SAND2012-2368C

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High Power Lasers for Sandia's Z-machine

Tools for creating and probing matter in extreme conditions

GSI Helmholtzzentrum fuer Schwerionenforschung GmbH
April 23-25, 2012

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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Outline

- **Technology:**
  - **Facility overview**
  - **System upgrades**
  - **Optics Coating Operation**

- **Experiments:**
  - **HALO laser:**
    - **New ns, 1w-4w capability**
    - **High rep-rate, moderate energy (25 J every 12 minutes)**
    - **Diagnostics calibration test bed for Z**

  - **Z-Beamlet laser:**
    - **Backlighting on Z**
    - **X-ray Thomson Scattering developments**

  - **Z-Petawatt laser**
    - **25 keV X-ray generation experiments**
    - **Proton generation experiments**
    - **Plasma mirror experiments**

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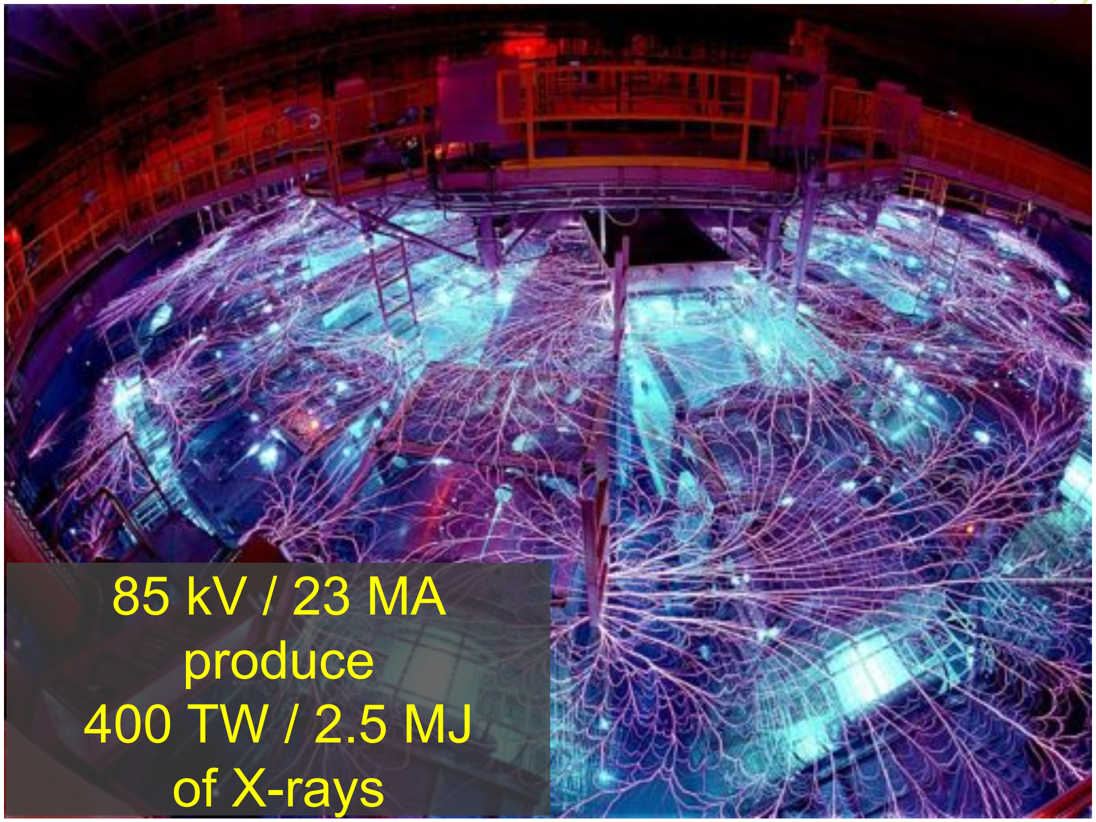
Primary Mission Motivation

HEDP on Z



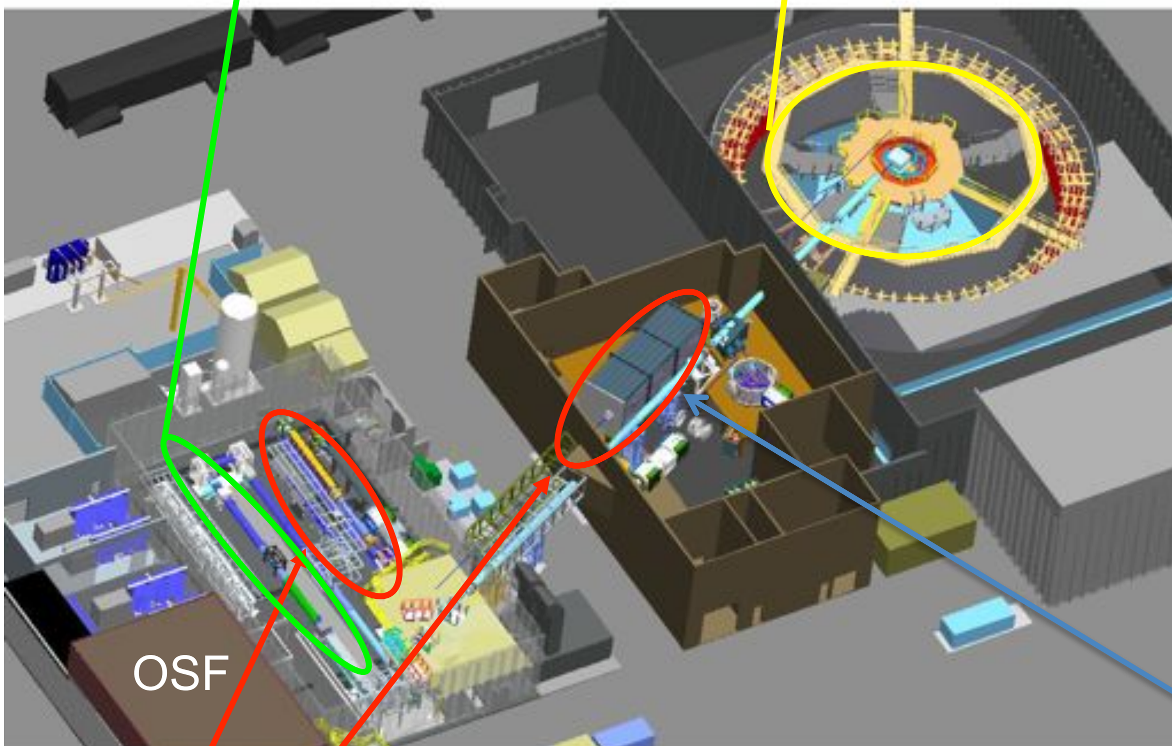
"Science from the Center of the Earth to Black Holes"
(http://www.sandia.gov/z-machine/)

Many HEDP experiments require high-energy x-ray backlighting as diagnostics:

- **ICF capsule compression**
- **dynamic material compression**
- **MRT instabilities**
- **complex hydrodynamics**
- **wire arrays**
- **astrophysical jets**

Facility Overview

ZBeamlet ns/ kJ Nd:Glass, 2ω



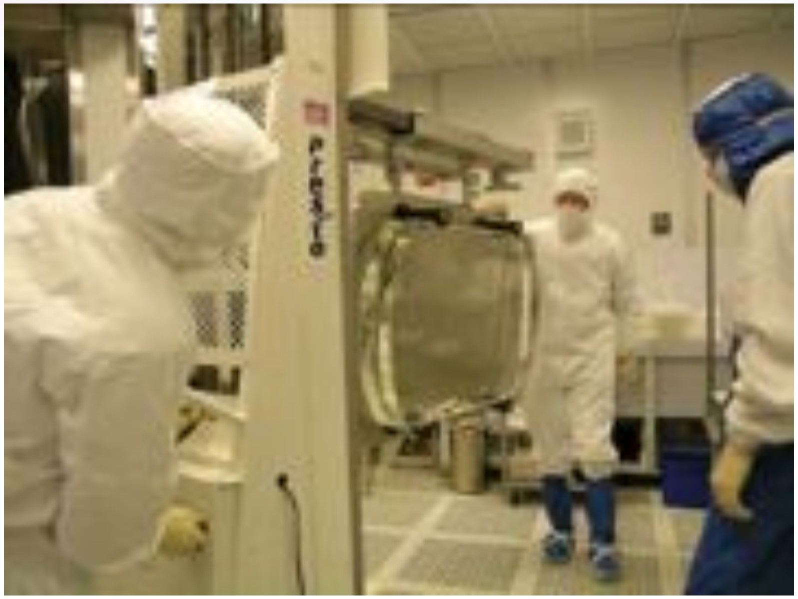
- The TW-class Z-Beamlet laser creates backlighting x-ray sources in the 1-9 keV range
- The Z-Petawatt laser creates backlighting above 8 keV (25 keV point design)
- HALO is used as a higher rep-rate test bed for diagnostics calibration and low-energy experiments

HALO: 0.3-10 ns, 5-50 J, 2w

ZPetawatt

On Z: 0.5 ps, 500 J or 10 ps, few kJ
Sub-aperture: 0.5-0.7 ps, 100 J (150-200 TW)
OPCPA + Nd:Glass

Large Scale Coating Operation



• Backlighting operations require a continuous supply of AR coated debris shields.

• To this end, we installed a 90” e-beam/ ion-assisted deposition coating chamber.

• Single-run capability: 3 at 94 cm optics
1 at 1.5 m option

• Recent coating efforts: Target Bay mirrors and Z-Petawatt needs, including 94 cm truncated HR mirrors, OAP.

• Independent damage testing (SPICA) has shown good test results:
- In the range of 17-25 J/cm^2 for AR
- In the range of 75-85 J/cm^2 for HR

• Successful application to both air and vacuum use

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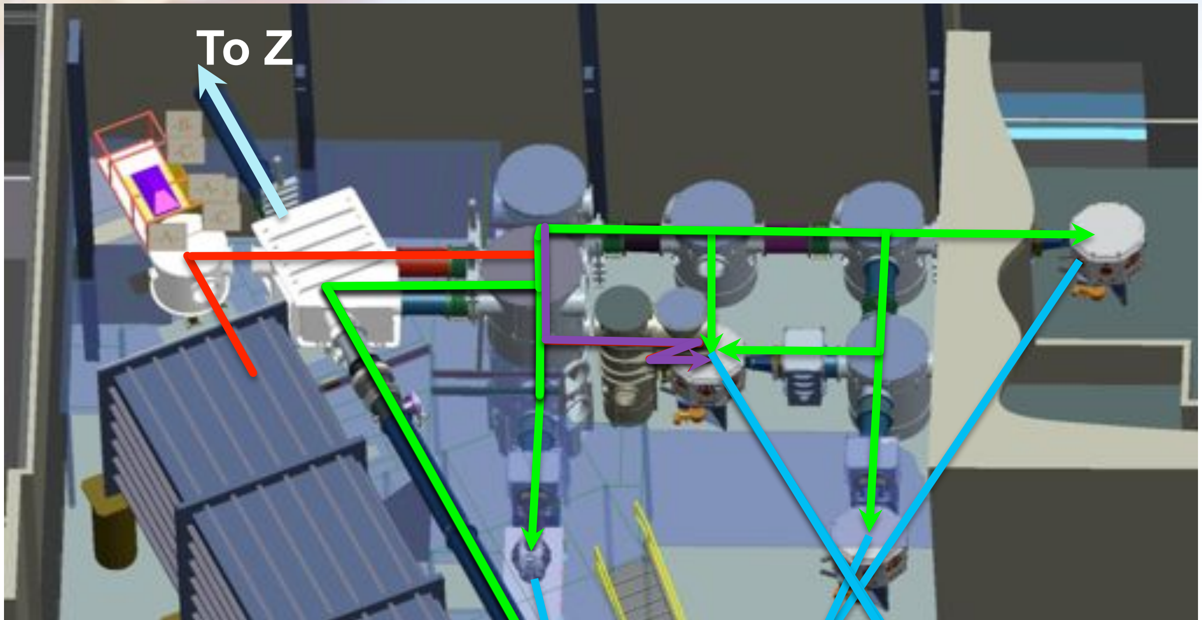
The Target Bay



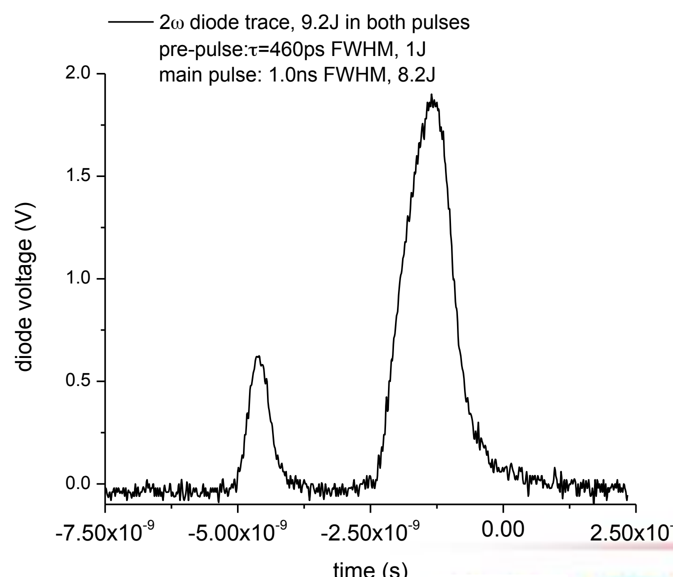
Target Chamber	On-Line	Fully Useful	F#	Spot Size (um)	Chamber size
Z-Beamlet (small)	5/2010	5/2010	6.25	50	80 cm
Diagnostic Calibration	2012	2013	6.25	50	1.5 m
Z-Beamlet (Large)	2012	2013	10	80	1.5 m
Z-Petawatt	2013	2013	4.5	6	1.5 m
			6.25	50	1.5 m

HALO

Laser Parameters

Operation Wavelength: 1064/532/266 nm
Pulse width: 300ps-10ns (120 J)
Energy at 300ps 20J (1064)- 12J (532)
Repetition Rate: Single Shot/10Hz/ Burst mode
Single pulse/ double pulse option, 4 pulse in prep.

Variable focusing options, from f/10 to f/3 optics
Max. intensity > 10^{16} W/cm^2



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Experiments on HALO

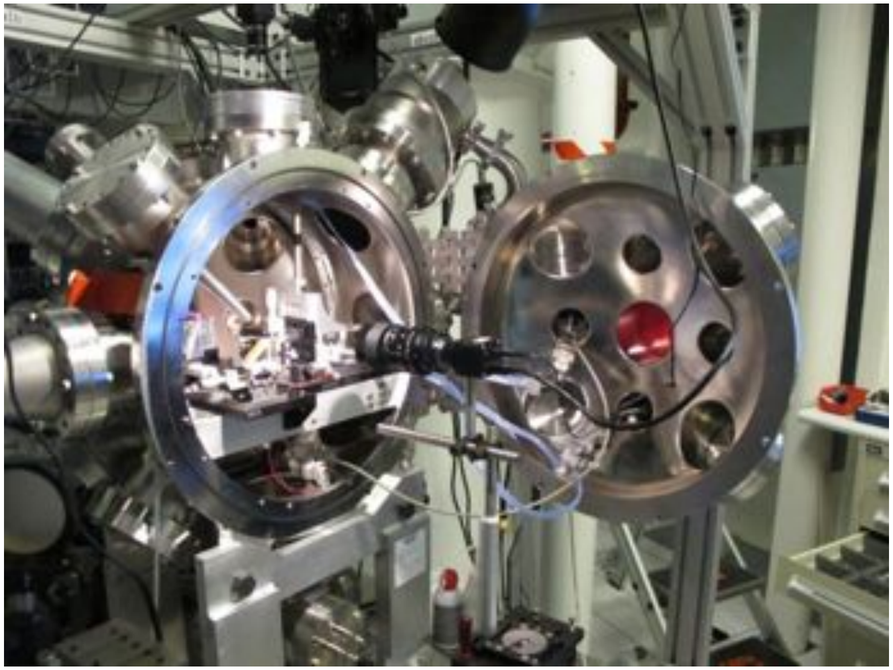
- NIF x-ray streak camera
  - calibration and timing validation
  - included 4w timing fiducial generation and detection

- Ultrafast X-ray imager
  - new 1ns, 4-frame, megapixel x-ray CCD, developed by Sandia
  - HALO generates fast x-ray pulse for testing
  - absolute yield measured with calibrated ultrafast (ps) x-ray diodes

- Ultrafast x-ray streak camera (sub-ps)
  - temporal calibration done on HALO

- Shockwaves in meteorite samples
  - in collab. with J. Remo, Harvard University
  - HALO creates shockwave in sample
  - measured with VISAR

