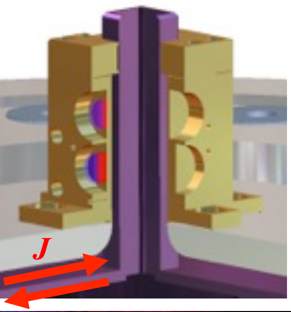

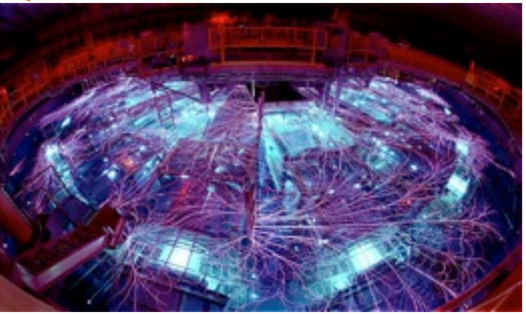

X-ray diffraction on Z

Tommy Ao and Marius Schollmeier

J. Benage, E. Field, M.W. Kimmel, J.L. Porter, P.K. Rambo, J. Schwarz, and C.T. Seagle

Sandia National Laboratories, Albuquerque, NM

Sandia National Laboratories

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Combining x-ray diffraction with Z's unique high energy density samples will provide benchmark quality data

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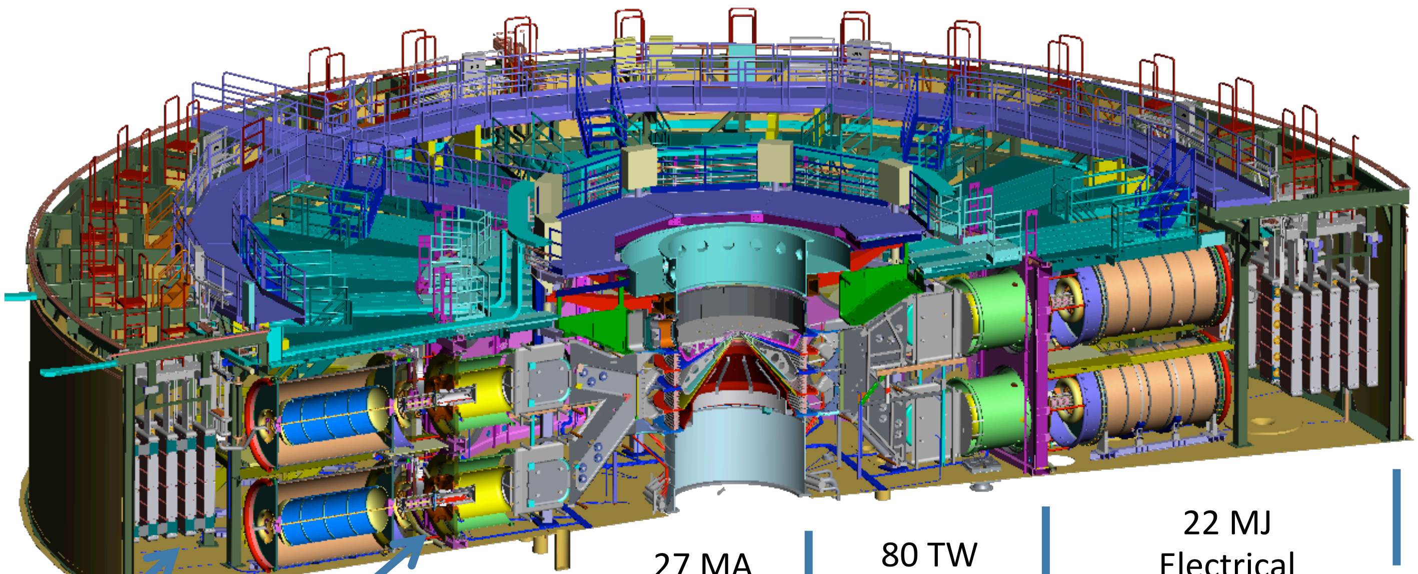
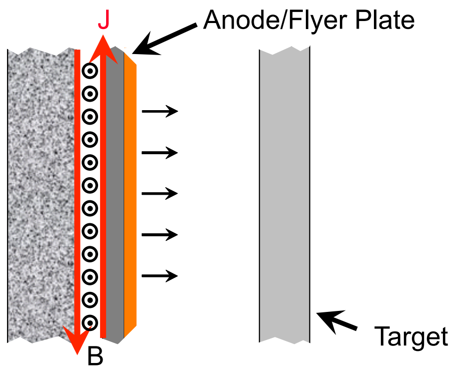
- Z's high energy density matter samples are large, uniform, long-lived and precisely characterized
- X-ray diffraction will expand diagnostic capabilities on Z beyond pressure and density measurements



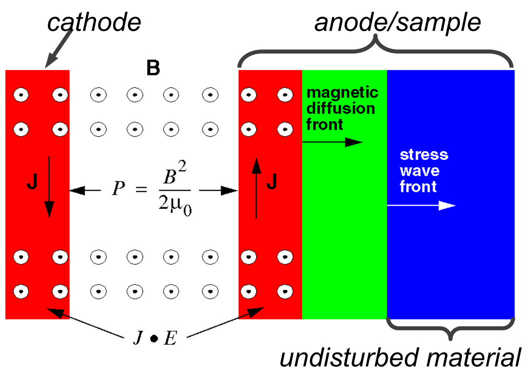
Operating Range: 11-27 MA

Z is a unique platform for equation-of-state studies

- Dynamic material properties (DMP) experiments



- Magnetically launched flyer plates for shock compression[1]
  - Flyer impact velocities to ~ 40 km/s
  - Hugoniot states to ~ 10 Mbar; 10,000 – 50,000 K
  - Pressure and density characterized ~ 1-2 %



- Ramp (shockless) compression[2]
  - Continuous quasi-isentropic compression to ~ 5 Mbar
  - Strain rates ~ 10^6-10^7 /s
  - Lower temperature states ~ 1000 – 3000 K

- Shock-ramp compression[3]
  - Initial flyer impact followed ramp loading
  - Complex loading path access off-Hugoniot states
  - Shock melt and ramp refreeze

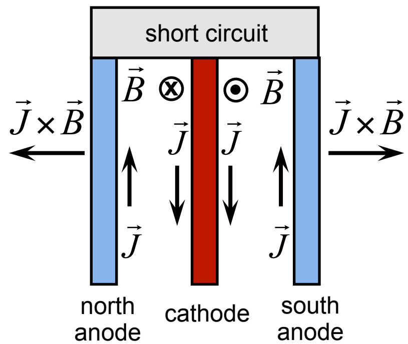
[1]R.W. Lemke *et al.*, J. Appl. Phys. **98**, 073530 (2005)

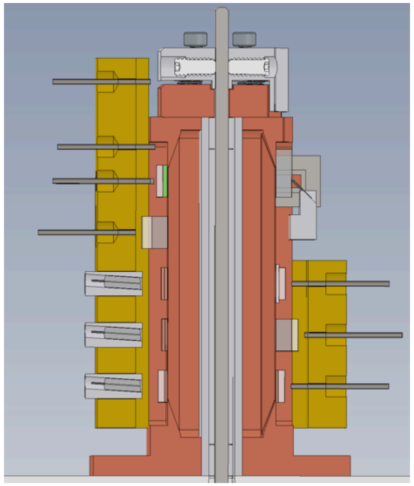
[2]J.-P. Davis *et al.*, Phys. Plasmas **12**, 056310 (2005)

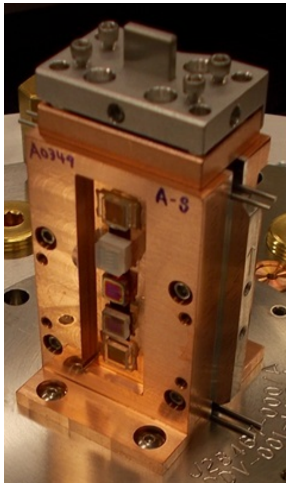
[3]C. T. Seagle *et al.*, Appl. Phys. Lett. **102**, 244104 (2013)

Z-DMP planar experiments

- Coaxial load[1]
  - Cathode stalk surrounded by anode panels
  - Dual pressures possible on north and south panels
  - Enclosed magnetic fields
  - More sample locations
  - Optimal for (flyer plate) shock compression

