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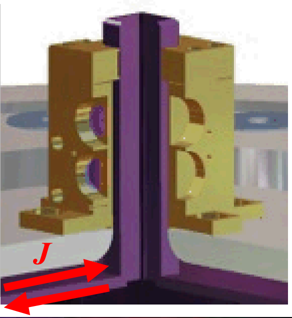
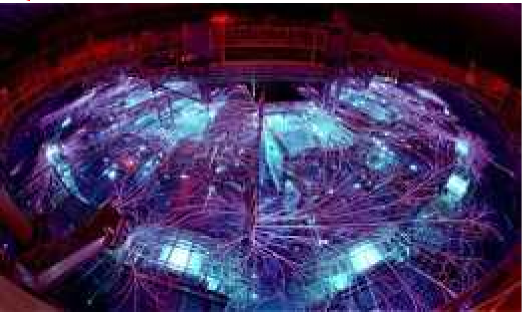


X-ray diffraction on Z



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

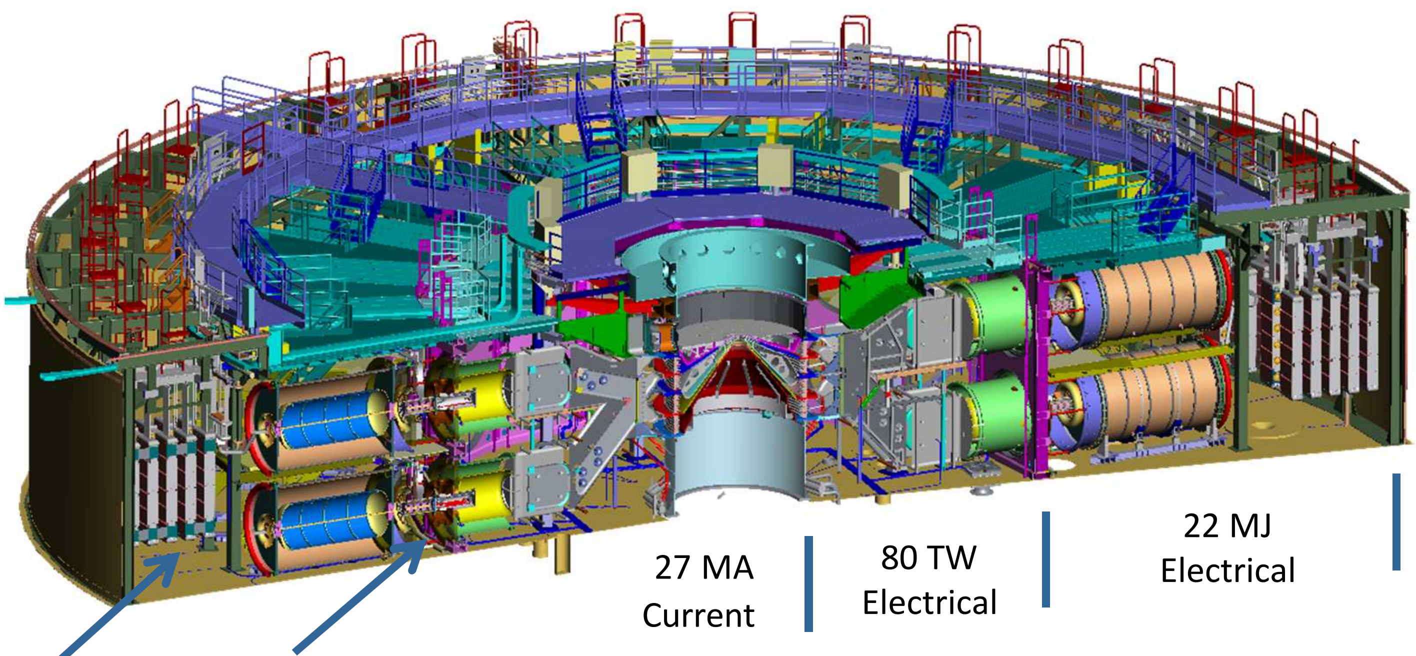
Exceptional service in the national interest

National ICF Diagnostics Working Group Meeting

Los Alamos National Laboratory, Los Alamos, NM, October 6-8, 2015

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

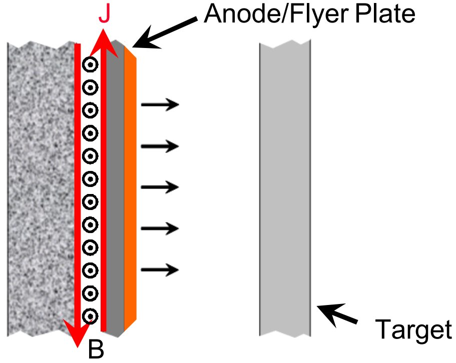
- Z's high energy density matter samples are large, uniform, long-lived and precisely characterized
- X-ray diffraction will expand diagnostic capabilities on Z beyond pressure and density measurements



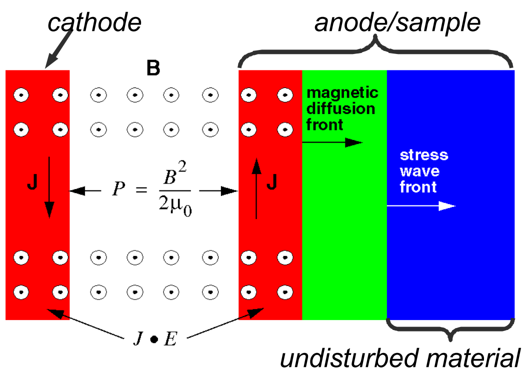
Operating Range: 11-27 MA

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

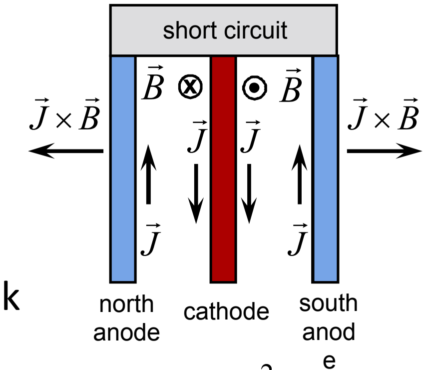
[1]R.W. Lemke *et al.*, J. Appl. Phys. **98**, 073530 (2005)

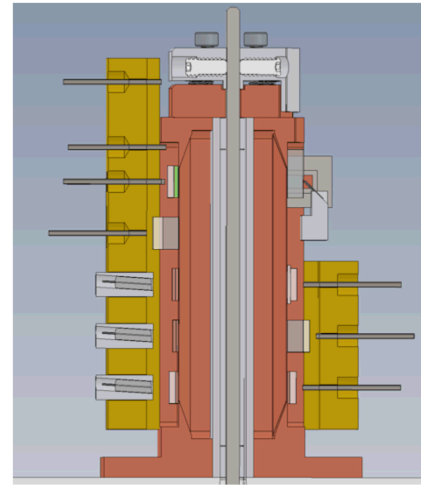
[2]J.-P. Davis *et al.*, Phys. Plasmas **12**, 056310 (2005)