- ZBL x-ray yield optimization and stabilization studies



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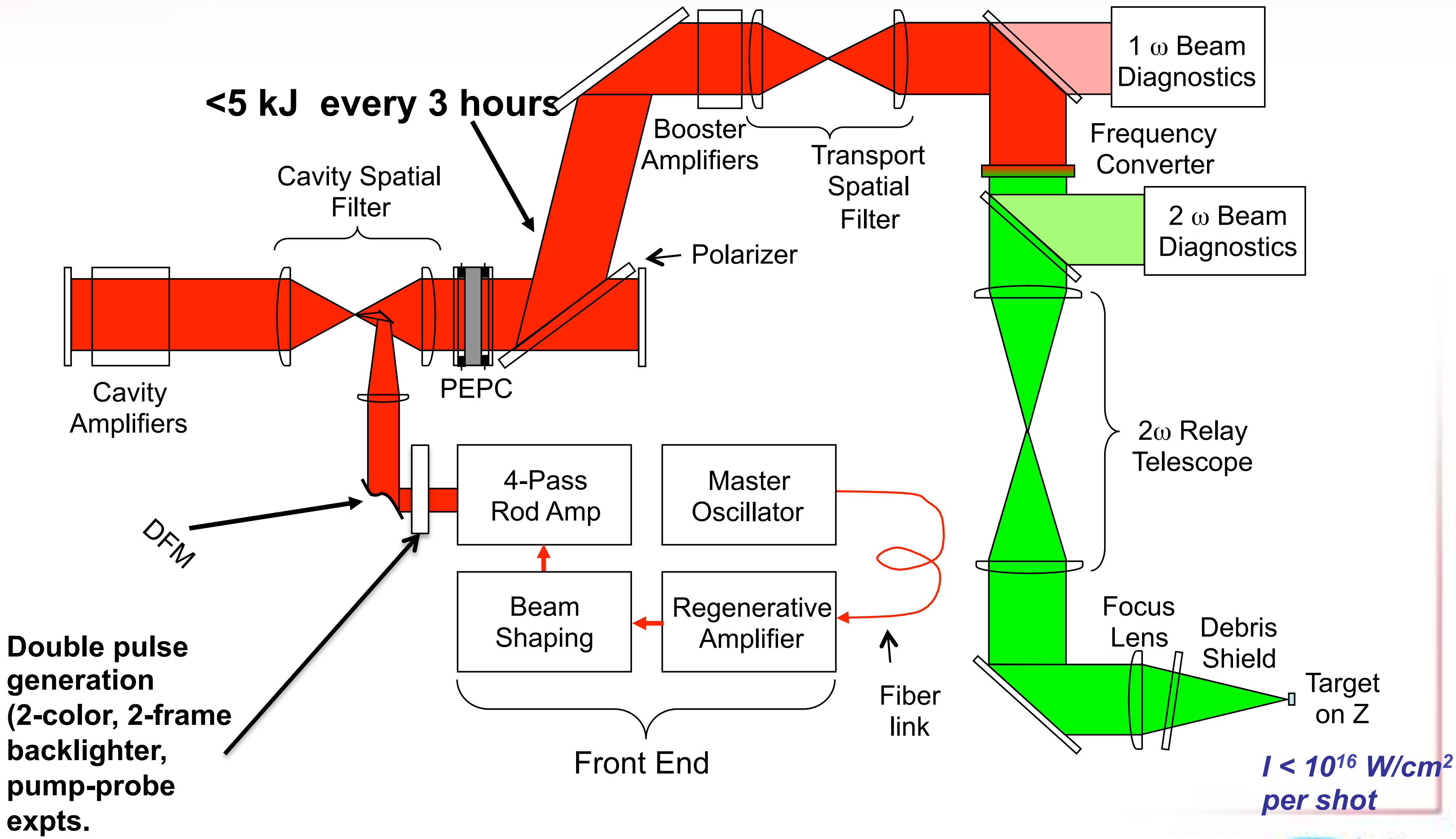
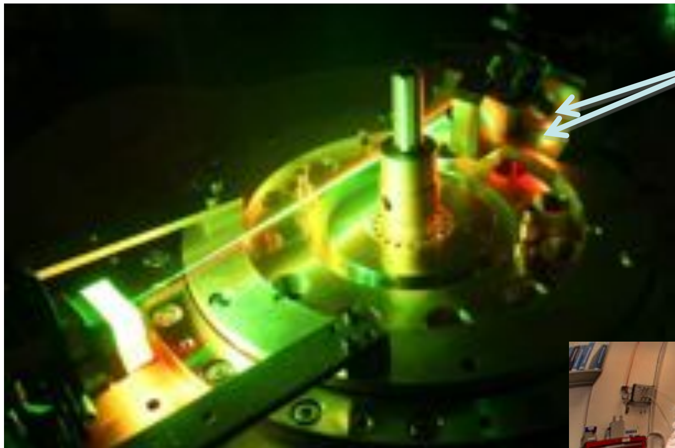
Z-Beamlet



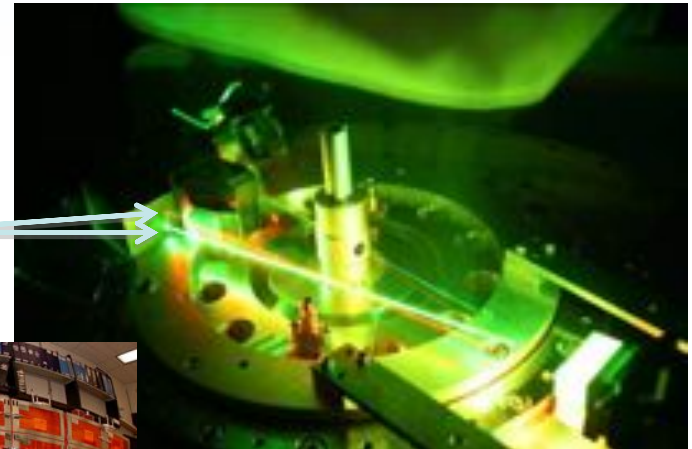
<5 kJ every 3 hours
Booster Amplifiers
Transport Spatial Filter
1 ω Beam Diagnostics
Frequency Converter
2 ω Beam Diagnostics
Cavity Spatial Filter
Polarizer
Cavity Amplifiers
PEPC
2ω Relay Telescope
4-Pass Rod Amp
Master Oscillator
DFM
Beam Shaping
Regenerative Amplifier
Fiber link
Focus Lens
Debris Shield
Target on Z
Front End
Double pulse generation (2-color, 2-frame backlighter, pump-probe expts.
I < 10^16 W/cm^2 per shot

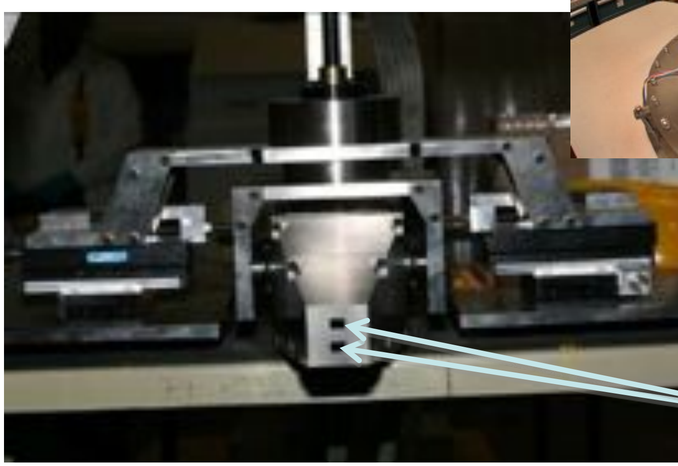
Curved-crystal imaging with 6 keV x-rays: 2-frame, 2-color backlighting



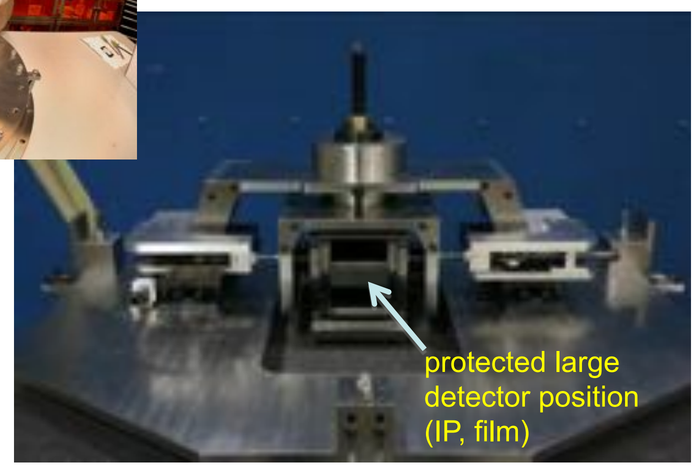
two separate laser targets

two separate images





two separate detector windows



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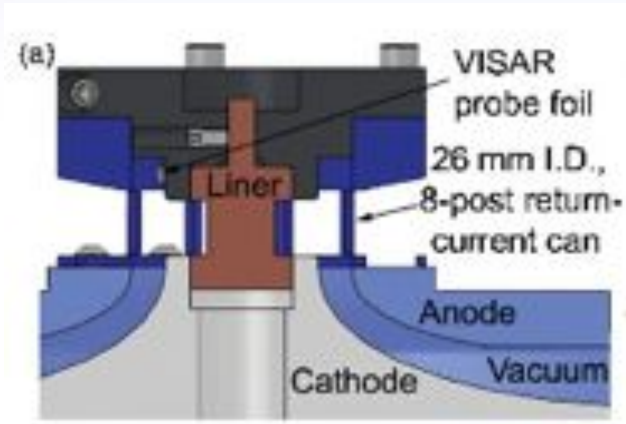
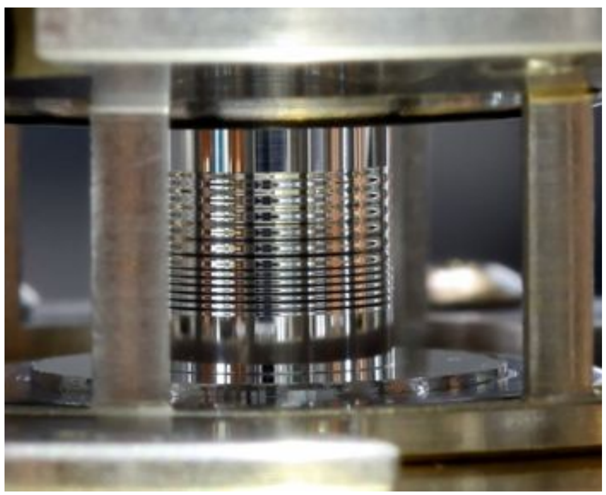
Seeded instabilities on liner implosions





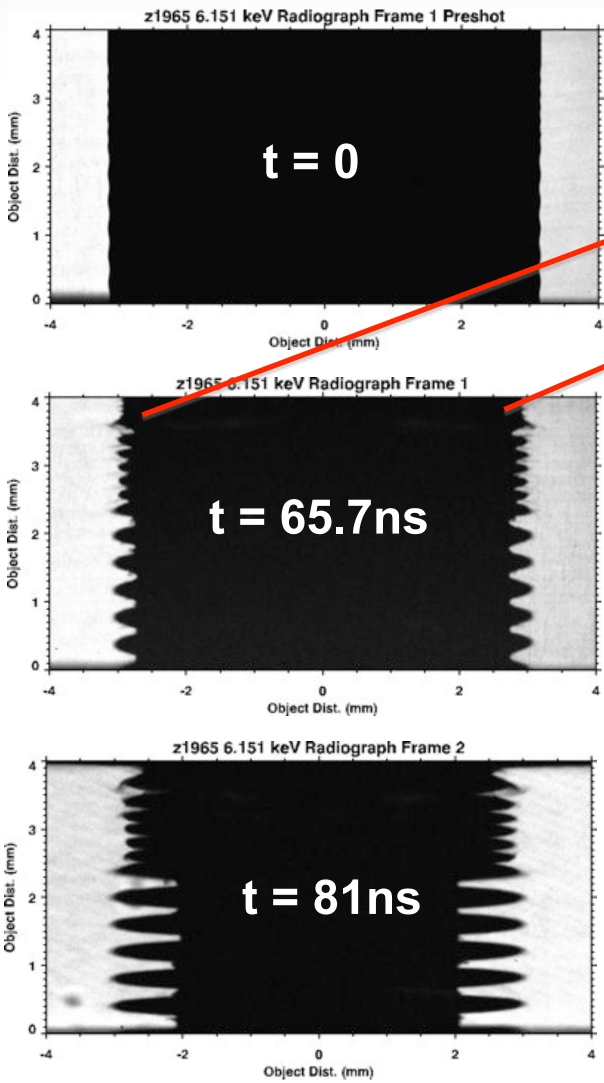
An implosion of an Al liner ('Lincoln' series), which is driven by Z, is developing hydrodynamic in-stabilities due to little perturbations in the material.

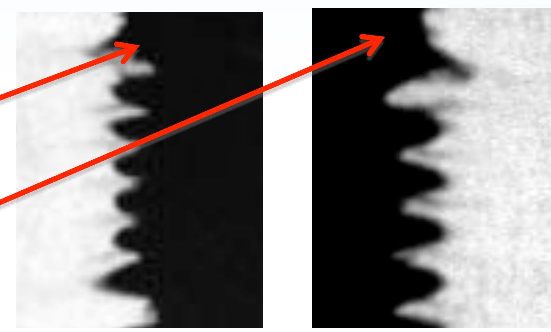
For the MAGnetized Liner Inertial Fusion (MAGLIF) concept[1], the liner implosion needs to be MRT-stable.

Experiments have been done to capture the evolution of the implosion by means of radiography.

images courtesy of D. Sinars
[1]S.A. Slutz et al., Phys. Plasmas 17, 056303 (2010)

Z-Beamlet radiographs on shot ‘z1965’





- First controlled experiments measuring the growth of the magneto-Rayleigh-Taylor instability in fast Z-pinch plasmas
- High spatial resolution (15 µm) provides high-quality data, and shows highly correlated, azimuthally symmetric jet formation
- The data is used for code benchmarking; increases credibility of those calculations[1]
- The hydrodynamics at the wall’s inner surface is of interest, though –> needs higher x-ray energies (Z-PW)

[1]see D. Sinars, Phys. Rev. Lett. 105, 185001 (2010)

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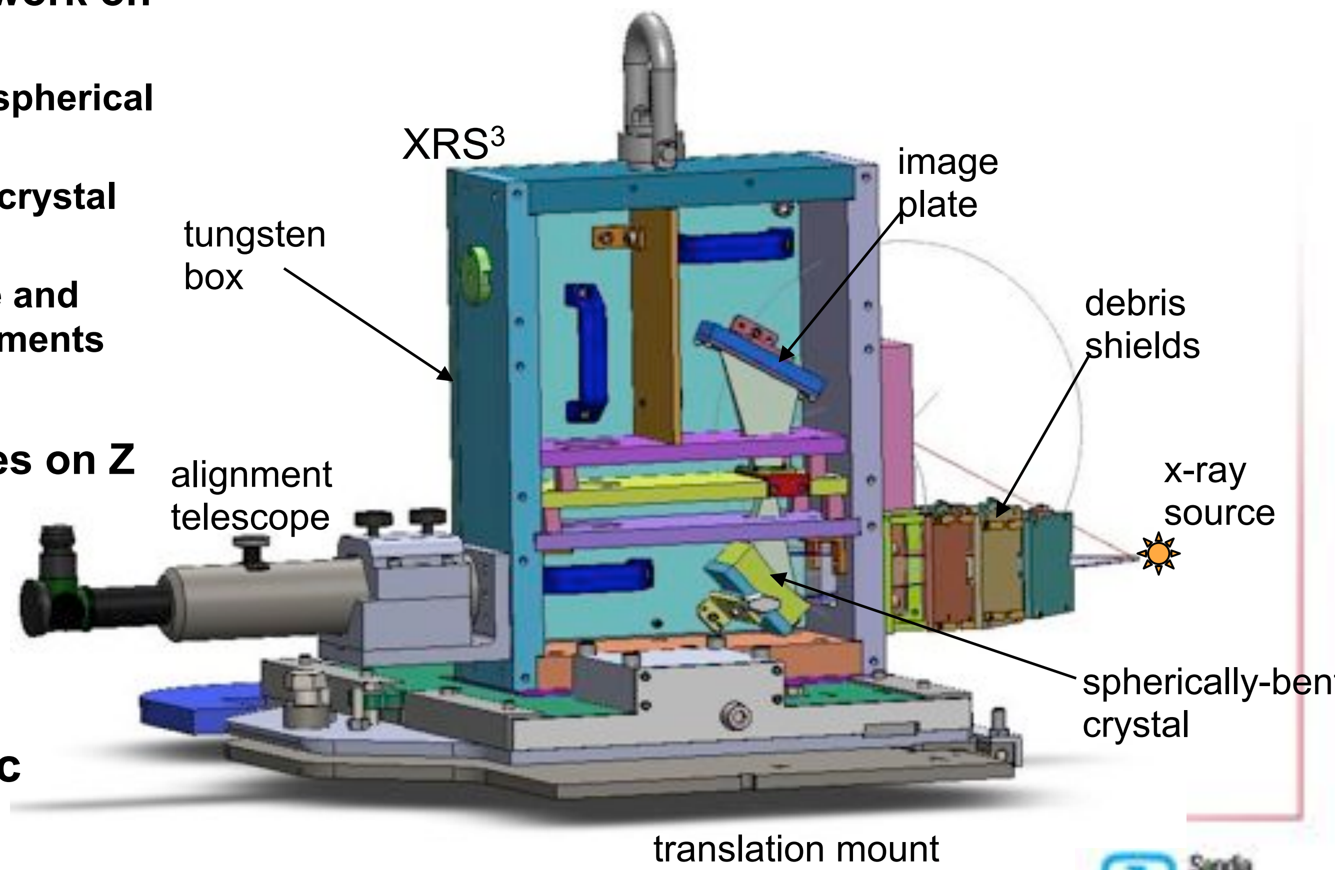
X-ray Thomson Scattering on Z

