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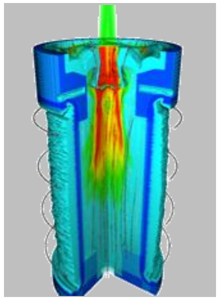

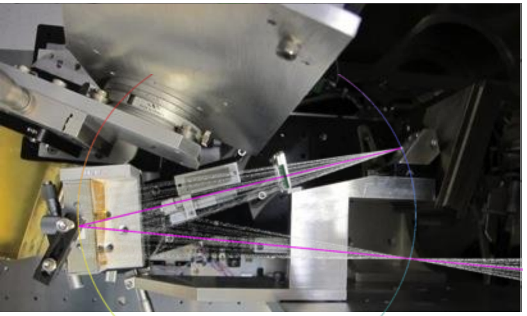

Applications for UXI Imagers on Z

Marius Schollmeier for Group 1680

Applications of CMOS cameras for Z review meeting

Sandia National Laboratories, NM

Dec 10, 2014

Exceptional service in the national interest

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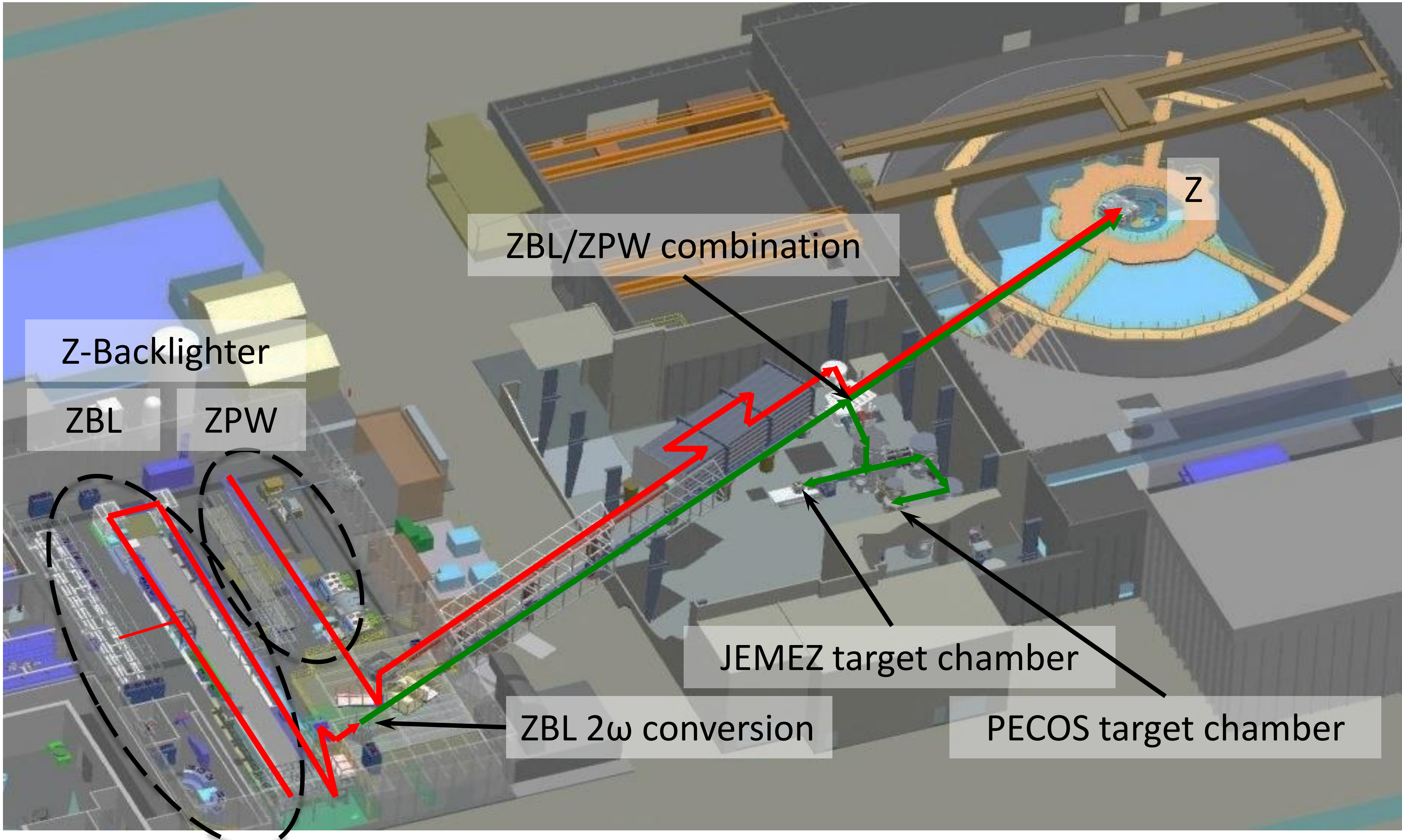
Contents

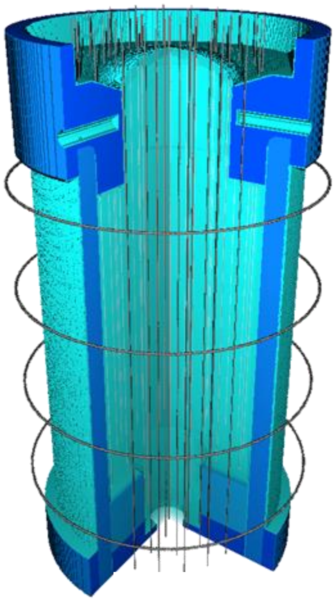
- Z and Z-Backlighter facility overview
- Magnetized Liner Inertial Fusion Experiments
- Multi-Frame, Single Line-of-Sight X-ray Imaging
- Time-gated, Absolute X-Ray Spectroscopy

Facility Overview

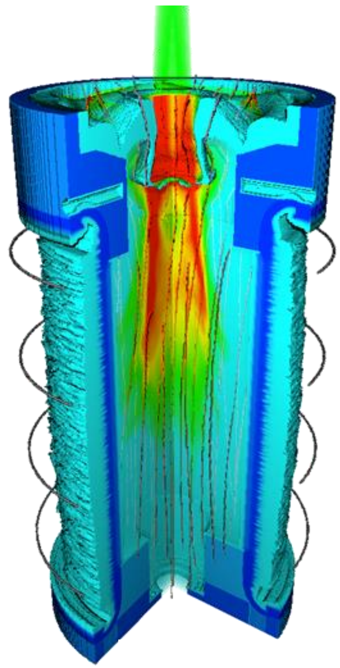


UXI for Magnetized Liner Inertial Fusion (MagLIF) Experiments

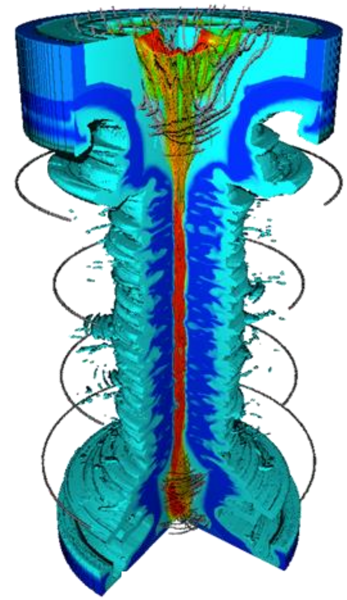
Magnetized Liner Inertial Fusion



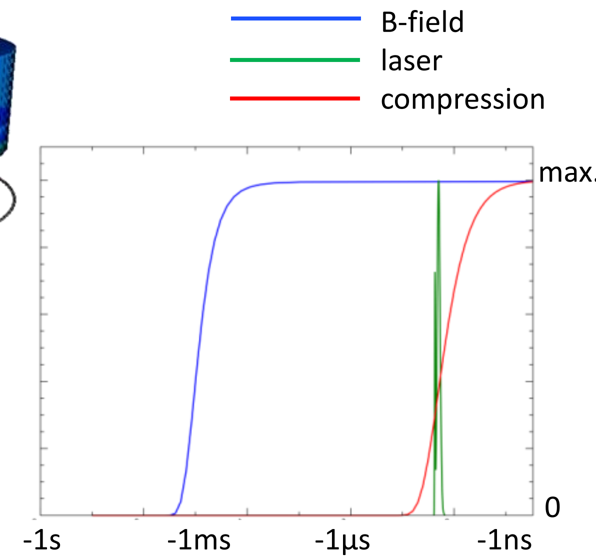
Magnetization
with external B-Field
(ABZ, 10-30 T)

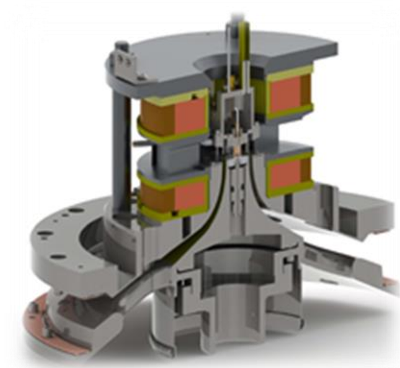


Laser heating
with Z-Beamlet
(2-6 kJ @ 2-6 ns)



Compression
with Z

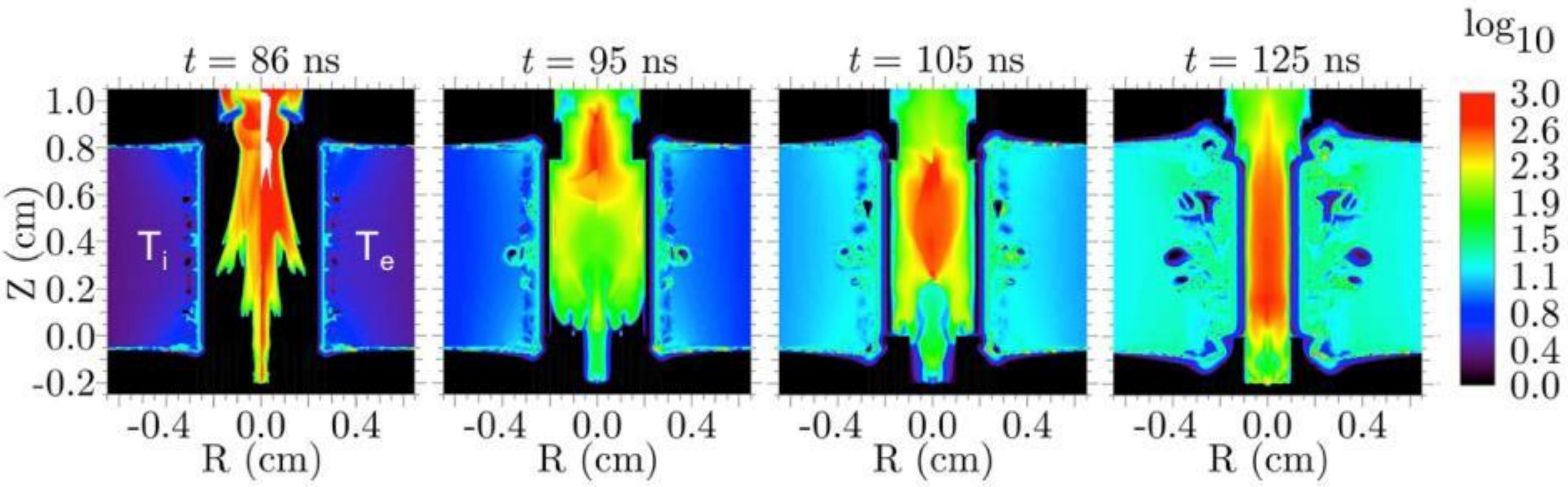




S. Slutz et al.: Physics of Plasmas **17**, 056303 (2010)

Simulated temperature evolution of a MagLIF experiment

- Parameters:
  - E_{las} = 2.2 kJ, 2 ns pulse with 0.5 ns picket at 2.5 ns prior to main pulse
  - Liner: AR =6, L = 7.5 mm, 1.5 mg/cc D_2, r_o = 2.79 mm, r = 1.5 mm LEH
- Temperature evolution:
  - 4 ns after laser pulse (t_0 = 80 ns): $kT_e \approx$ 1 keV
  - 13 ns later: $kT_e \approx$ 100 eV
  - 23 ns later: $kT_e \approx$ 300 eV



A.B. Sefkow et al., Phys. Plasmas 21, 072711 (2014)

Use noble gas as diagnostics tracer for temperature measurement

- 1D laser bremsstrahlung absorption model
- Fixed absorption length: 7.5 mm
- Fixed laser energy: 2 kJ