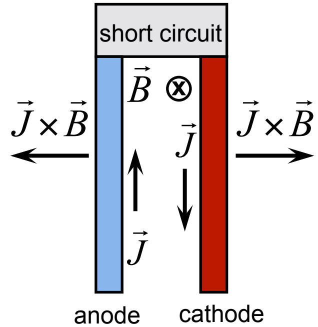


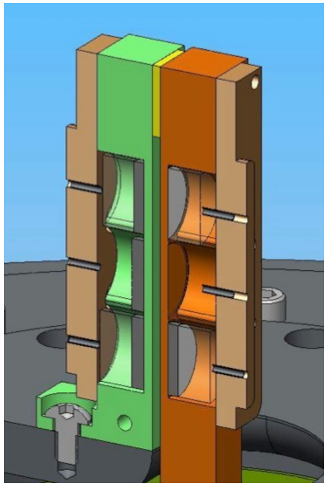




$$P = \frac{B^2}{2\mu_0}$$

- Stripline load[2]
  - Identical pressure on both cathode and anode panels
  - Higher current density and pressure
  - Open magnetic fields
  - Optimal for high-pressure ramp compression



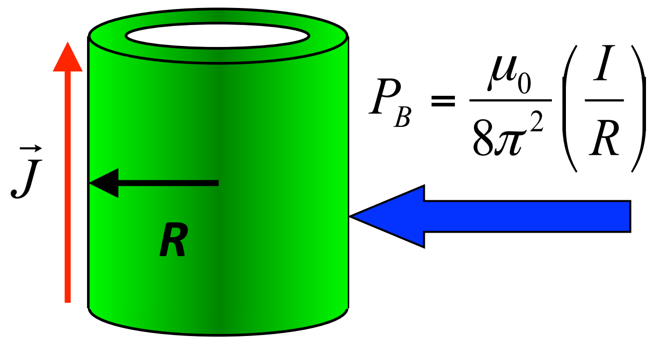


[1]M. D. Knudson *et al.*, J. Appl. Phys. **94**, 4420 (2003)

[2]R. W. Lemke *et al.*, Int. J. Impact Eng. **38**, 480 (2011)

Z-DMP cylindrical experiments

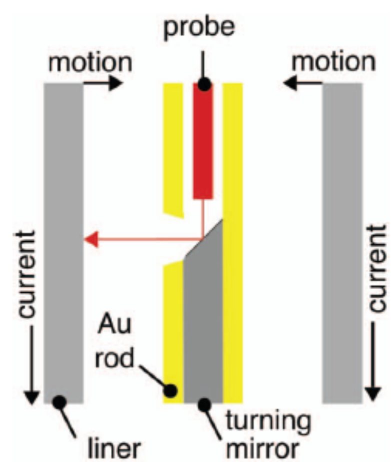
- Cylindrical implosion reaches extreme pressure states[1]
  - Current pulse shaping creates ramp-wave compression
  - Quasi-isentropic compression to 20 Mbar

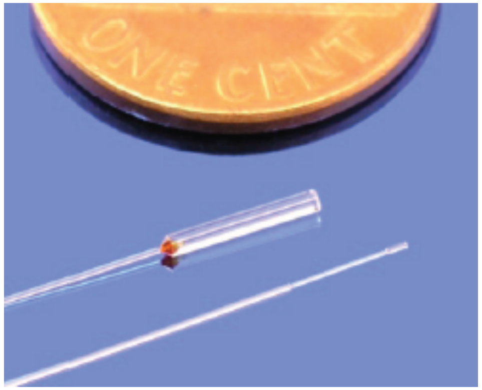


$$P_B = \frac{\mu_0}{8\pi^2}\left(\frac{I}{R}\right)^2$$

I = 20 MA
R = 1 mm
$P_B \approx$ 64 Mbar

- Diagnostics are challenging[2]
  - Limited space
  - Miniature probes
  - Velocities well beyond 10 km/s



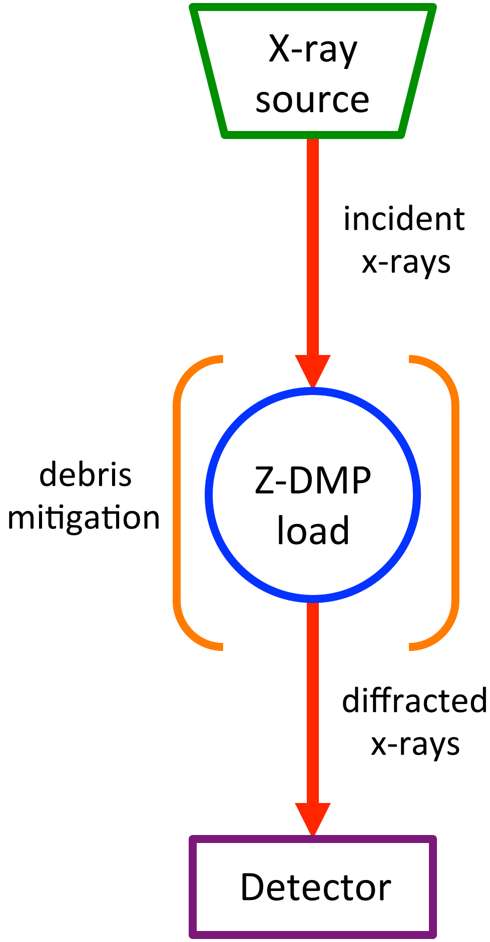


[1]M. R. Martin *et al.*, Phys. Plasmas **19**, 056310 (2012)

[2]D. H. Dolan *et al.*, Rev. Sci. Instrum. **84**, 055102 (2013)

3 key components to x-ray diffraction on Z-DMP experiments

- Produce source x-rays
  - Laser irradiate metal foil
  - X-pinch
  - X-ray diode
- Generate high-pressure state
  - Z-DMP load
  - Debris mitigation
  - X-ray background
- Detect diffracted x-rays
  - Image plate
  - Scintillator/phosphor
  - Streak camera
  - CCD

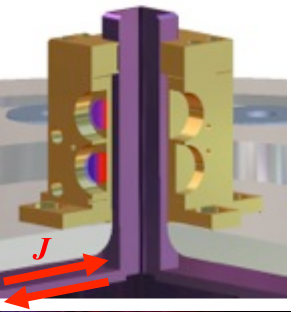


Challenges of x-ray diffraction on Z

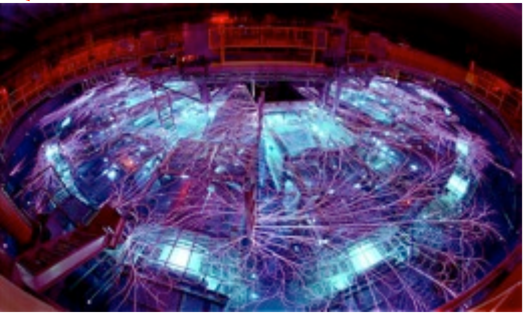
- Target parameters
  - Large and thick samples
  - Reflection geometry
  - Containment targets
    - Inserting incident x-rays
    - Extracting diffracted x-rays
- Destructive environment of Z-DMP load
  - Prevent catastrophic vacuum breach
  - Protect ZBL
  - Retrieve data
- X-ray background
  - High energy photons (up to 10 MeV) produced
  - Sufficient signal-to-noise
- Electromagnetic pulse (EMP)
  - Fry electronics

Addressing challenges of Z-XRD

- High photon energy (>10 keV), short duration (< 1ns) multi-pulse x-ray source
  - Penetrate into thick targets
  - Temporally resolve phase transformations
- Placing image plate, x-ray CCD, and x-ray streak camera near load
  - Robust x-ray and EMP shielding
  - Advanced debris mitigation
- Convert diffracted x-rays into visible photons
  - X-ray phosphor/scintillator near load
  - Transport light out of load region (fiber or open optics relay)



Laser-driven dynamic x-ray diffraction at Sandia



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Laser and source requirements