- **Potential of XRTS on Z**
  - **Critical diagnostic to expand the scientific capabilities of Z**
  - **Temperature, phase, dynamic structure factors, and ionization information**

- **Progress of XRTS work on ZBL**
  - **X-ray scattering spherical spectrometer**
  - **Spherically bent crystal calibrations**
  - **ZBL x-ray source and scattering experiments**

- **Preparation activities on Z**



Project lead by Jim Bailey, Tommy Ao, Eric Harding

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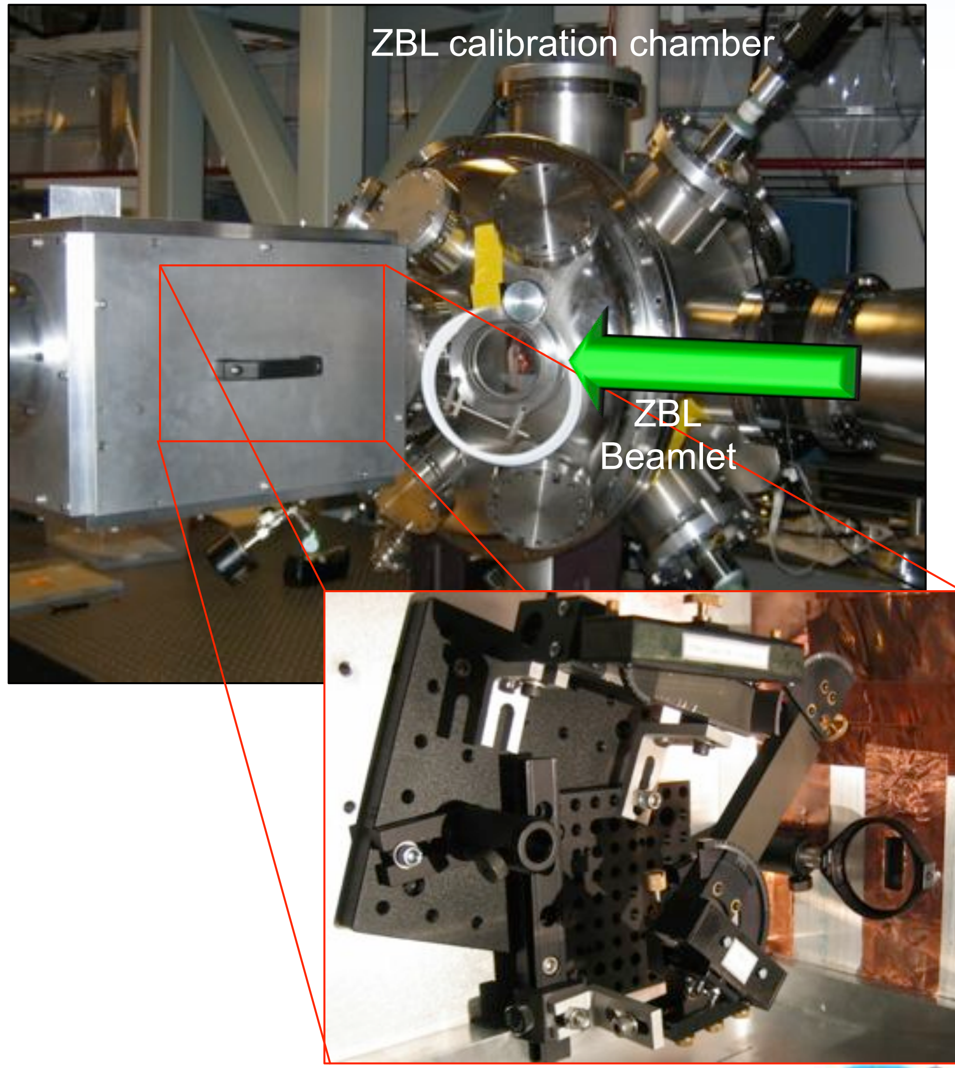
XRTS-ZBL experiments

- **X-ray source characterization**
  - **Mn-He$_\alpha$ (6.181 keV) and satellites**
  - **More monochromatic x-ray lines (e.g. V-He$_\beta$)**
  - **Study angular dependence of x-ray spectra**

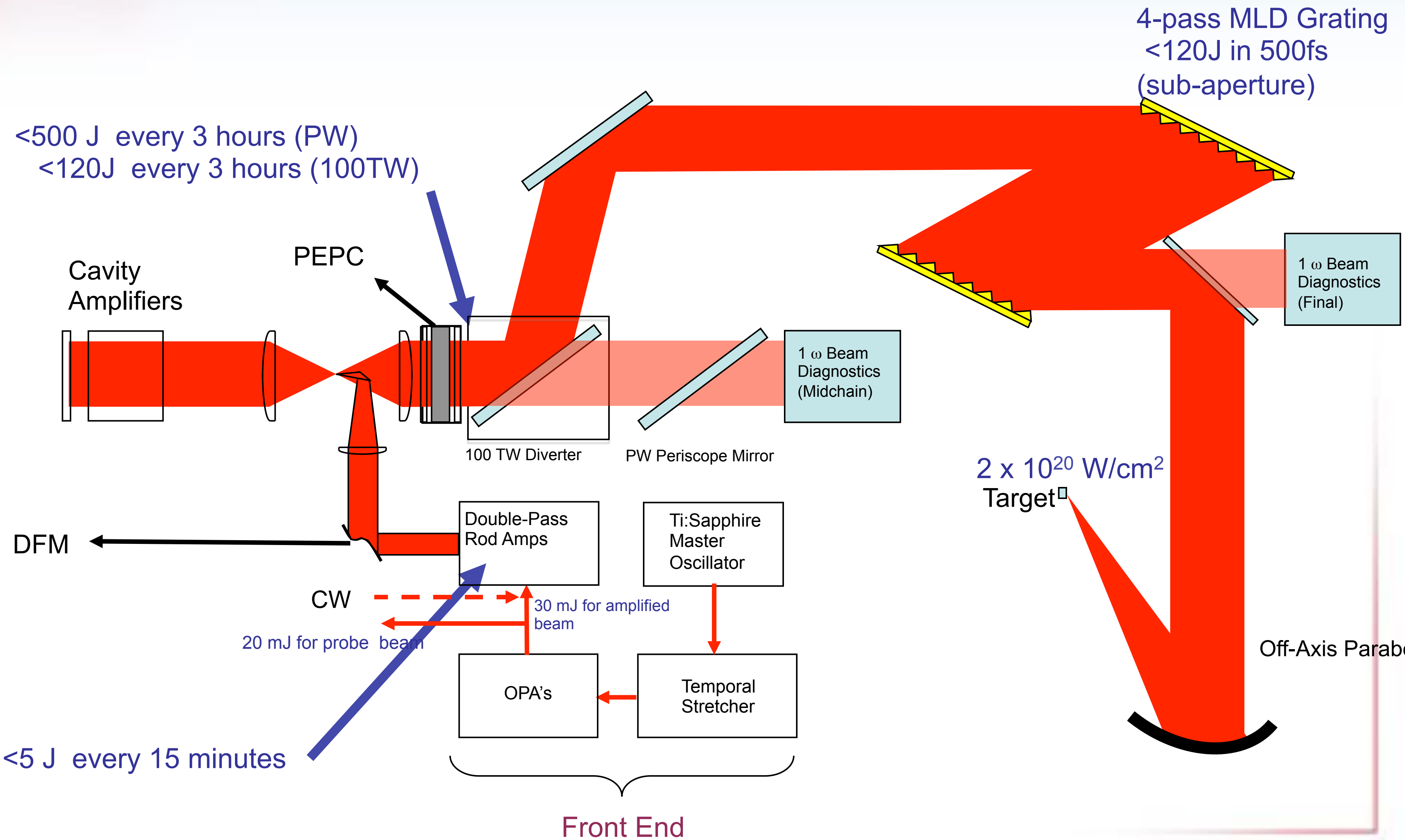
- **XRTS from CH foam and Al foils showed encouraging signals**

- **Next: XRTS from heated samples, using ZBL double pulse**



focusing spectrometer with spatial resolution (FSSR)
Quartz 2023 , r = 150 mm

Petawatt



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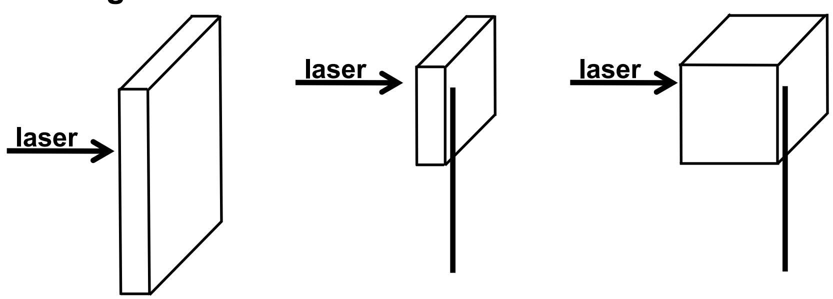
Experiments with ZPW: 25 keV x-ray source characterization

100 TW target area:

laser parameters:

- **E = 60-160 J, t_p = 0.5 – 50 ps**
- **focal spot: 6 µm FWHM**

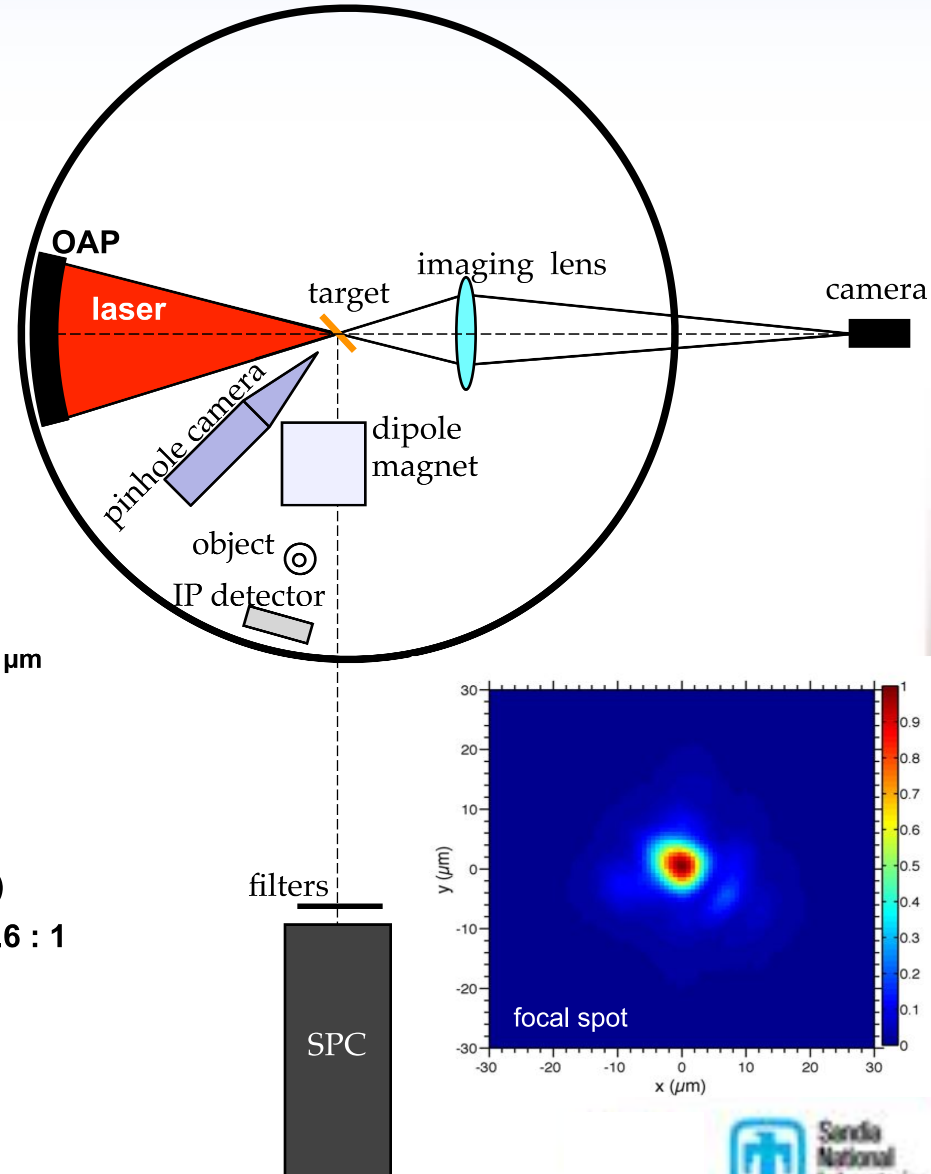
tin targets:



mm-size foils 20 µm or 100 µm thick

20 µm x (150 µm)^2 mass-reduced foils

cubes with 100 µm sides



test objects:

- **Al cylinders (Liner of "Lincoln"-type and custom made)**
- **Test mesh: 127 µm spacing, 53 µm thickness, magn.: 3.6 : 1**
- **Cu step wedge with 200 µm steps, contact radiograph**
- **knife edge measurements**

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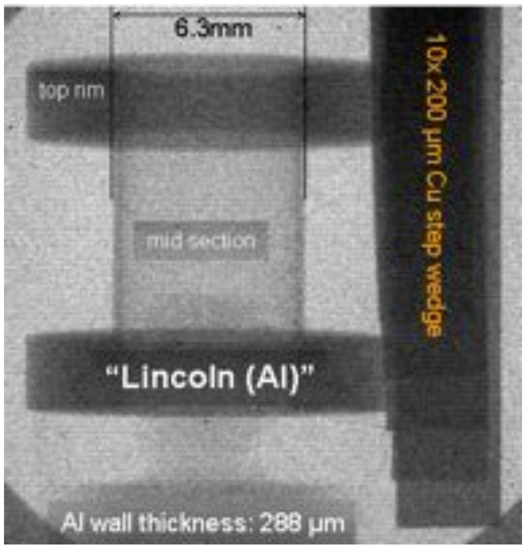
Experiments with ZPW: First data on Al liner radiography

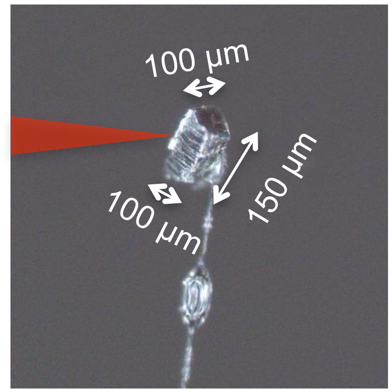
Main objects:
- find the right filter combination for optimum S/N and mech. stability on Z
- electron shielding (dipole magnet, low-Z material)



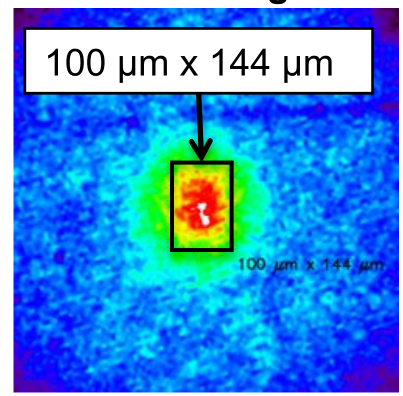
Reproduction of step-wedge, mesh and radiograph:

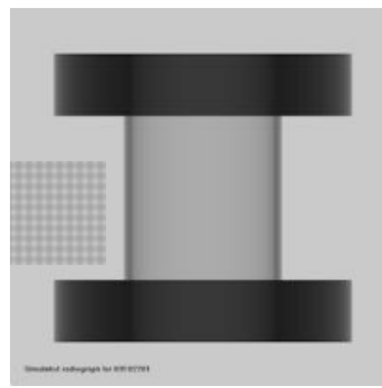
- 45% 25 keV K_α
- 55% Bremsstrahlung: exponential distribution
- simulated radiographs for various shots indicate:
  50-70% K_α
  kT_{brems}=400-900 keV
- 4π conversion efficiency measured by Single Hit CCD: $\eta \sim 2 \times 10^{-4}$

‘cube’ target

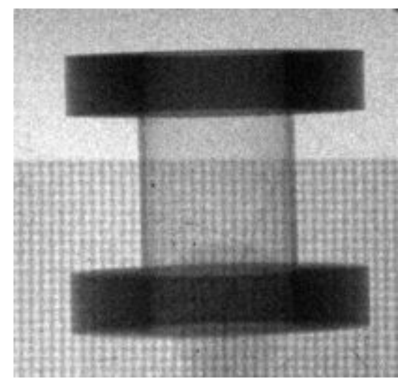


pinhole image with ‘cube’ target





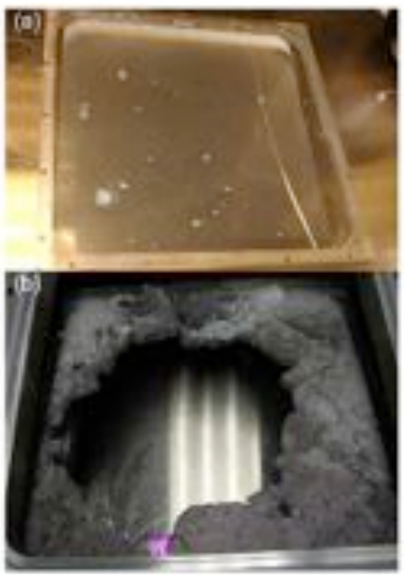
simulated radiograph



actual radiograph

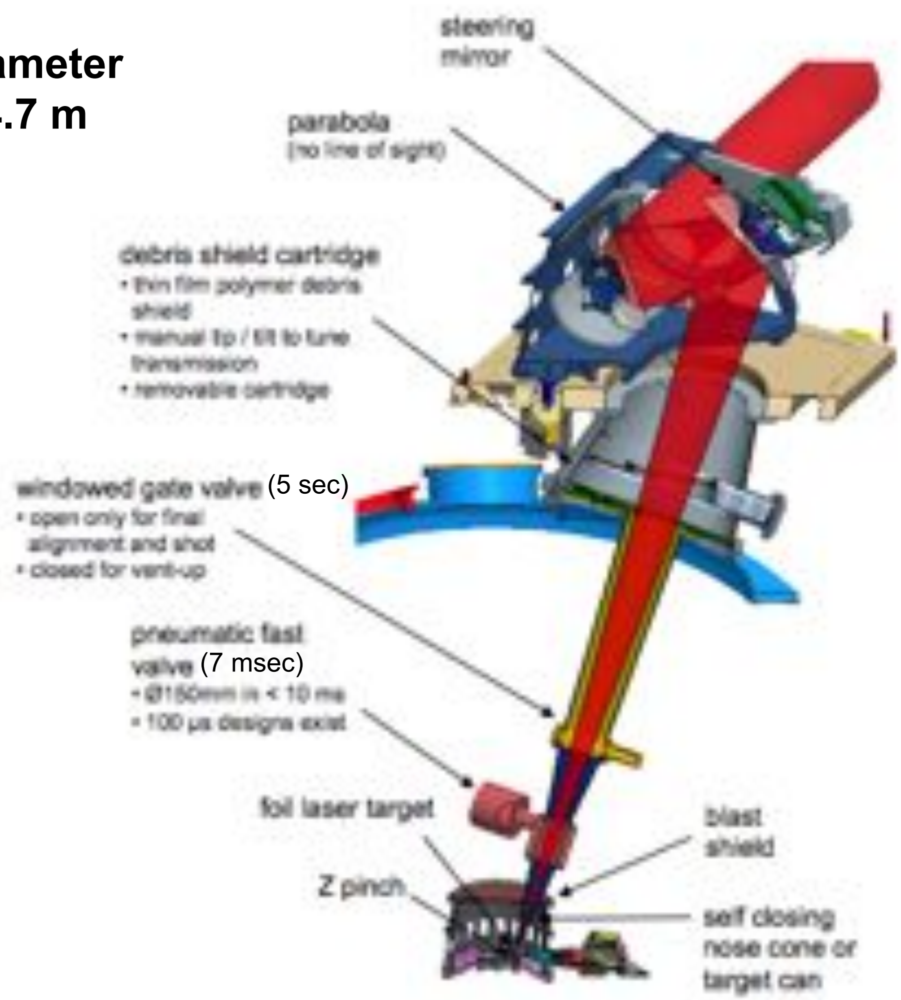
Application on Z: debris protection is an issue

- laser beam: up to 500 J, few ps, 43 cm diameter
- OAP: 75 cm dia., 60° off-axis, f/# = 11, F=4.7 m
- steering mirror behind OAP
- various debris protection devices



2 ZBL (ns) debris shields after Z shot

Al focusing cone enclosure inside Z



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

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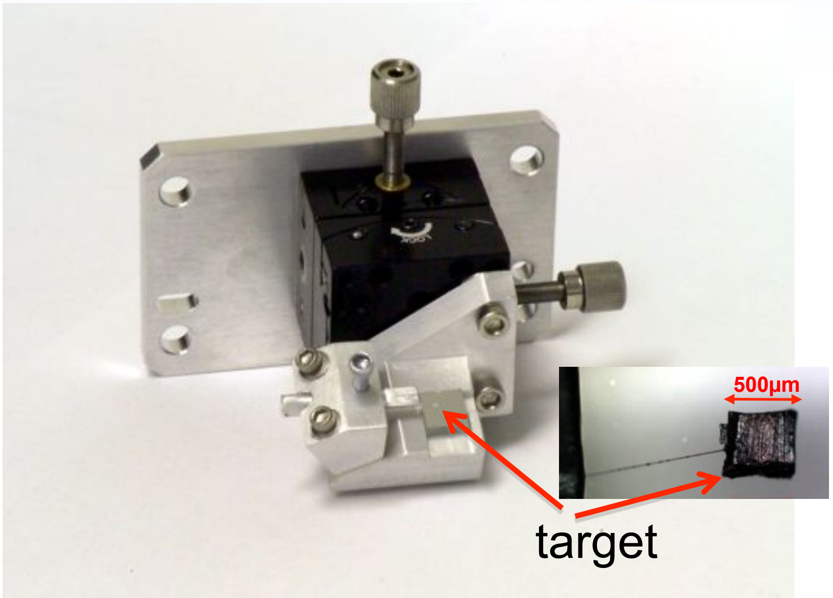
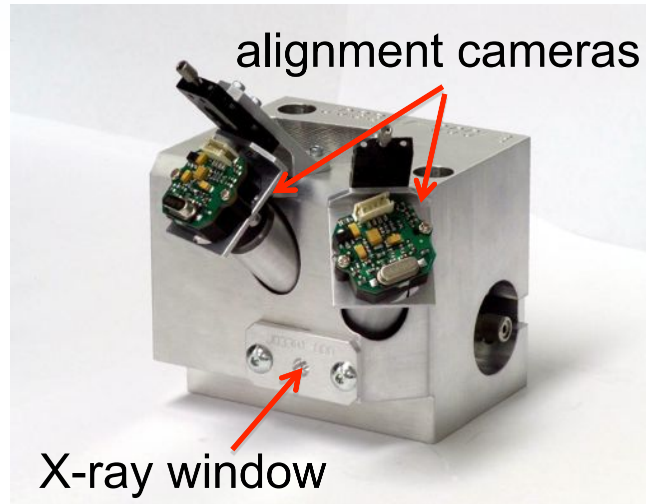
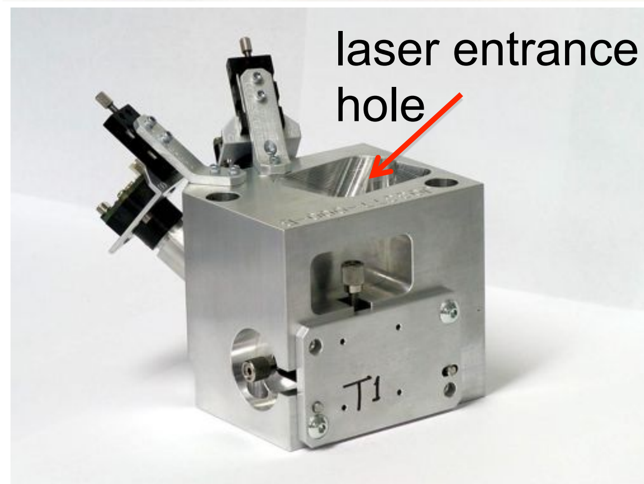
assembled target/debris protection box







A box with two microscope-CCD cameras was developed to hold the target while allowing precision alignment and debris protection.

The X-ray window was chosen to be a combination of mostly Be and Kapton.

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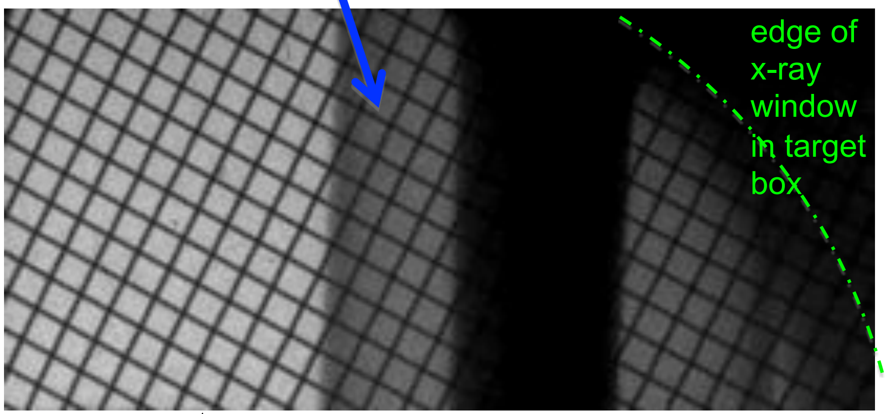
First 25 keV shot into inactive Z

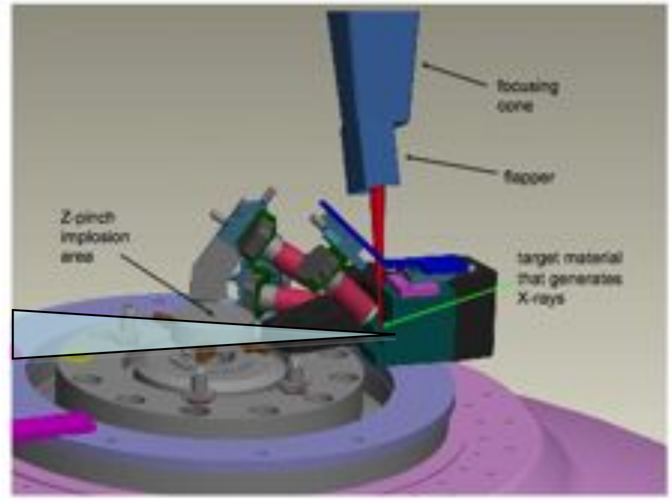
Al liner, 2x magnified



return current post of Z

contact radiograph of Cu mesh

laser energy: 200 J
pulse duration: 5 ps (measured with fast streak camera)
laser power: 40 TW
focal spot: ~ 50 µm FWHM (estimate)
laser intensity: ~ 2 x 10^{18} W/cm^2



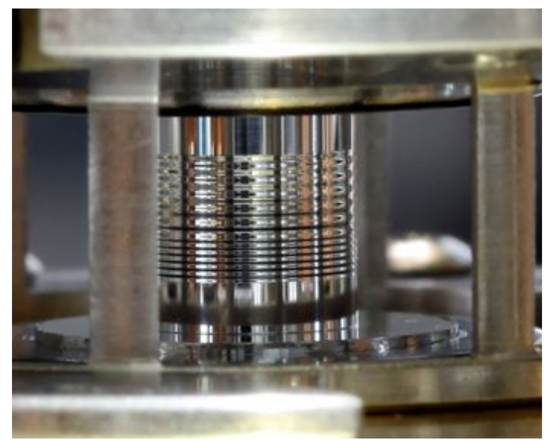
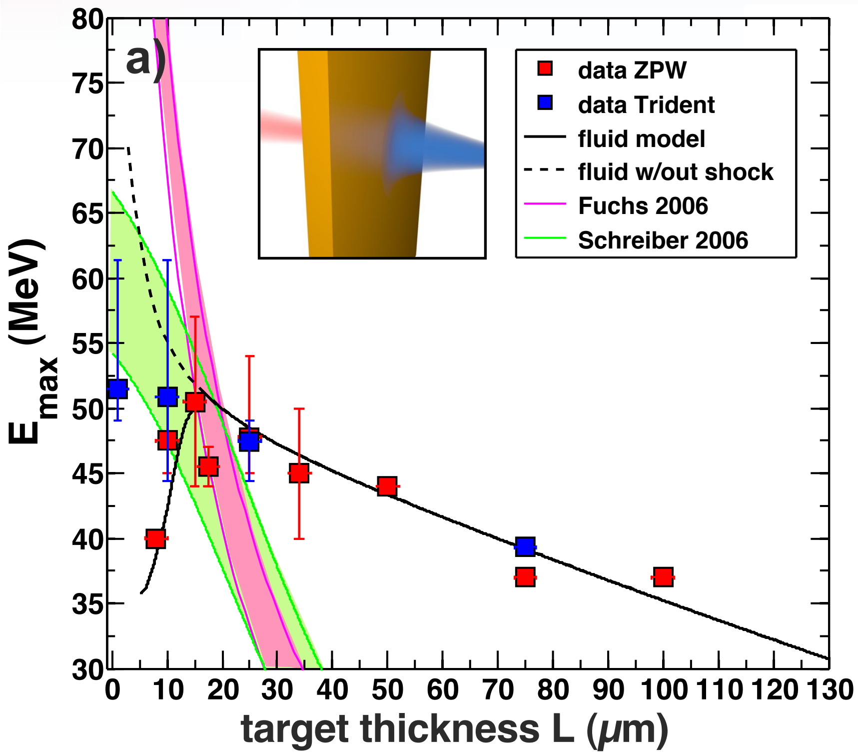
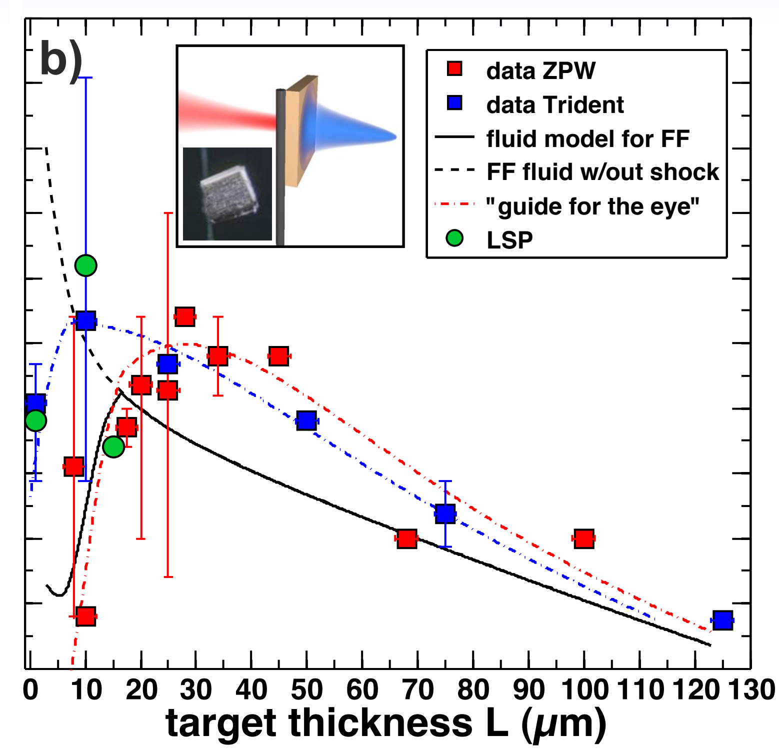


Image taken from a different angle
(to clarify radiography image)

High-energy ion acceleration





Flat foils:

- 50 MeV average
- 57 MeV peak at ZPW (15 μm)
- 61 MeV peak at Trident (1-10 μm)

Reduced mass targets:

- 57 MeV average (14% higher)
- 65 MeV peak at ZPW (14%)*
- 75 MeV peak at Trident (23%)*
- Stronger shot-to-shot fluctuations

* highest TNSA proton energies ever observed

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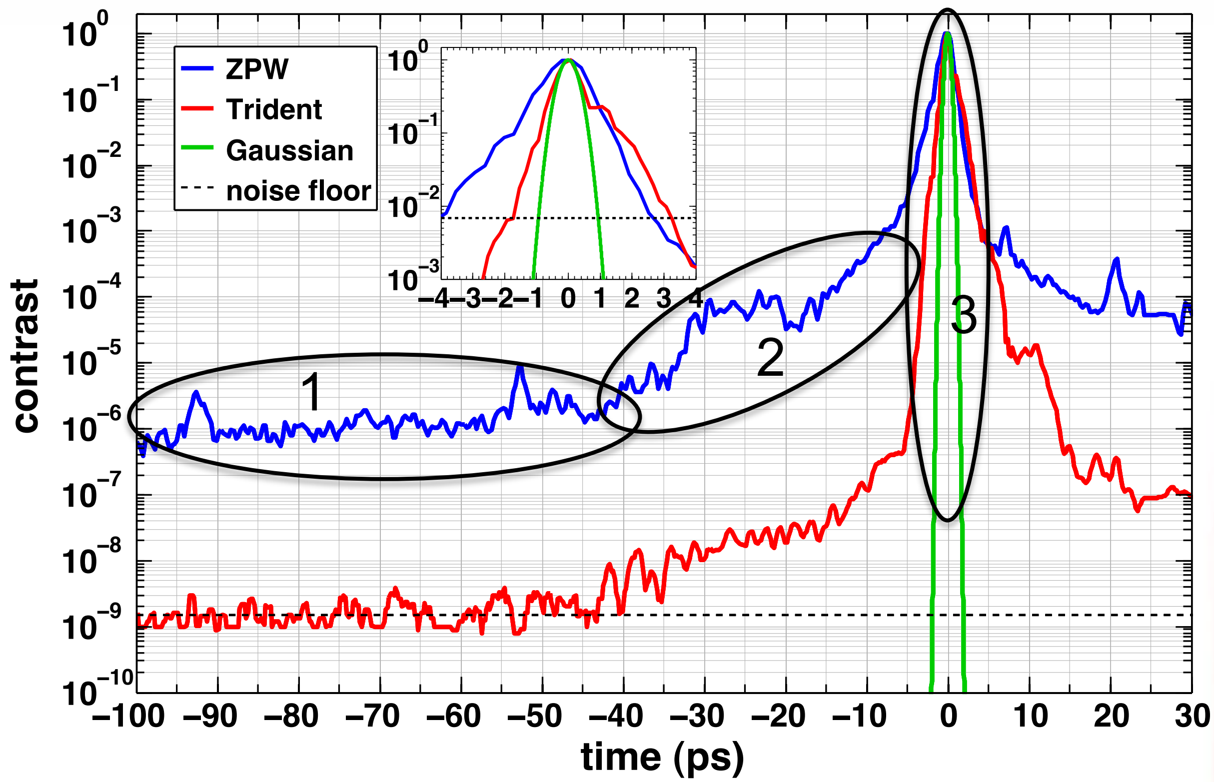
Laser temporal contrast

Three regions:
1. ns prepulse pedestal
2. ps prepulse ramp
3. main pulse rise time

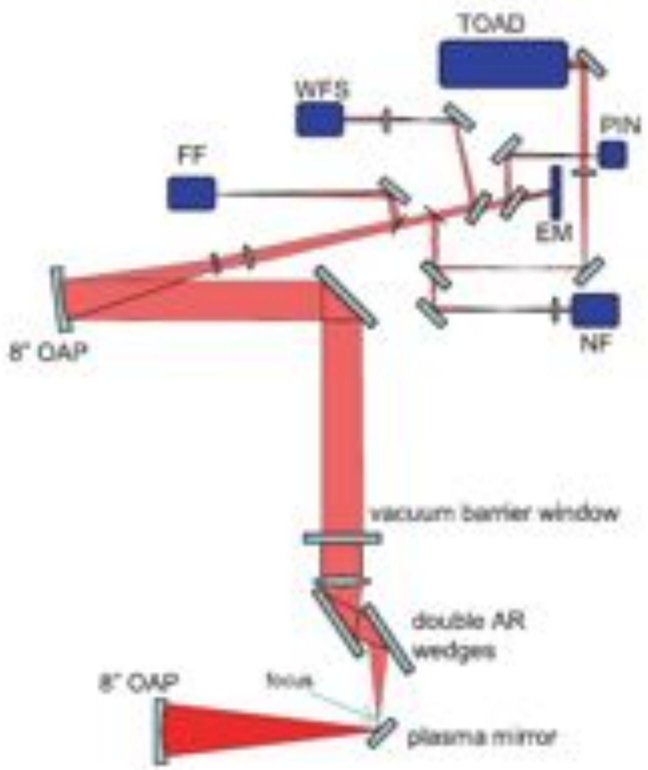
Region 1:
- creates shockwave going thru target (v ~ 5 μm/ns)
- well understood by 2D hydro

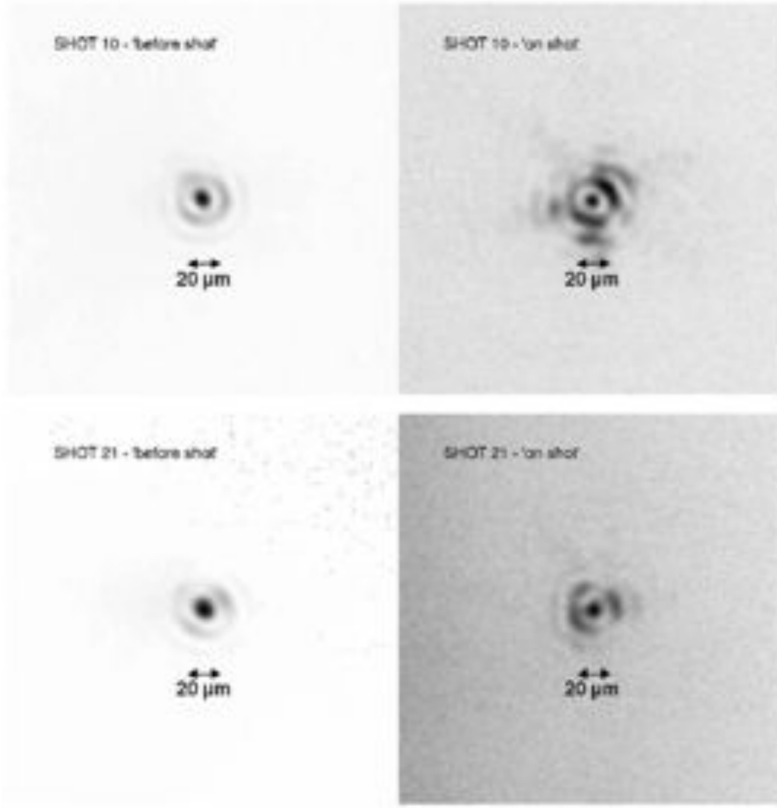
Region 2:
- can create hot electrons and radiative preheat
- reasonably well understood, no pre-heat of rear side

Region 3:
- can create MeV electrons
- requires hybrid PIC/ large-scale PIC modeling
- simulation jobs are running



Contrast improvements: Plasma mirrors





- Fluence on mirror: 20-30 J/cm^2
- Reflection efficiency: 30-40%
- Strongly aberrated focal spot on shot!

Plasma mirrors

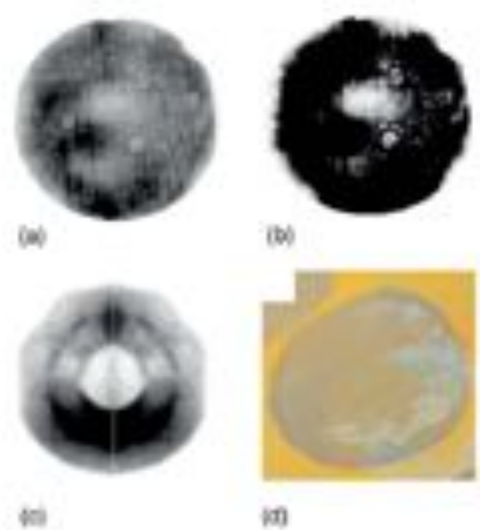
Explanation:

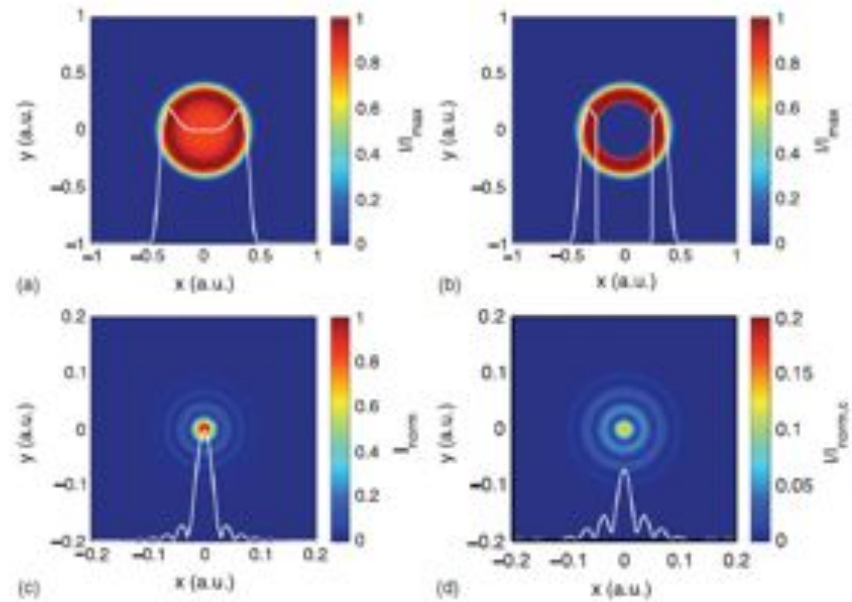
• **Plasma mirror operated near threshold, too close to near field**

$$R_i(x, y) \propto \sigma_n \, I^{n_\gamma}(x, y),$$

$$n_\gamma = \left\lceil \frac{E_{mat}}{E_\gamma} \right\rceil \doteq \min \left\{ n \in \mathbb{N} \mid n \geq \frac{E_{mat}}{E_\gamma} \right\},$$

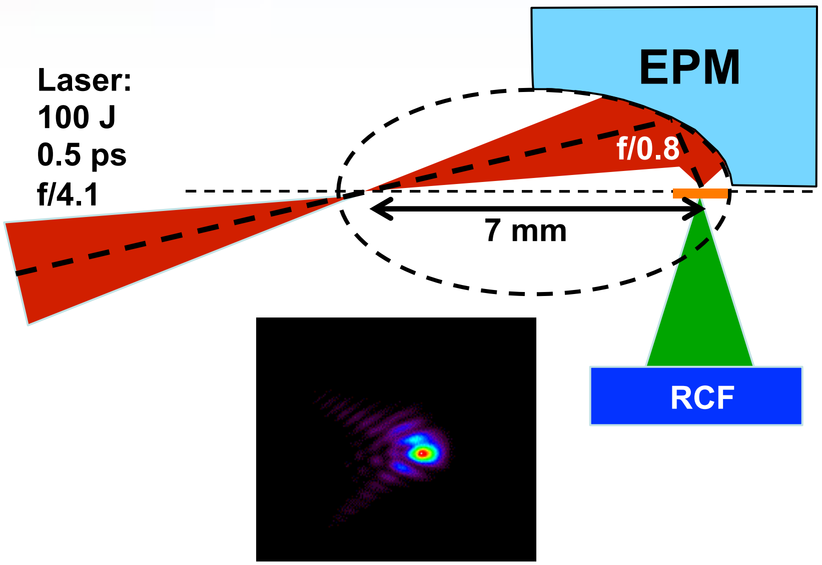
n = 4 → beam only partly reflected





See M. Geissel, MS *et al.*, Rev. Sci. Instrum. 32, 053101 (2011)

Ellipsoidal plasma mirrors (EPM)

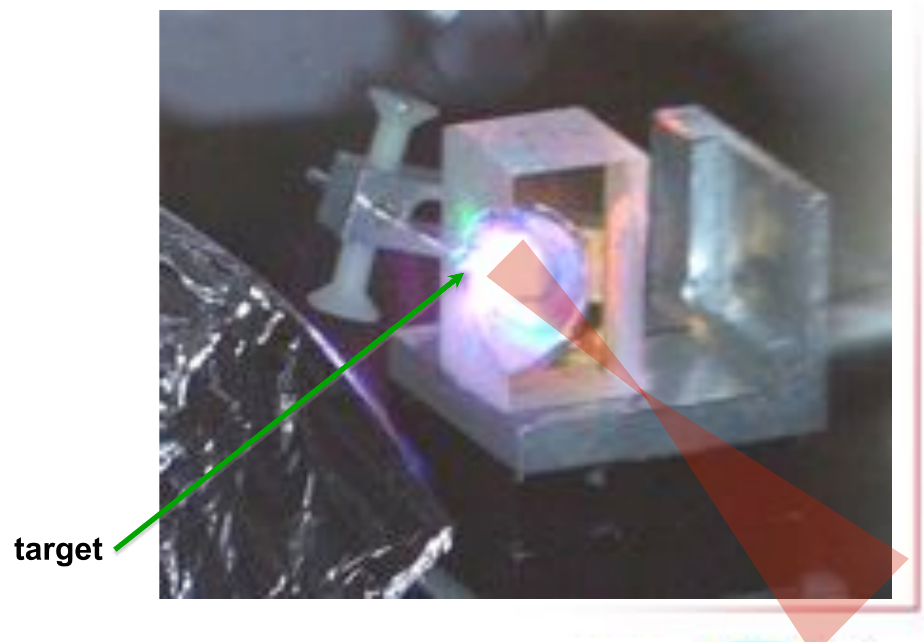


Focus size: ~ 2 µm FWHM
Target: 50 x 50 x 1 µm^3 Al

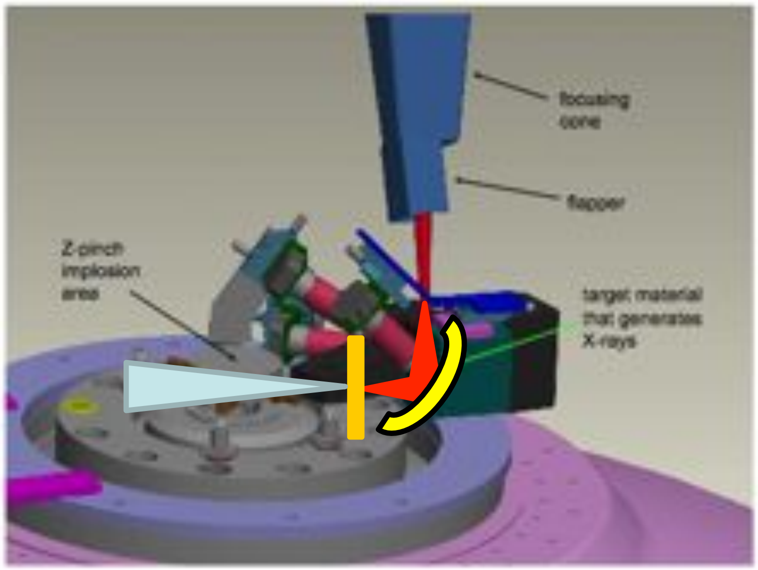
Fluence on mirror: 340 ± 50 J/cm^2

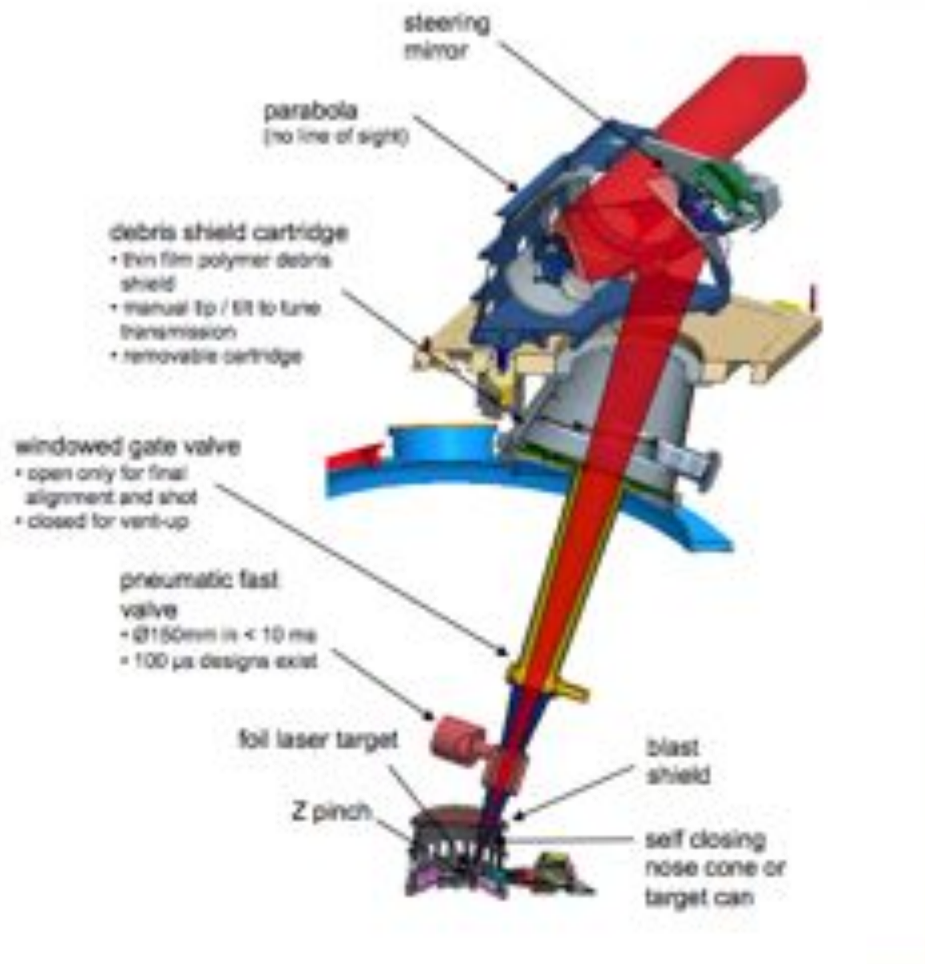
Proton Energy with EPM: 45 MeV
Proton Energy with flat PM: 25 MeV

in collaboration with LULI (France) and Osaka University (Japan)