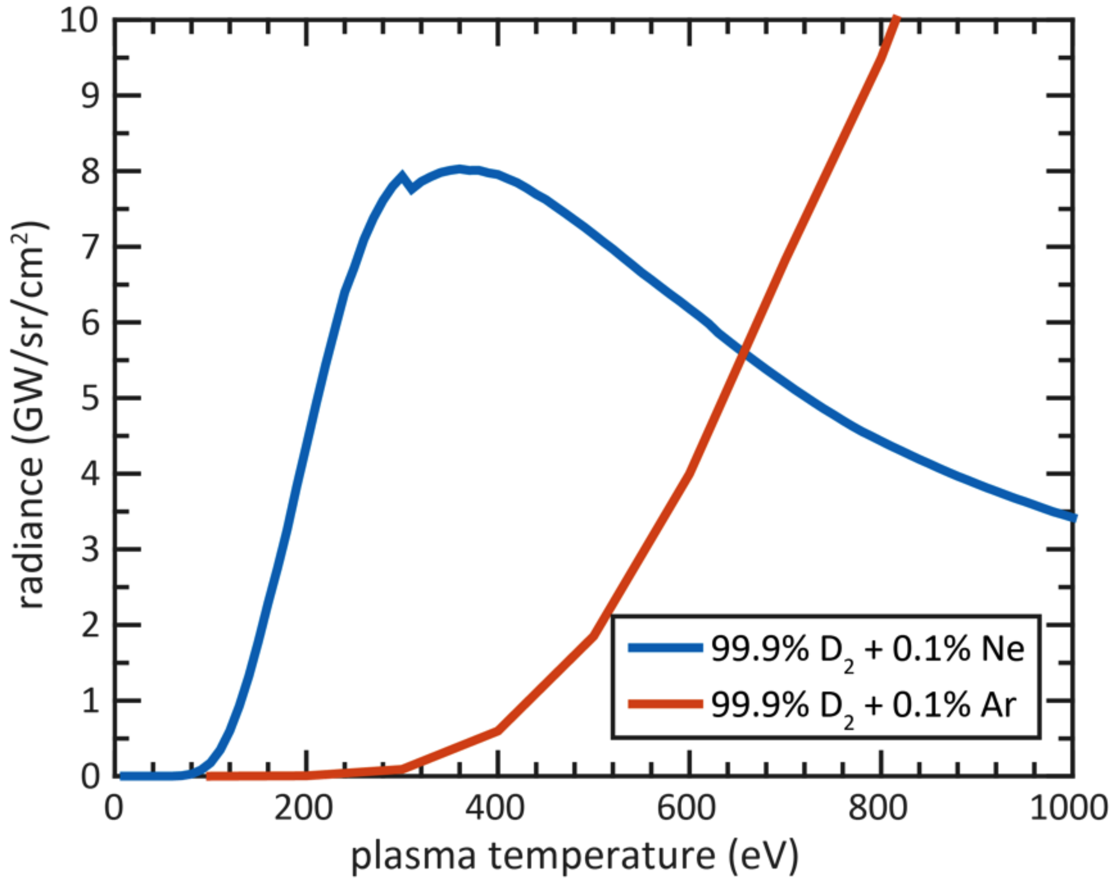
Fill Gas or Mixture	Fill Pressure (atm)	T_e (eV)	n_e ($\times 10^{20}$ cm^{-3})	n_i ($\times 10^{20}$ cm^{-3})	Average ionization
D_2	**15.6**	**861**	**4.06**	**4.06**	**1**
D_2 + 1% Ar	13.4	932	4.00	3.48	1.15
D_2 + 0.1% Ar	**15.3**	**869**	**4.00**	**3.98**	**1.008**
D_2 + 1% Ne	14.1	911	4.00	3.67	1.09
D_2 + 0.1% Ne	**15.4**	**868**	**4.04**	**4.00**	**1.01**

- 0.1 % of Ne/Ar does not change laser absorption compared to pure D_2
- However, A.B. Sefkow's simulations indicate 50% *n* yield degradation for 0.1% Ar

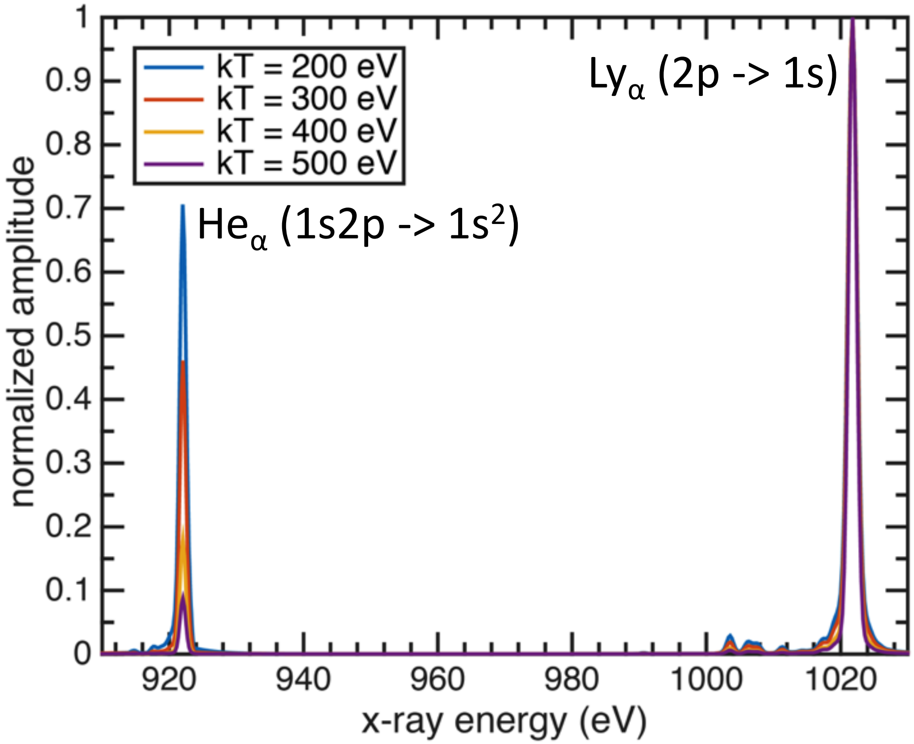
Ne and Ar integrated radiance calculations

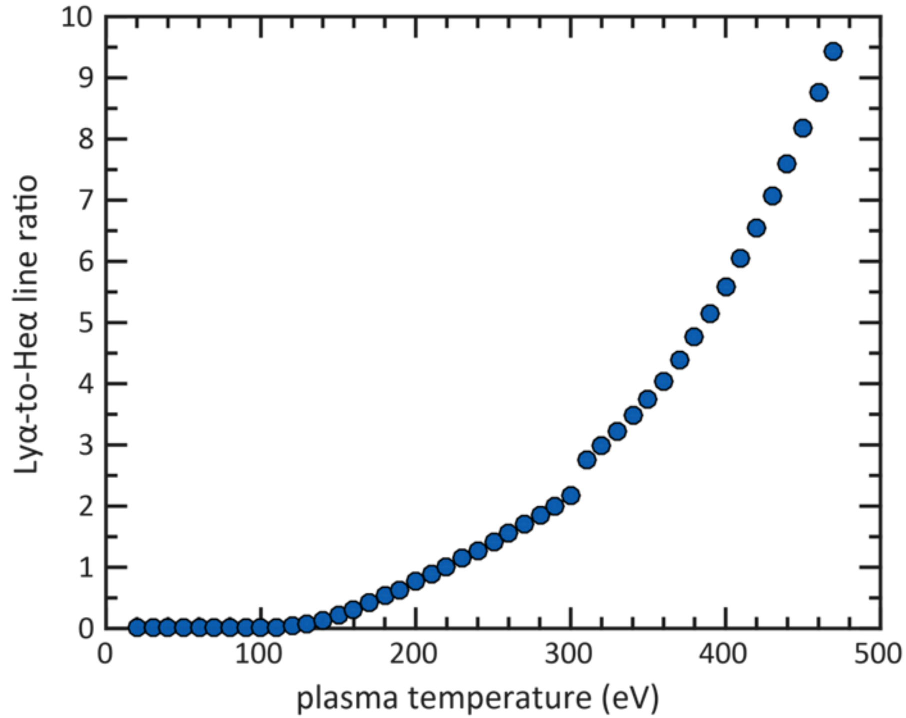
PrismSPECT simulations:

- Planar geometry, 1 cm long
- Steady-state, 1-T Maxwellian, Non-LTE
- Integral over H-like, He-like spectral lines



Ne spectra vs. plasma temperature





Axial Imaging and Thermometry (AXIAT)

Deliverable:

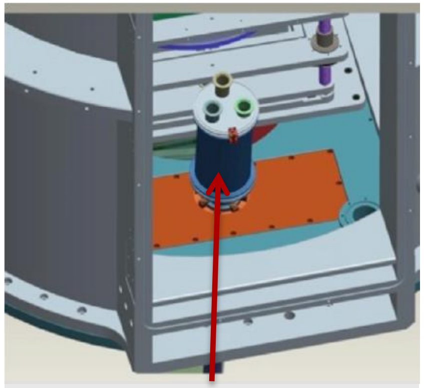
$k_B T_{e,i}(r,z,t)$ during and shortly after laser irradiation

Technique:

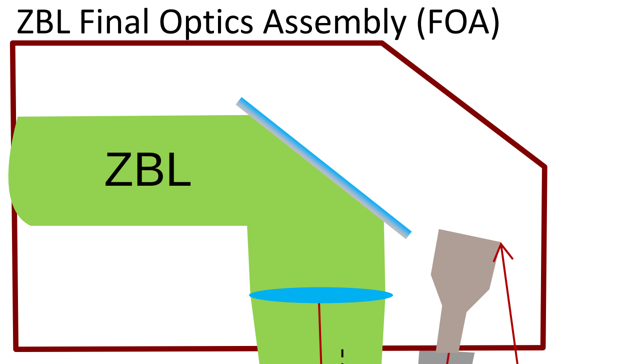
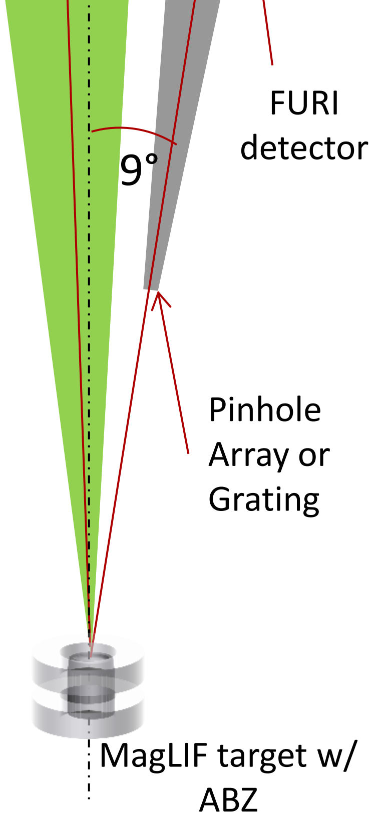
Time-gated x-ray emission spectroscopy & pyrometry of Ne tracer gas

Implementation:

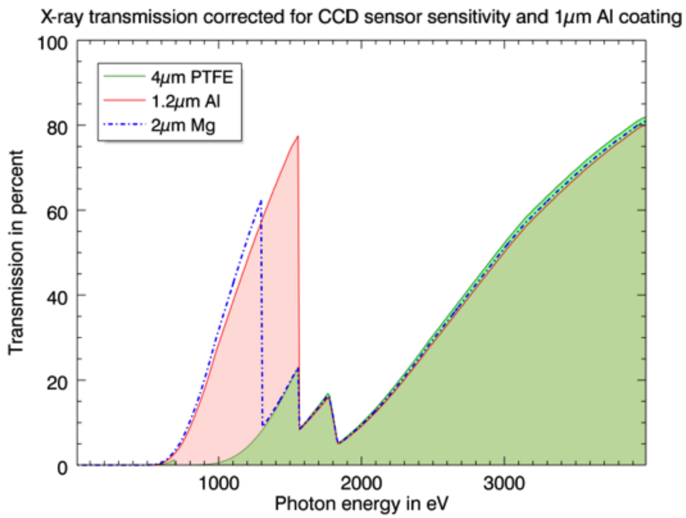
1. Field X-ray pinhole camera in FOA (FURI)
2. Assess temperatures based on Ross-filtered images from 1
3. Field spectrometer in FOA to measure plasma temperature from H- and He-like ion line ratios (FURI)
4. Benchmark detectors with blastwave experiments in PECOS target chamber (FURI, HIPPOGRIFF)

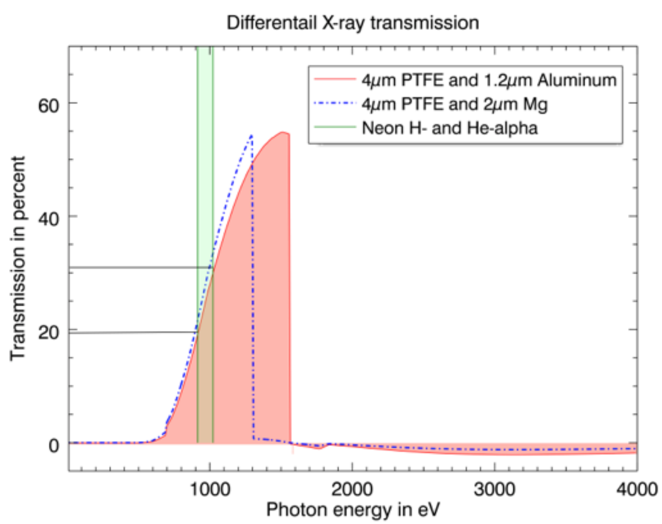


Commercial vacuum parts to house FURI camera

Ross filter pairs to discriminate Ne





Ross filter pairs can discriminate Ne-emission from background

Everything else NEON	Mg filtered data
-	
Everything else	PTFE filtered data
=	
NEON	difference