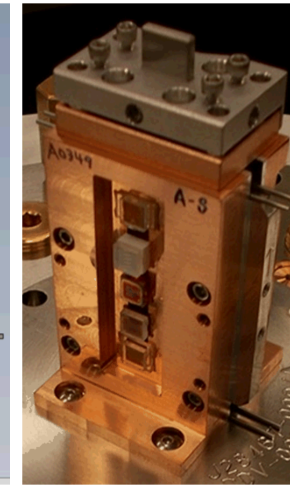
[3]C. T. Seagle *et al.*, Appl. Phys. Lett. **102**, 244104 (2013)

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

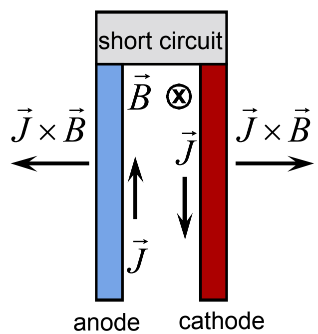


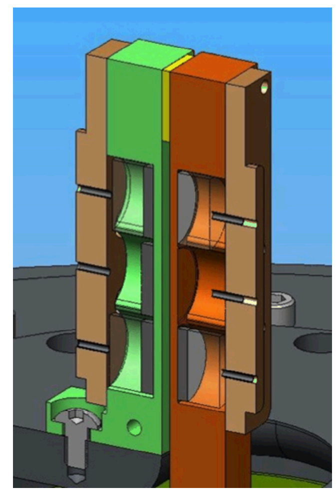




$$P=\frac{B^2}{2\mu_0}$$

- 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



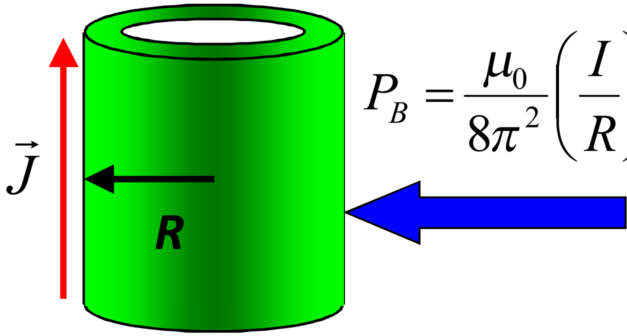


[1]M. D. Knudson *et al.*, J. Appl. Phys. **94**, 4420 (2003)

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

Z-DMP cylindrical experiments

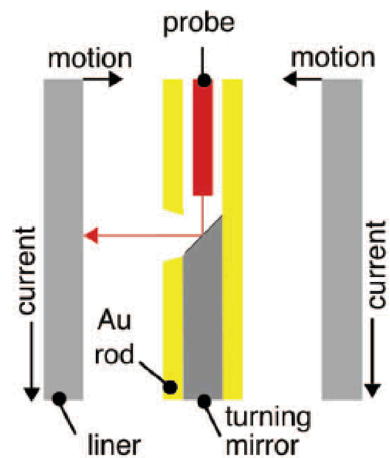
- Cylindrical implosion reaches extreme pressure states[1]
  - Current pulse shaping creates ramp-wave compression
  - Quasi-isentropic compression to 20 Mbar

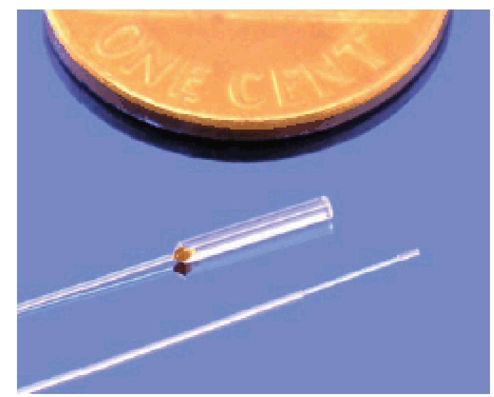


$$P_B = \frac{\mu_0}{8\pi^2}\left(\frac{I}{R}\right)^2$$

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



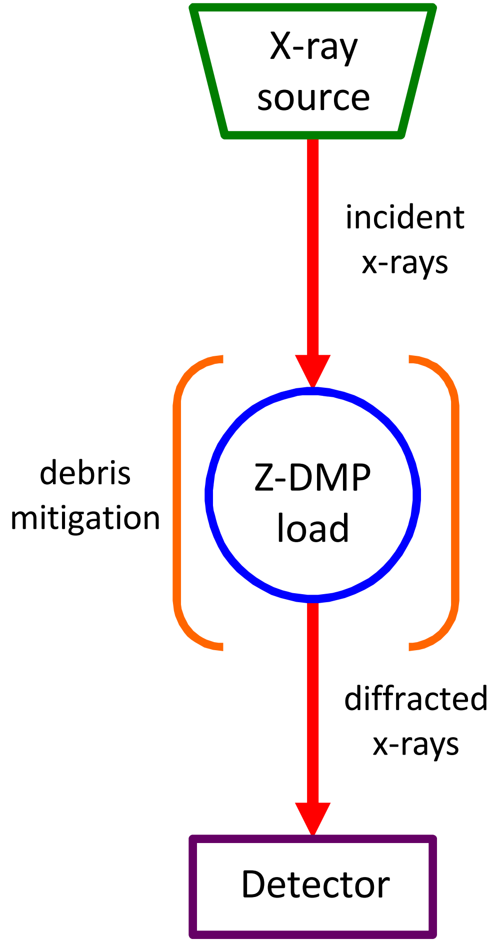


[1]M. R. Martin *et al.*, Phys. Plasmas **19**, 056310 (2012)

[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

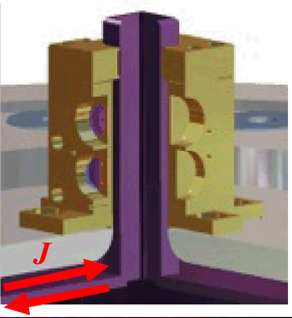


Challenges of x-ray diffraction on Z

- 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

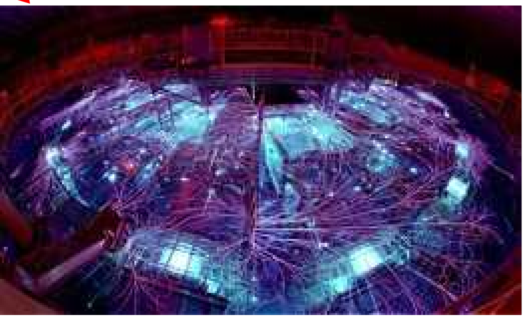
Addressing challenges of Z-XRD

- 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)



Z

Z Beamlet



Sandia National Laboratories

Exceptional service in the national interest

Laser-driven dynamic x-ray diffraction at Sandia

Tommy Ao and Marius Schollmeier

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

Sandia National Laboratories, Albuquerque, NM

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Los Alamos National Laboratory, Los Alamos, NM, October 6-8, 2015

