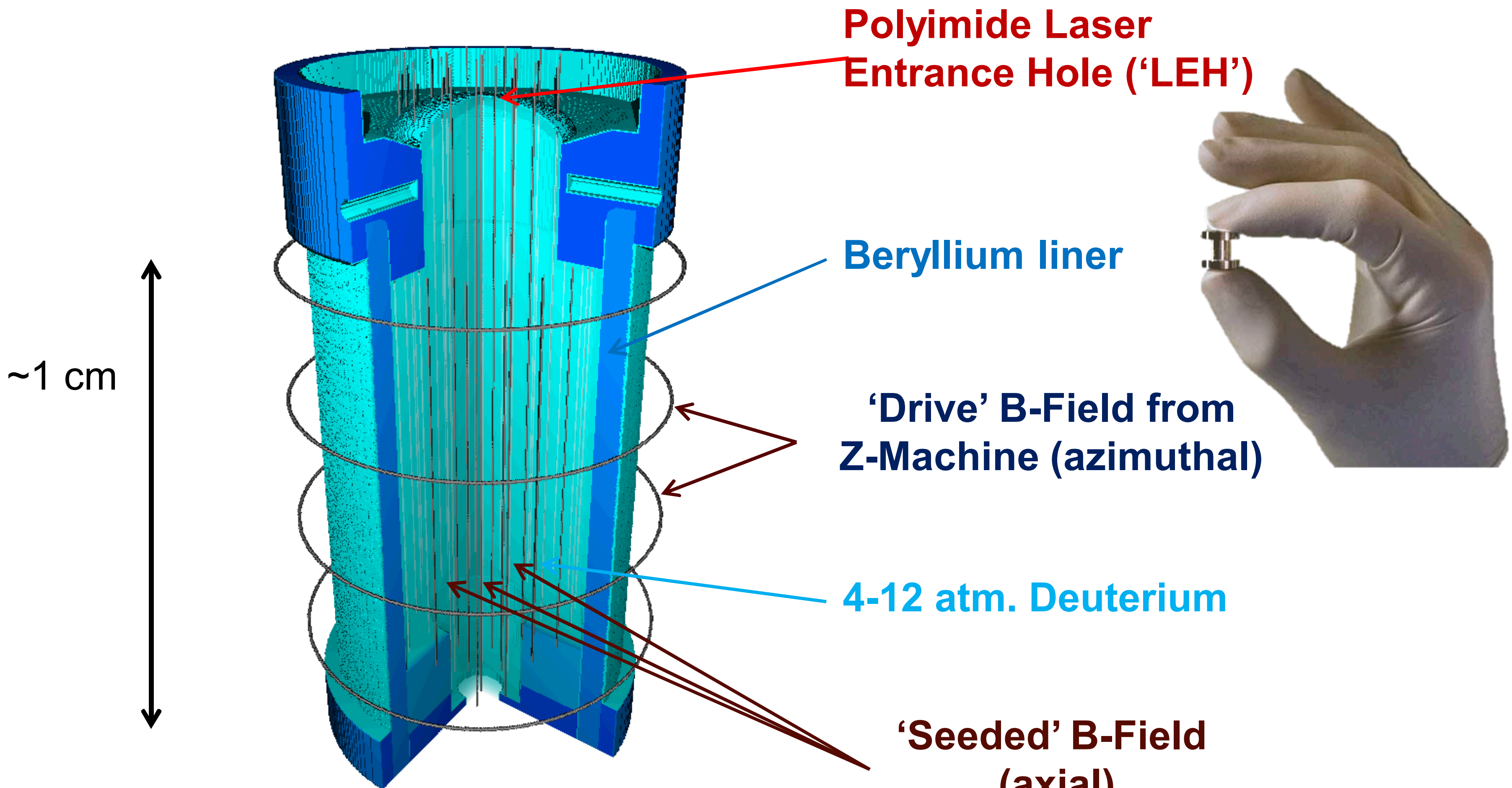
Target Bay



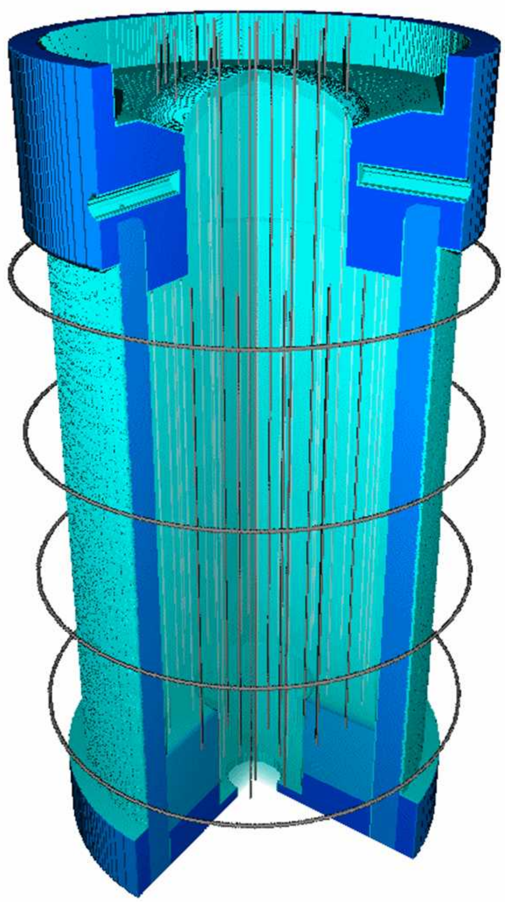
Chama Chamber
and beam transport
ZPW
ZBL
Chaco
Chamber
Chama
Chamber
Conchas
Chamber
Pecos
Chamber
Chaco
Laser
Jemez
Chamber
Pecos Chamber