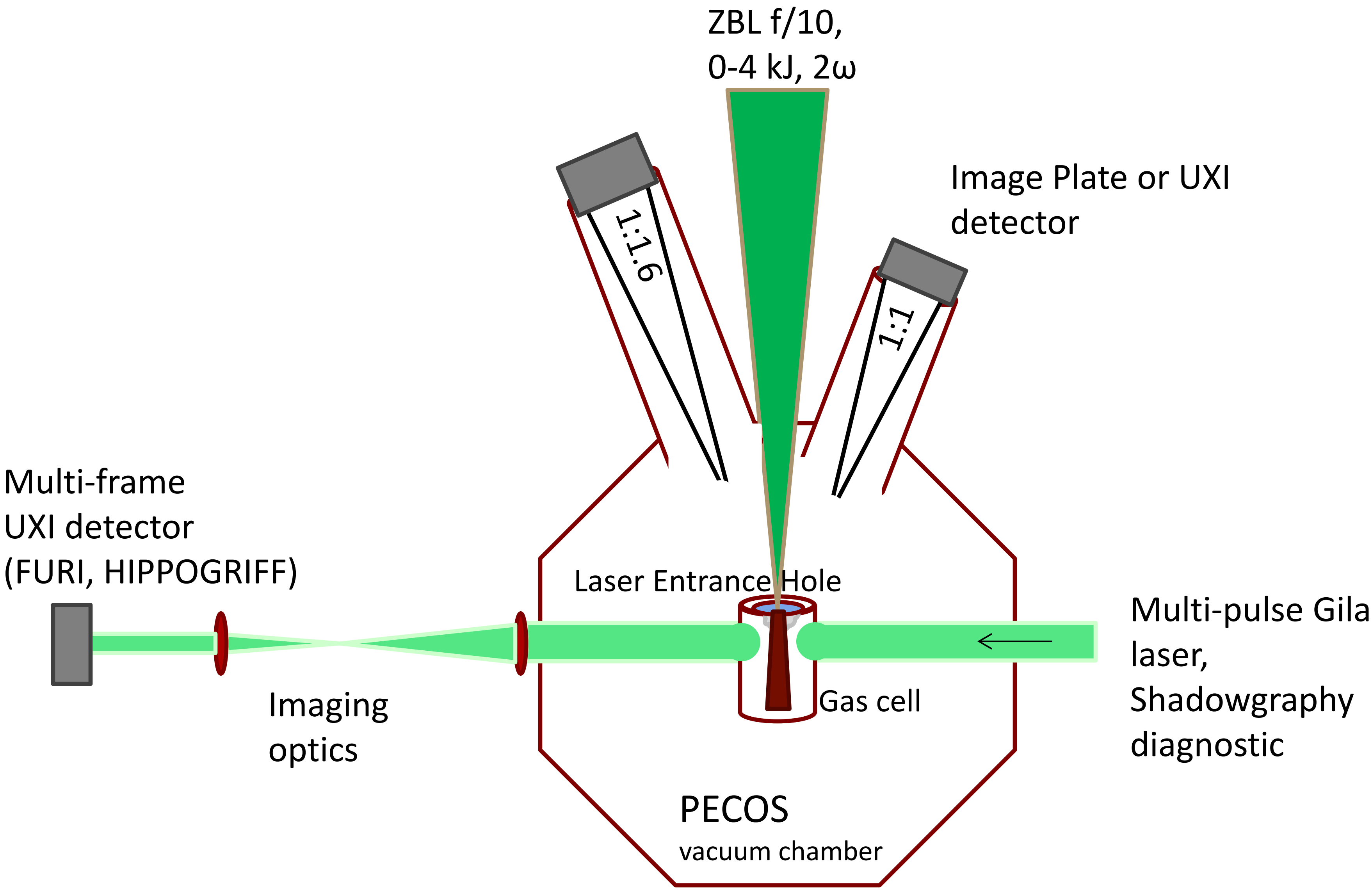
Pinhole camera photometrics

- Assumptions:
  - 1:1 magnification, 300 µm diameter in 1.5 m distance
  - PHC images whole LEH (r = 1.5 mm), area A_{LEH}: 0.07 cm^2

- Source Radiance $d^2\Phi/(dAd\Omega)$: 5×10^9 W/cm^2/sr
- PHC solid angle dΩ: 3.14×10^{-8} sr
- Filter/LEH transmission* T_{total}: 0.2
- Emitted energy in **5 ns**, $E_{ph} = d^2\Phi/(dAd\Omega) \times d\Omega \times dA_{LEH} \times T_{total} \times$ 5 ns: 11 nJ
- Total number of 1 keV photons: 7×10^7
- Number of pixels $A_{LEH}/(25\ \mu m)^2$: 11,200
- Photons per pixel: 6100
- Signal:
  - **FURI (DQE ≈ 50%): ≈ 10^6 e^-**
  - IP: ≈ 1 PSL

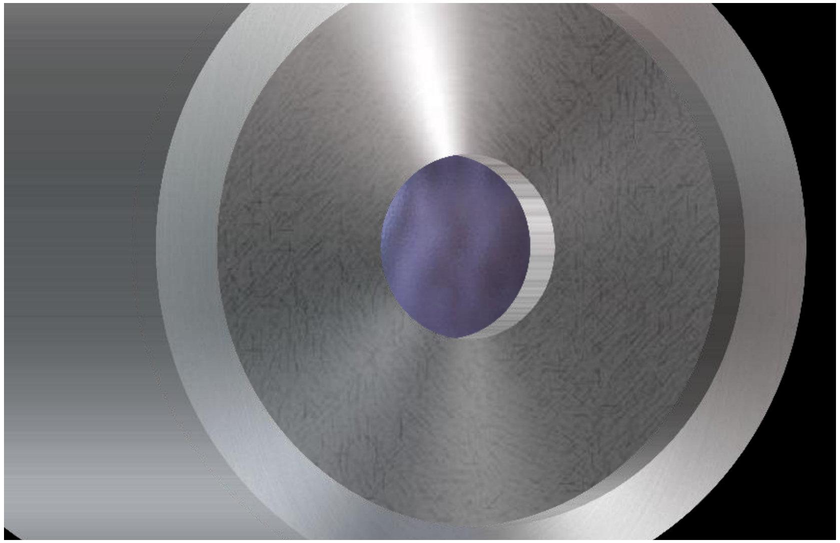
*1 µm Al on FURI, 2 µm polyimide LEH, 1.2 µm Al Ross filter

Calibration experiments @ PECOS

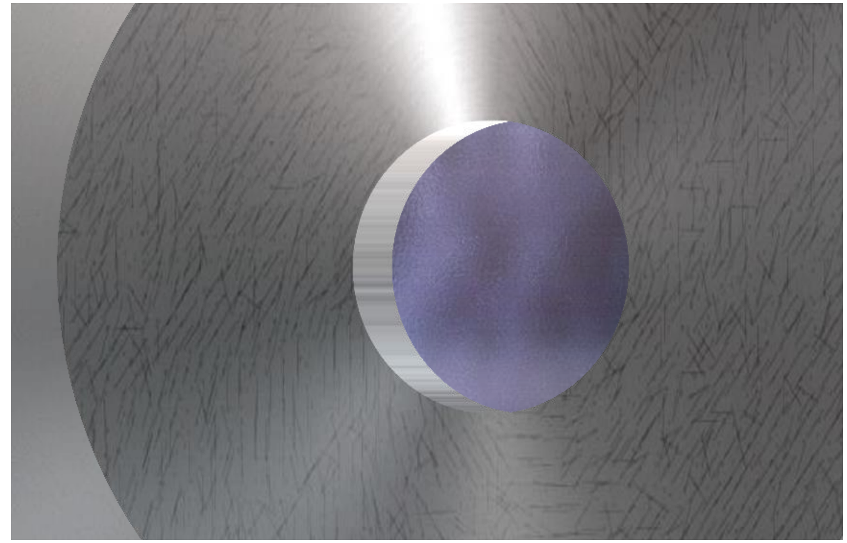


PHC Anticipated Field of View

North-East Viewport



North-West Viewport

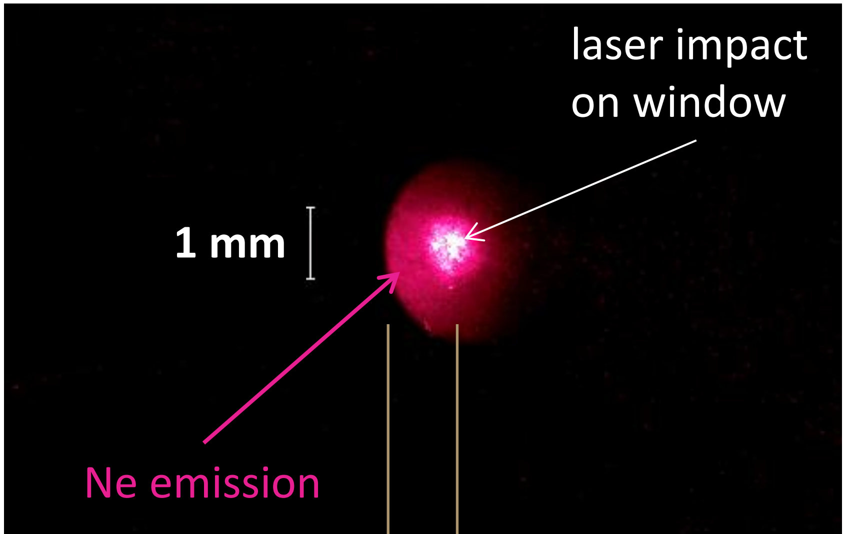


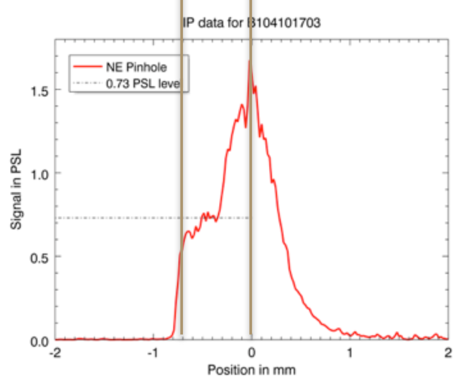
New FOA Prototype Pinhole Camera
100 µm pinhole
Magnification 1:1
Detector: Image Plate
Resolution (object plane) : ≈100 µm

Pecos Pinhole Camera
100 µm pinhole
Magnification 1.6:1
Detector: CCD
Resolution (object plane): ≈80 µm

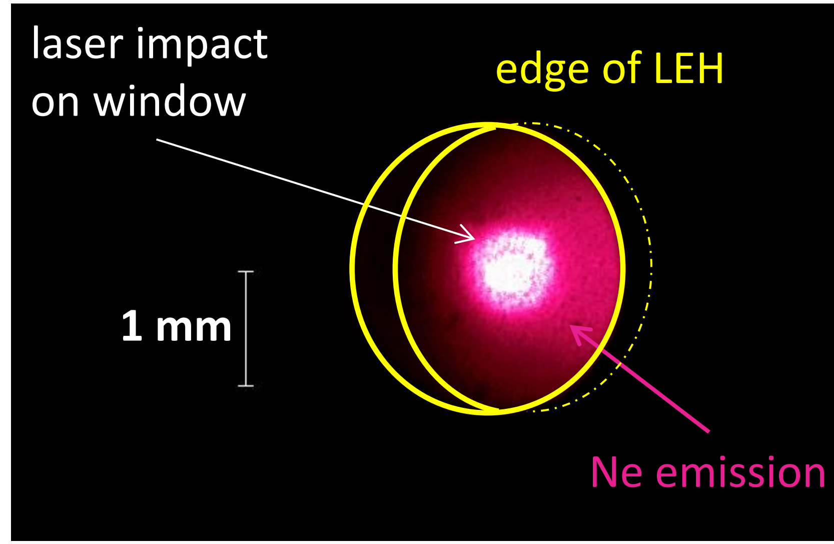
Neon Emission on ZBL shot B14101703 (270 torr Ne)