U.S. DEPARTMENT OF ENERGY

NNSA

Laser and source requirements

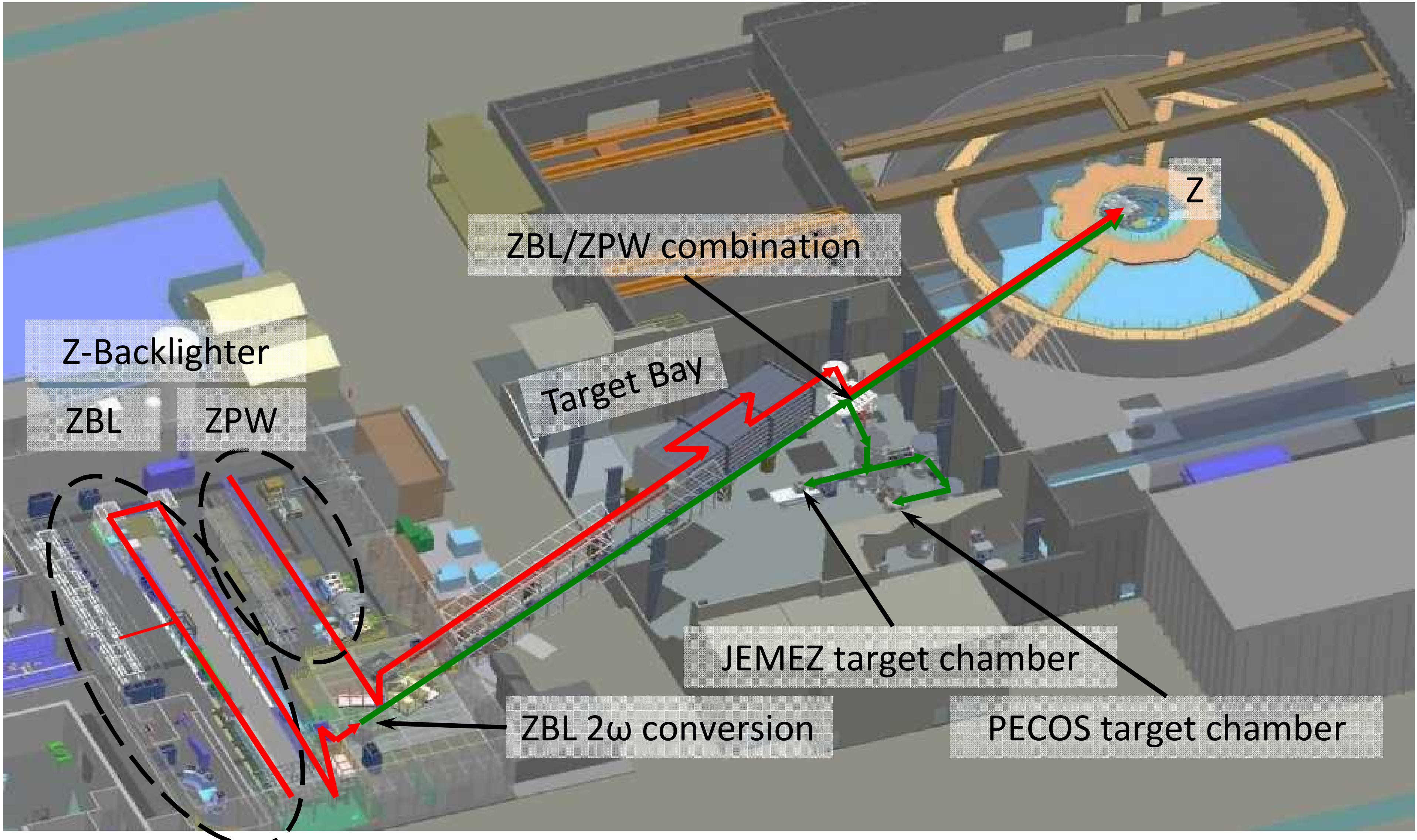
Source:
- Above 10 keV due to thick targets
- Monochromatic
- Short emission duration (1 ns or below)
- Multi-pulse with >5 ns inter-pulse delays

→ 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

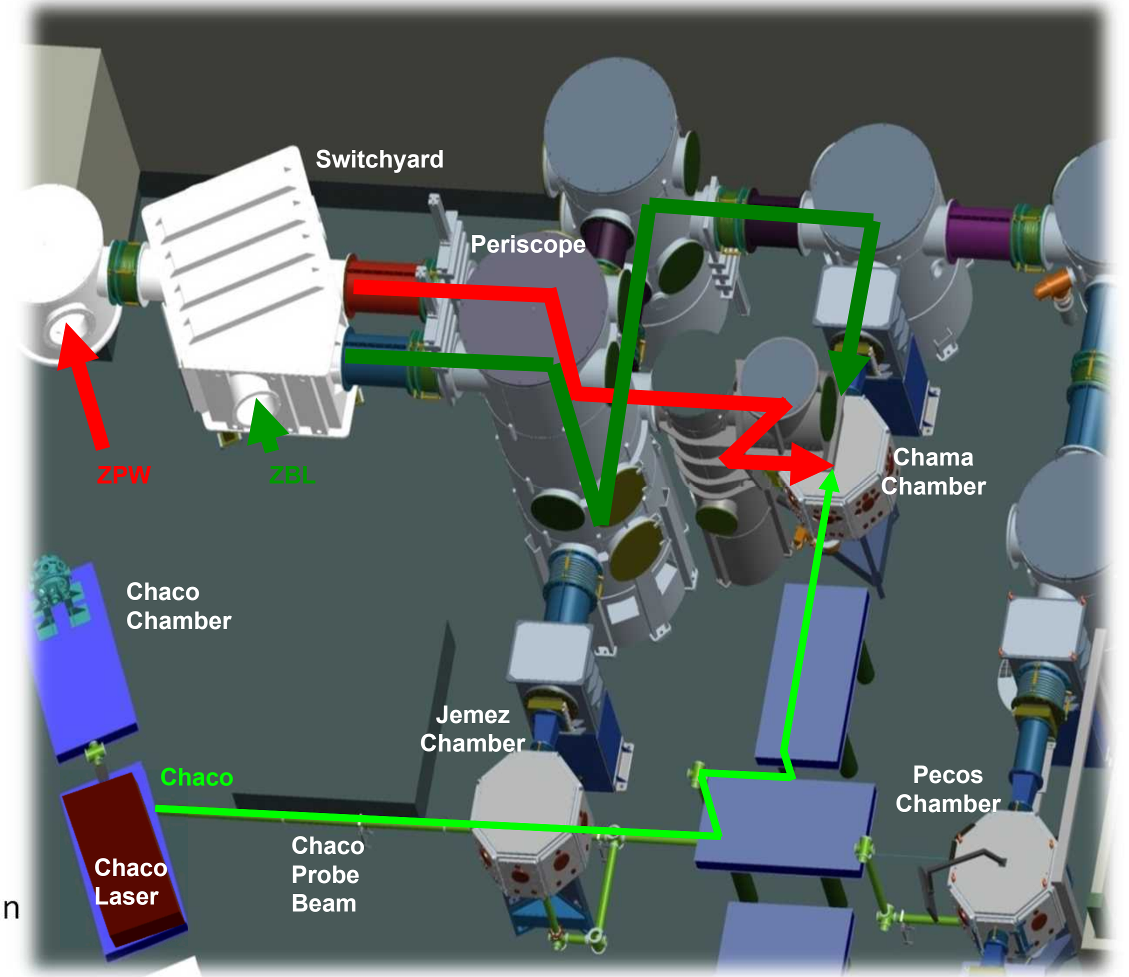
New target chamber (CHAMA)