MagLIF

Magnetized Liner Inertial Fusion

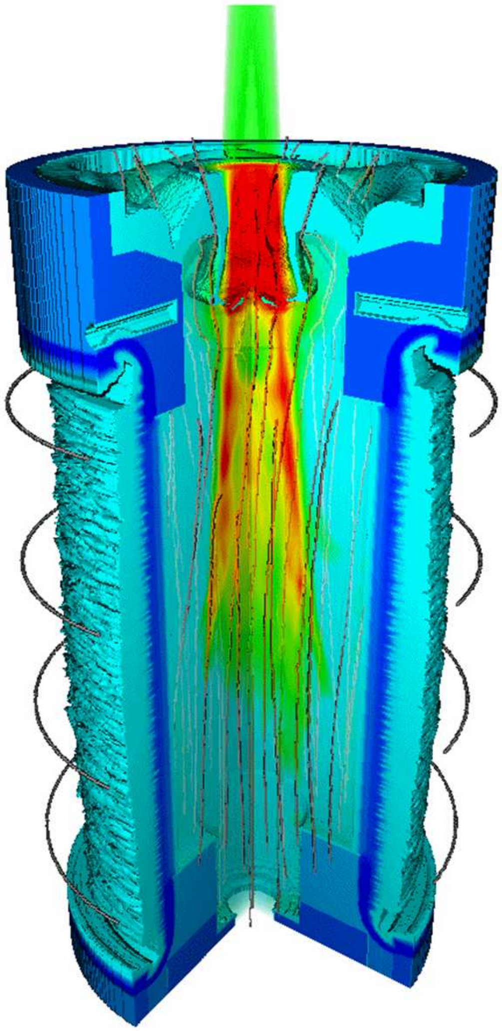


Magnetized Liner Inertial Fusion

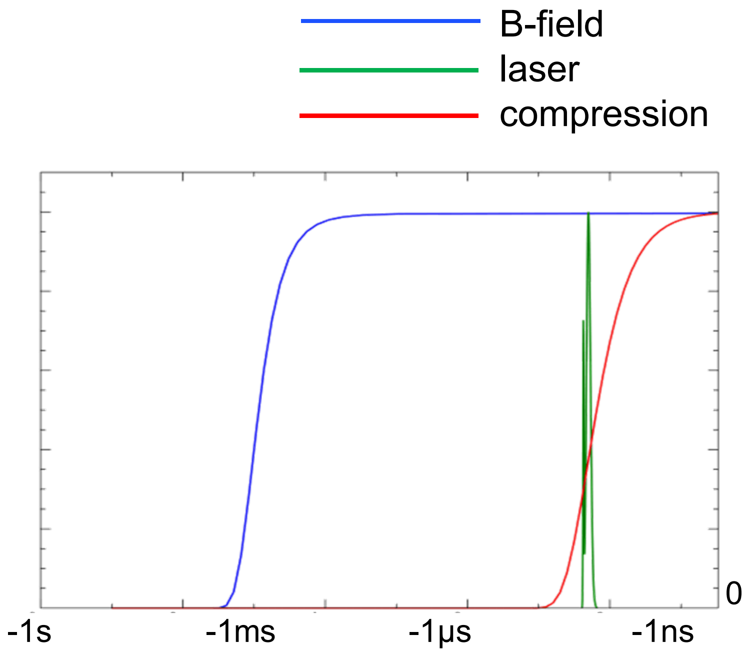


- B-Field from Z machine drive current starts to compress the Be lines and fuel
- Z-Beamlet injects several kJ of energy at 527nm into fuel
  - Magnetization of fuel
  - Minimizes heat conduction losses
  - B-Field compression
  - Stagnation temperature is proportional to initial temperature

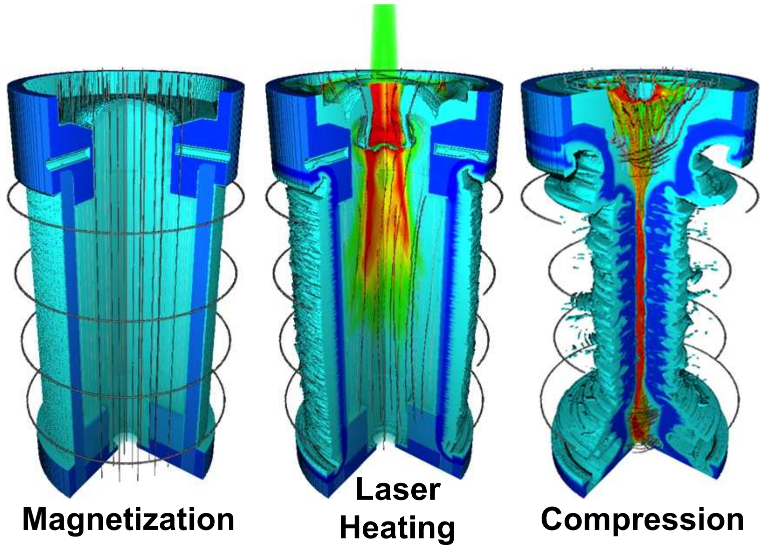
Magnetized Liner Inertial Fusion

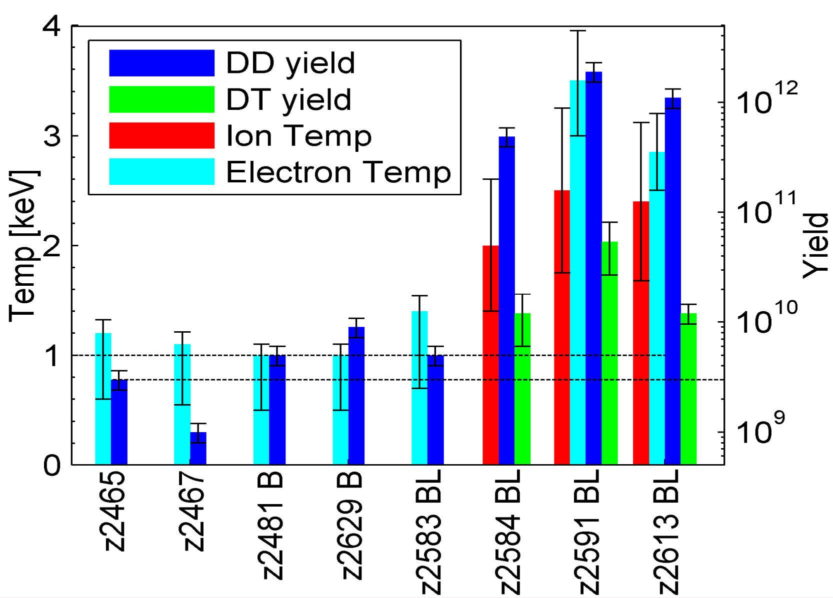


- Fuel compresses to densities and temperatures enabling thermonuclear fusion



Magnetized Liner Inertial Fusion



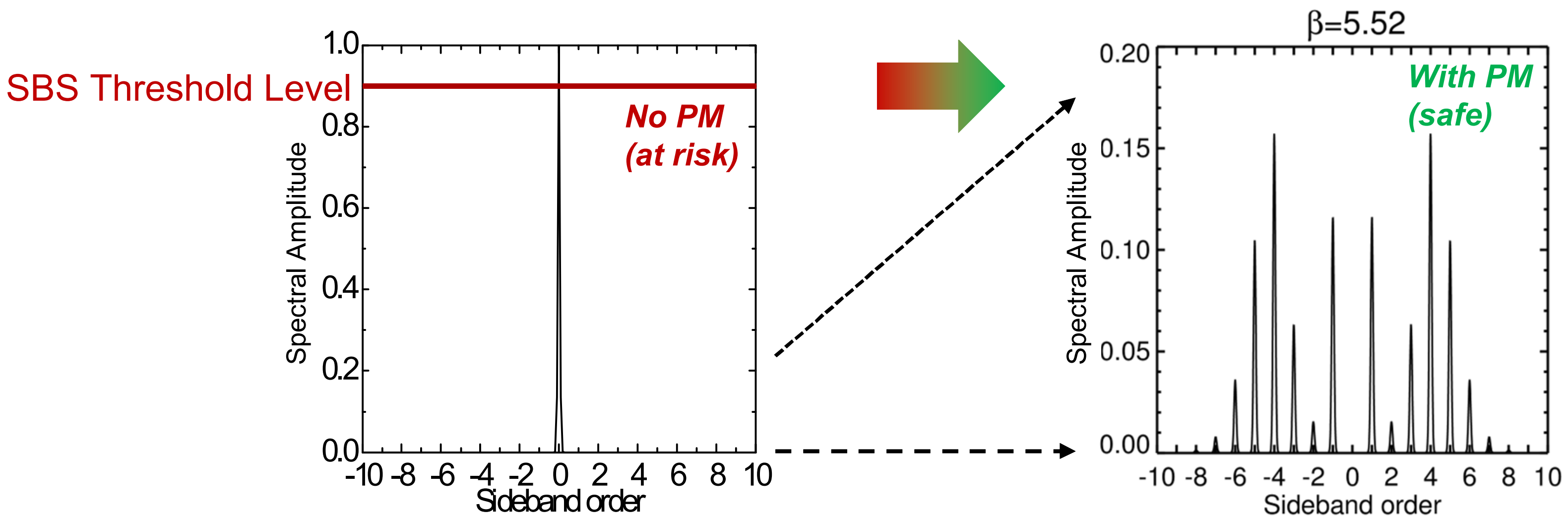


- Point Design:
  - 30 Tesla initial magnetic field
  - Laser heating of ~3 mg/cm^3 D_2 fuel produces ~250 eV plasma
  - Thick (AR=6) Be liner with R_0=2.7 mm, peak velocity ~100 km/s for a 27 MA peak current drive
  - At stagnation the fuel absorbs 120 kJ, reaches 8 keV and ~0.5 g/cm^3, and is highly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