North-East Viewport





North-West Viewport



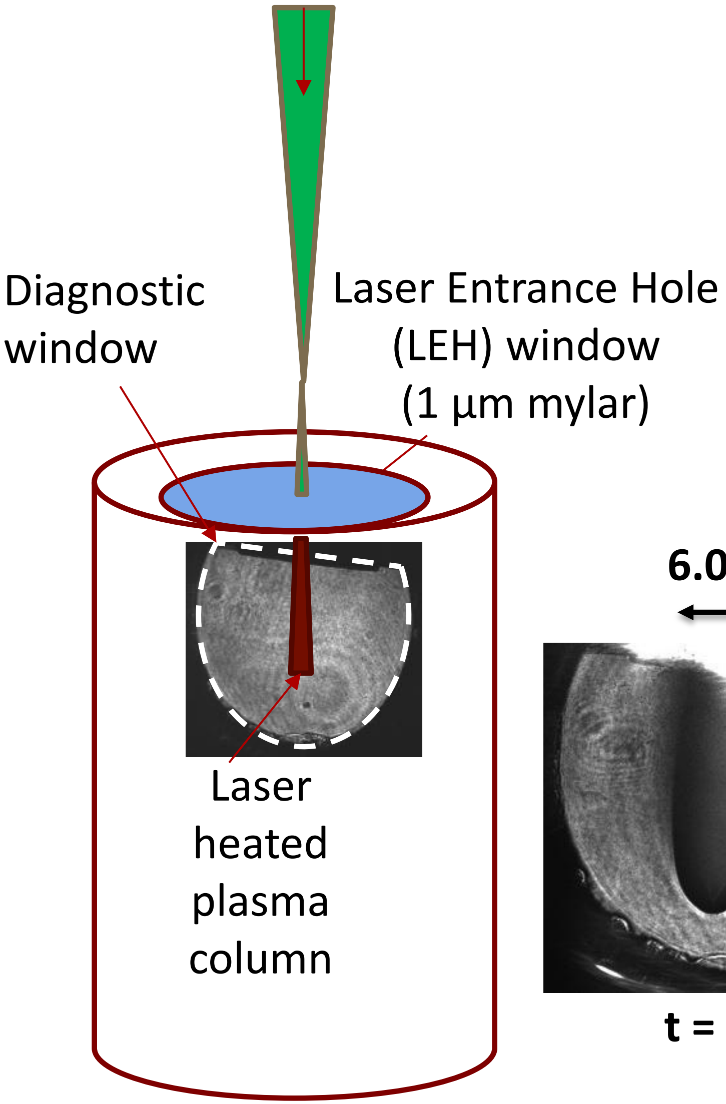
<u>Signal estimate:</u>

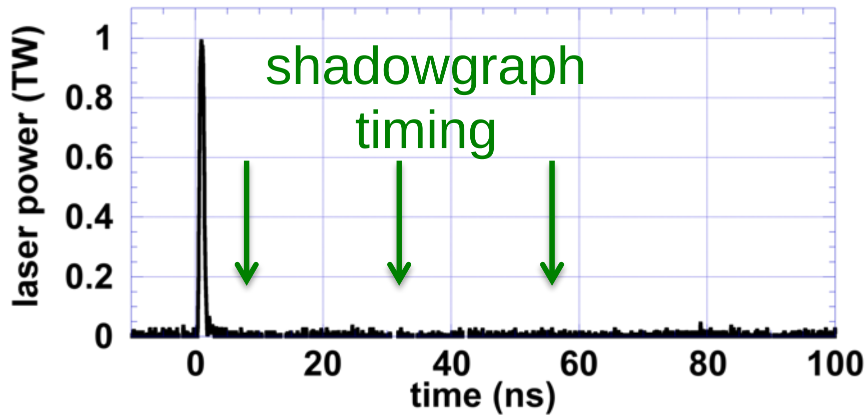
Laser pulse:	0.5ns (pre) + 2ns (main)
Pulse duration behind window:	≈1ns
Ne radiance (300 eV):	2×10^{10} W/cm^2/sr
IP response:	1.8×10^{-4} PSL/phot.
Filter transmission:	0.28

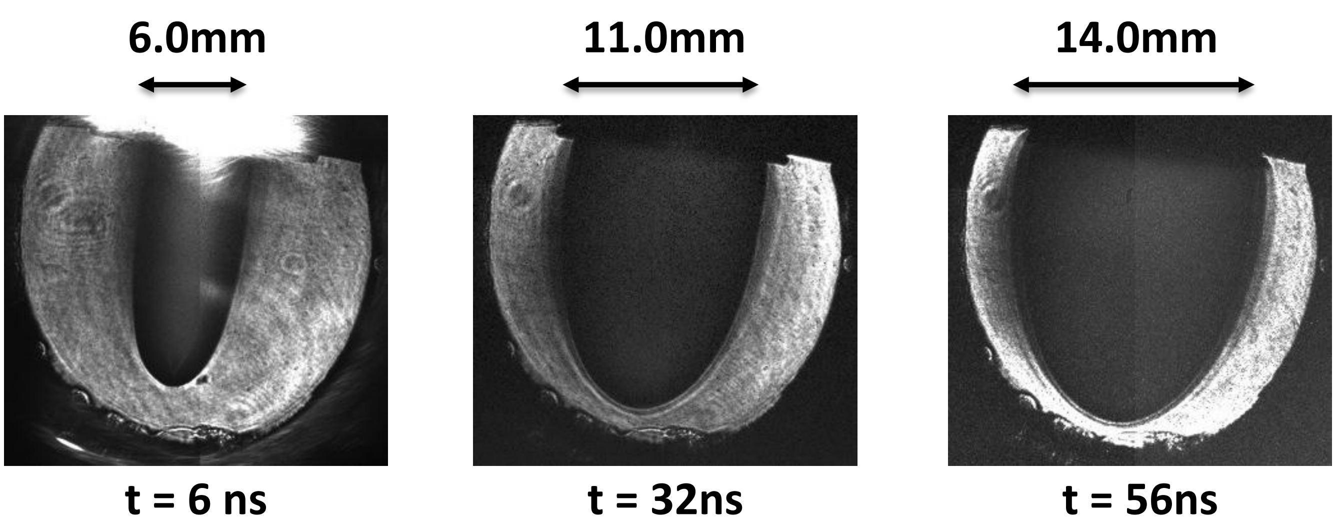
Prediction for IP signal at $kT_e > 200$ eV: **1-2 PSL**

<u>Measurement (corrected for fading):</u> **1.6 PSL**

Laser launches cylindrical blast wave







ZBL: 1.8kJ/2ns, 300J prepulse, 1 mm dia., focus at window **Target:** 1 µm-thick Mylar LEH, 247 Torr neon gas fill

Blastwaves can be used to diagnose energy deposition

- Blastwave radius with time: $R(t) = C\left(\frac{E}{\rho_0}\right)^{1/5} t^{2/5}$

- Adiabatic index of 1.4 for diatomic gas: $C = 1$

$$E = \frac{\rho_0 R^5}{t^2}$$

- Experimental $R(t)$ give a typical BW energy ≈80-100 J for a 1 kJ ZBL shot (without beam smoothing)

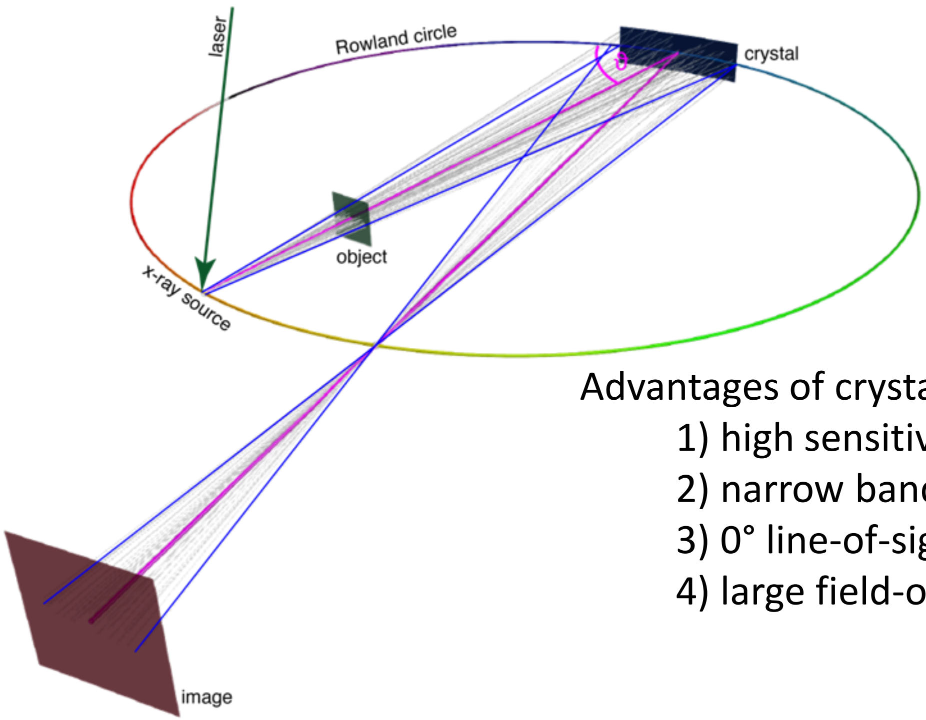
Summary: UXI cameras for MagLIF

- Diagnose the gas temperature evolution during and after the laser-heating phase:
  - PHC camera requirements:
    - 1-10 ns exposure time
    - >2 frames
    - Sensor calibrated for 1 keV x-rays
    - UXI in Final Optics Assembly on Z
  - Blastwave camera requirements:
    - 1-10 ns exposure time (gated by laser pulses)
    - >4 frames
    - Sensor sensitive to 532 nm
    - UXI outside of vacuum chamber

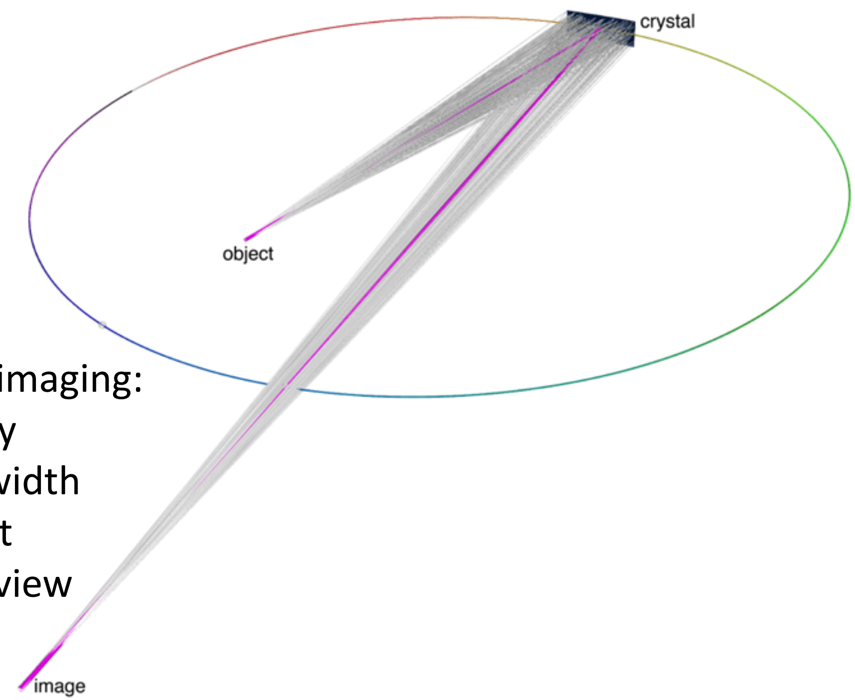
Time-sequence x-ray imaging of Z experiments

X-ray imaging with spherical crystals

Backlighting



Imaging



Advantages of crystal imaging:
1) high sensitivity
2) narrow bandwidth
3) 0° line-of-sight
4) large field-of-view

Diagnose dynamics of imploding liners:
- for EOS studies (liner radius vs. time)
- for hydrodynamic stability studies

Diagnose MagLIF experiments:
- 3.1 keV Ar emission during laser preheat
- 6 & 9 keV x-ray emission during stagnation

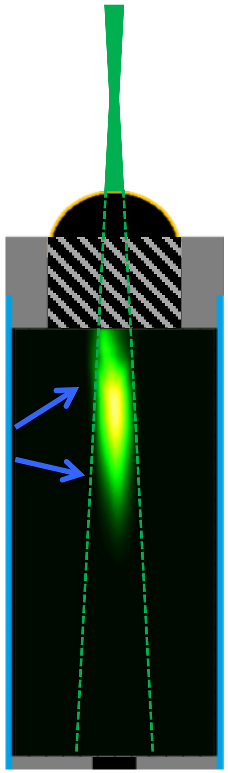
Time integrated, self-emission imaging

- X-ray imaging has provided valuable data for MagLIF and is now being extended to other targets on Z
- Outstanding question:

  How does the spatial structure of the emission vary with time?
- Time dependent data will help us better understand the liner stability at stagnation
- With UXI, preheat and stagnation images could be captured in one shot