Improving focal spot and pointing stability on Z with EPM





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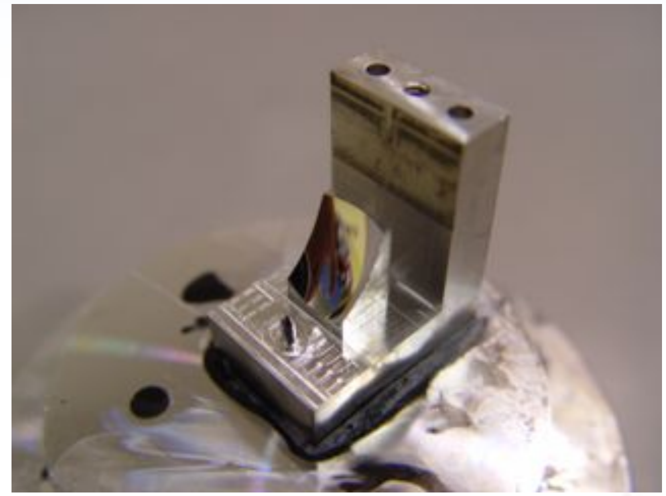
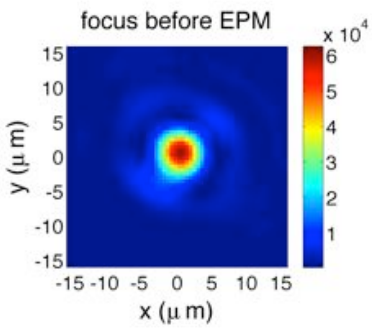
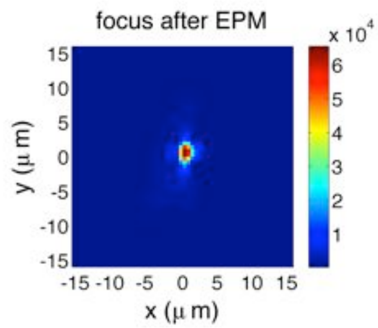
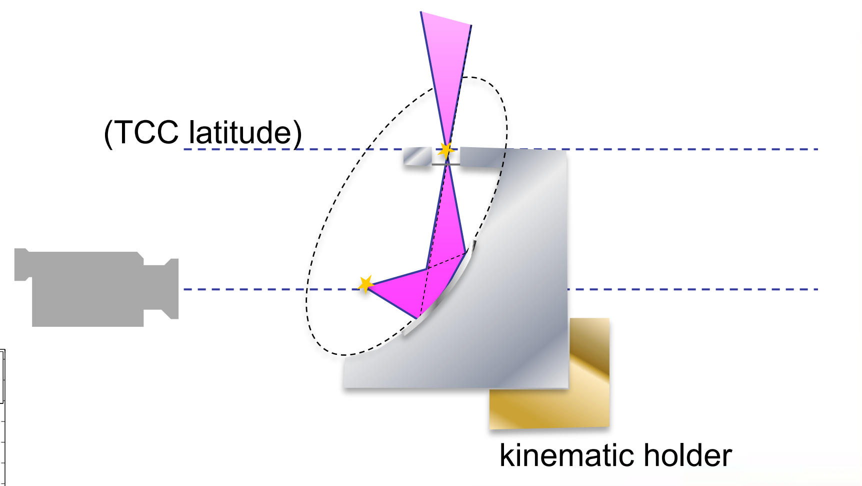
Towards an alignment-free EPM

- Application on Z requires little to no alignment of laser target cassette assembly
- French/Japanese prototype EPM alignment took half a day on 100 TW chamber!
- New device includes built-in alignment datums
- All critical parts (EPM surface, datums, mounting points) are diamond-turned in a single production run, allowing full control within machine precision
- Will be easily exchangeable to ‘shot EPM’, no further alignment necessary

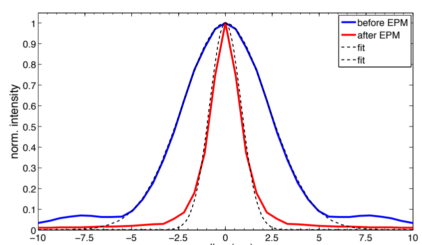








Gaussian fits:
- 5.4 µm FWHM before EPM
- 1.98 µm FWHM after EPM
- De-magnification: 2.72



Conclusions

- **System Upgrades**
  - **HALO completely re-build to be a target shooter**
  - **Large coater upgrades/ coating of OAP, gratings**
  - **Further completion of Target Area**
  - **Planned for CY 2012: 6 kJ at 2w upgrade of ZBL for MagLIF**

- **Experiments**
  - **Diagnostic calibration work**
  - **X-ray backlighting, X-ray scattering**
  - **High-energy X-ray backlighting**
  - **Proton acceleration with large foils and MLT**
  - **Plasma mirror experiments**

Supplementary Materials

Challenge Coating:
ZPW FOA Fold Mirror (75 cm)

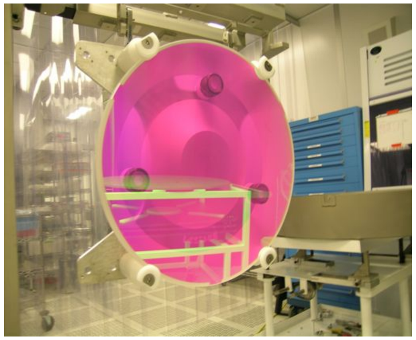
Requirements:

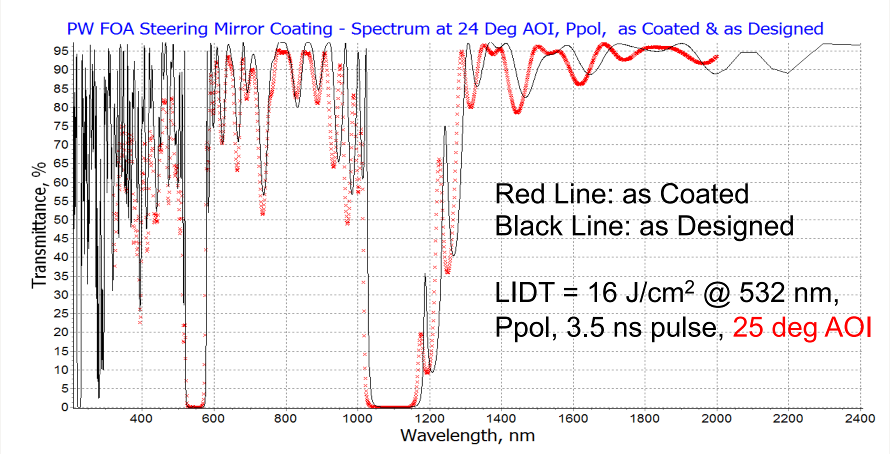
- **Dual wavelength**
- **Large range of AOIs (24 to 47°)**
- **Both s & p polarizations (R>99.6%)**
- **1054nm +/- 6nm (1w)**
- **527nm +/- 3nm (2w)**
- **High LIDT's:**
  - **> 2 J/cm² for fs pulses/1w**
  - **> 10 J/cm² for ns pulses/2w**

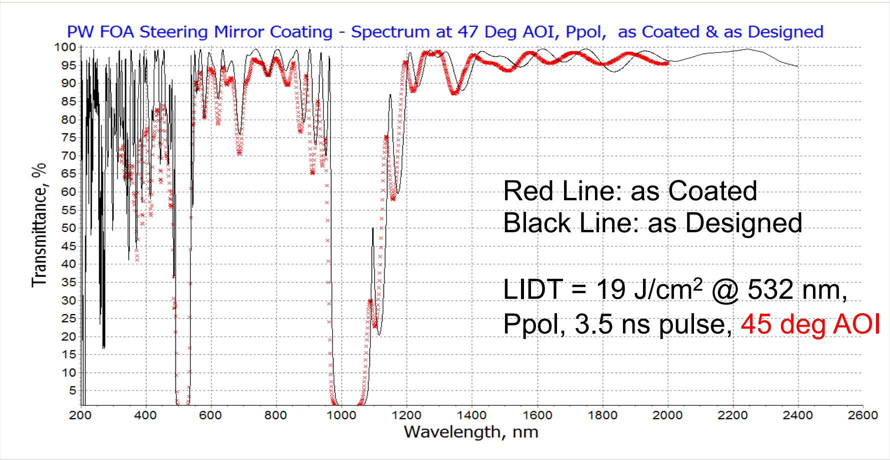
Reality:

- **LIDT ~ 1.4 J/cm² for fs pulses/1w**
  > 15 J/cm² for ns pulses/2w

- **Success achieved with a 50 layer coating**





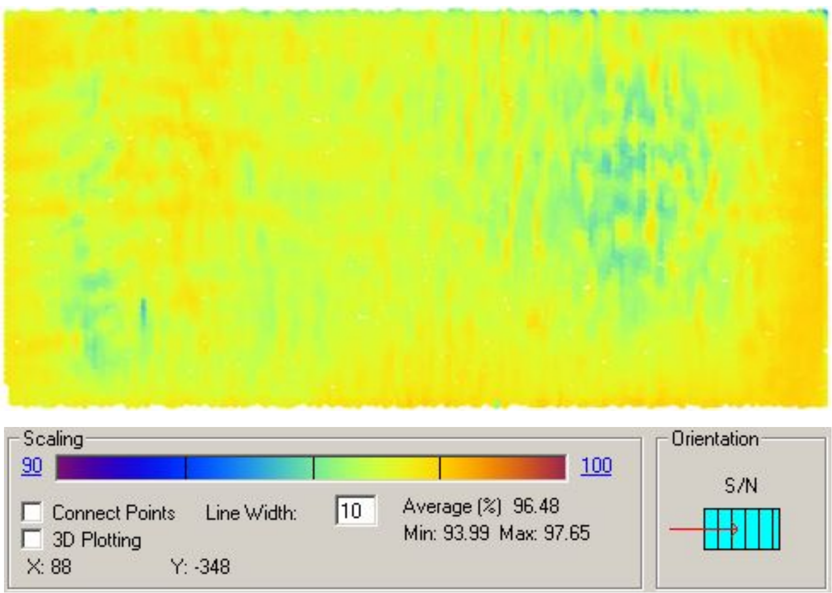


Large MLD Grating Upgrade

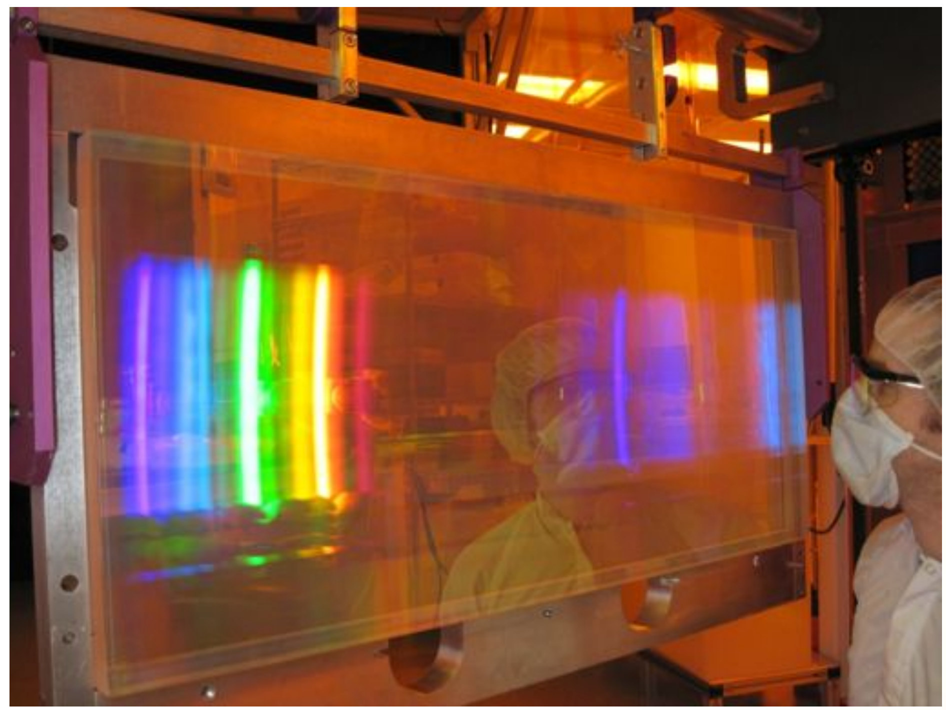
• Short pulse laser energy is currently limited by the LIDT of the old NOVA gold gratings from LLNL.

• Acquired 4 ea. 94cm x 42cm, 1740l/mm multi layer dielectric (MLD) gratings from PGL with required damage threshold of:

- >1 J/cm^2 at 500fs
- >3 J/cm^2 at 10ps



Diffraction efficiency in 1st order >96%



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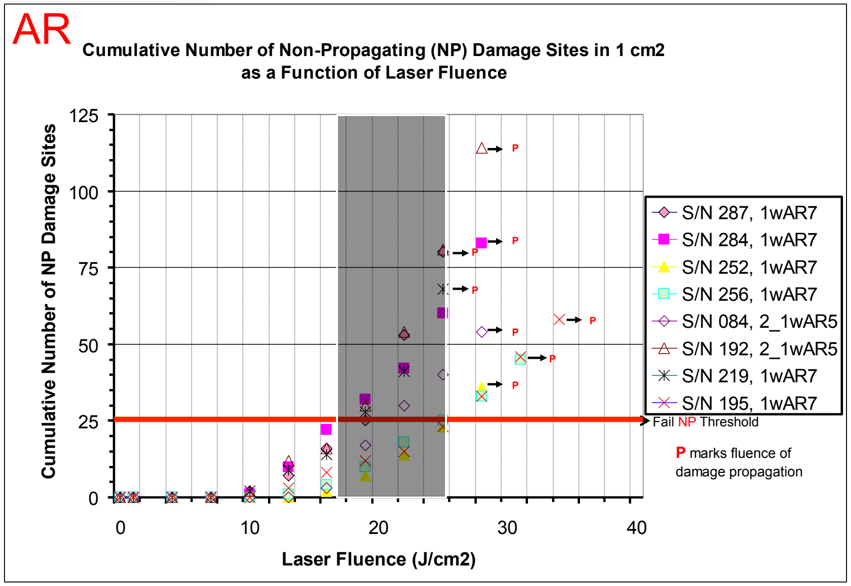
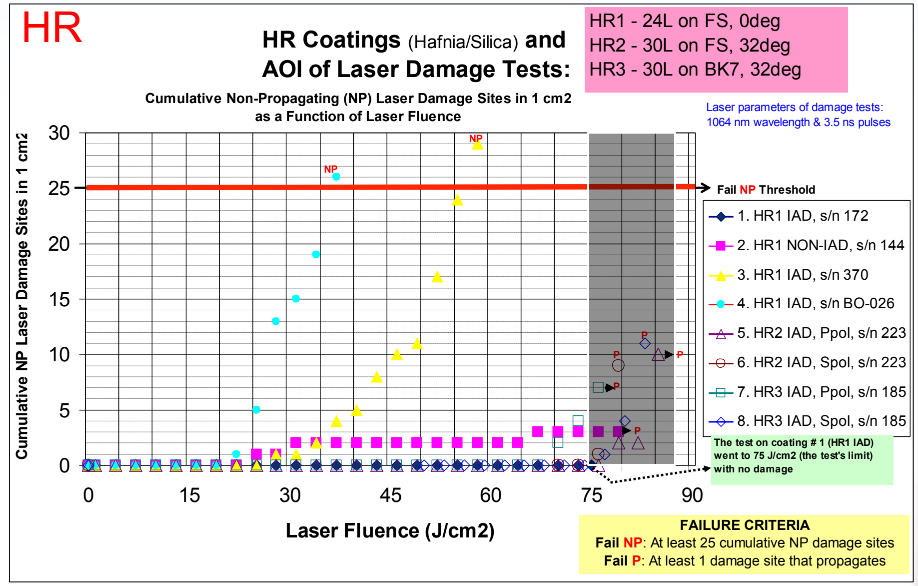
Coating quality





- Independent damage testing (SPICA) has shown good test results. Using a definition of 25 cumulated damage sites (non-propagating) gives 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
- Successful application to both air and vacuum use environments.