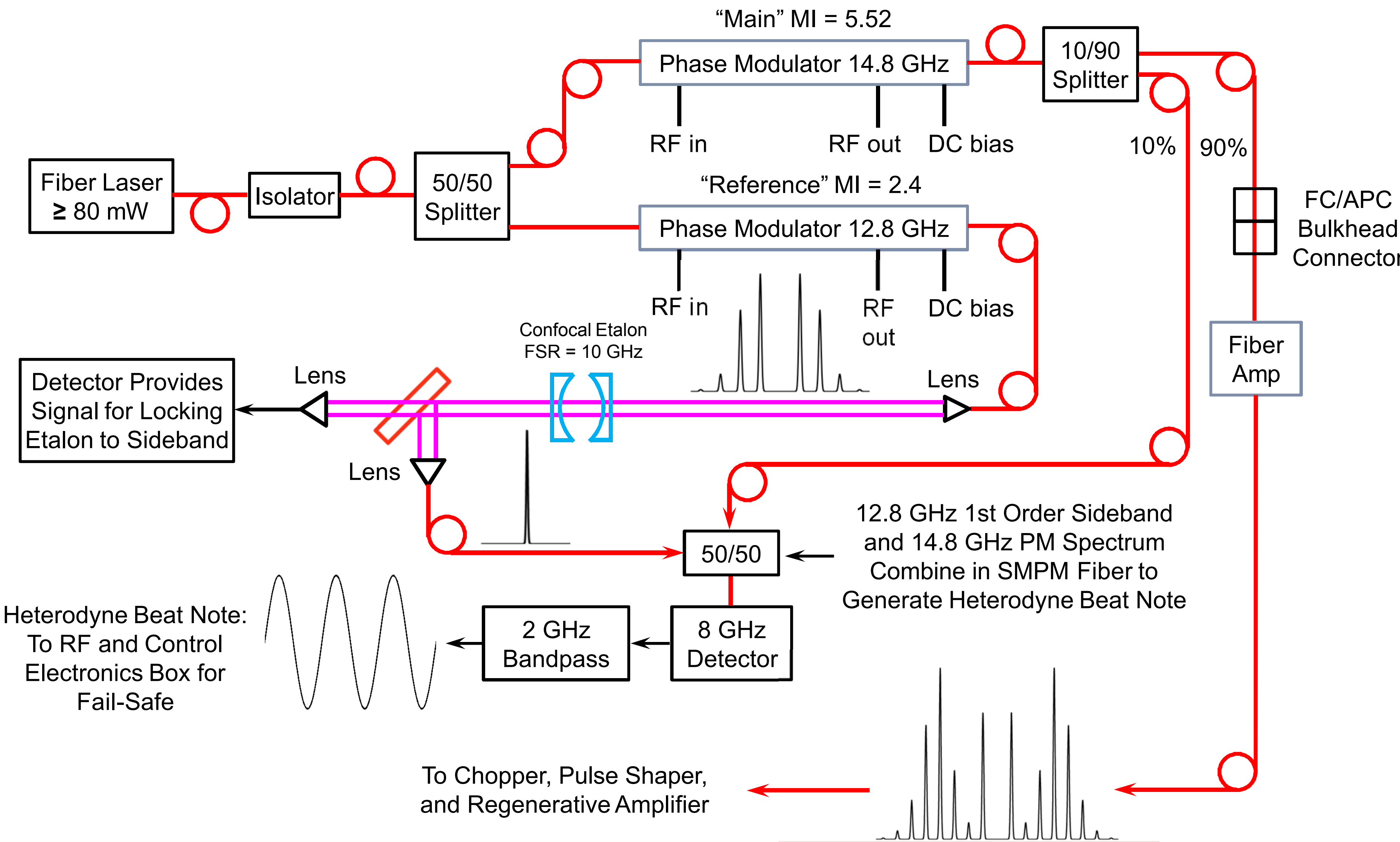
Upgrades Prompted by MagLIF

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

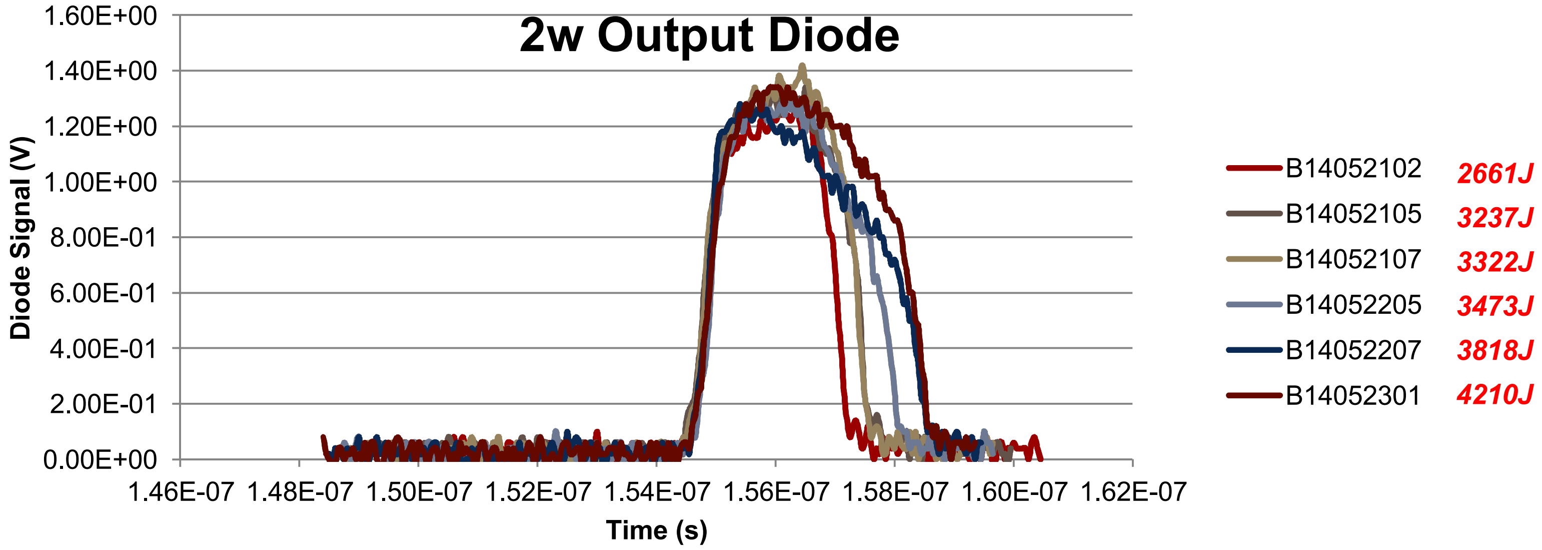


Design for PM and Heterodyne



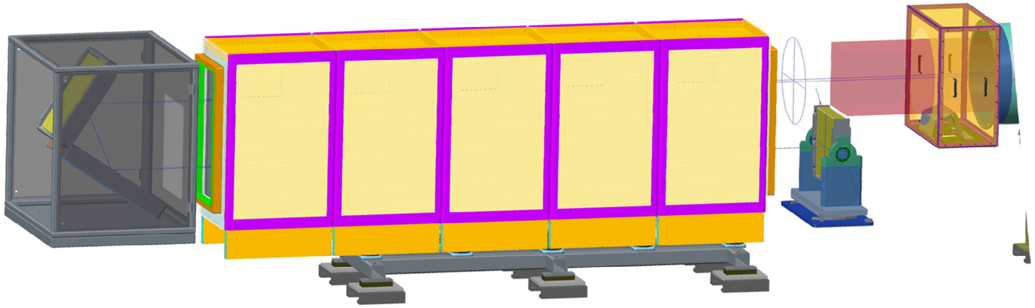
SBS suppression: Results

- 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.