- 1st chamber to use ZBL, ZPW & CHACO
- anticipated activation: Q1, FY16

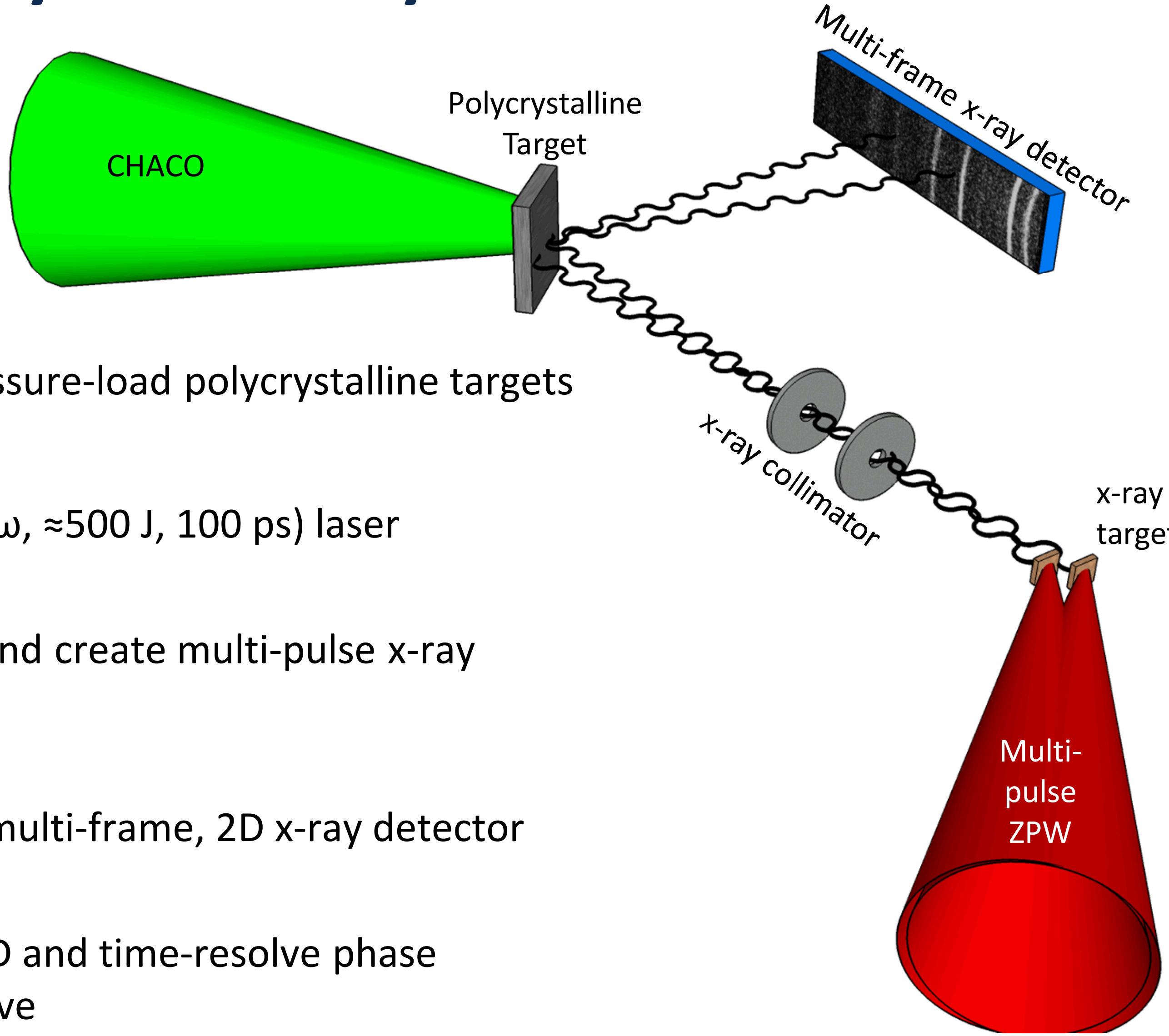
Laser systems:

- 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

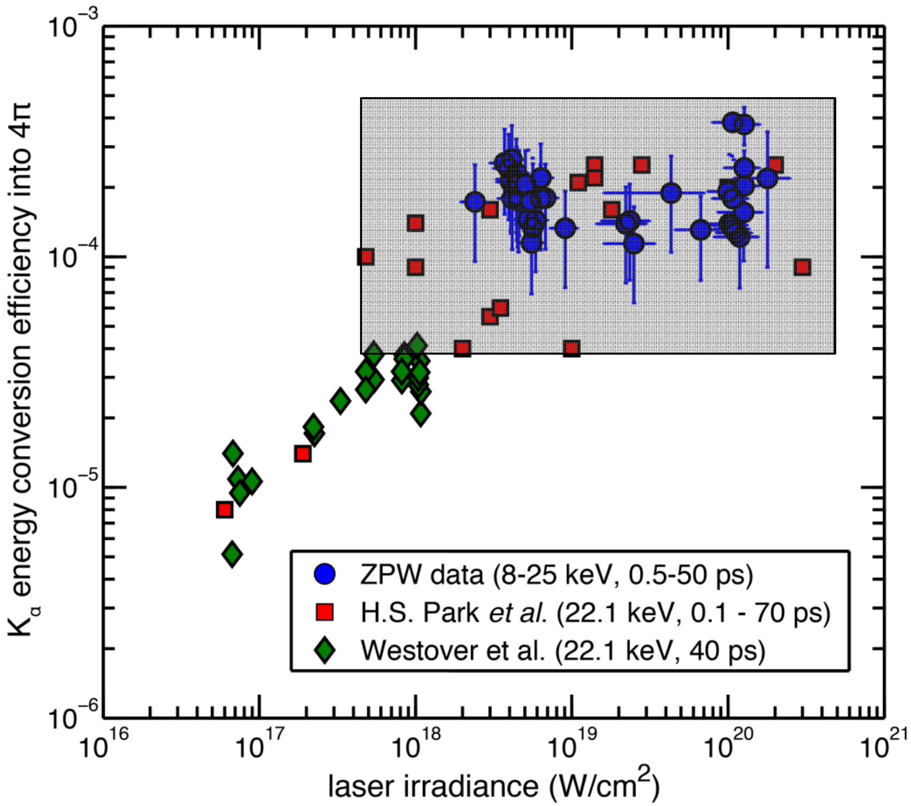


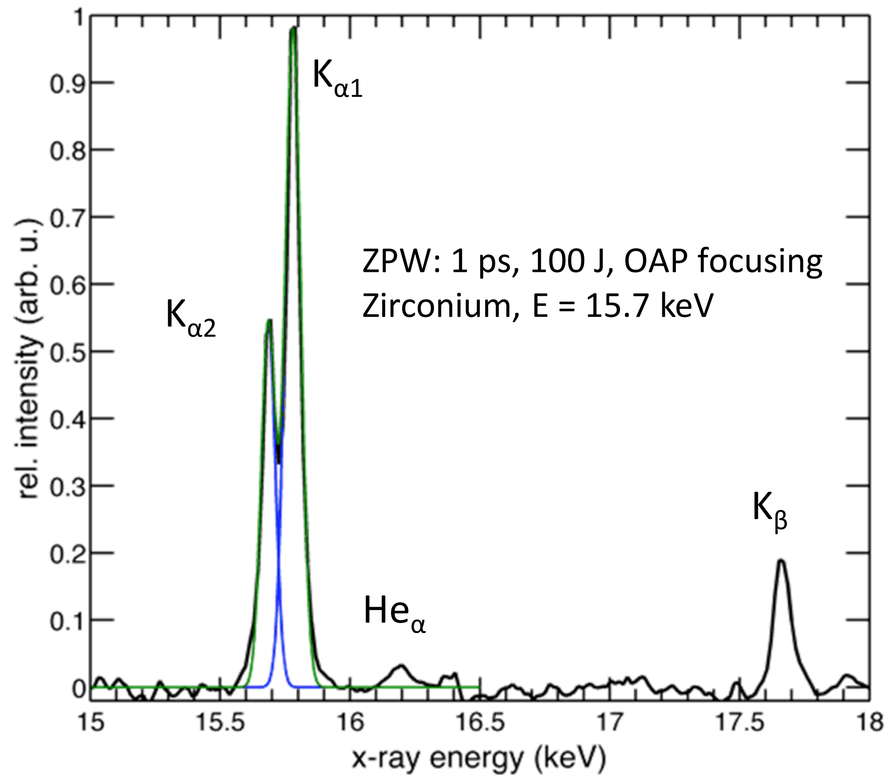
Laser-driven dynamic x-ray diffraction



- 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

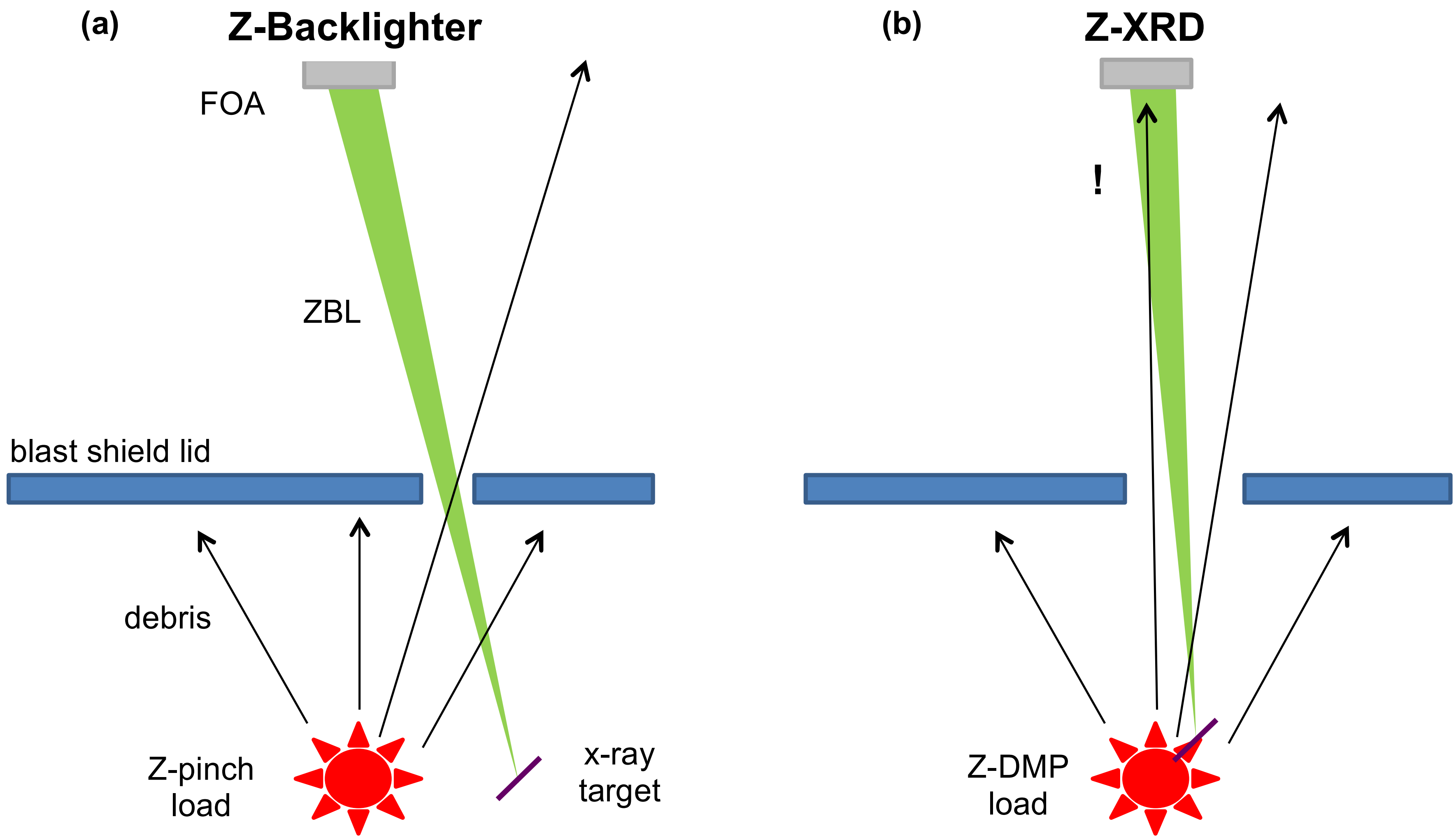
Sub-ns laser-created x-ray sources





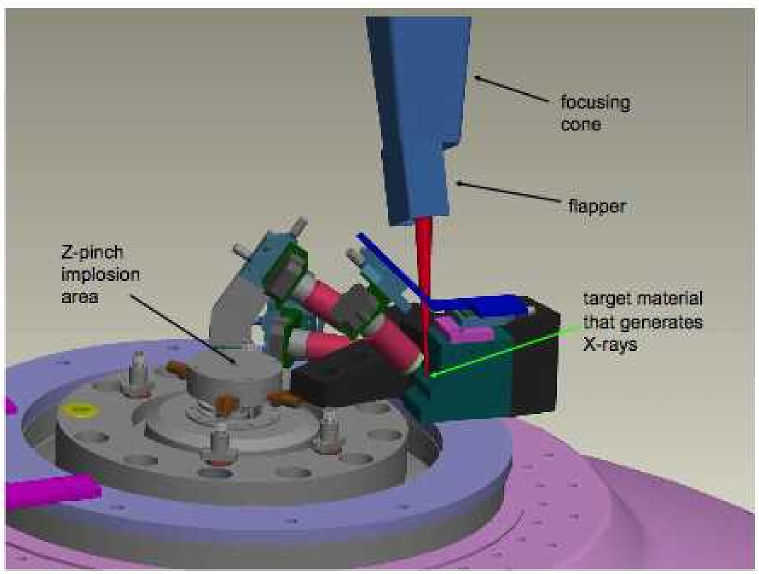
- Lens-based focusing of ZPW requires 100-ps-scale pulse duration
  - How efficient is 100-ps x-ray generation?
  - What is the photon yield?
  - How "clean" is the spectrum (He_α)?
  - What is the x-ray pulse duration?
  - What is the optimum target size?