Self-emission images from MagLIF targets on Z

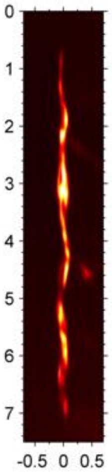
Preheat



3 keV x-rays

Stagnation

z2613

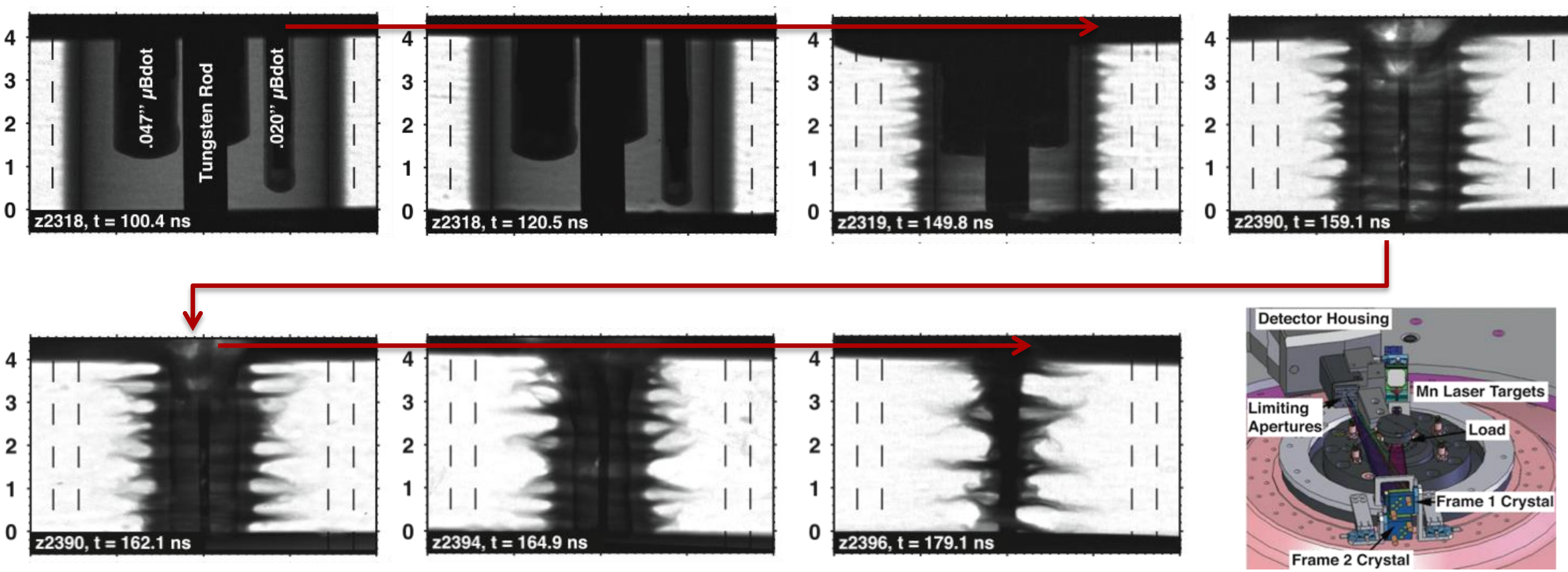


[mm]

6 and 9 keV x-rays

Graphics from Matt Gomez’s APS-DPP invited talk (2014)

Imploding liner 'movies' require several shots



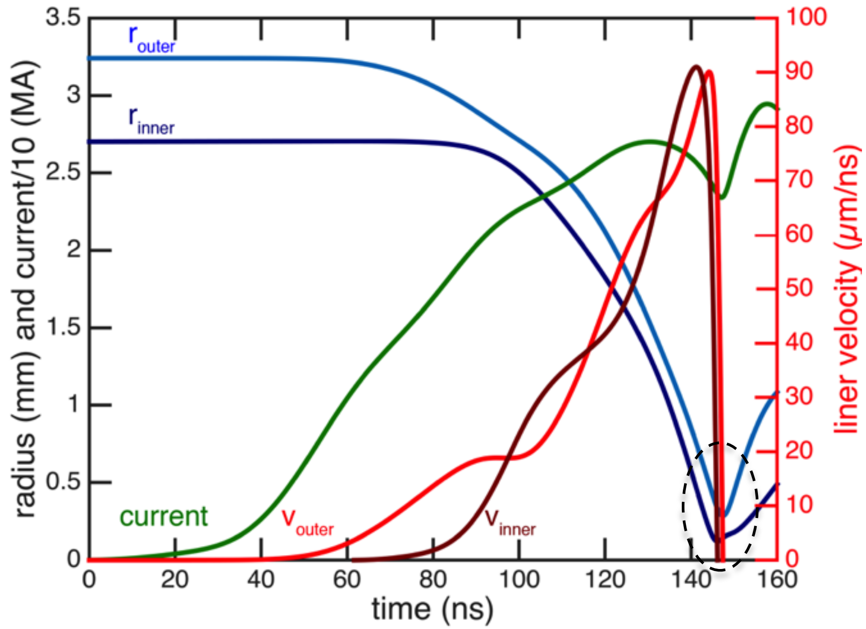
This series: 7 frames, 4 Z shots

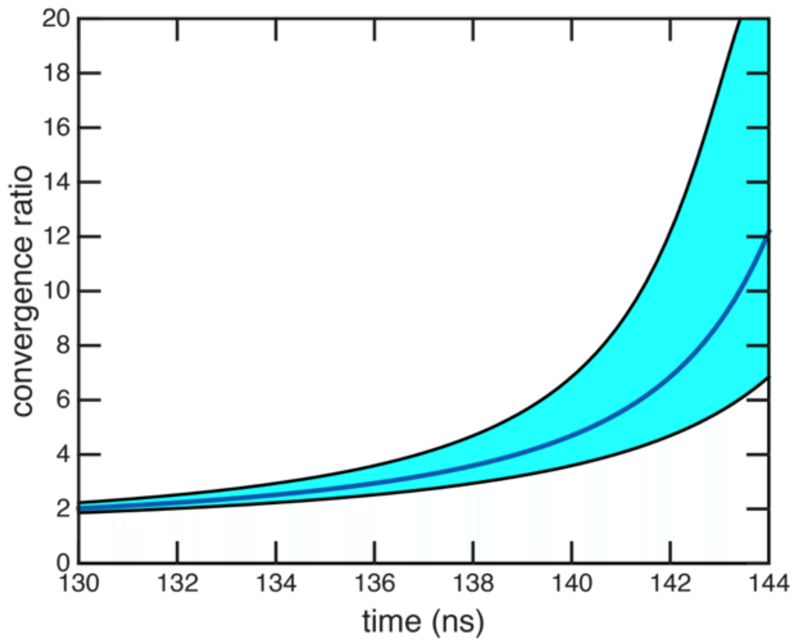
- 8 crystals + 4 hardware sets consumed
- Δt = 80 ns, ≈20 ns inter-frame time
- Could be replaced by 2 × UXI with 4 frames to record movie in single shot
- Time-gating performed by ZBL x-ray pulse, relaxes constraints on gate time

Timing jitter complicates assessment of stagnation conditions

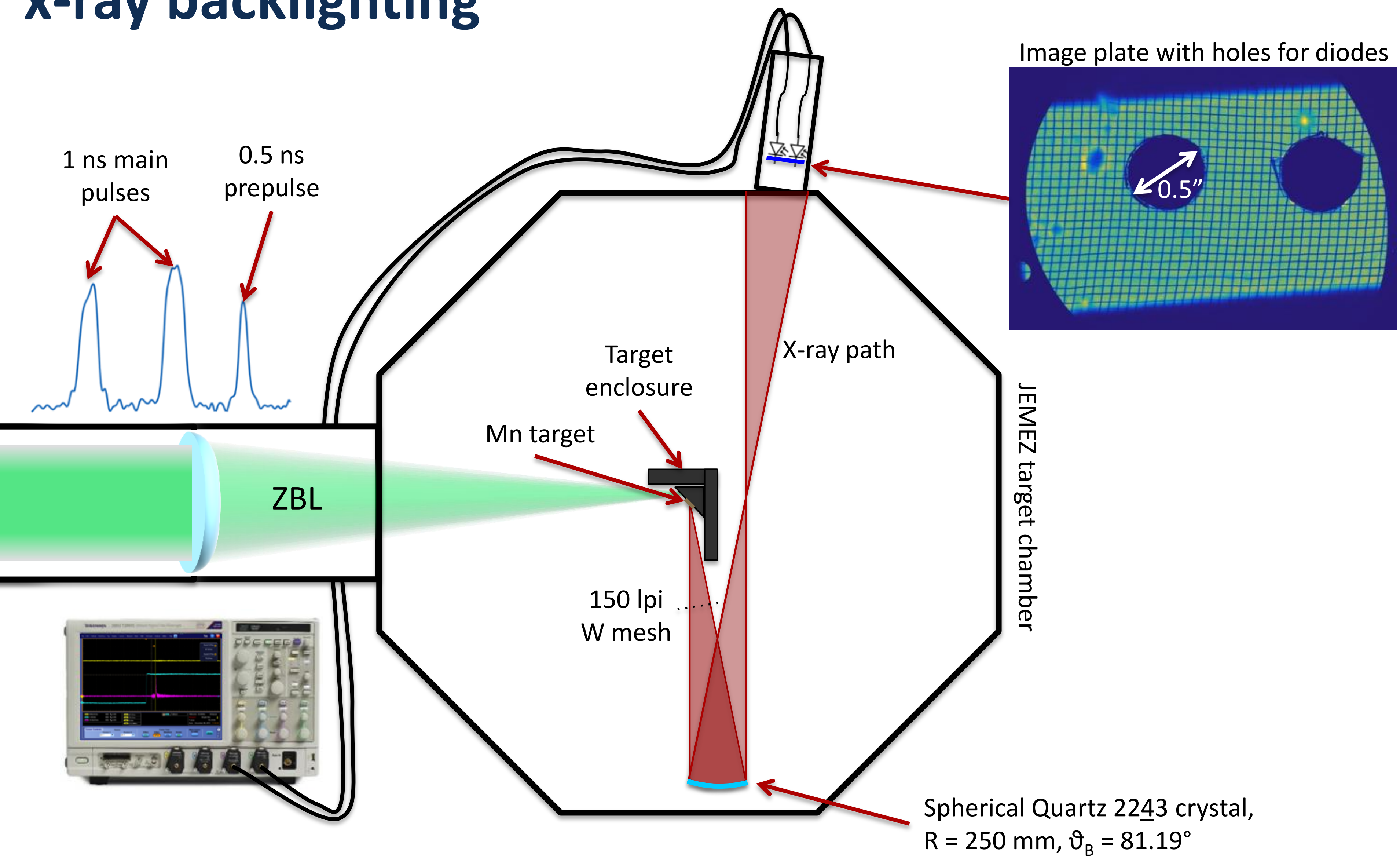
- 1D model data by R.D. McBride
- Similar to MagLIF point design:
  - Beryllium liner with r_{outer} = 3.24 mm, AR = 6
  - B_0 = 30 T, $\rho_{fuel,0}$ = 3 mg/cc, $kT_{fuel,0}$ = 250 eV

- Jitter of Z is ±2 ns, which leads to "hit or miss" for $C_R > 5$
- Need more frames per shot to increase data return and likelihood of capturing liner near stagnation

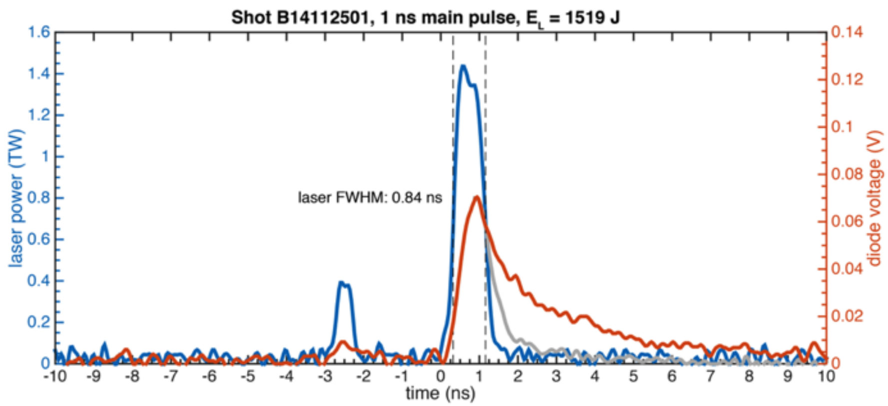


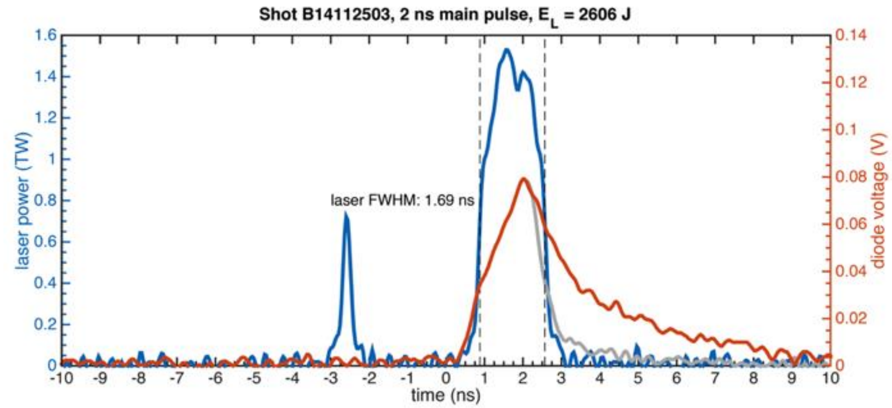


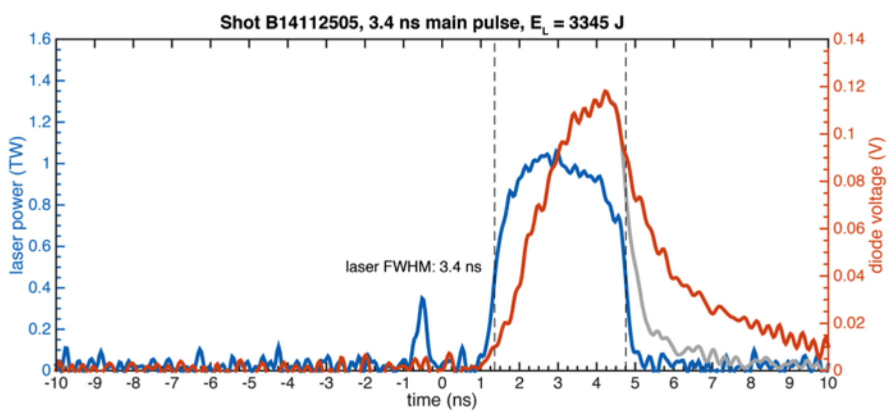
Single line-of-sight, multi-pulse, 6.1 keV x-ray backlighting