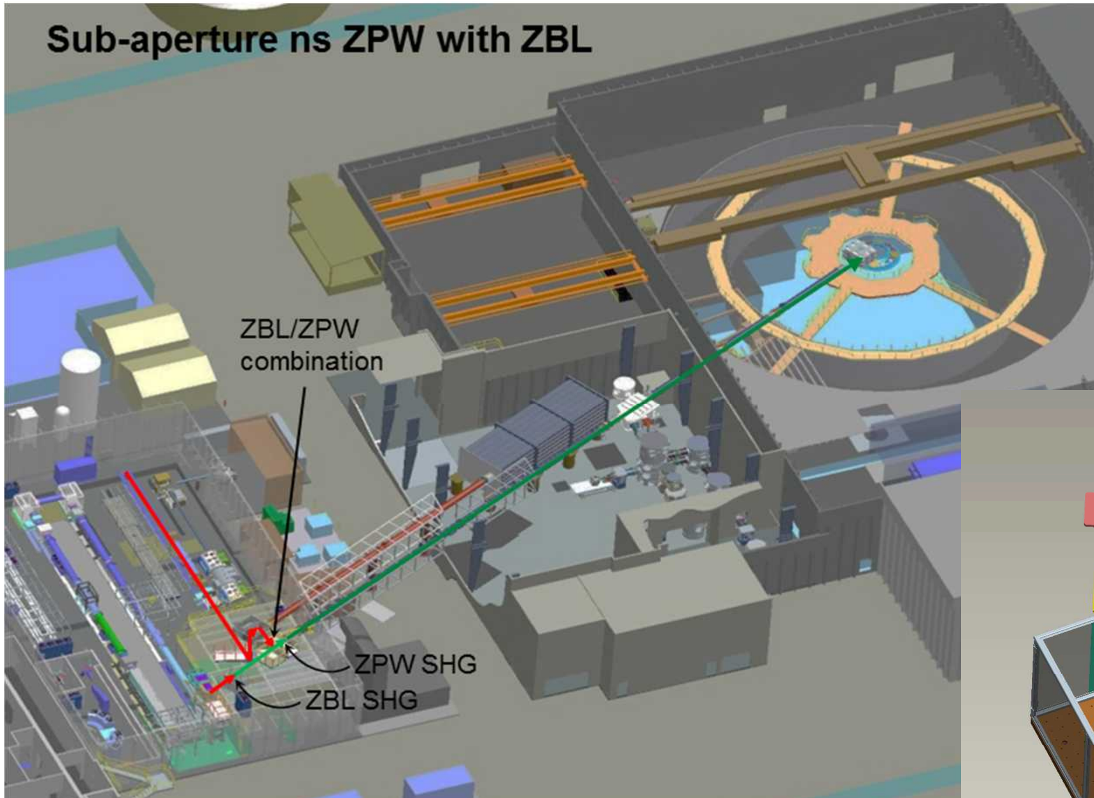


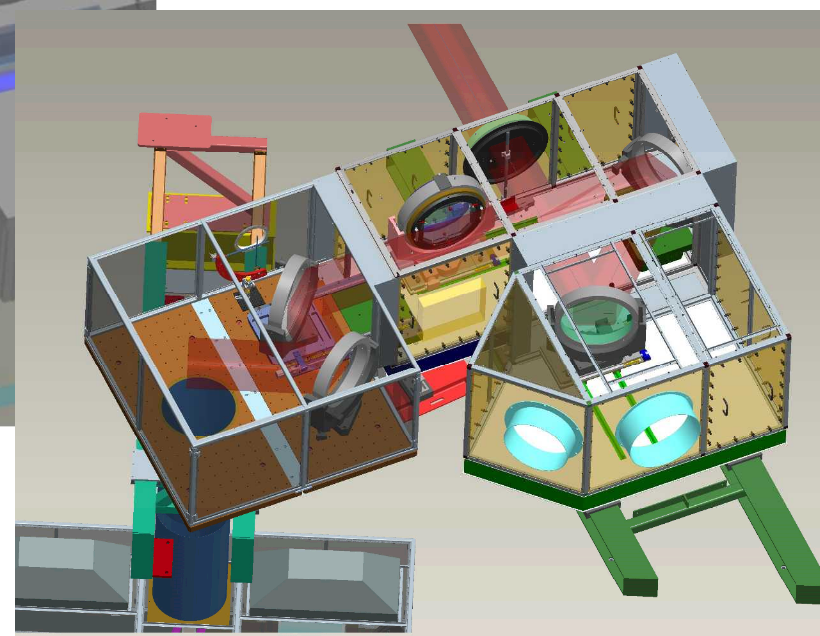
Z-Petawatt in long pulse mode

- 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





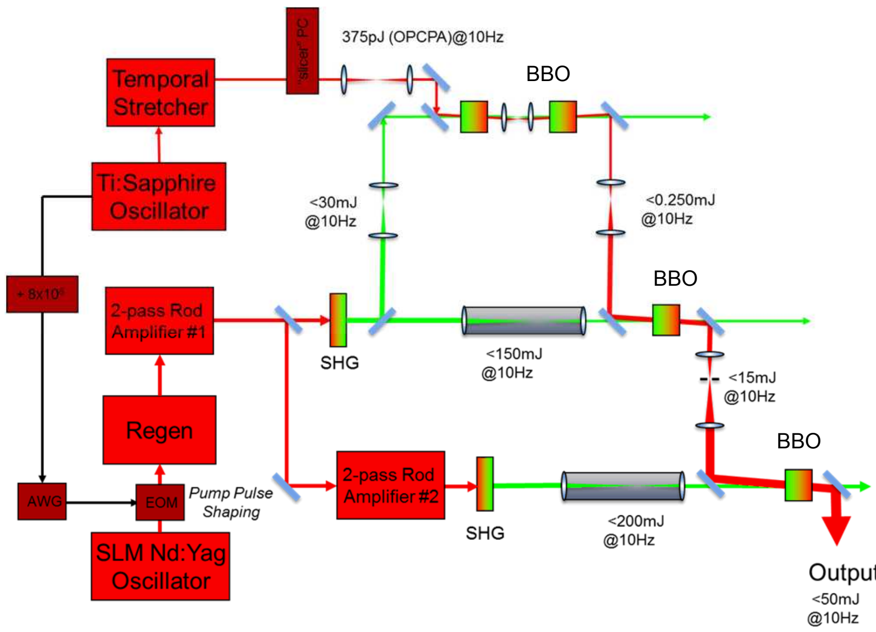
- Projected 2ω energy:
  - 500 J at sub-aperture this CY
  - 3 kJ at Full aperture (years)