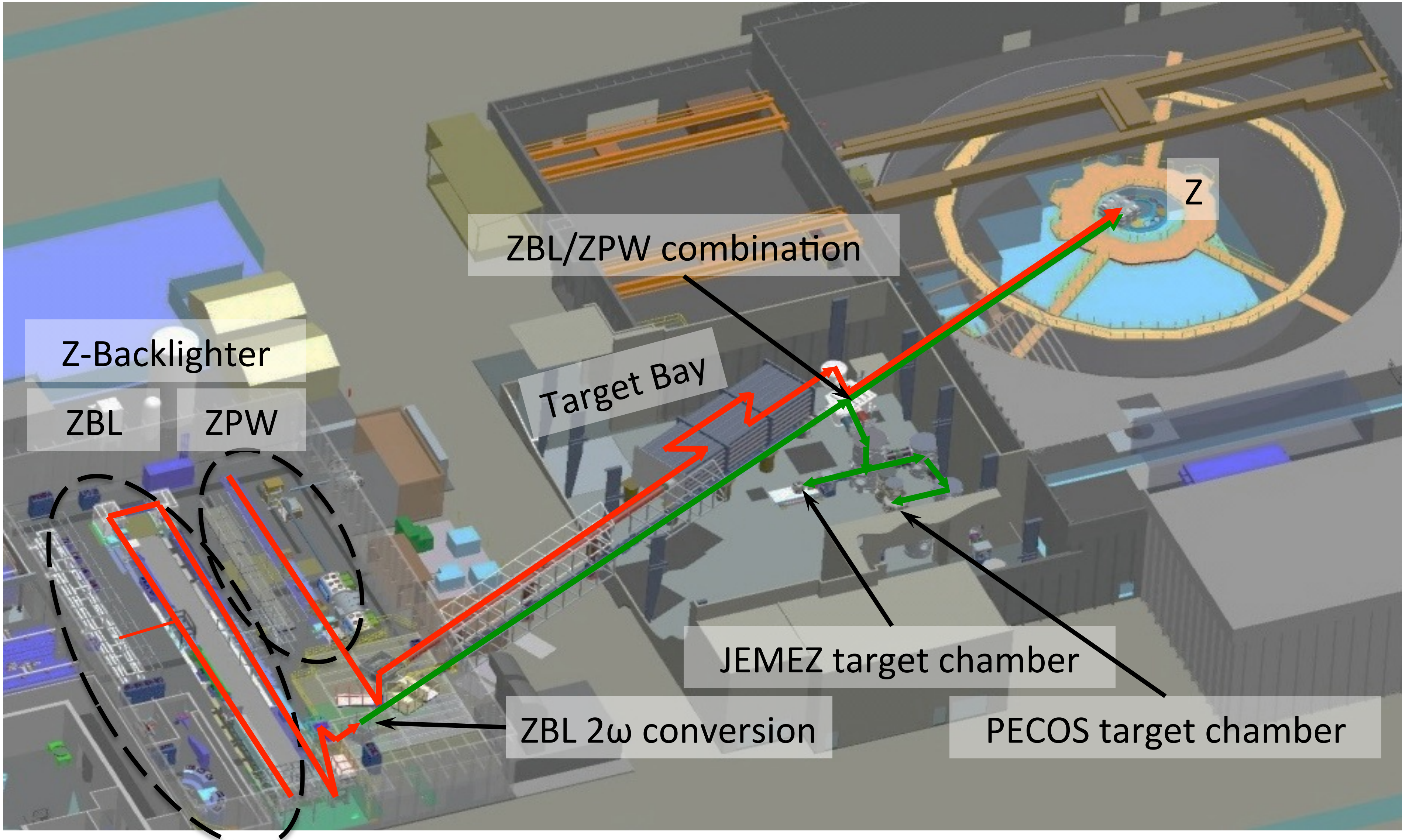
Source:
- Above 10 keV due to thick targets
- Monochromatic
- Short emission duration (1 ns or below)
- Multi-pulse with >5 ns inter-pulse delays

→ use multiple Kα bursts from period-5 transition metals (15-25 keV)

Laser and focusing hardware:
- Multi-pulse capability
- Sub-ns pulse duration
- Final focusing optics well-shielded from Z debris
- Z vacuum protection when debris protection does not hold