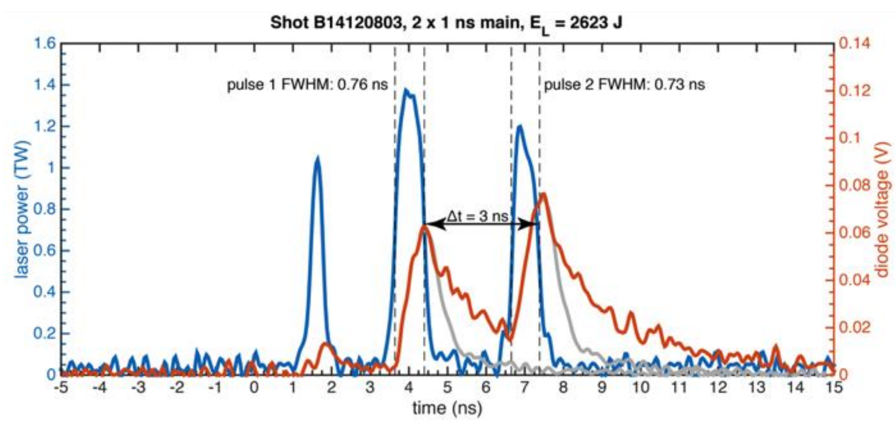


6.151 keV x-ray pulse follows laser pulse









A FURI camera with blocked sensor has been successfully tested on a similar shot. Full exposure shots will follow next.

A multi-frame, single LOS, gated detector is needed to provide the desired temporal resolution for imaging

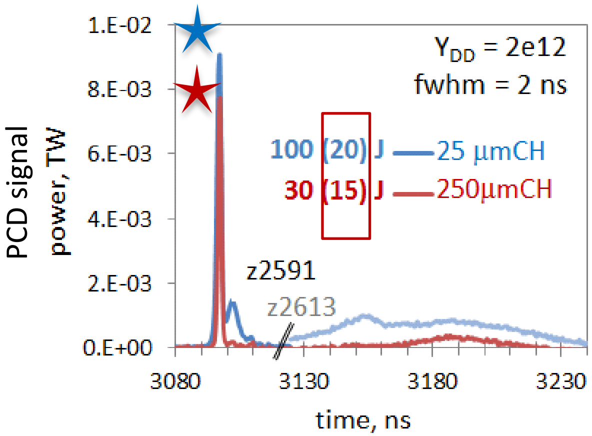
Experiment[1]	Gate time	Min. Inter-frame delay	# of frames	FOV at target or Detector size	X-ray Detection Range	UXI device
MagLIF preheat imaging[2]	1 ns	1 ns	4-8	1 x 0.6 cm (6 x 3.6 cm)	3 to 5 keV	Acca (tiling)
MagLIF stagnation imaging[2]	0.25 to 0.5 ns	0.5 ns	8-16	1 x 0.1 cm (6 x 0.6 cm)	6 and 9 keV (possibly 12 keV)	Acca (tiling)
Backlighting[3]	3-4 ns	2 ns	2	1 x 0.5 cm (6 x 3 cm)	6-8 keV	Acca (tiling)

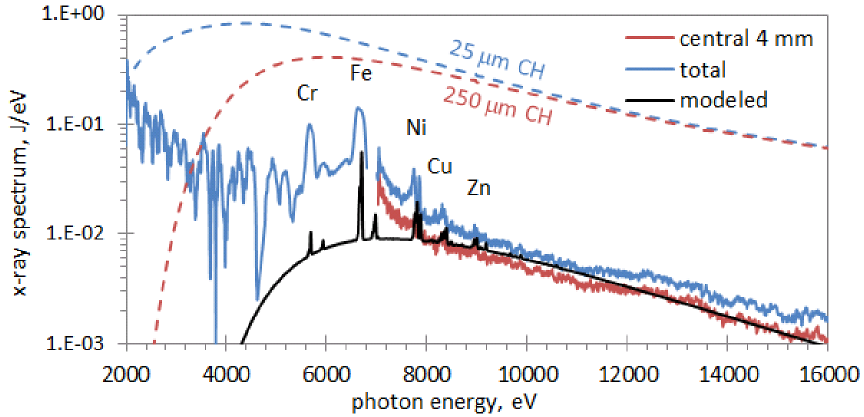
[1]All experiments may benefit from the removal of early/late-time background signals
[2]At present, the imager is setup for an image magnification of 6x. In this case, 25 x 25 µm pixels will provide good resolution
[3]Time-gating performed by laser pulses

Time-gated, absolute spectroscopy

Calibrated, time-gated spectroscopy could be transformative for MagLIF

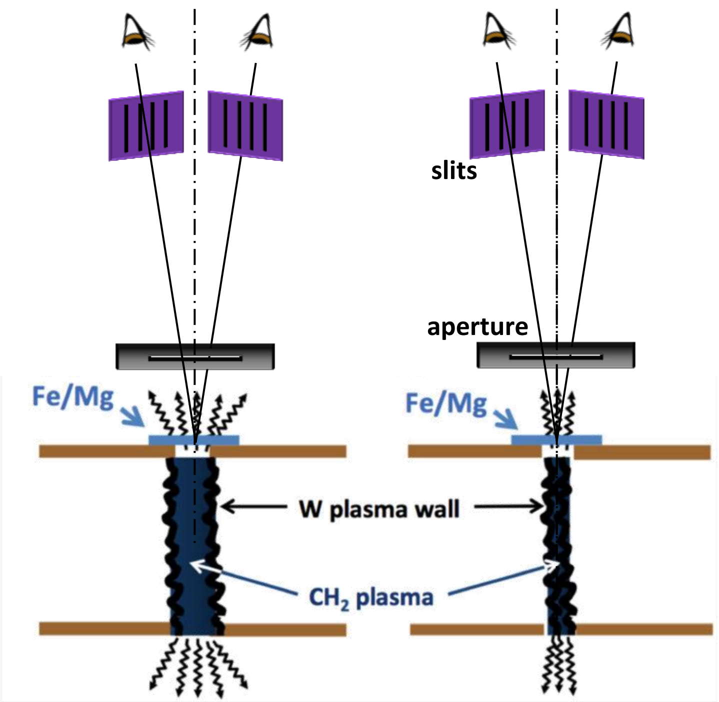
Sandia National Laboratories

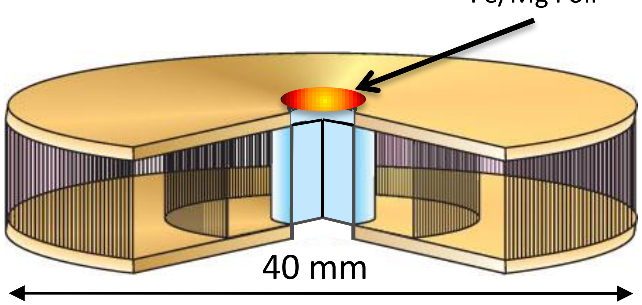


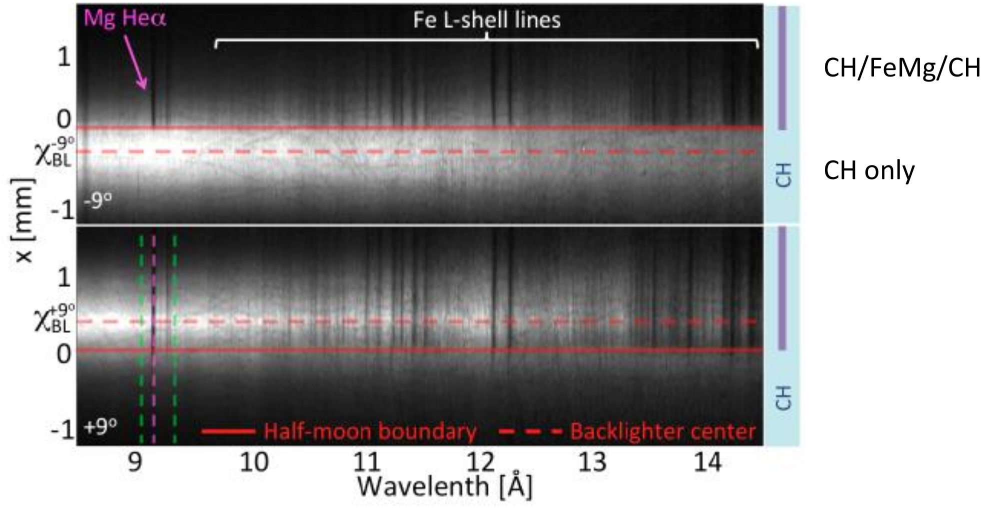


- Photo Conducting Detectors (PCD, ≈40% uncertainties) used to “absolutely calibrate” emission spectra → infer fuel density and mix at stagnation
- Time-gated spectroscopy with MCPs: poor S/N, poor spatial resolution (especially for E > 10 keV), and highly variable response (even across strip)
- Time-gated spectroscopy with UXI detectors could provide deep details about the evolution of T, density, and mix. UXI requirements:
  - 0.5 - 1 ns gates
  - ≈25 µm spatial resolution
  - E = 4 – 16 keV
  - In-chamber operation (?) for high S/N of 10–100 J (≈10 GW) x-rays through Be

Calibrated, time-gated spectroscopy could have high impact on opacity experiments

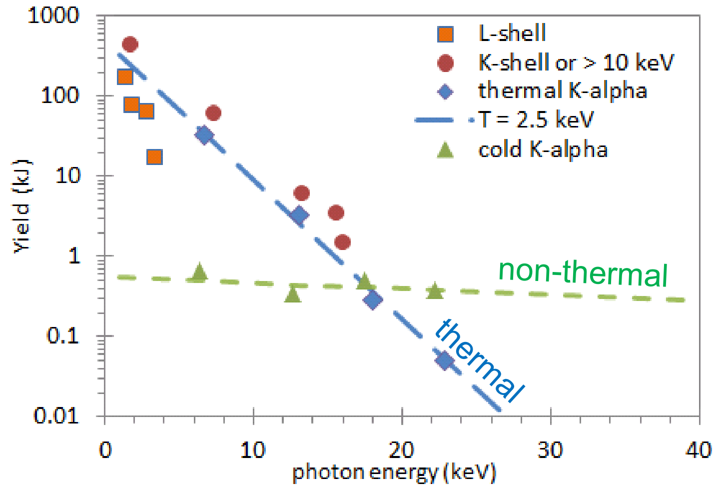




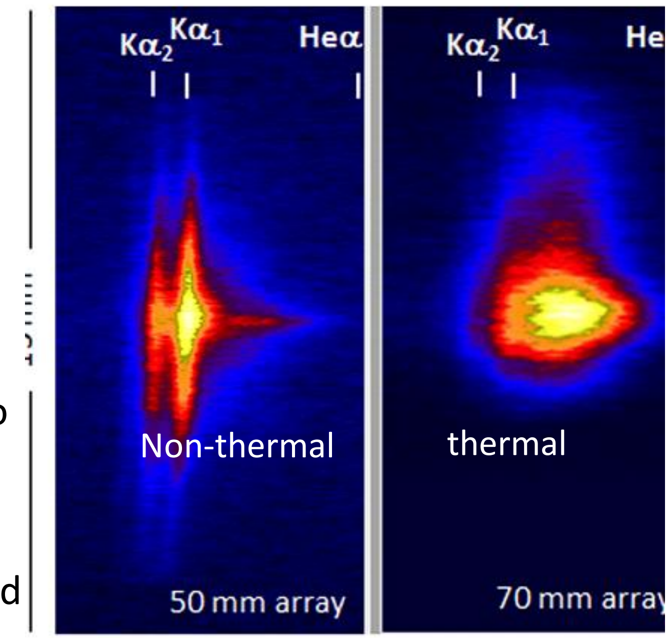


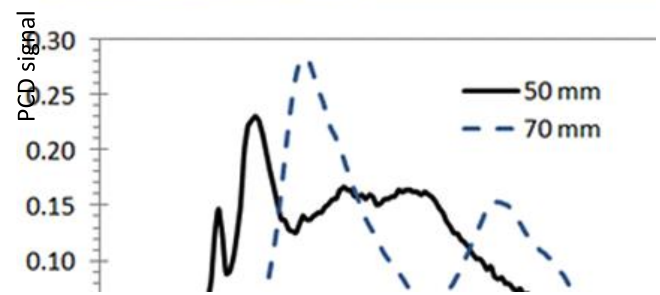
- Multiple simultaneous images (6) used to achieve high S/N
- Instruments need to be cross-calibrated for transmission
- Present system is time-integrated: How does integration of self-emission affect the measurement?
- UXI requirements:
  - ≈1 ns gates
  - ≈25 µm spatial resolution
  - E = 0.5 – 2 keV