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

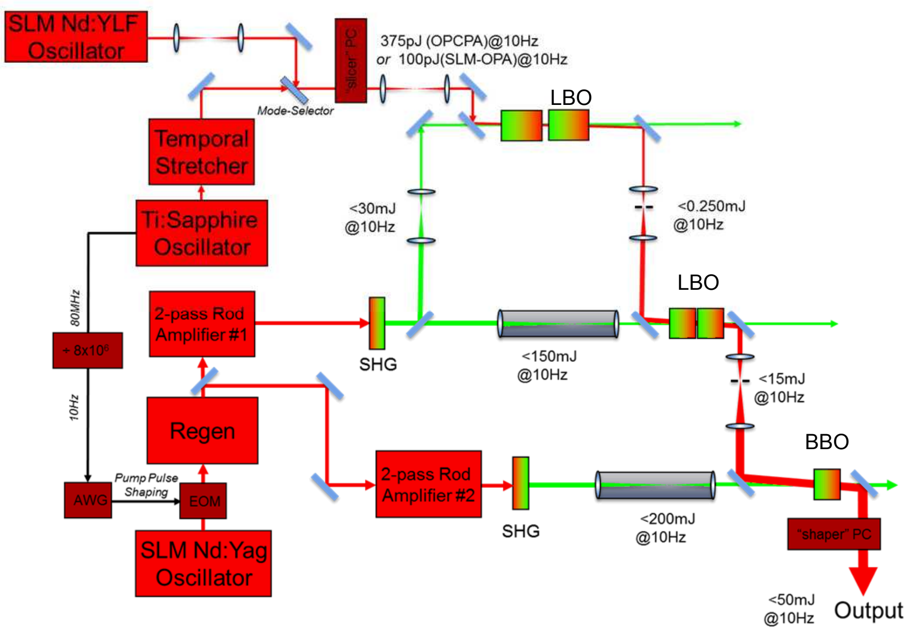
OPCPA changes required

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

Old

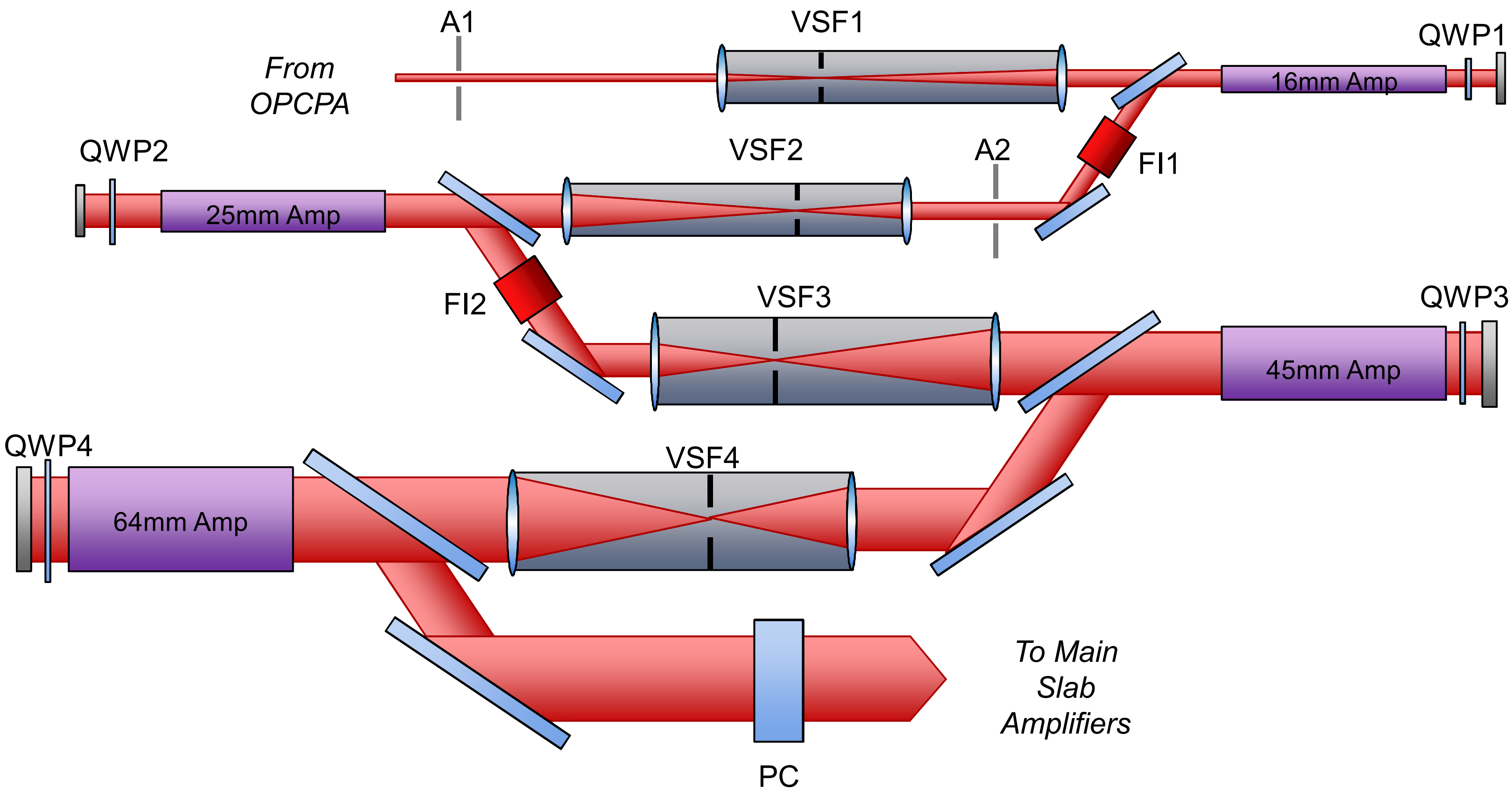


New



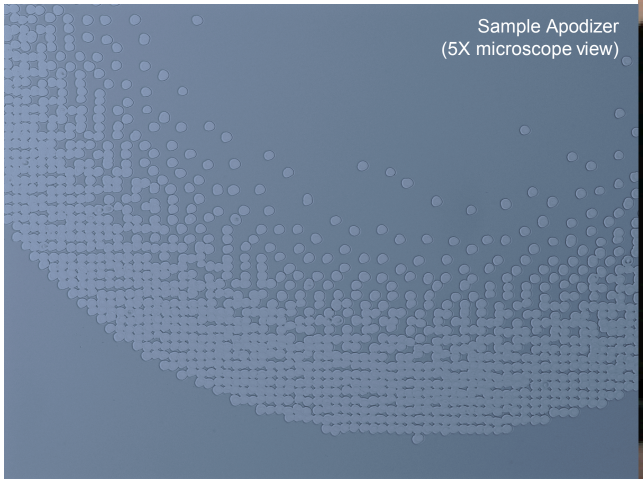
New rod amp layout

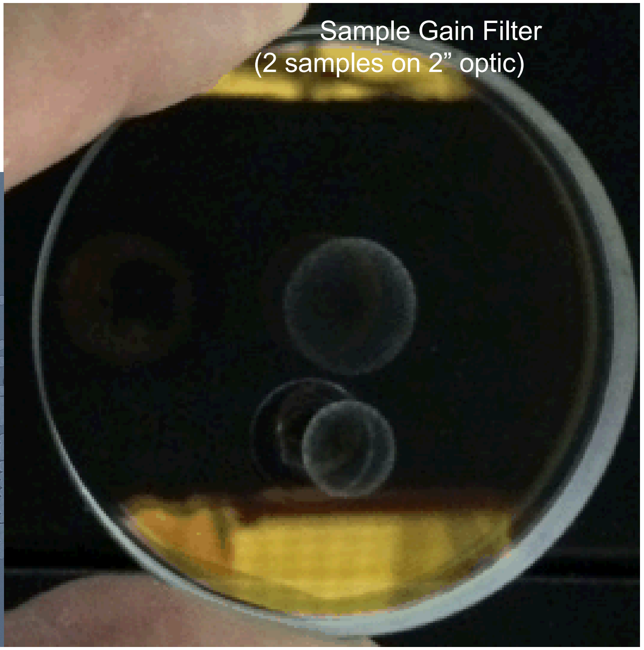
- Future plans require long pulse kJ PW at full beam aperture
  - Additional rod amps needed for higher seeding of main amps