→ modify ZPW for multi-pulse, 100-ps operation & use existing ZBL lens focusing

Facility Overview

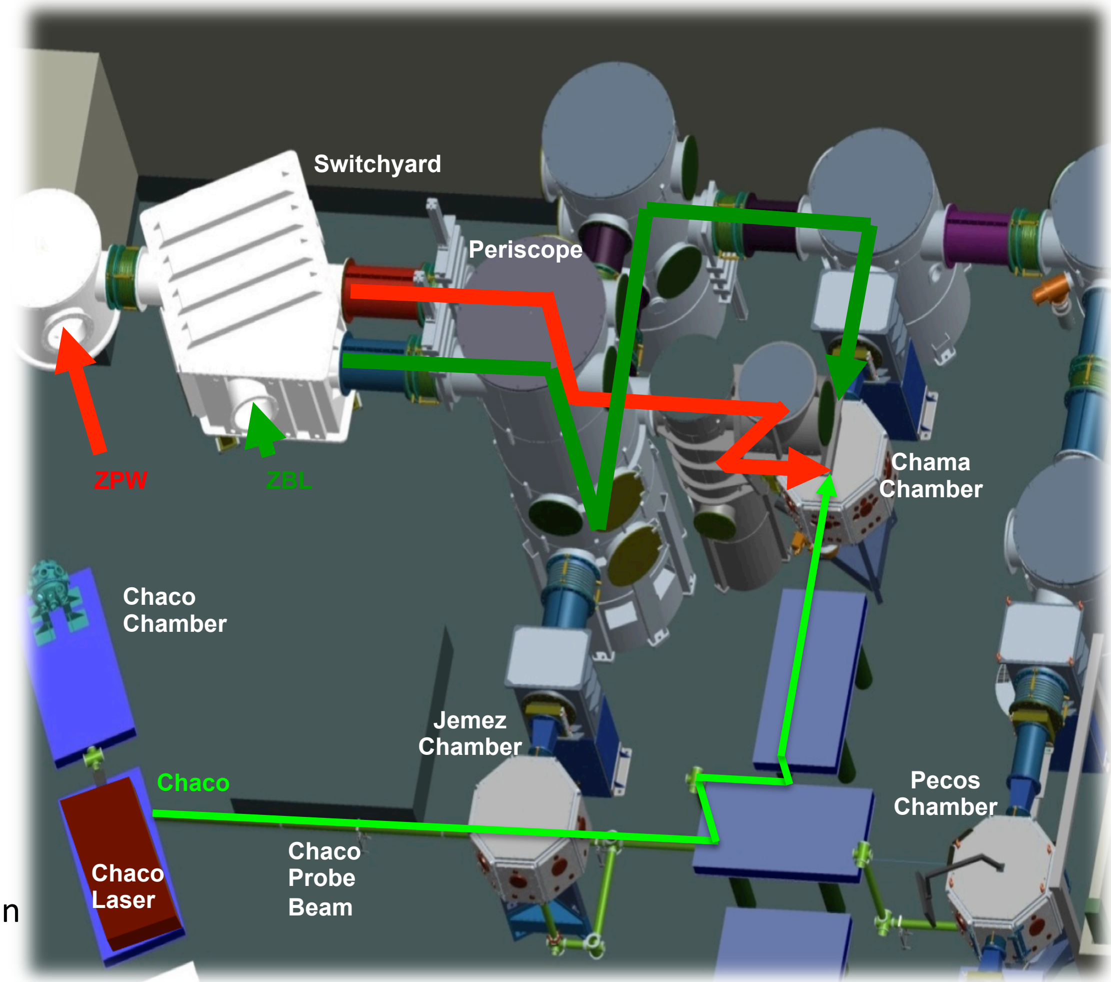


Target Bay Overview

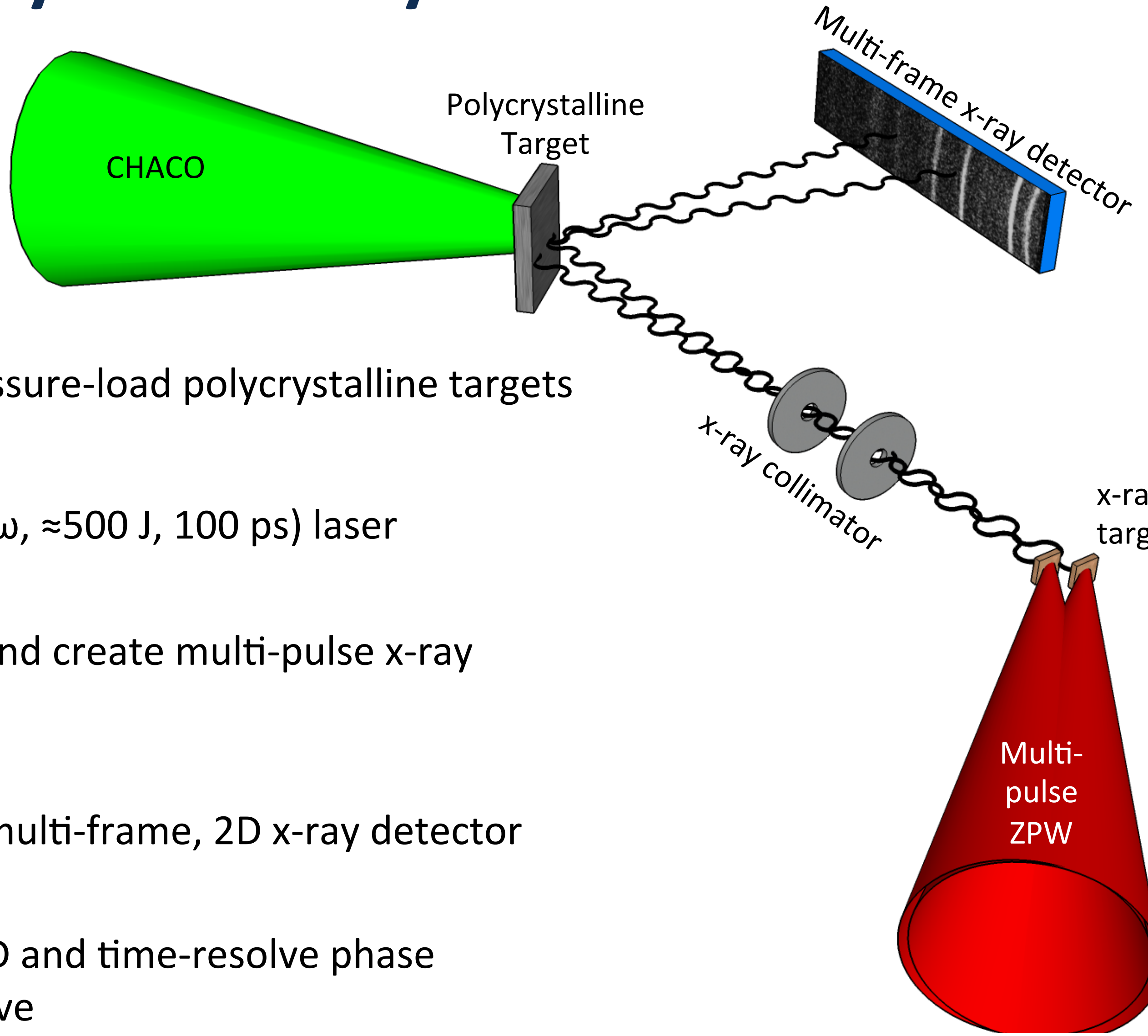
New target chamber (CHAMA)
- 1st chamber to use ZBL, ZPW & CHACO
- anticipated activation: Q1, FY16

Laser systems:
- Chaco laser to load diffraction targets
- Up to 50J/532nm/5-10ns
- Status:
  - Laser operational
  - Beam delivery to CHAMA under construction

- ZPW to create x-ray source
- Up to ~400J/1054nm/50-200ps
- Energy is limited due to gold gratings and B-integral issues in final focal lens
- Status:
  - Laser operational
  - Optics being coated
  - Mounting hardware under construction

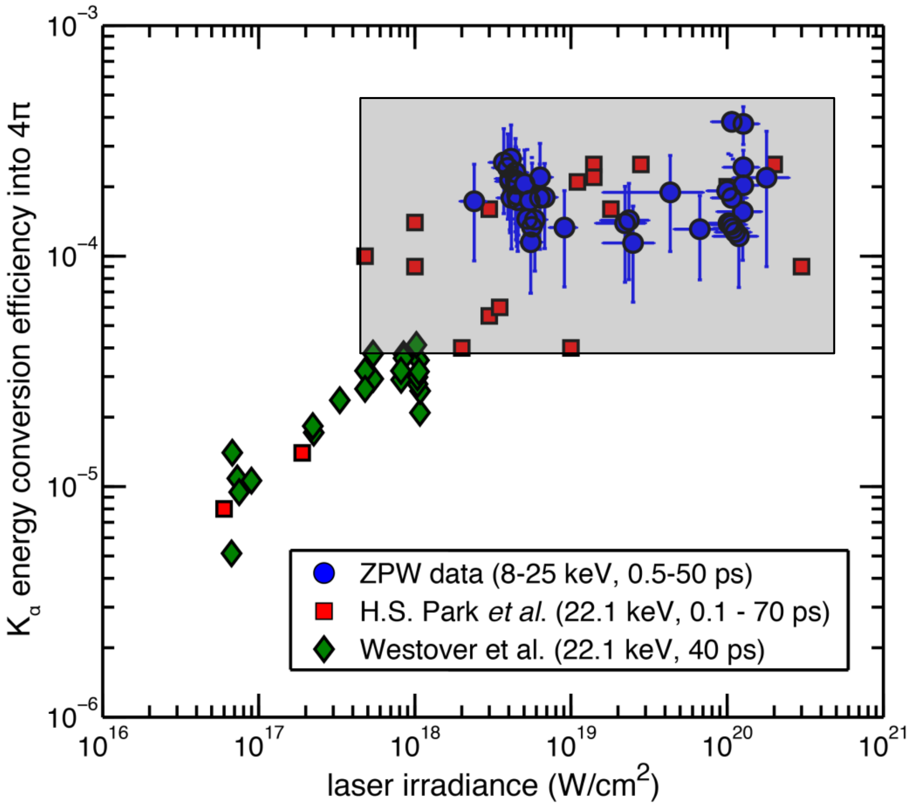


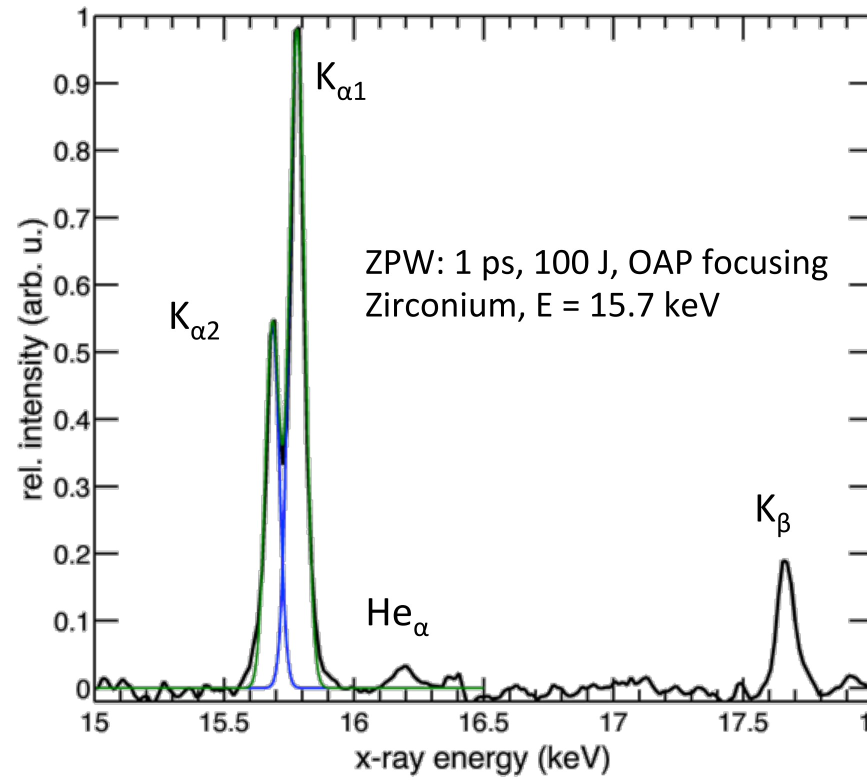
Laser-driven dynamic x-ray diffraction



- Use CHACO laser to pressure-load polycrystalline targets to 1-10 Gpa
- Use Z-Petawatt (ZPW, 1ω, ≈500 J, 100 ps) laser
- Focus ZPW with a lens and create multi-pulse x-ray source (Δt ≈ 2-20 ns)
- Design and implement multi-frame, 2D x-ray detector
- Perform multi-pulse XRD and time-resolve phase changes during laser drive

Sub-ns laser-created x-ray sources





- Lens-based focusing of ZPW requires 100-ps-scale pulse duration
  - How efficient is 100-ps x-ray generation?
  - What is the photon yield?
  - How “clean” is the spectrum (He_α)?
  - What is the x-ray pulse duration?
  - What is the optimum target size?