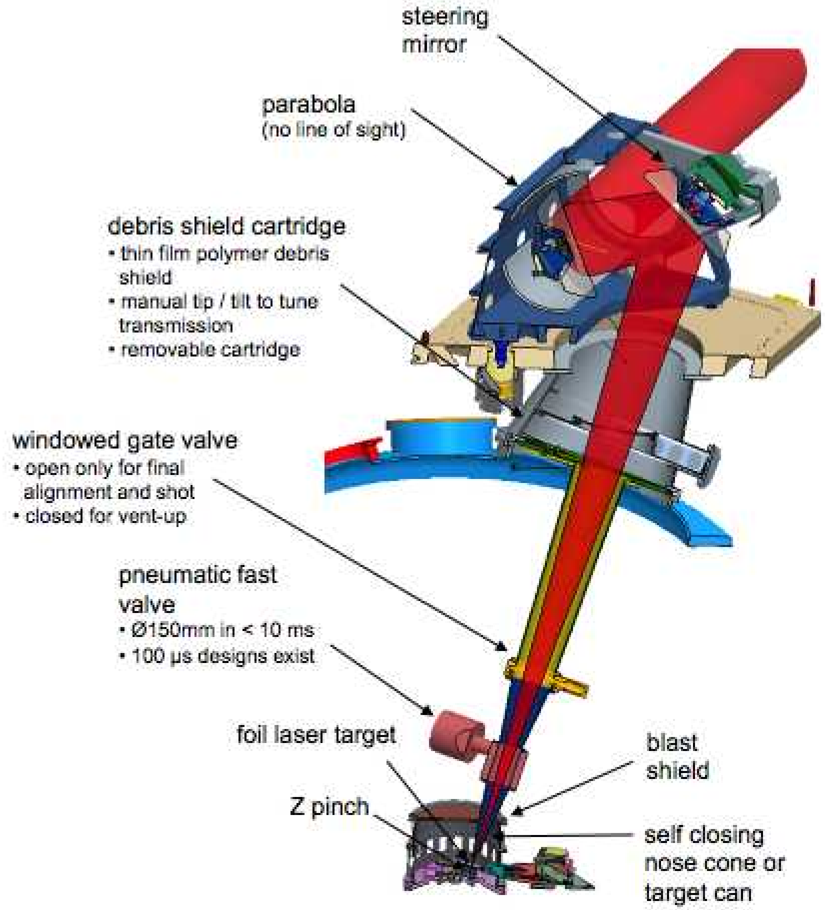
Debris generation at Z



current ZPW Final Optics Assembly for Z

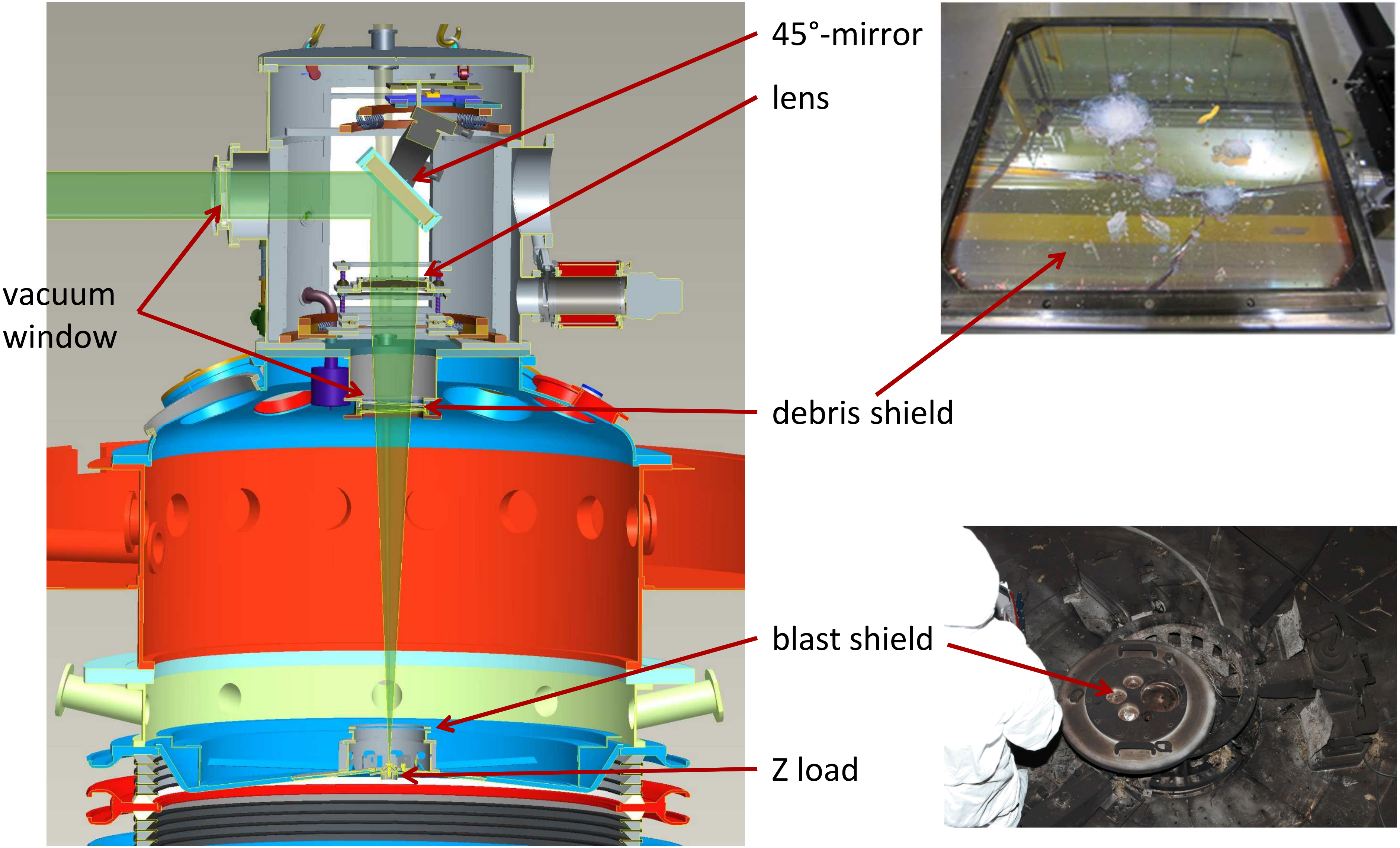
- ZPW:
  - 43x43 cm beam
  - 500 J, 500 fs
  - F/# = 11 parabola (f = 4.73 m)
- FOA is designed for off-axis, sub-ps irradiation of backlighter targets