First long-pulse results

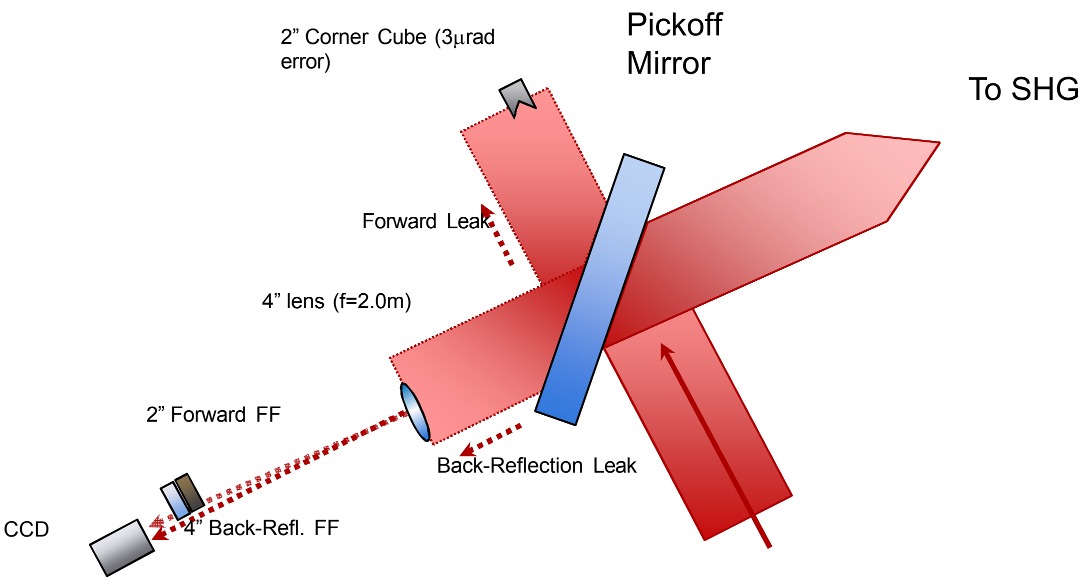
- Completed spatio/temporal pulse shaping to pre-compensate gain-distortions.
  - Spatial pre-compensation with laser machined apodizers
  - Temporal pre-compensation with Pockels cells
- Using the new SLM seed source, early gain tests show a double pass main amplifier gain of 120x => 330J total.

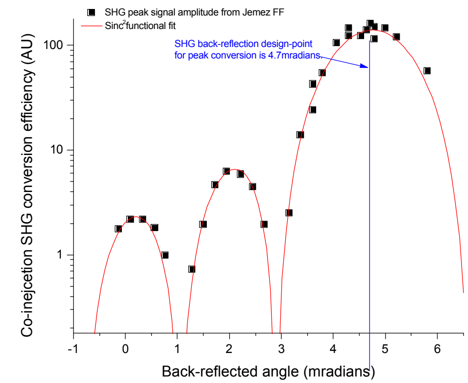


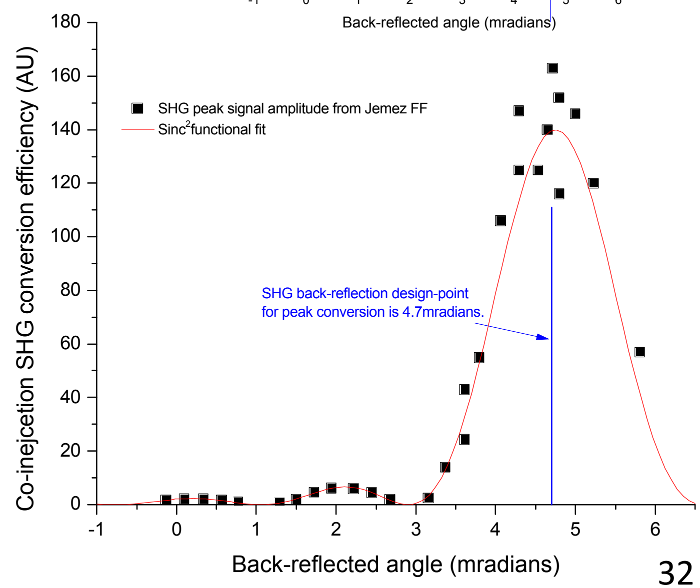


First co-injection 2ω light

- Use clever alignment technique to measure and optimize SHG crystal alignment

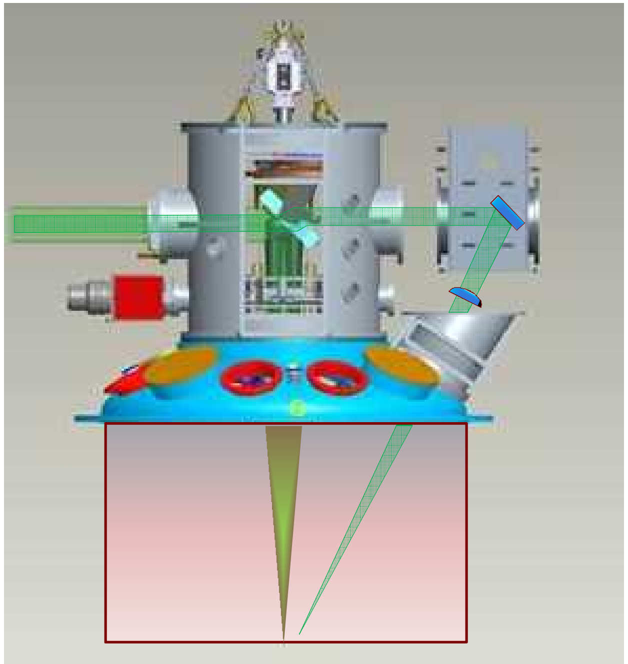






Z-Petawatt Backlighting

- Use frequency doubled, ns co-injected PW
- Polarization beamsplitter will separate the beams in the FOA
- Second harmonic will have higher x-ray conversion efficiency and provides inherent back-reflection protection.
- Long pulse beam will not be able to generate x-rays > 8keV.



