Hard x-ray imaging on NIF

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LLNL-PRES-XXXXXX
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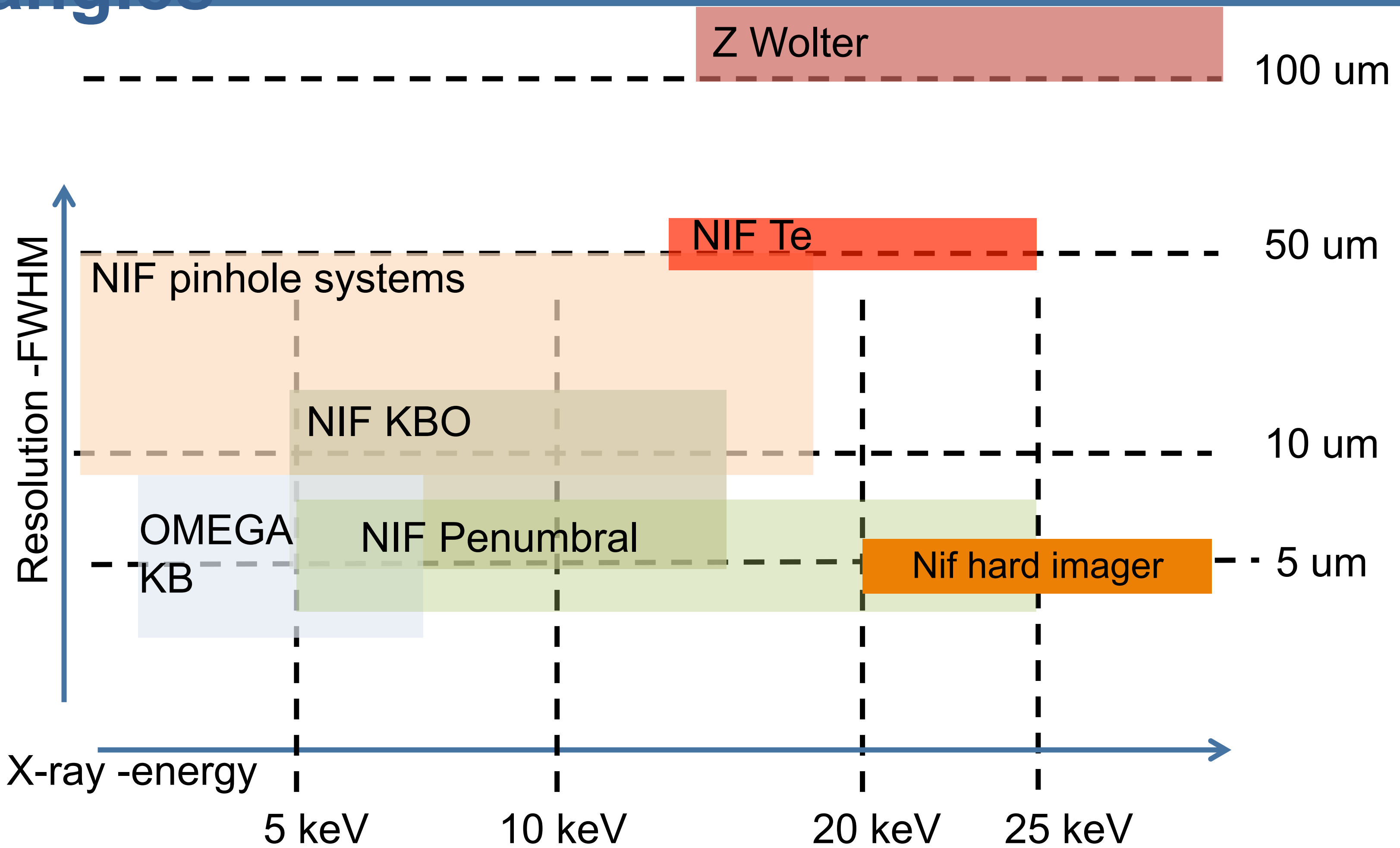
Overview of hard X-ray imaging

- Summary of existing imaging systems for ICF and HED plasmas
- Motivational experiments that require hard x-ray imaging
- Simple specification of the ideal system
- Issues common in hard x-ray imaging. It's all about the collection efficiency!
- Implementations at NIF (and Z) of high throughput (large solid angle) x-ray microscopes for hard x-ray imaging
- Replicated shell Wolters and the R&D challenge of reaching 5 μm resolution
- What other microscope systems fit the bill?