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

Optics protection for on-axis irradiation



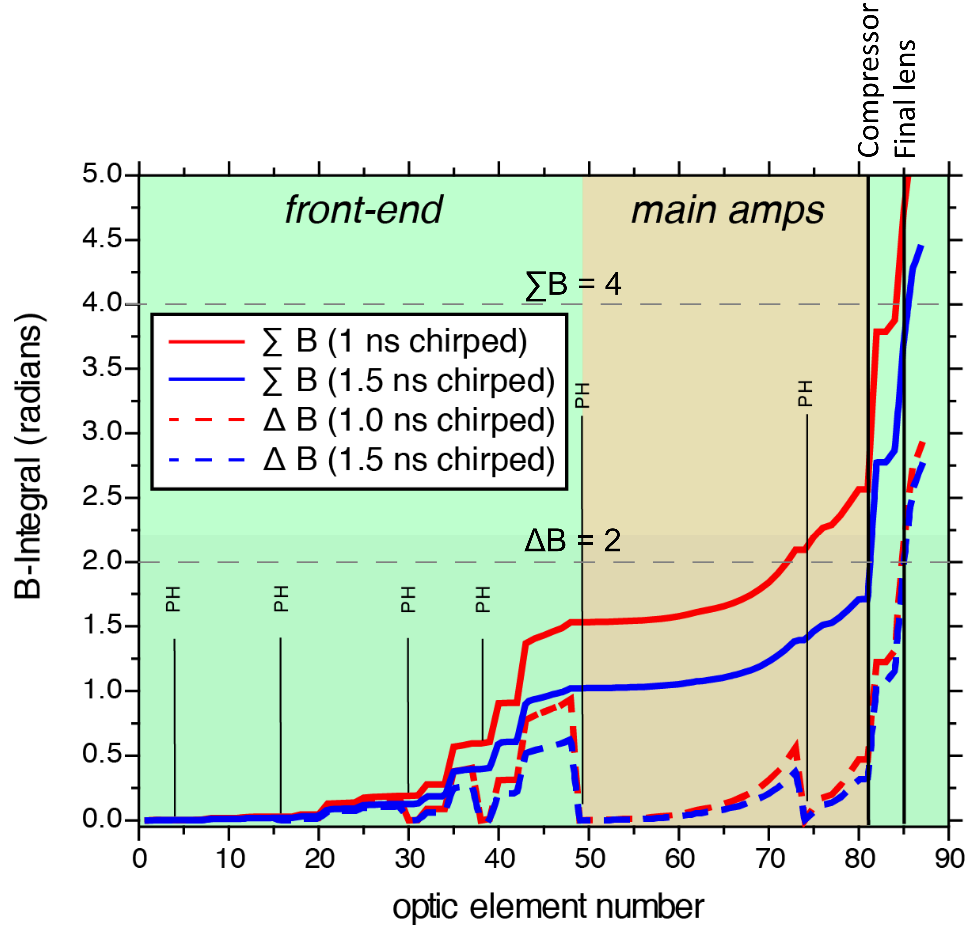
B-Integral considerations

- 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):

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

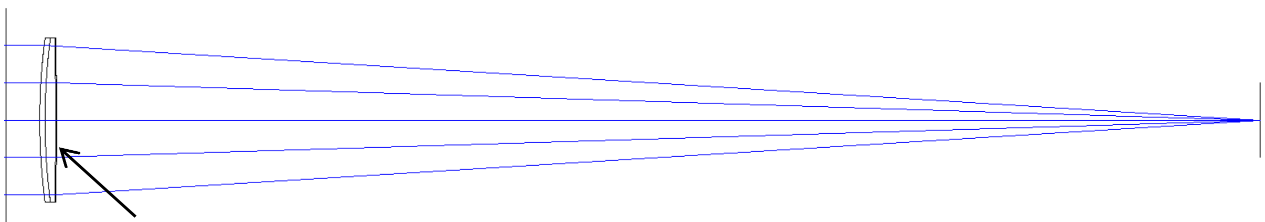
- Limits:
  - Total accumulated nonlinear phase must be **$\sum B < 4$** to avoid whole-beam self-focusing effects (i.e., focal spot shifting)
  - "small" spatial defects can be stripped at pinholes of spatial filters. B-integral between pinholes resets to 0 at each pinhole. Keep **$\Delta B < 2$**

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



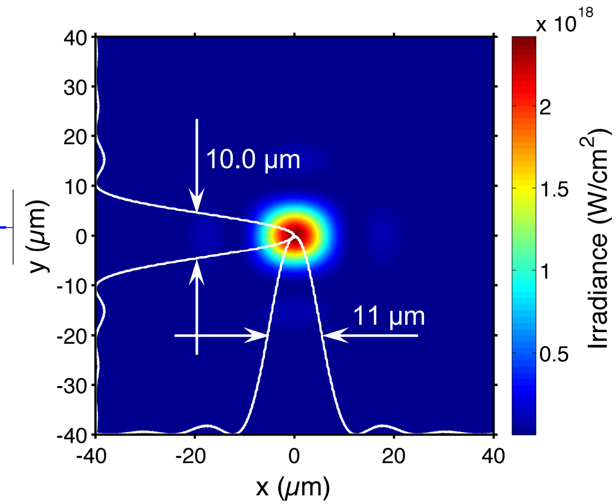
Expected laser focal spot and intensity

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



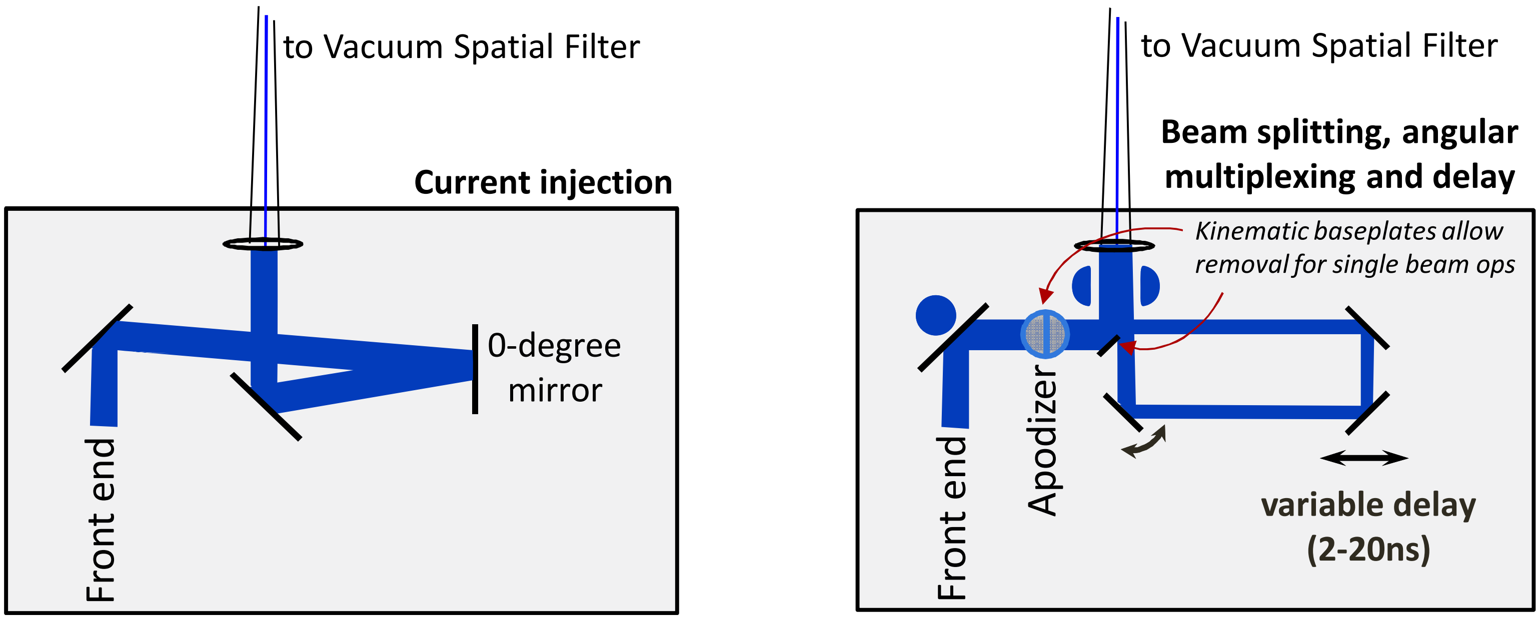
f = 3.2m Asphere, 4.5 cm center thickness
No vacuum windows or debris shields accounted for