Beam Quality Improvements

Beam smoothing: Phase-plate

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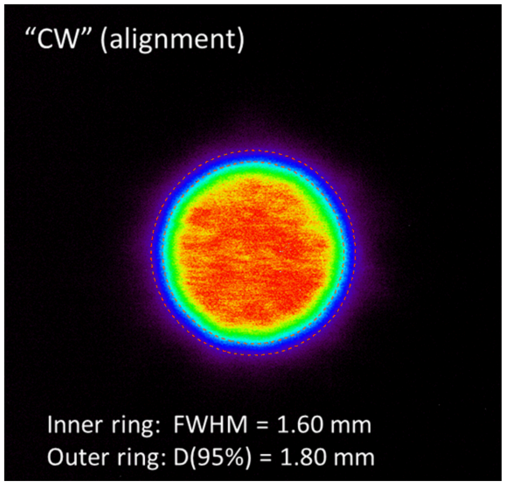
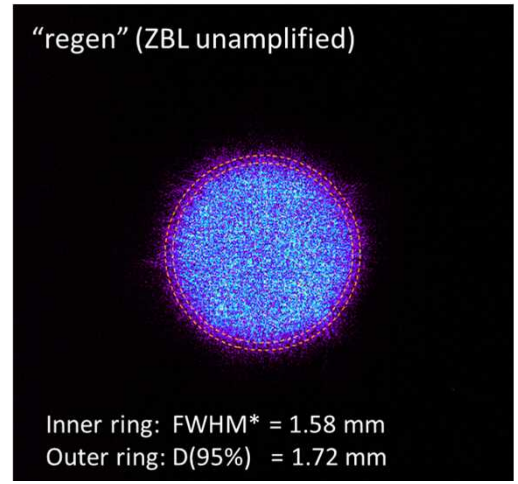
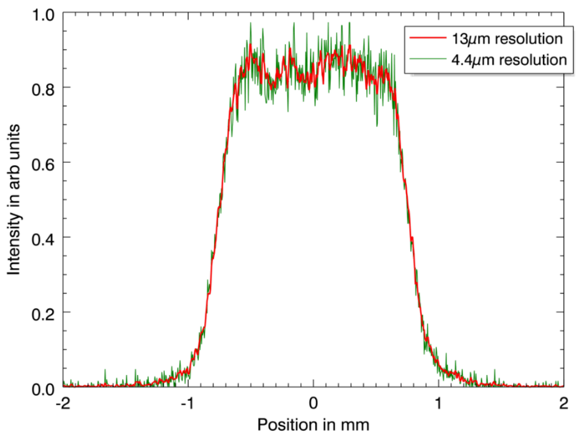
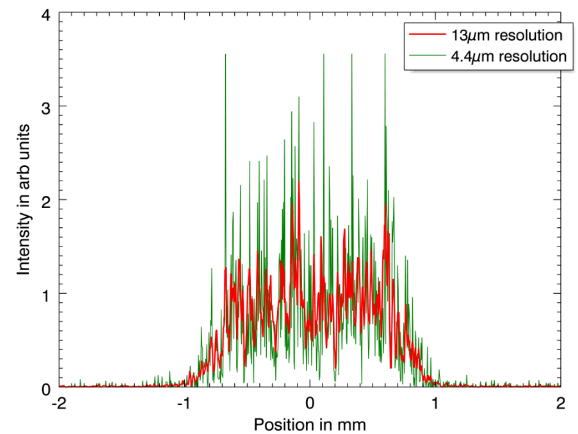
- LLE phase-plate loaner optimized for 1.8mm diameter focus



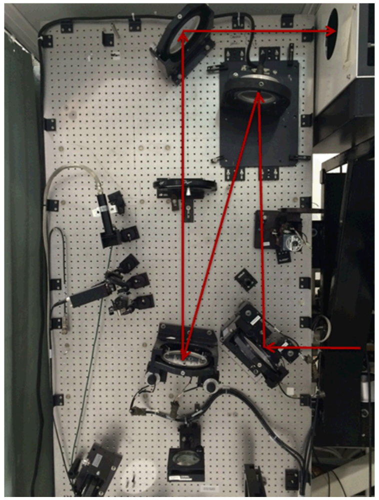






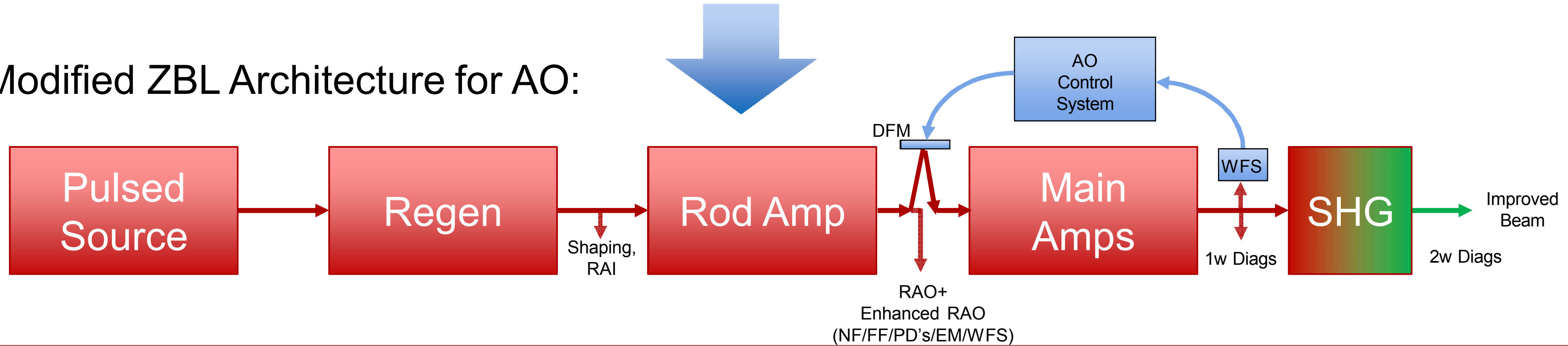
Adaptive Optics (AO) on Z-Beamlet

- 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

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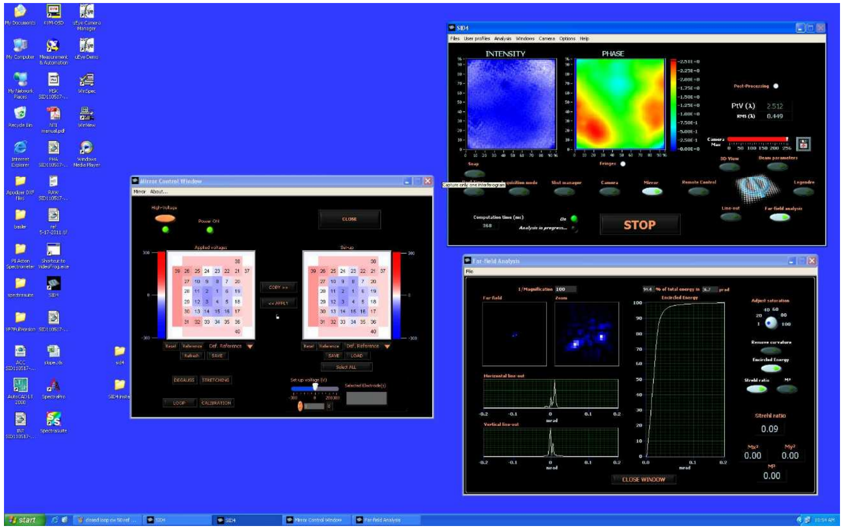
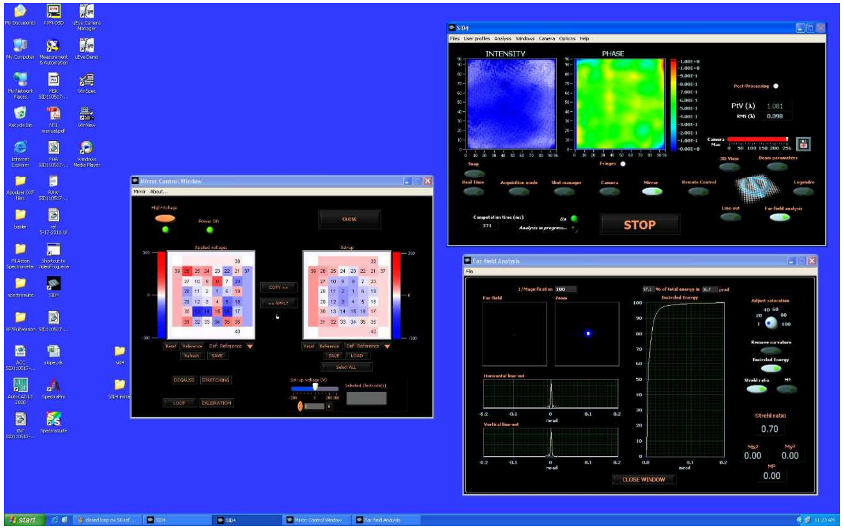
- Static aberrations were previously significant due to a faulty large waveplate (since replaced):
  - PV: 2.5 waves, RMS: 0.45 waves, Strehl: 0.09
- When closing the loop with a cw alignment beam, we achieve:
  - PV: 1.1 wave, RMS: 0.1 wave, Strehl: 0.70