* 1064nm, 3.5ns pulse, 1.06mm spot scanned to fill $1cm^2$ with 2300 shots for each of 13 levels from 1-37 J/cm^2, NP sites are of size 15µm

Dual Wavelength HR optics: LIDT

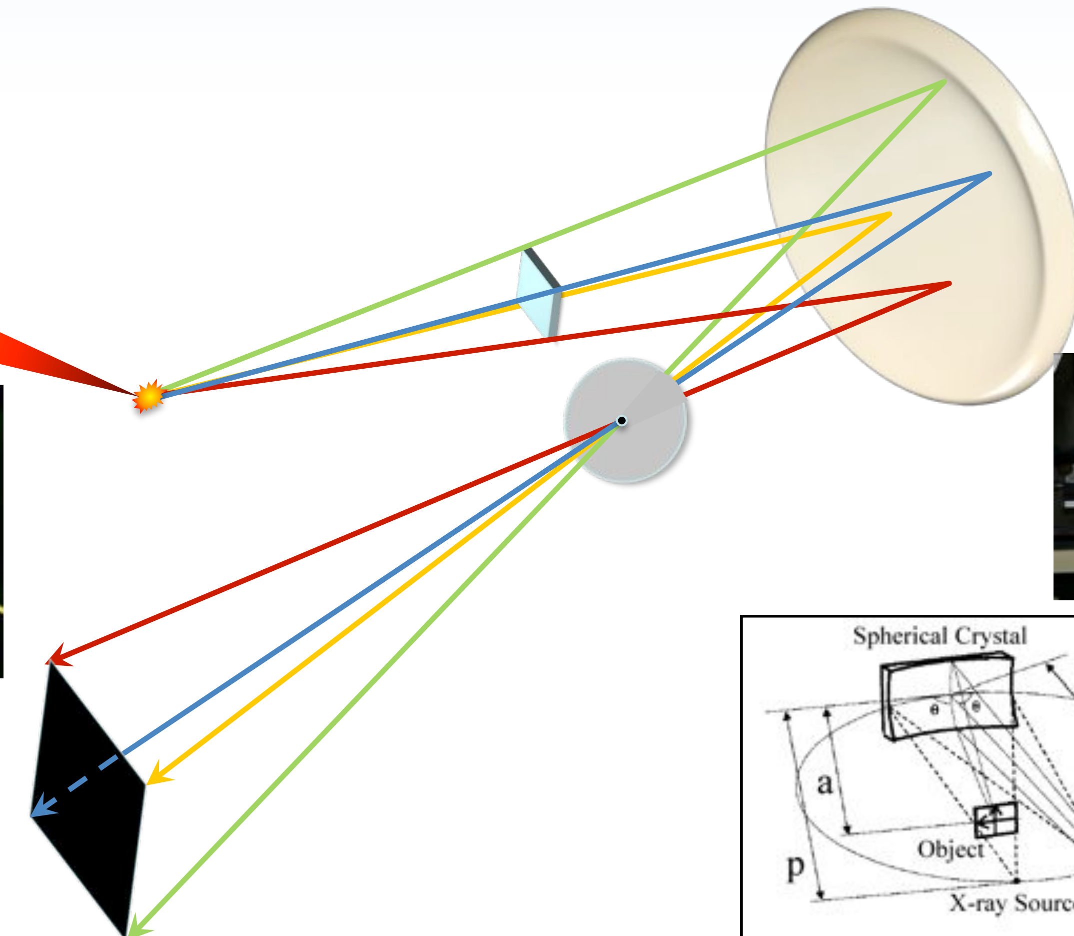
- Short/long pulse laser damage testing was performed in house on Sandia custom dichroic coatings that will allow beam combination of Z-Beamlet and Z-Petawatt.
- Petawatt fluence is limited to ~1J/cm^2 at 1054nm and 500fs
- Z-Beamlet fluences do not exceed 8J/cm^2.

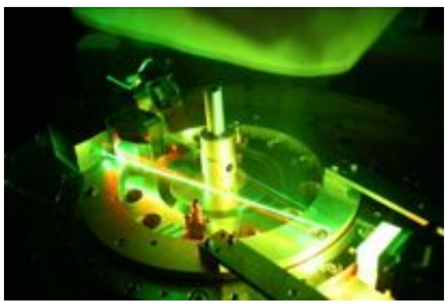
	LIDT
Laser 1 (350 fs) only	1.32 J/cm^2
Laser 2 (7 ns) only	70.1 J/cm^2

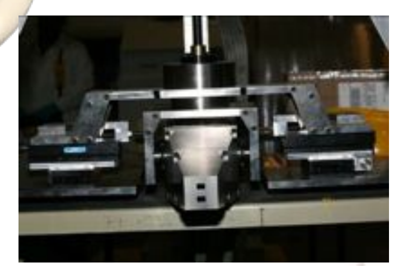
Laser 2: 8.1J/cm^2	Laser 1 LIDT
Laser 1 20ns before Laser 2	1.32 J/cm^2
Laser 1 and Laser 2 co-temporal	1.05 J/cm^2
Laser 1 20ns after Laser 2	1.32J/cm^2

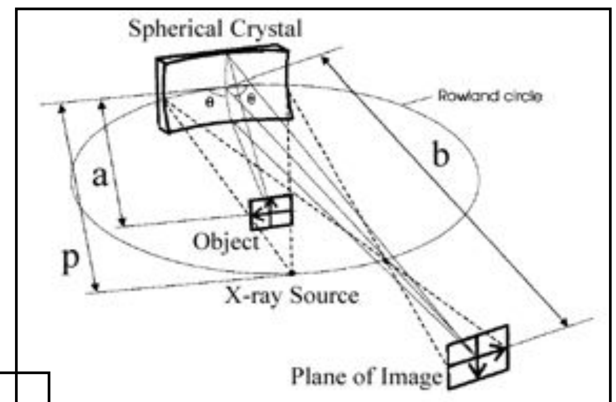
Laser 2: 16.8 J/cm^2	Laser 1 LIDT
Laser 1 20ns before Laser 2	1.32 J/cm^2
Laser 1 and Laser 2 co-temporal	0.75 J/cm^2
Laser 1 20ns after Laser 2	1.32J/cm^2

Curved Crystal Imaging



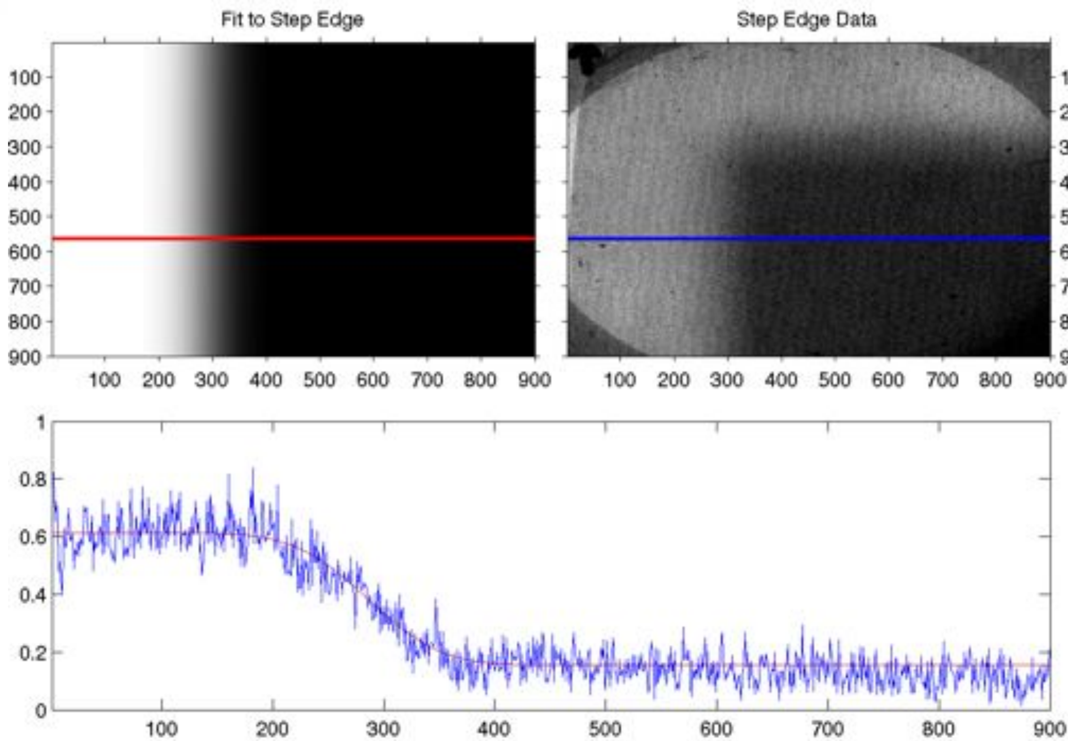


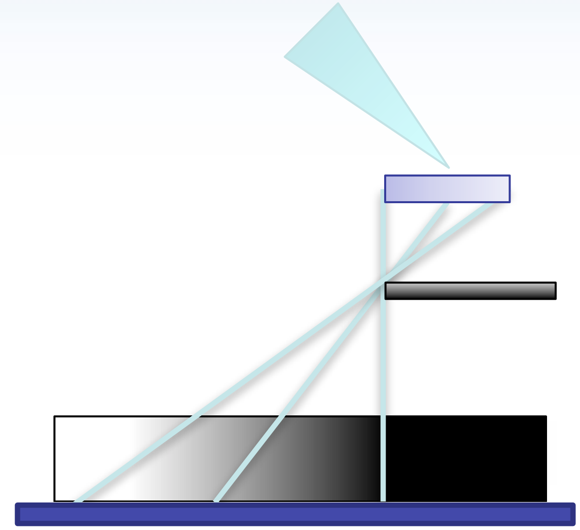


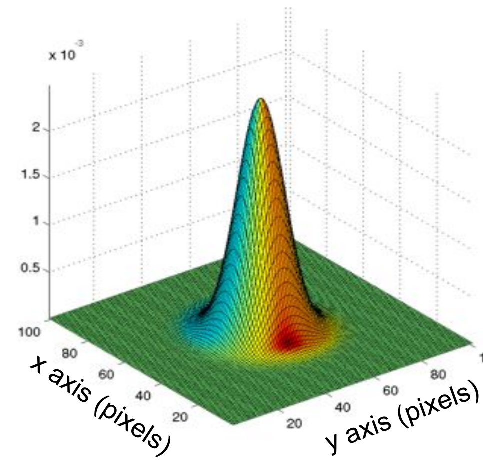


<u>Bent-crystal Imaging</u>
- Monochromatic (~0.5 eV bandpass)
- 10 micron resolution
- Large field of view (e.g. 20 mm x 4 mm)
- Debris mitigation