Debris generation at Z

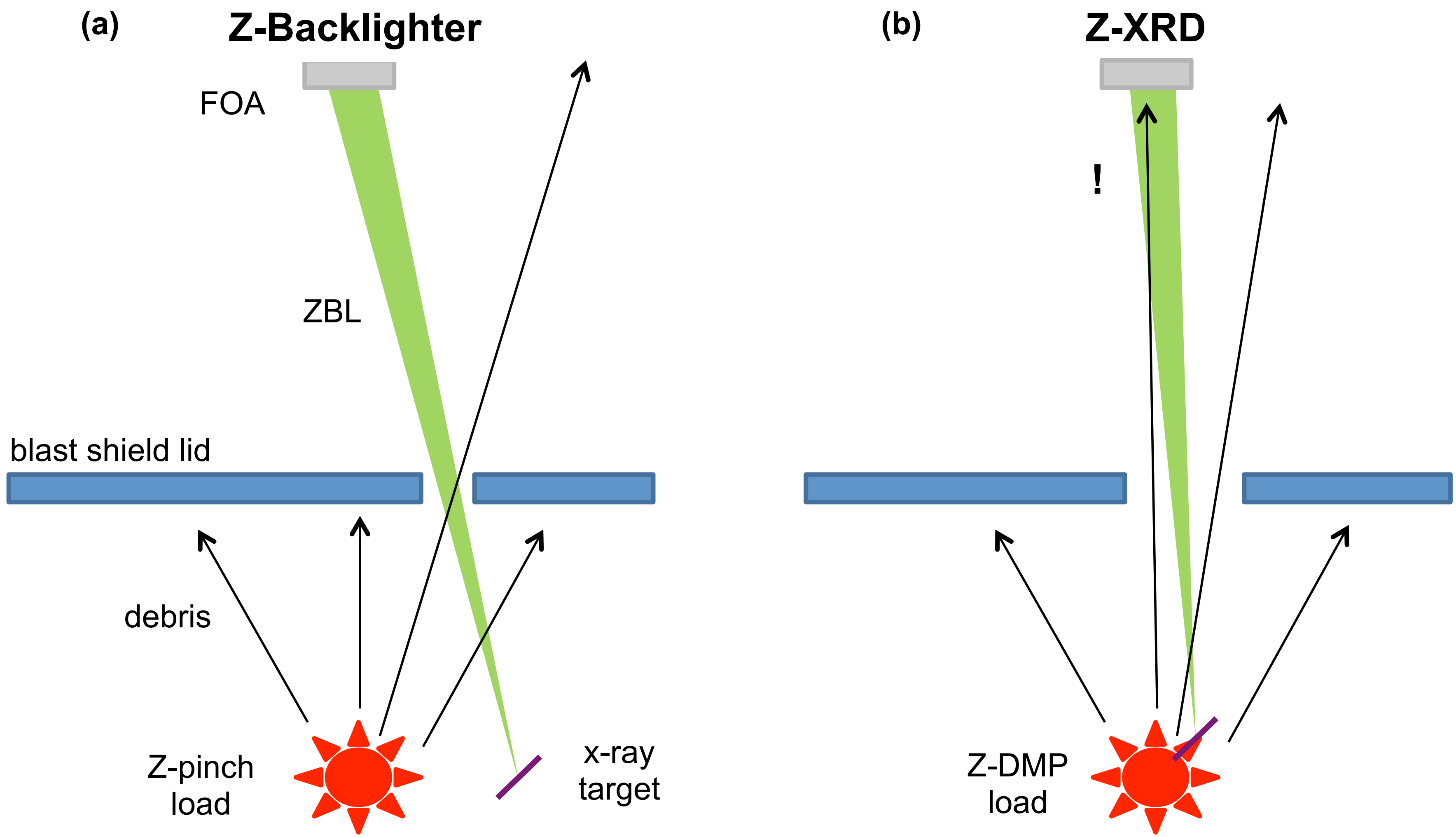
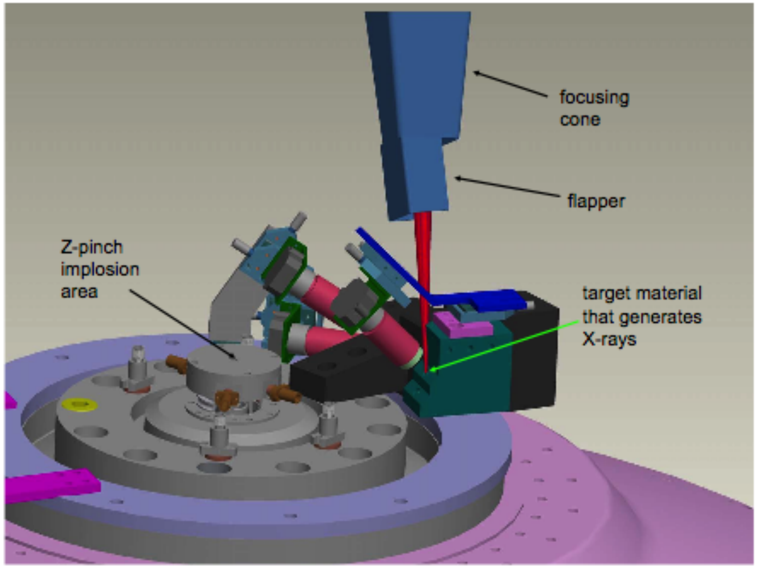


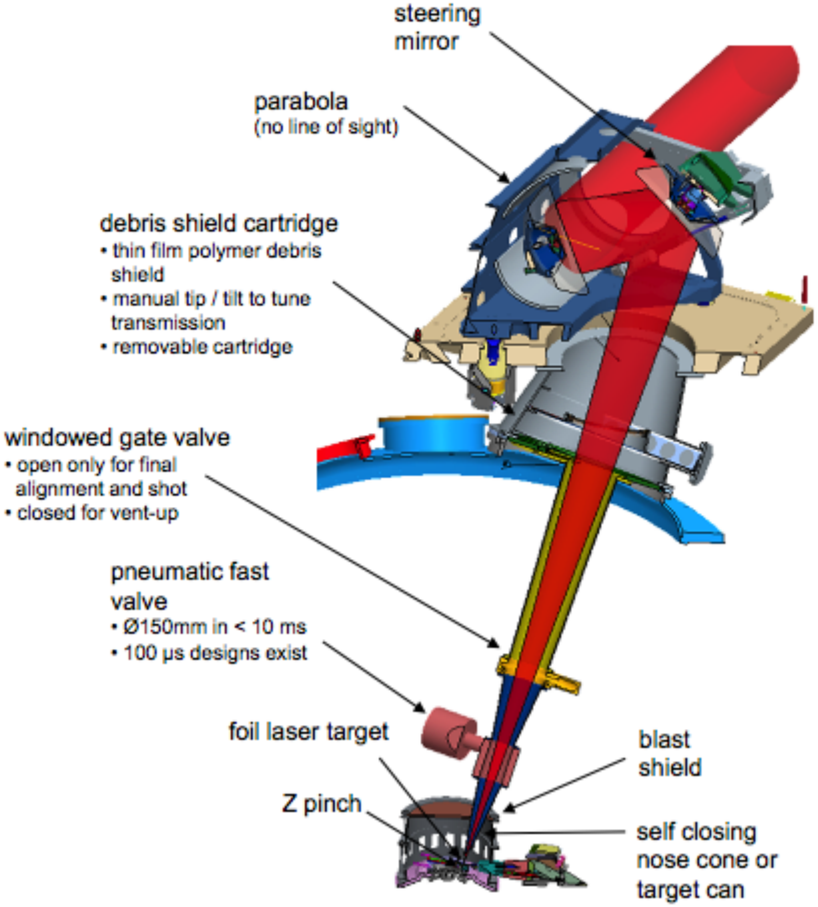
Image taken from J.E. Bailey *et al.*, Sandia Report SAND2012-7998 (2012)

current ZPW Final Optics Assembly for Z

- ZPW:
  - 43x43 cm beam
  - 500 J, 500 fs
  - F/# = 11 parabola (f = 4.73 m)