AO on full system shot

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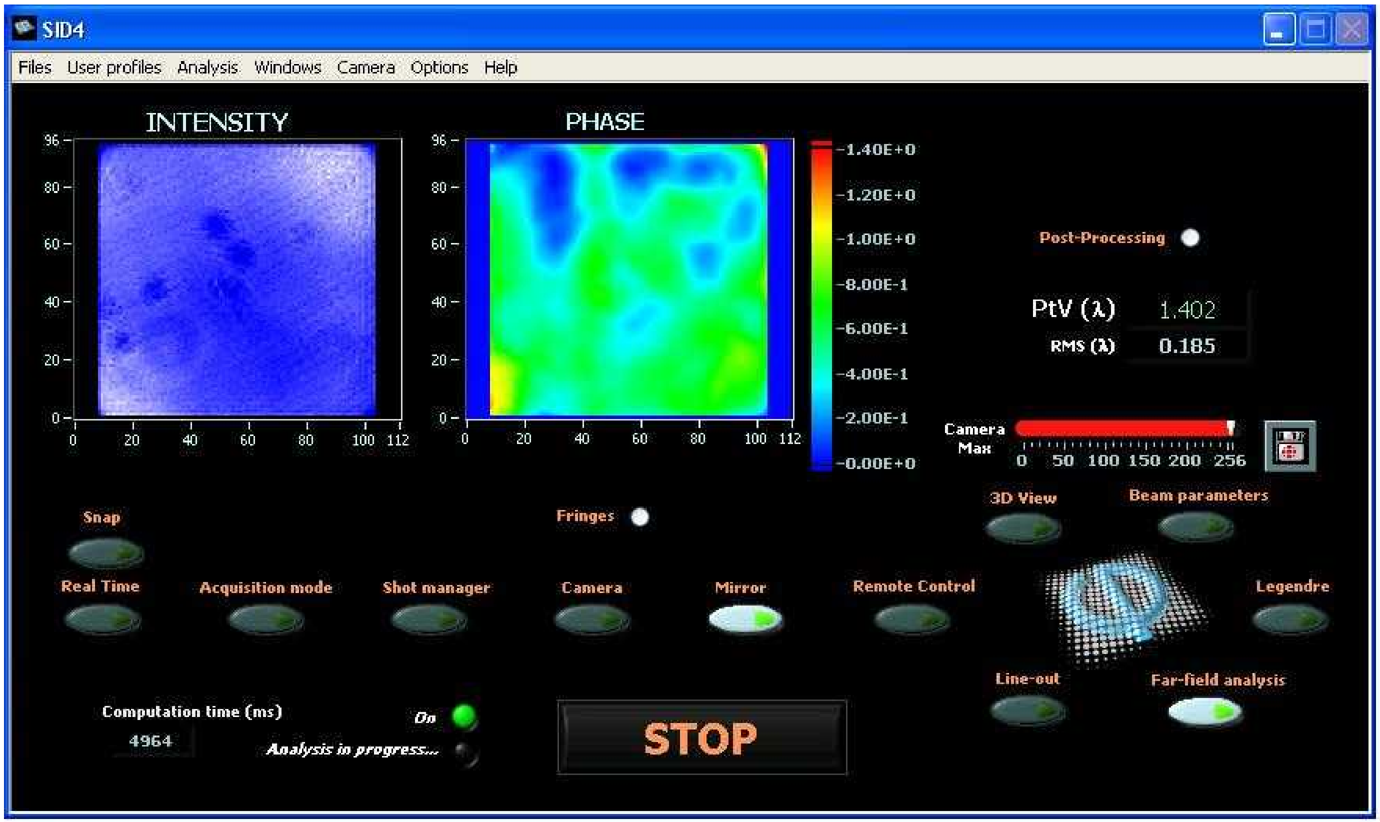
- First attempt to correct full system shot.



Full system shot with AO

Full system shot without AO

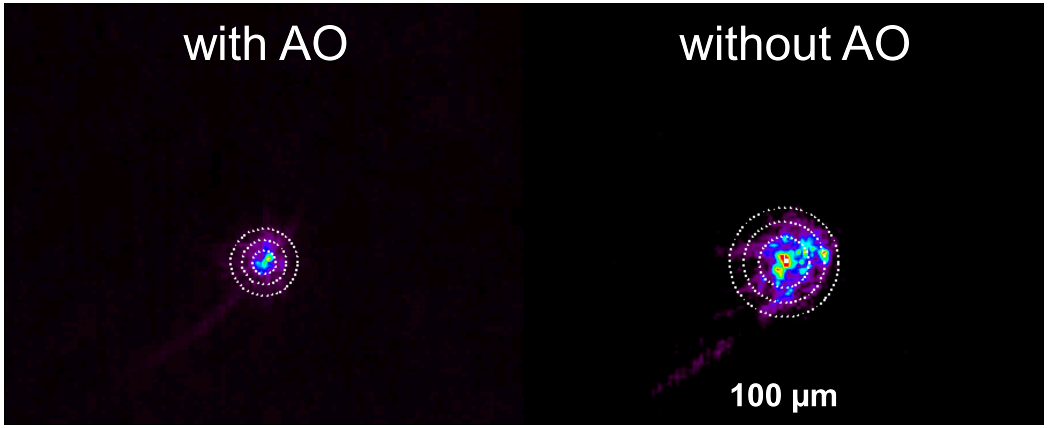
Conclusion

- 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

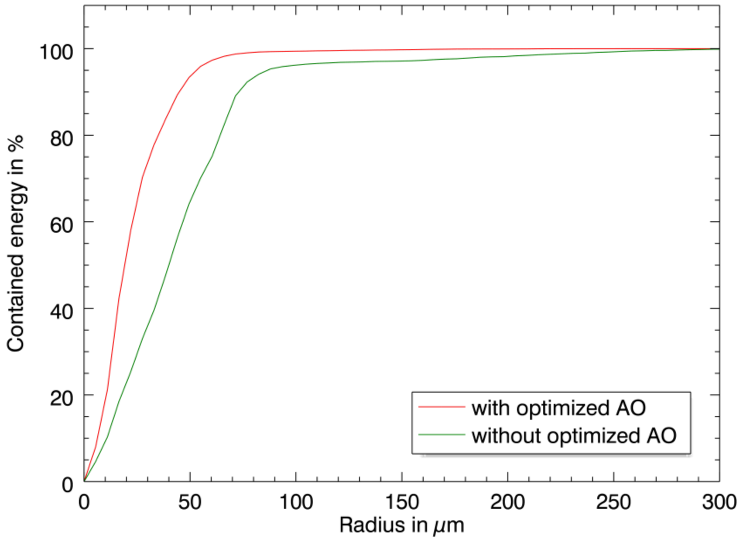
AO correction of regen beam

- 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



Chaco Laser Architecture