knife edge: source size measurement



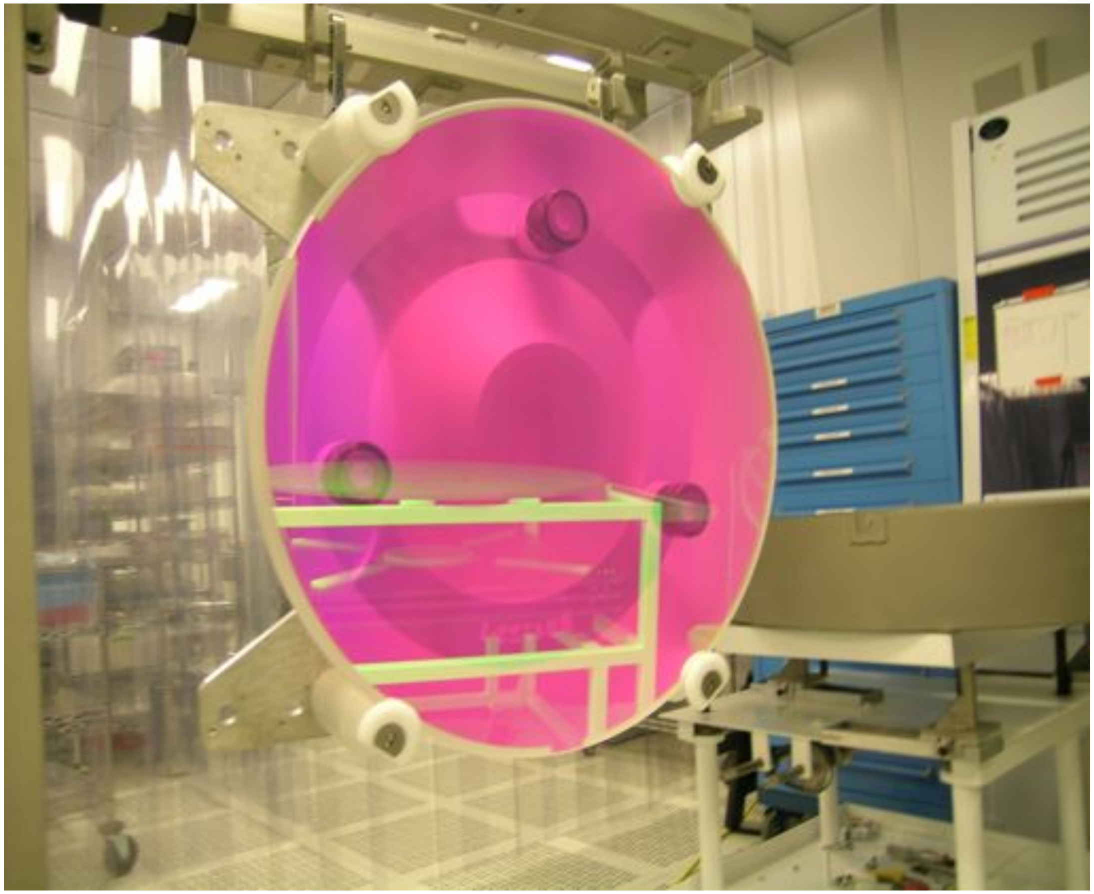




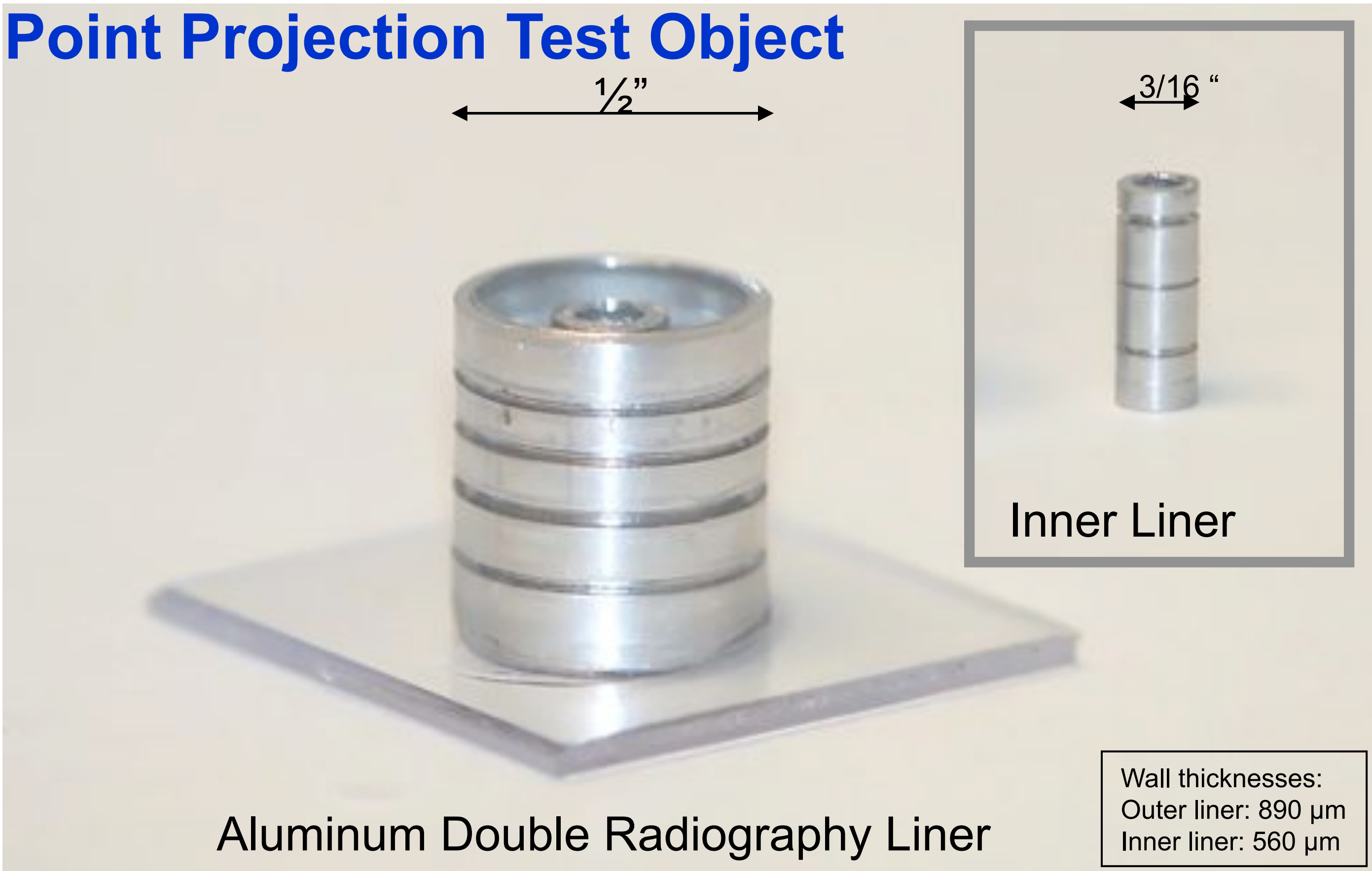
- **magnification: M = 20**
- **image scale in pixels**
- **FWHM of PSF: 18.8 px (470 µm)**
- **actual target size: 440 x 480 x 100 µm^3**

PW OAP: Coated Product

- **75 cm (29.5”) diameter Fused Silica substrate**
- **Sculpted back surface**
- **Optic weight ~ 200 lb**
- **50 layer IAD coating**
- **High dollar amount**



25 keV radiograph of test object



25 keV radiograph of test object

Backlighter target:

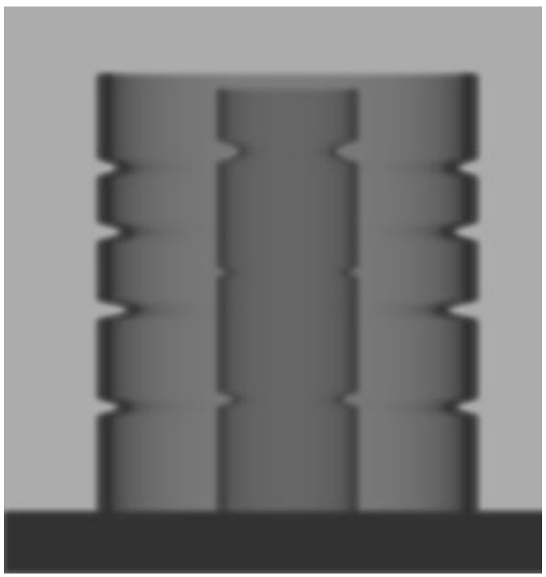
500 µm x 500 µm x 100 µm (size determined by safe alignment and pointing limits of Z-Petawatt in the Center Section of Z)

Filters:

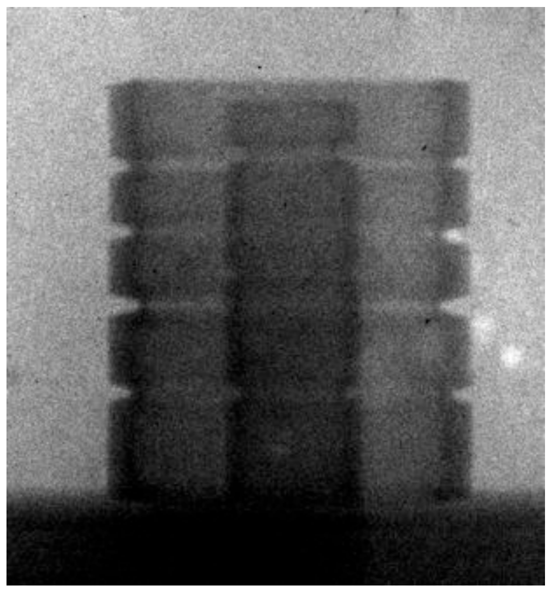
50 µm Cd (75 µm In), 8*250 µm Kapton, 5* 250 µm Al, 0.5 mm Be

Data processing:

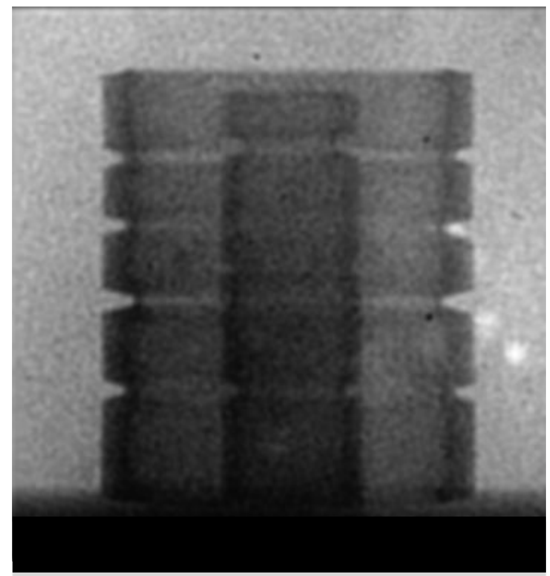
Deconvolution of source size (measured with knife edge), FFT noise filter



simulated radiograph
(500 µm X-ray source)



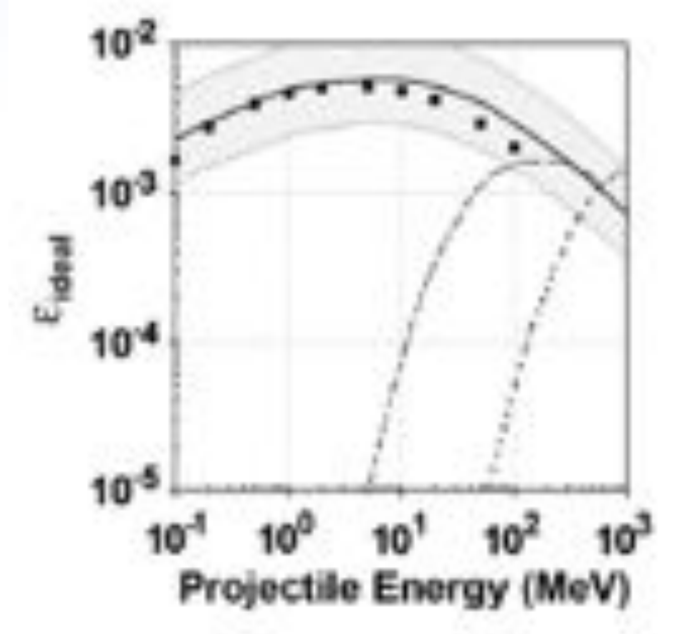
measured radiograph



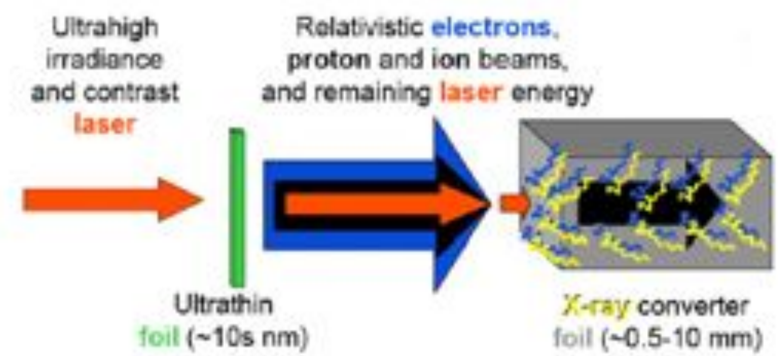
measured radiograph
w/ enhancement

Proposed concept: Enhanced K_α-yield with two-stage target

Motivation:
- calculate ideal Ka-generation with mono-energetic, single particles (e^-, p^+, C)
- global maximum at 10 MeV for electrons
- confirmed by ITS Monte-Carlo simulations
- this approach predicts 5e-3 conversion
- current efficiencies are O(1e-4)
- 50x higher possible



Ultrahigh-intensity laser (10^{21} W/cm^2) with ultrahigh contrast ($>10^{12}$) can generate almost entirely 10's of MeV electrons from ultrathin foils (10's of nm), a.k.a. break-out afterburner effect



Proposed concept: Use a 2-stage approach
- laser irradiates converter foil to generate short pulse of MeV electrons
- electrons propagate into Ka converter target and generate x-rays
- drawback: requires long converter targets (mm)

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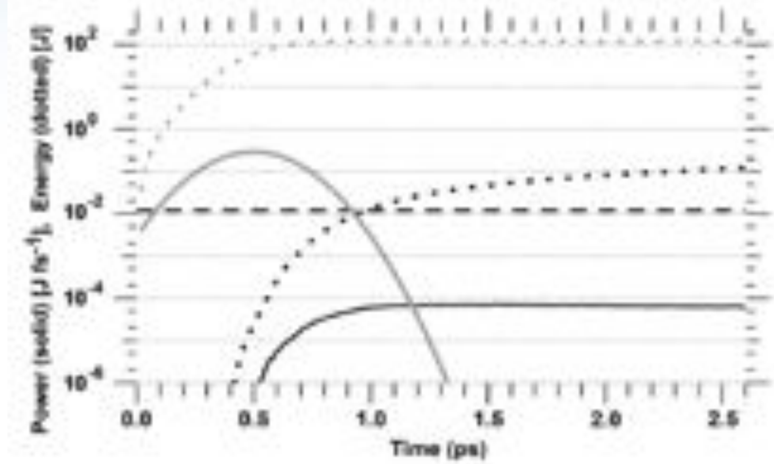
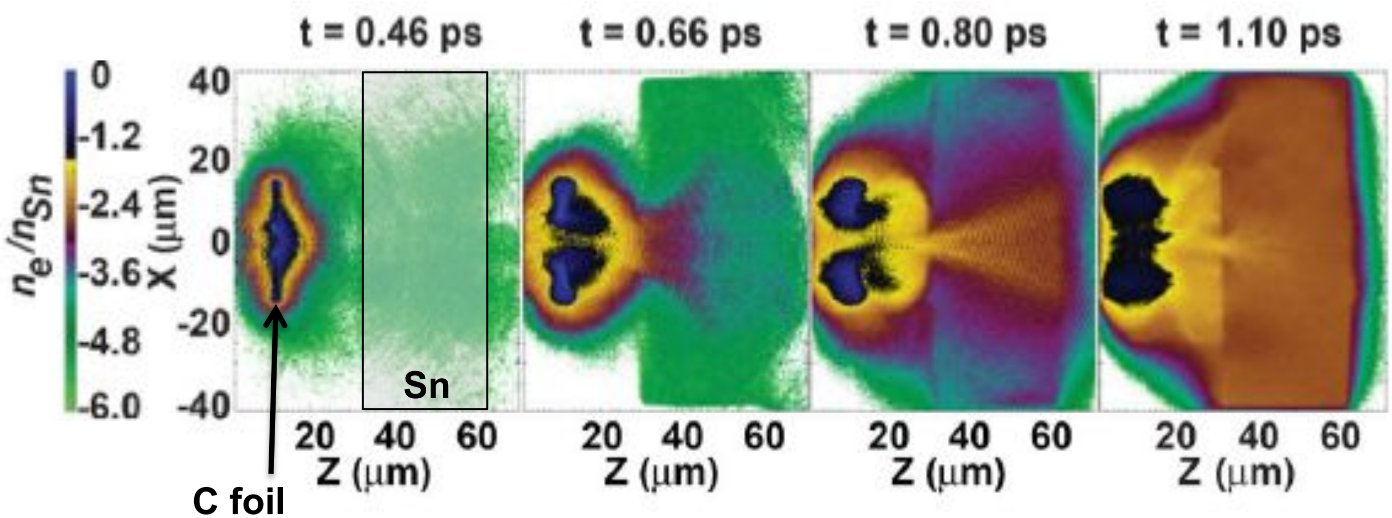
Proposed concept: Enhanced Ka-yield with two-stage target

LSP simulation:
- **fully explicit and kinetic**
- **coupled to ITS for photon generation**
- **no free parameters other than laser pulse input**

→ 10x higher yield than direct-foil irradiation after 2.5 ps





see A.B. Sefkow, G.R. Bennett, M. Geissel, MS., et al., PRL 106, 235002 (2011)

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Energy spectra (for 25 μm thickness)

Energy spectra closely follow quasi-neutral expansion[1]:

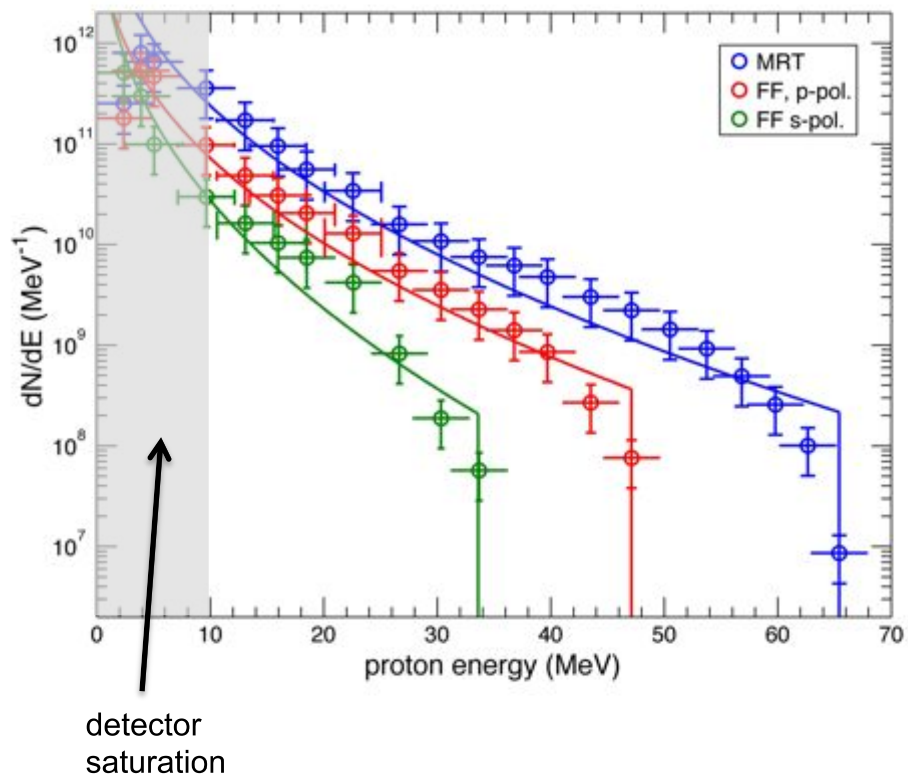
$$\frac{\mathrm{d}N}{\mathrm{d}E} = \frac{N_0}{\sqrt{2\,E\,k_B T_e}}\, e^{-\sqrt{\frac{2E}{k_B T_e}}}$$

Flat foil (FF), s-polarized:
$N_0 = 1.8 \times 10^{13}$
$k_B T_e = 0.76$ MeV

Flat foil, p-polarized:
$N_0 = 1.8 \times 10^{13}$
$k_B T_e = 1.4$ MeV

Mass-reduced target (MRT), p-polarized:
$N_0 = 6 \times 10^{13}$
$k_B T_e = 1.4$ MeV

$k_B T_e$ from ponderomotive potential: 4 MeV
N_{total} on MRT rear surface[2]: ~ 6×10^{13}



[1]P. Mora, Phys. Rev. Lett. 90, 185002 (2003)
[2]M. Allen et al., Phys. Rev. Lett. 93, 265004 (2004)