At higher photon energies, time-gated spectroscopy will provide critical information about K_α production

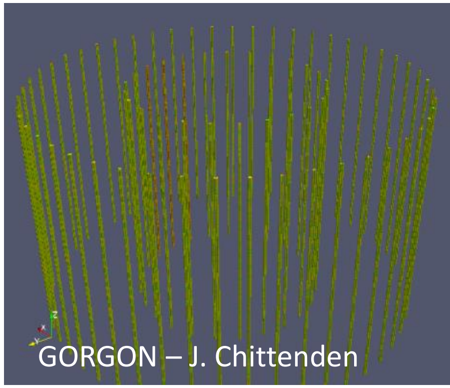


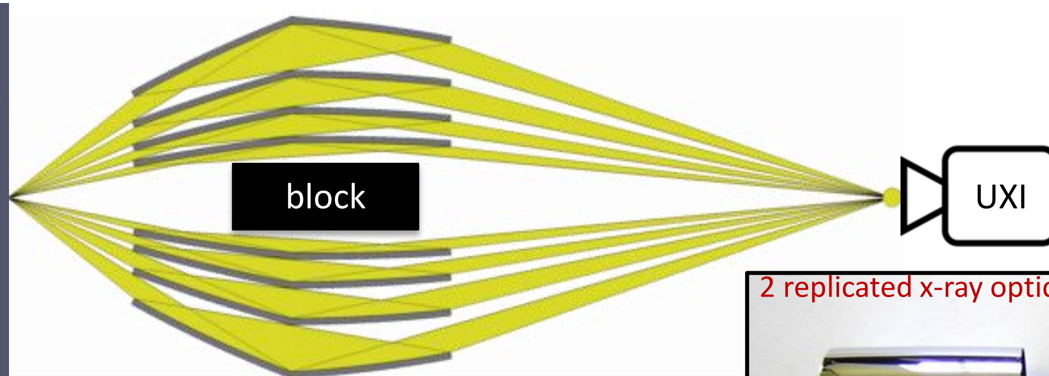
- Cold K_α emission from wire arrays could be an efficient way to produce high-energy emission (Ampleford LDRD; cf. short-pulse lasers)
- However: yields and hypotheses about non-thermal origin and evolution rely strongly on ill-calibrated PCDs
- UXI requirements:
  - 1 - 2 ns gates
  - ≈100 µm spatial resolution
  - E = 10 – 30 keV
  - In-chamber operation for high S/N of ≈1kJ (≈100 GW) high-energy x-rays



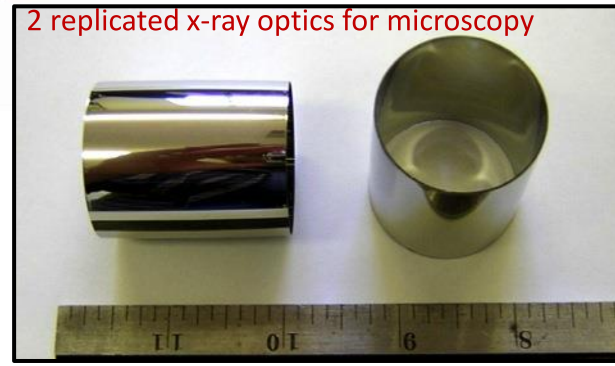


UXI + Wolter microscope for >10 keV imaging





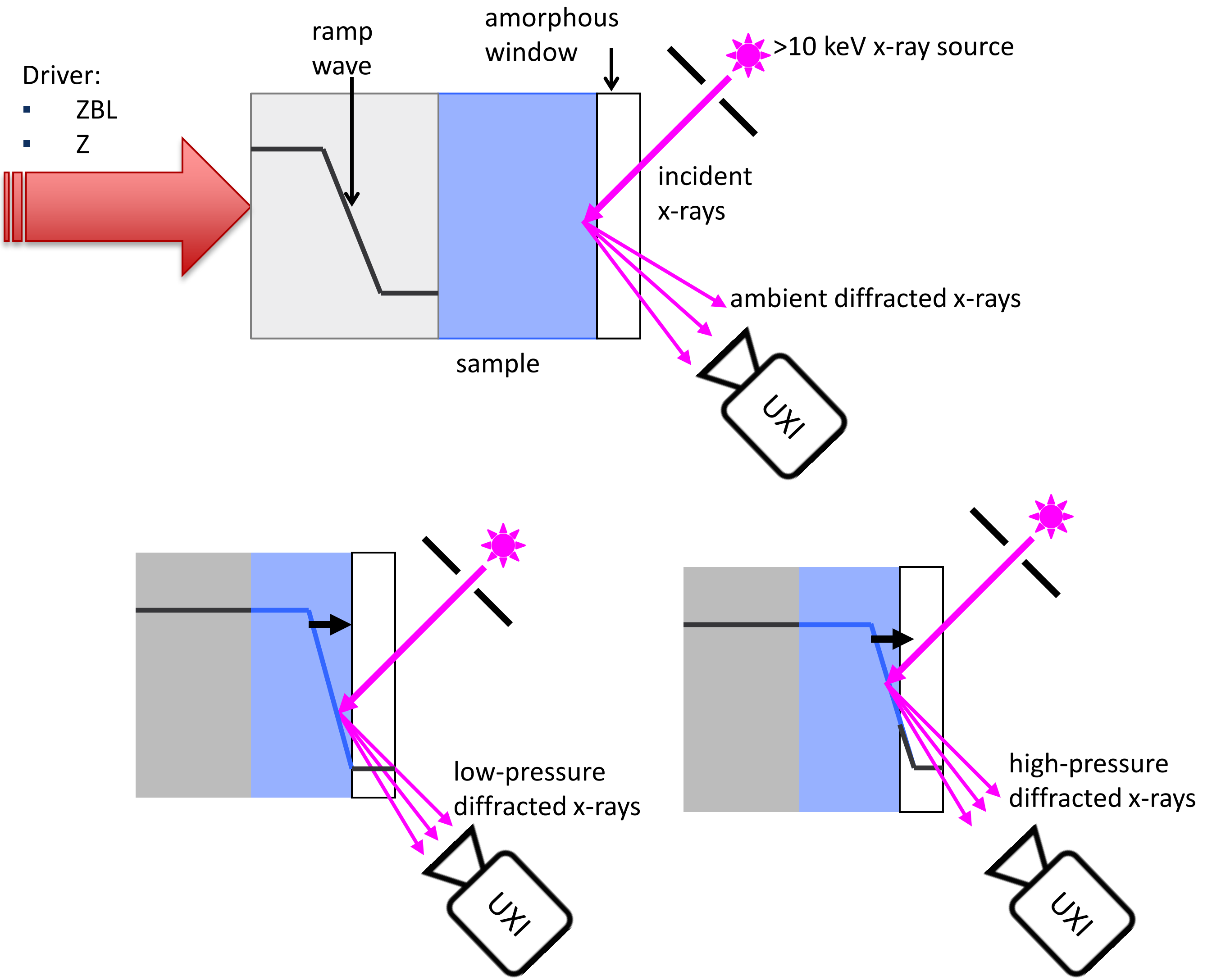
nested Wolter optics



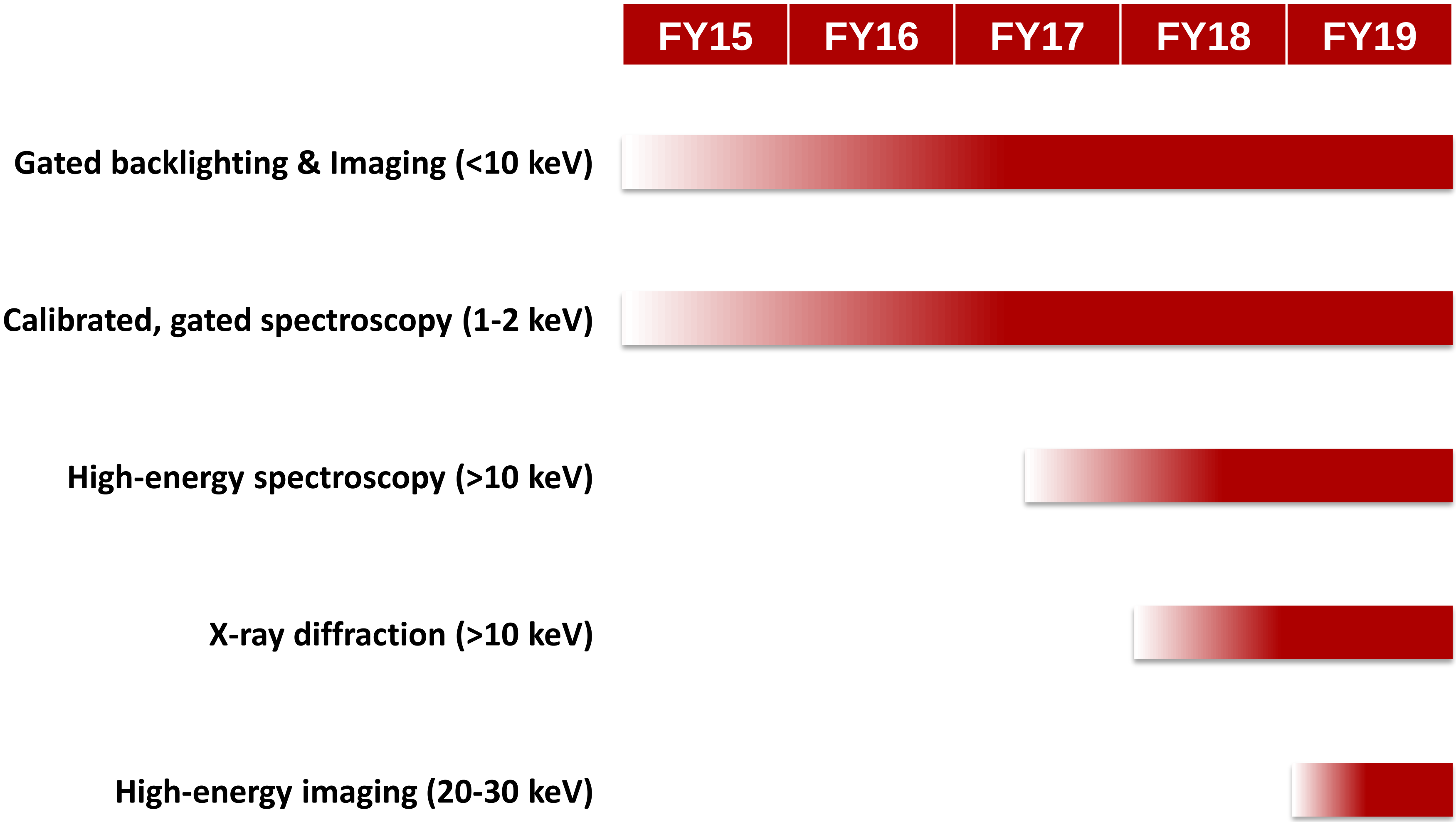
- Wolter microscope: hyperboloidal + ellipsoidal grazing incidence mirrors
- UXI + Wolter microscope may provide time-resolved, >20 keV imaging of non-thermal z-pinch x-ray sources
- Electroformed Ni replicated multi-layer Wolter optic at 8 ± 1 keV with <200 µm spatial resolution over 1 cm FOV has been demonstrated [1]; 30 keV with 10-20 µm may be feasible

[1] M.J. Pivovaroff *et al.*, Proc. SPIE **5923,** 59230B (2005)