Simulated focused beam profile



Multi-frame ZPW modification

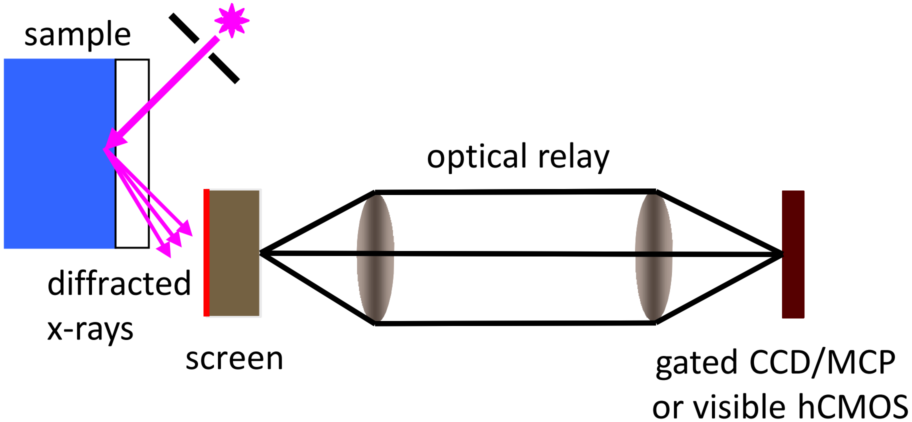
- Concept:
  - Spatially split beam before injection into main amp section
  - Full delay adjustment (2-20 ns)
  - *Separated* far-field spots (2 targets)
  - Similar to Z-Beamlet multi-frame backlighter (MFB) concept but without certain energy losses (except for apodization strip at 10% level)
  - Compatible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



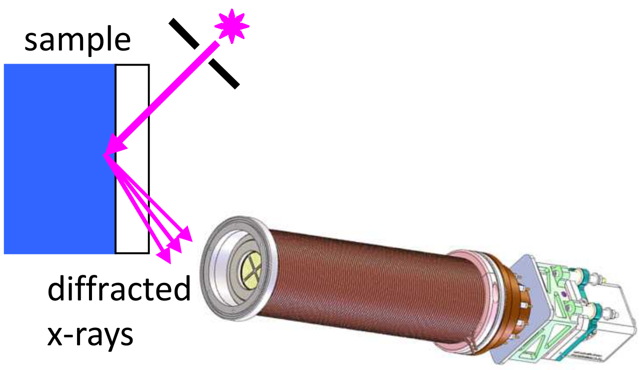
Multi-frame, time-resolved detector ideas

- 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



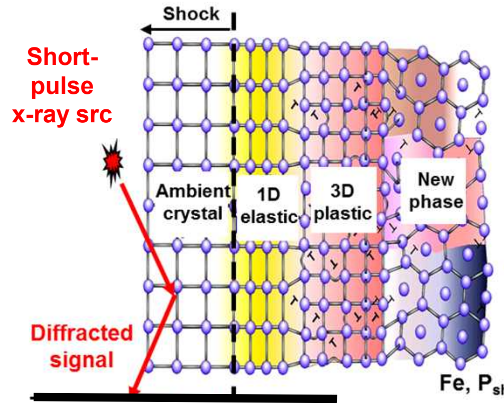
- Alternative: DIXI + hCMOS
  - Not clear how close DIXI can be to the target
  - Requires further investigation



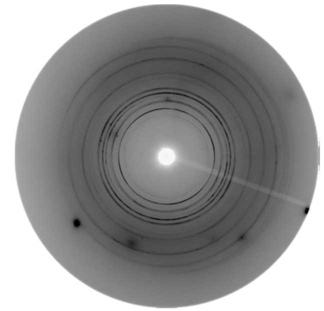
END

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

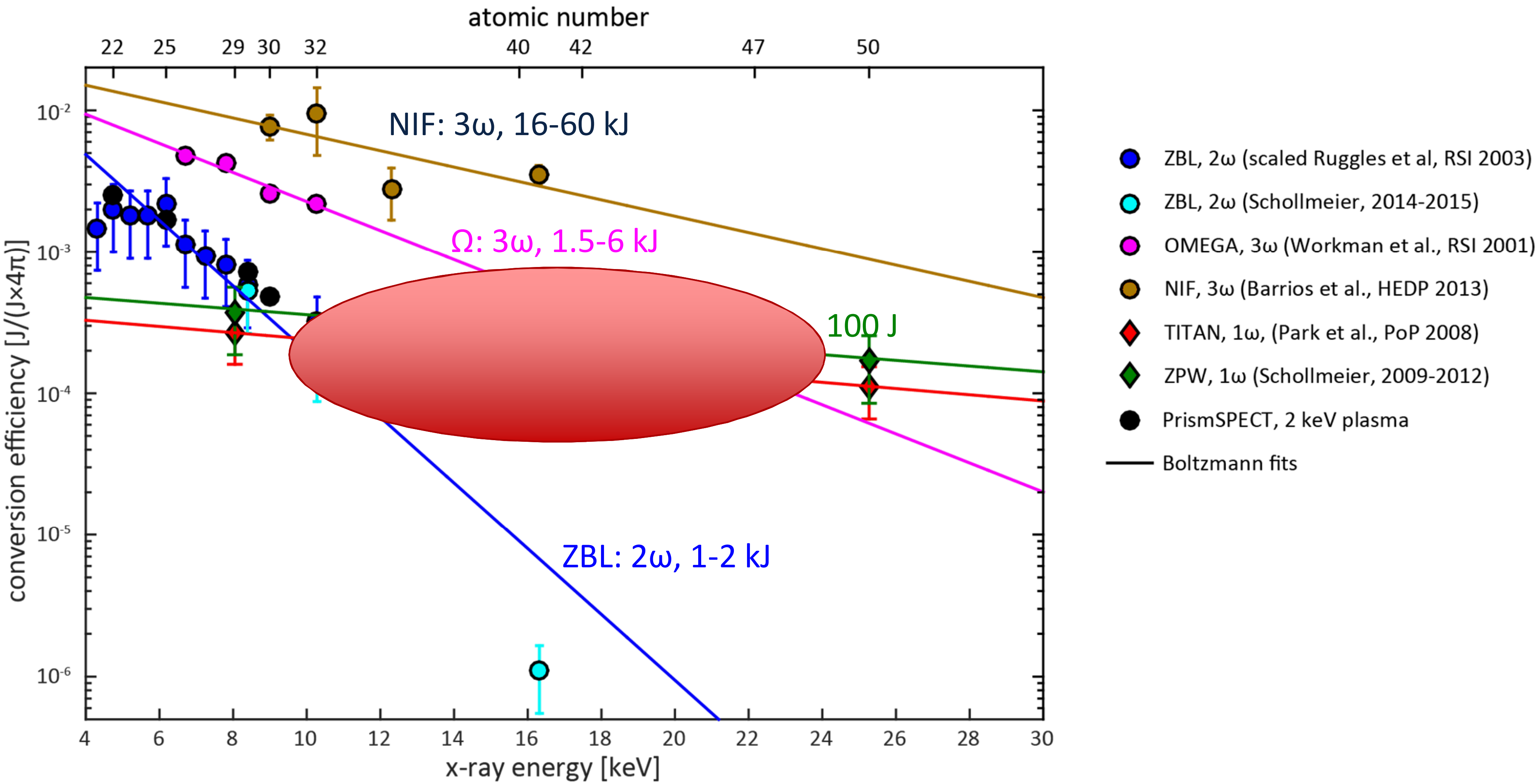


[Lorenzana, LDRD-SI (2005-2008)]



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
- ~~Wavelength multiplexing~~
  - ~~Separated by diffraction grating~~

Grating Cost

- 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