To image ICF plasmas above 20 keV with suitable resolution requires large solid angles



Detectors, sources and back lighters are weaker/ less efficient at high energy, demanding better collection efficiency per res. element from the imaging system

Motivation to pursue hard X-ray imaging on NIF

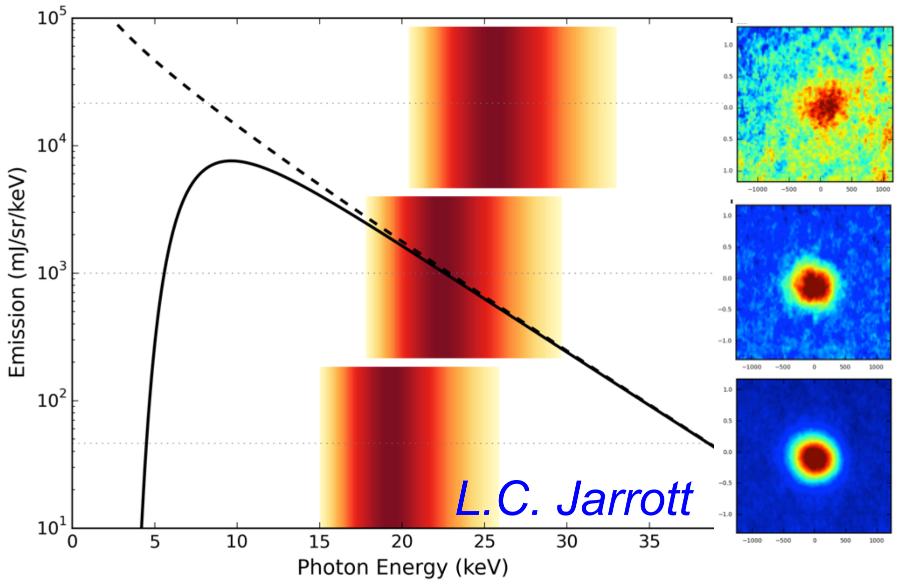
- ICF
  - Hot spot temperature (>15 keV, 5 μm)
  - Hot spot shape (>15 keV, 5 μm)
  - Close in radiograph (>16keV, monochromatic, 5 μm)
  - Shell density
    - Compton (>50keV, broad band, better served with point projection)
    - Self compton (50keV, mono chromatic?)
  - Double shell? (>20 keV self emission?)
- Material strength (>20keV, monochromatic, <10μm)

Difficulties of imaging Hard X-ray in ICF/ HED

- Weak sources (comparatively)
- Short life time (< 1 ns, requiring high speed detectors)
- Low DQE detectors (~1%)
- Low resolution detectors (FWHM >50 μm)
- Bright low energy emission which needs to be filtered out

We have begun measuring spatially and time integrated hot spot temperature

T_e measurement,(N160411-001)
(50 μm pinholes @ 10 cm)



Measured source:

$$I = 2e^{-\left(\frac{E-11}{kT_e}\right)} \quad \text{J/sr/keV}$$

Where kT_e and *hv* in keV. kT_e~4 keV

Existing resolved imaging- not shown is at ~ 10 keV

Goal: Spatial resolved T_e measurement.
Requires 5 μm PSF, ~50 μm image, S/N >10 ~1keV bands @ *15, 20,*25 keV

N160411-001-999: I_CH_DT_672CH_BBB T. Ma: High Foot DT, DU 672 hohl 0.6mg/cc 4He, 1xSi, T-1 (175um) capsule, 1.45 MJ, 360 TW, dl=0/0