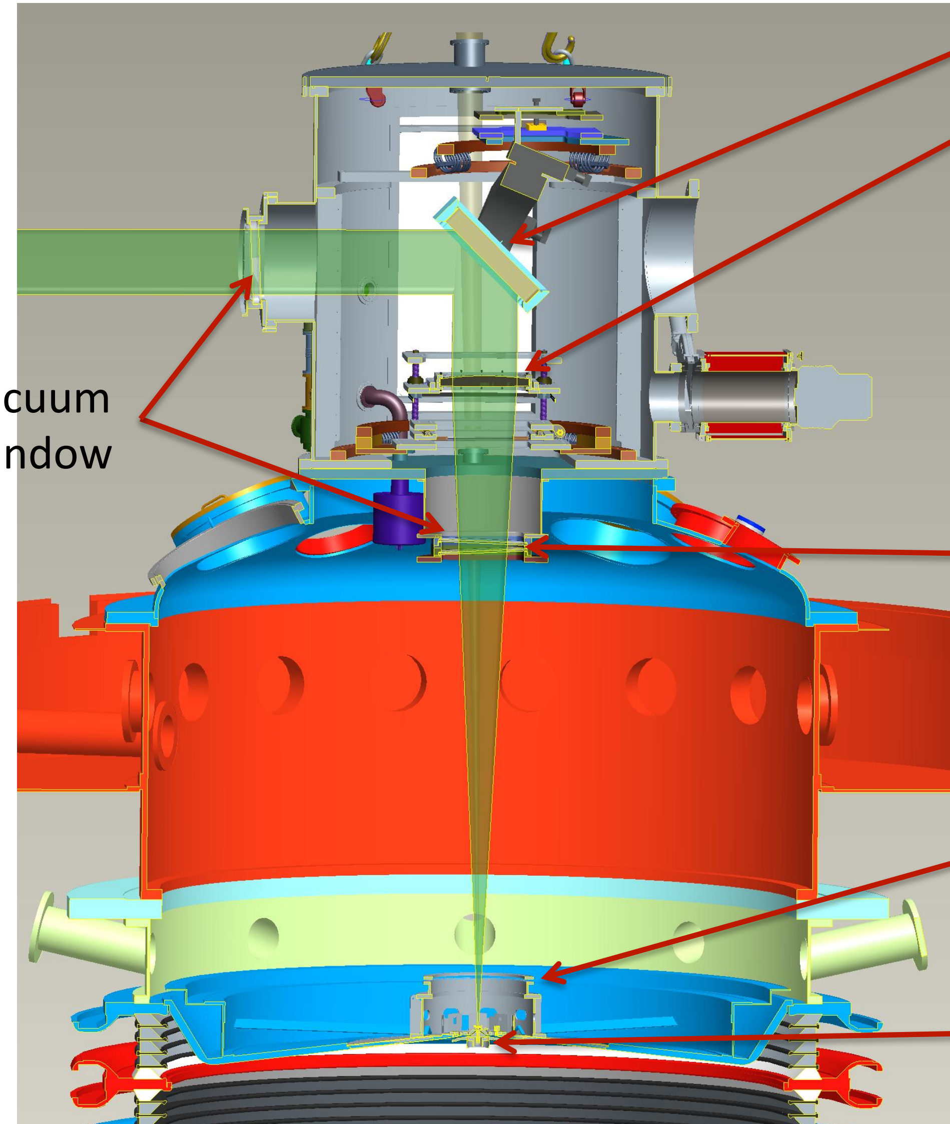
- FOA is designed for off-axis, sub-ps irradiation of backlighter targets





J. Schwarz et al., PRST-AB 13, 041001 (2010)

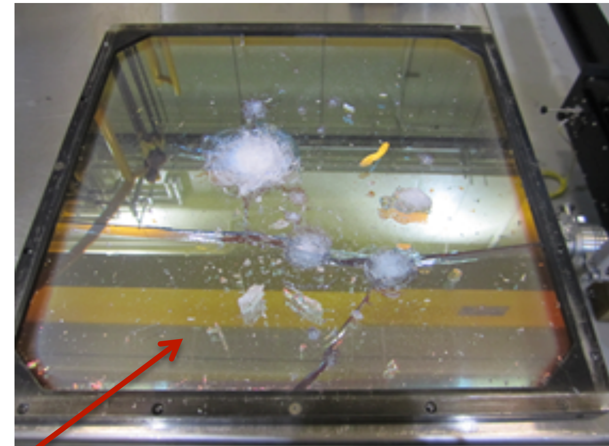
Optics protection for on-axis irradiation



vacuum
window

45°-mirror

lens



debris shield

blast shield

Z load

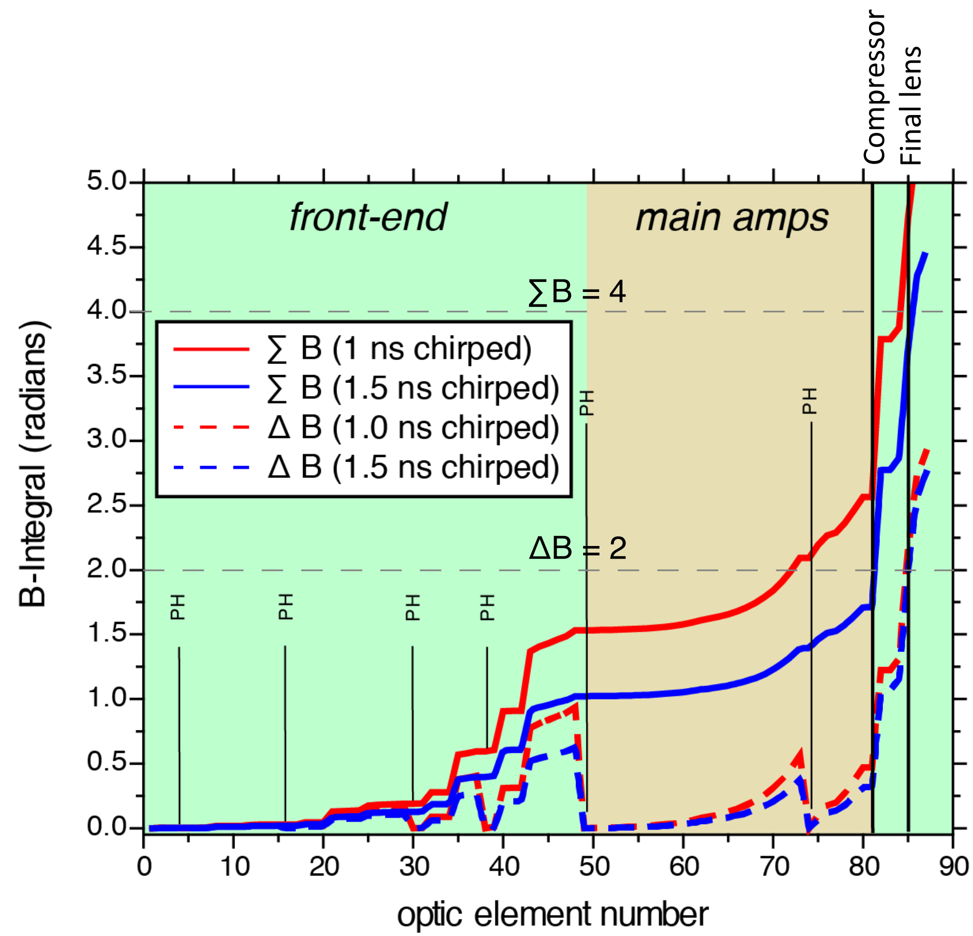
B-Integral considerations

- Refractive index depends on intensity: $n(I) = n_0 + n_2 I$
- Intense laser propagation then has a nonlinear component to phase ($\Phi = 2\pi/\lambda\ n(I)\ z$), which accumulates (called B-integral):