X-ray diffraction of ramp states requires time-resolved capability

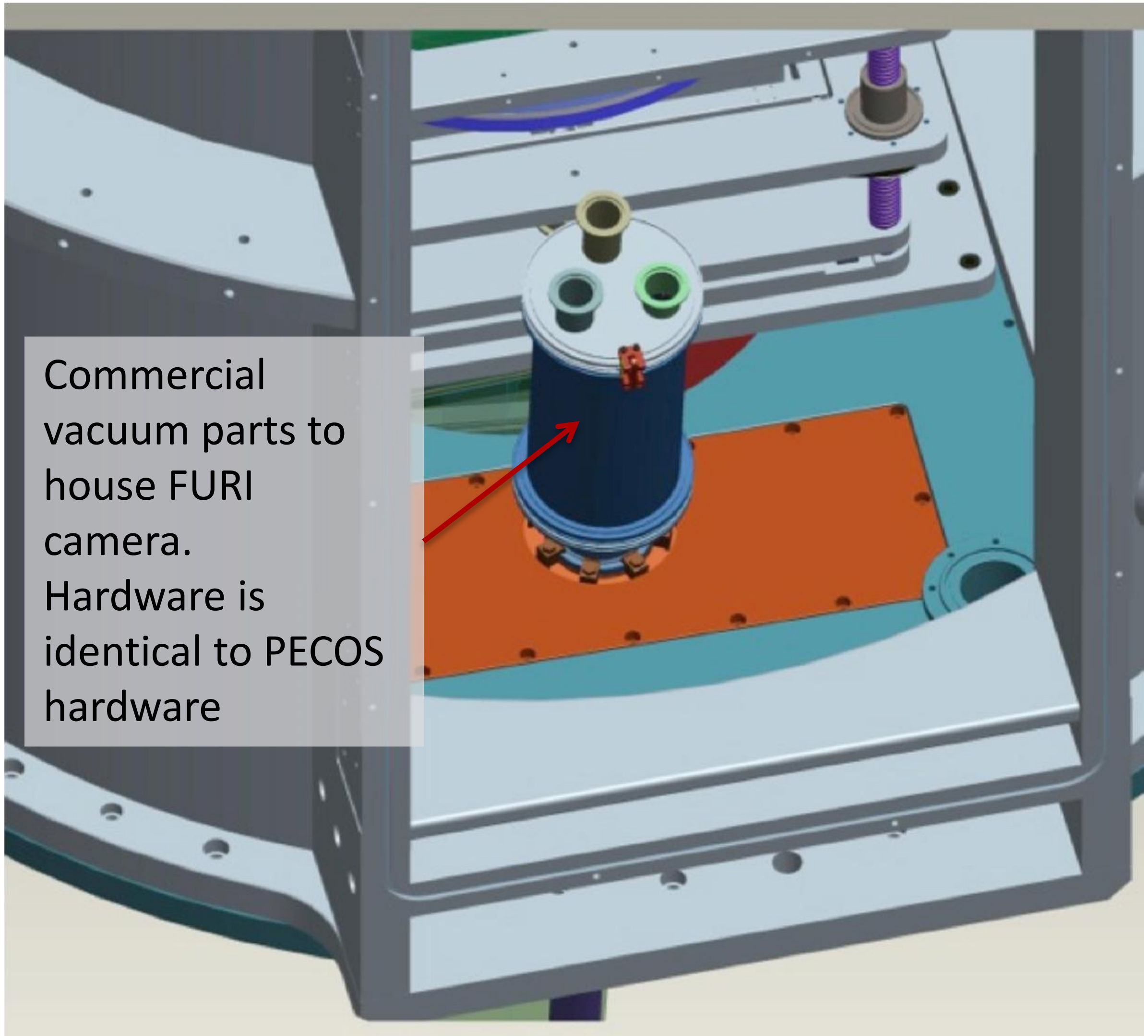


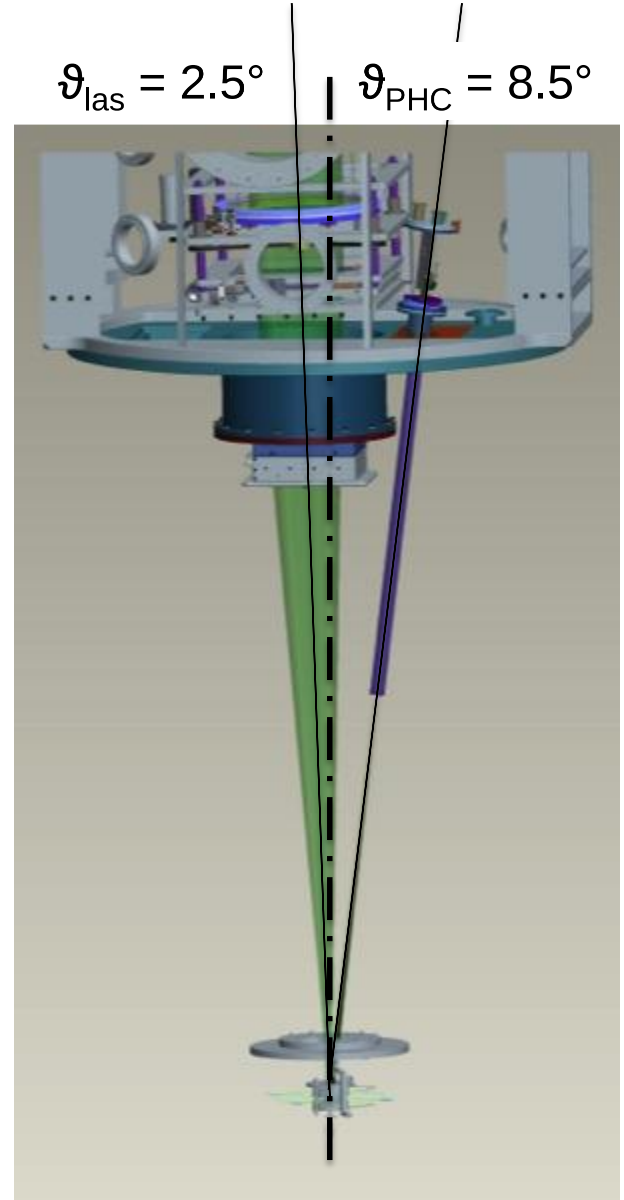
Roadmap for diagnostic development



Backup slides

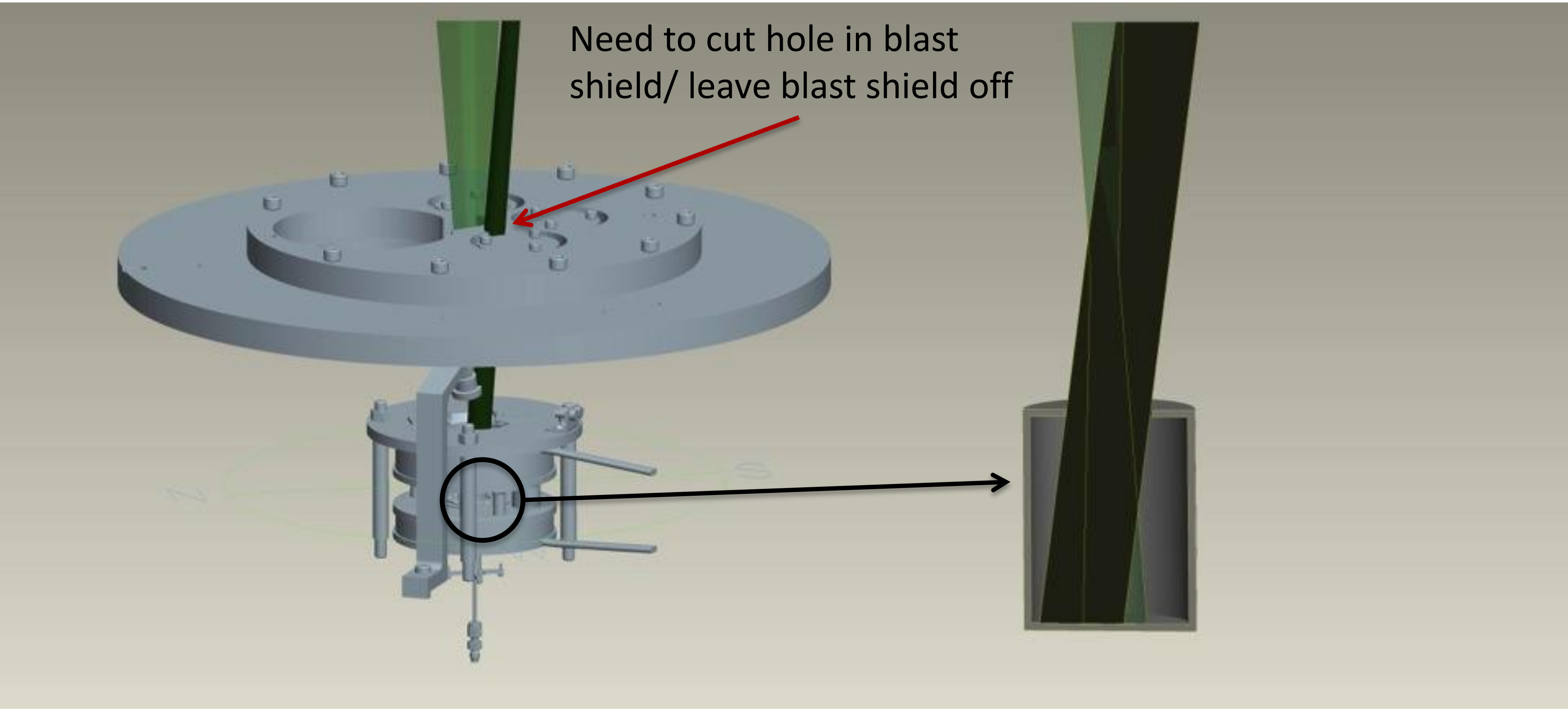
AXIAT pinhole camera



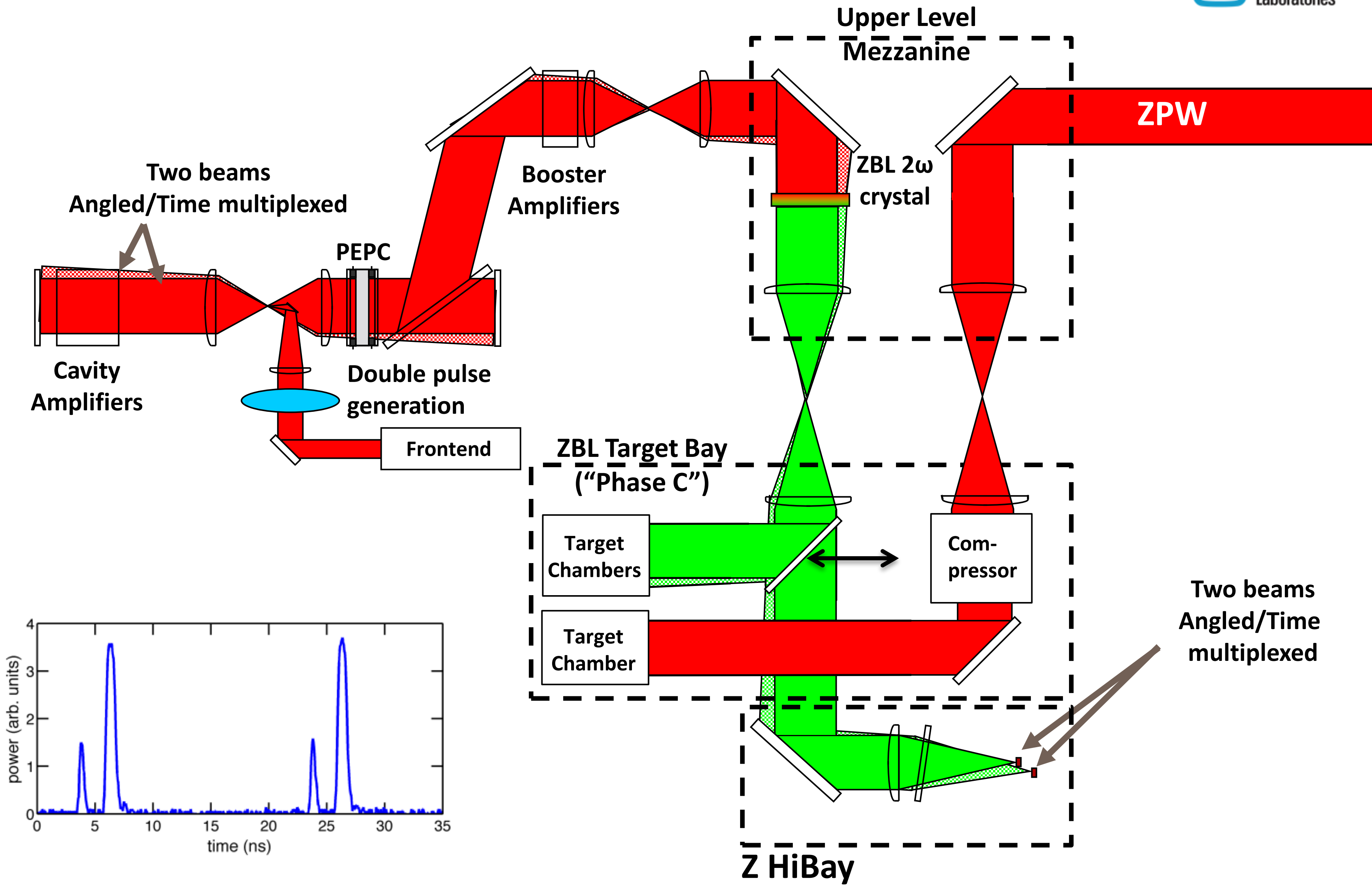


PHC Field of View

- FURI chip size: 25 × 11 mm^2
- Image size: ≈3 mm diameter
- FURI is large enough for 6 pinhole images
- Camera electronics has been successfully fielded on downline shots



ZBL 2-frame backlighter



Liner convergence ratio

- Calculations by P.F. Knapp
- Analytic calculation to compare the transmission through a Be liner for different photon energies
- Eddy liner:
  - r_{outer} = 3.84 mm
  - r_{inner} = 3.44 mm
  - th = 400 µm
  - AR = 9.6
- Roosevelt liner:
  - r_{outer} = 2.79 mm
  - r_{inner} = 2.325 mm
  - th = 465 µm
  - AR = 6