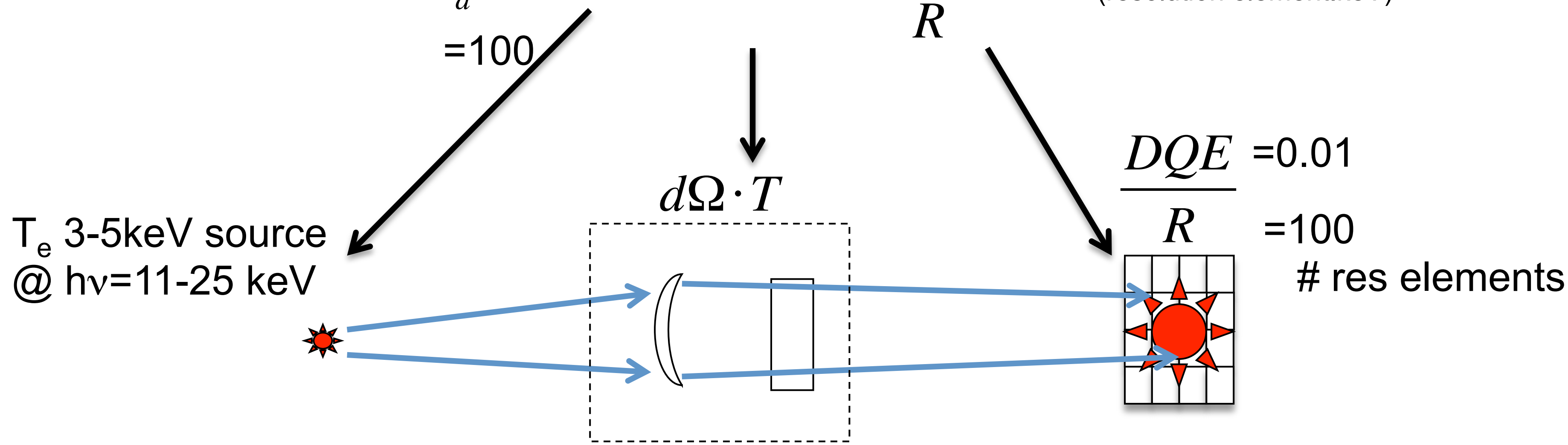
The "ideal" specification for a T_e measurement

An example for Hot spot T_e measurement:

$$I_d = 2e^{-\left(\frac{E-11}{kT_e}\right)} \cdot d\Omega \cdot T \cdot \frac{DQE}{R}$$

Detected photons/
(resolution element.keV)