$$B = \frac{2\pi}{\lambda} \int_0^L n_2(z) I(z)\ \mathrm{d}z$$

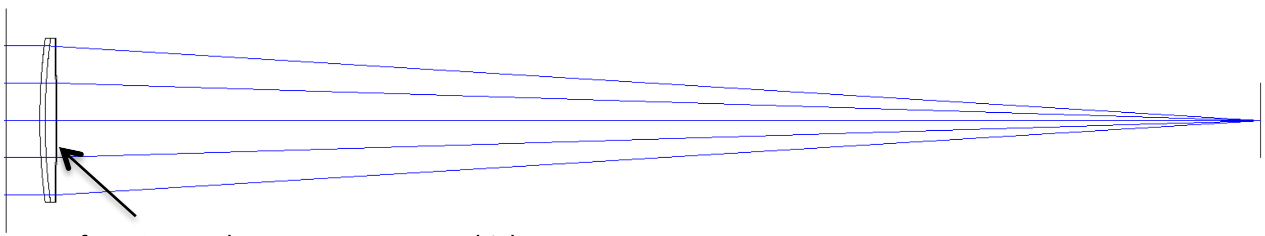
- Limits:
  - Total accumulated nonlinear phase must be **$\sum B < 4$** to avoid whole-beam self-focusing effects (i.e., focal spot shifting)
  - "small" spatial defects can be stripped at pinholes of spatial filters. B-integral between pinholes resets to 0 at each pinhole. Keep **$\Delta B < 2$**

$\Longrightarrow$ Amplify pulse with 1-1.5 ns chirp, then compress to ≈100 ps prior to focusing



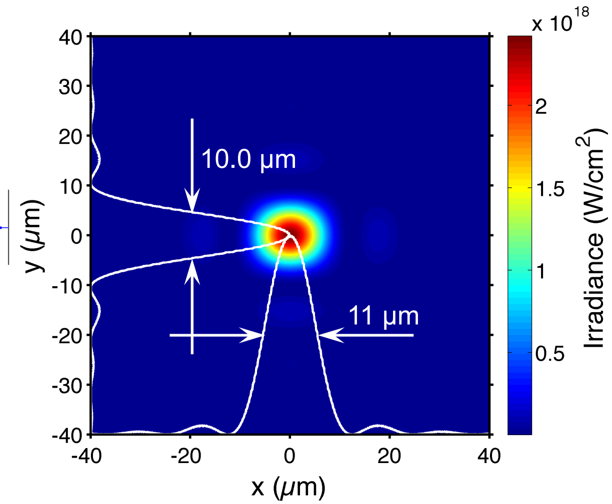
Expected laser focal spot and intensity

- ZEMAX modeling with the existing ZBL lens to focus a 10 TW (1 kJ/ 100 ps) ZPW beam indicates:
  - $\approx 1.2 \times 10^{10}$ W/cm^2 at the lens (matches B-Integral model)
  - focal spot: 11 µm × 10 µm (FWHM)
  - $\approx 8 \times 10^{18}$ W/cm^2 at the best focus



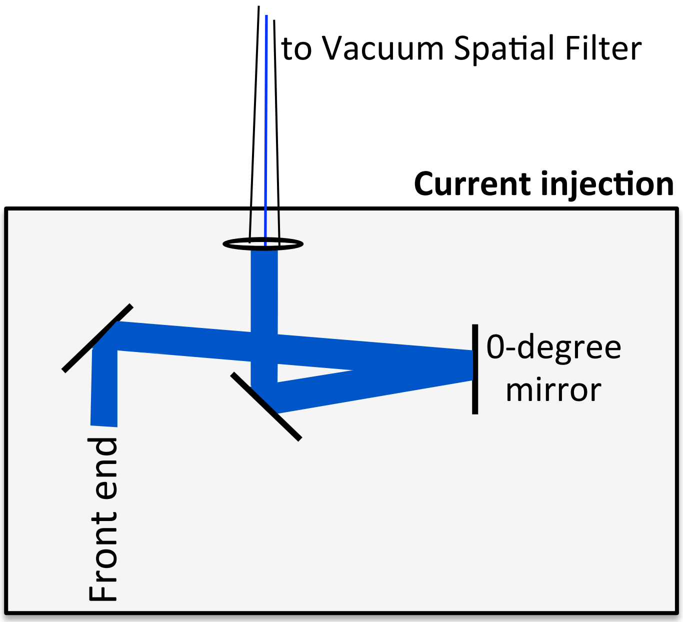
f = 3.2m Asphere, 4.5 cm center thickness
No vacuum windows or debris shields accounted for

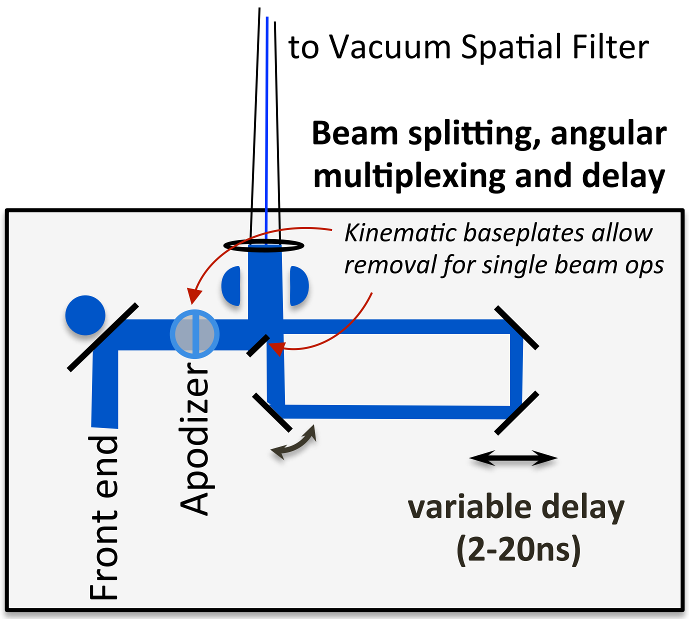
Simulated focused beam profile



Multi-frame ZPW modification

- Concept:
  - Spatially split beam before injection into main amp section
  - Full delay adjustment (2-20 ns)
  - *Separated* far-field spots (2 targets)
  - Similar to Z-Beamlet multi-frame backlighter (MFB) concept but without certain energy losses (except for apodization strip at 10% level)
  - Compatible with vacuum compressor in Target Bay
  - Allows 2 beams with each at 500J/0.1ns or 1kJ/0.2ns (B-integral limited)

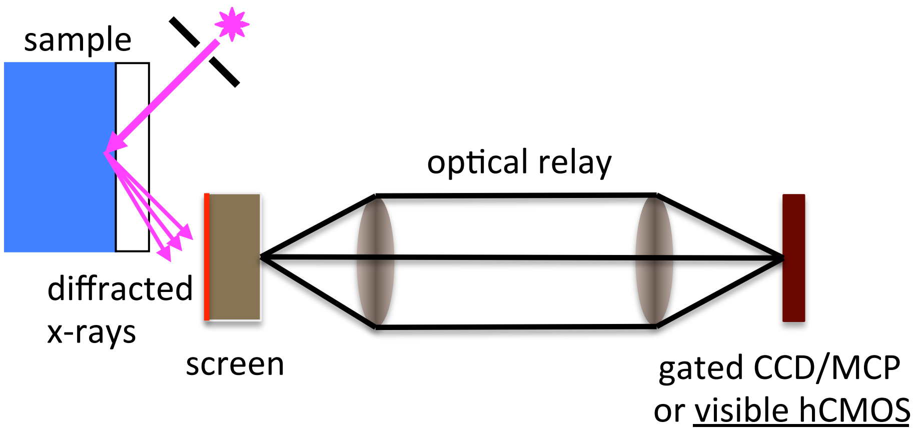




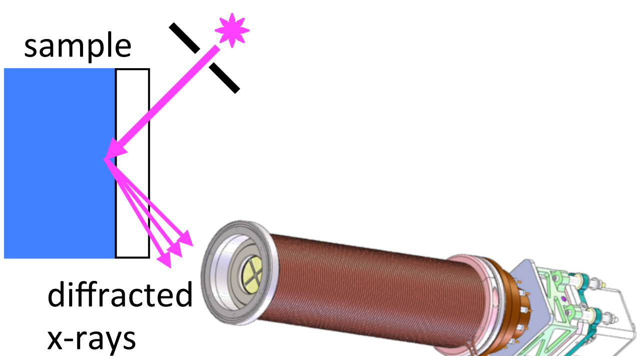
Multi-frame, time-resolved detector ideas

- First measurements will be time-integrated
  - Use image plate as detector

- later: Scintillator/Phosphor screen + relay optics
  - Single-frame with CCD camera
  - Multi-frame operation with hCMOS camera



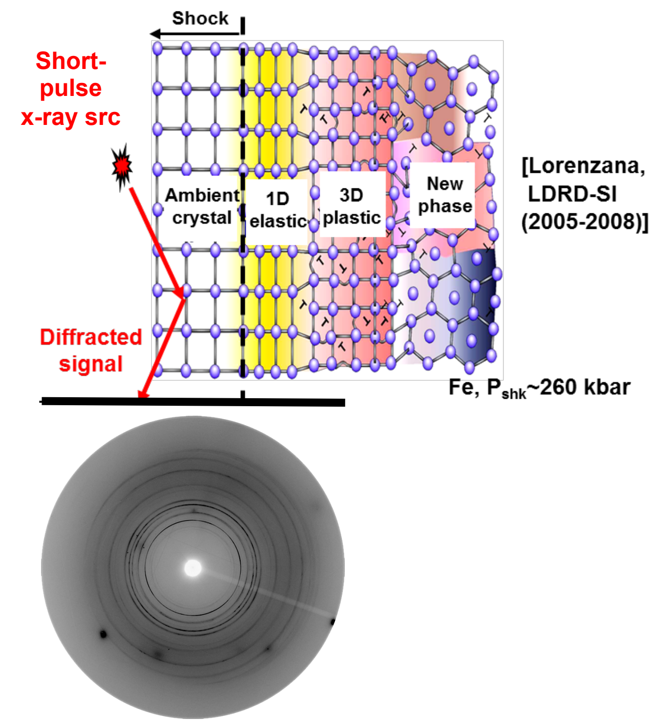
- Alternative: DIXI + hCMOS
  - Not clear how close DIXI can be to the target
  - Requires further investigation



END

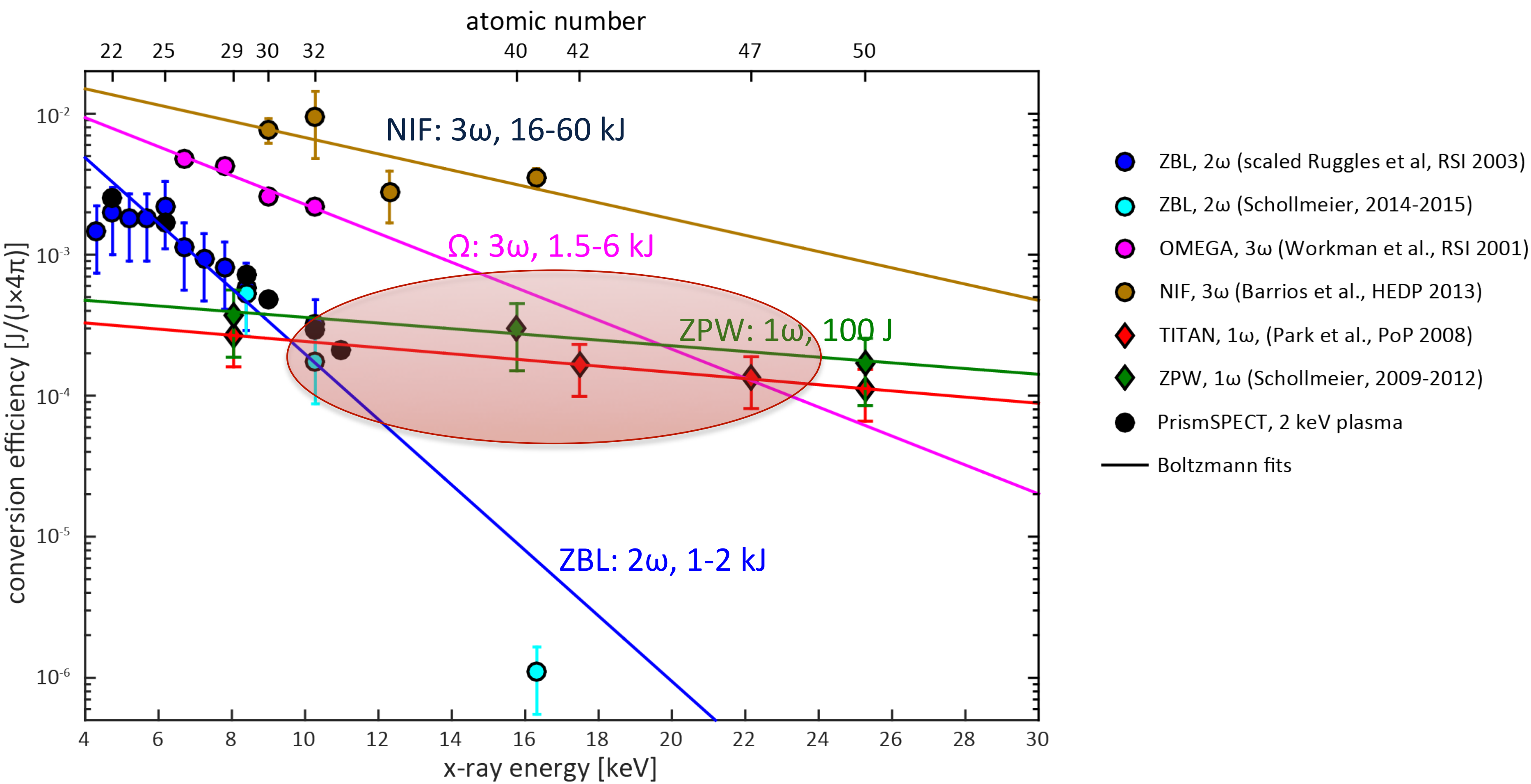
Diagnosing material lattice dynamics during a dynamic compression experiment

- What?
  - Characterize phase transformations that occur in dynamically compressed condensed matter on ns time scales and nm spatial scales
- Why?
  - Such information enables to determinate how material behaves under extreme conditions
  - For most materials, there are very few constraints on existing models for phase transitions under dynamic loading
- How?
  - perform **time-resolved, x-ray diffraction** measurements on dynamically compressed, polycrystalline matter (dynamic x-ray diffraction, DXRD)
  - Requires **sub-ns x-ray probe** to resolve dynamics
  - High-Z material requires **>10 keV x-rays**
  - Use **short-pulse laser** to create source
  - Modify short-pulse laser system for **dual pulse** operation to temporally resolve phase transition dynamics



Cartoon from https://str.llnl.gov/str/JulAug06/Lorenzana.html

Z-Backlighter facility laser-to-x-ray conversion efficiency scaling



Focusing ZPW with a lens: Multi-pulse operation

Options Considered for ZBL MFB

- Angle multiplexing
  - Via lateral pinhole offset

Grating Cost

- ~~Wavelength multiplexing~~
  - ~~Separated by diffraction grating~~
- Aperture division multiplexing
  - Separated by wedge refraction
- Combinations of these

Options Considered for Two Color ZPW/ZBL Backlighting

Insufficient DI

- ~~Wavelength- 1w and 2w beams could be separated by dichroic coatings~~
  - ~~ZBL is 70% 2w and 30% 1w (1w could be stripped in 986)~~
  - ~~ZPW is 100% 1w~~

Gratings give one Polariz.

- ~~Polarization- Polarizers could separate vertical and horizontally polarized pulses~~
  - ~~ZBL 1w is horizontal, 2w is vertical~~
  - ~~ZPW is horizontal for gold gratings (current), vertical for MLD gratings (required for high energy) or horizontal for bypassing the gratings.~~

Gratings give one Polariz.

- ~~Temporal- Pockels cell could be used in conjunction with polarizers to differentially direct temporally separated pulses~~
  - ~~Redirection needs to be done at full size but full size PEPC is too slow for the required delays.~~
- Spatial- Aperture division could redirect a portion of the beam
  - 15% of the ZBL MagLIF heating beam could be split off with aperture division
  - Reduces energy for heating
  - How much energy is needed for backlighting?

B-Integral

- ~~Partial reflection/diffraction- A partial reflector/director could redirect 15% of the beam~~
  - ~~How much energy is needed for backlighting?~~

For ZPW MFB, it is best to consider either aperture or angle multiplexing or a combination.

Lens-based focusing