=100

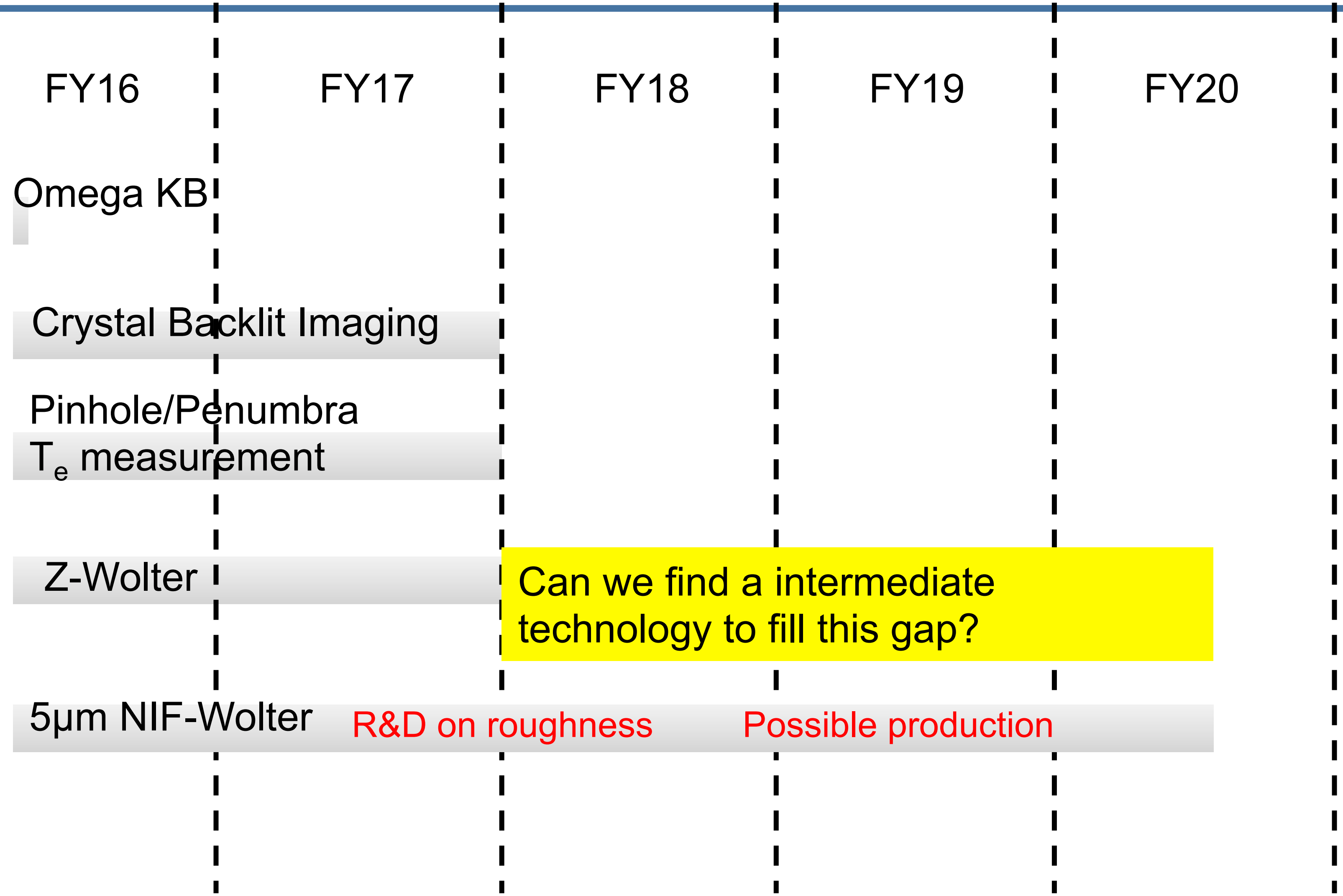


Solid angle * Throughput should be $>10^{-7}$, we need $>\sim 10^{-6}$ to allow shot to shot variation in shape, T_e and size and time resolution

We have started investigating how to meet the requirement with new microscope systems

- To date, (with some notable exceptions) NIF has focused on variations of pinhole and slit imaging
  - We have recently built KB
- Crystal backlight imaging (CBI)
- Penumbra
- Wolters

Time line to achieve a high energy imaging system for HED /ICF

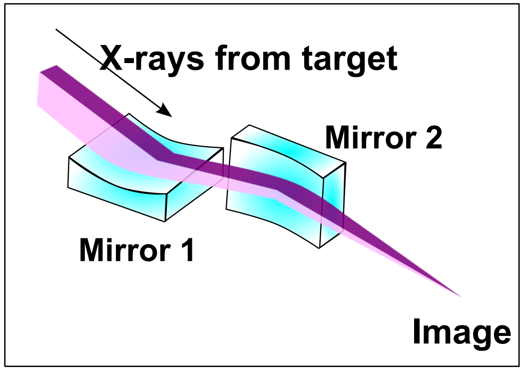


KB's and Toroidal optics play a role for hotspot imaging at lower energies

- We have recently developed and implemented a Kirkpatrick-Baez imager (KBO)
  - Limited in solid angle

- We are in discussions exploring similar 2-mirror imaging systems (Toroids) that have a larger solid angle.. See P. Troussel et al.,
  - ? How many could we get
  - ? How quickly can we make it happen

Kirkpatrick-Baez Scheme

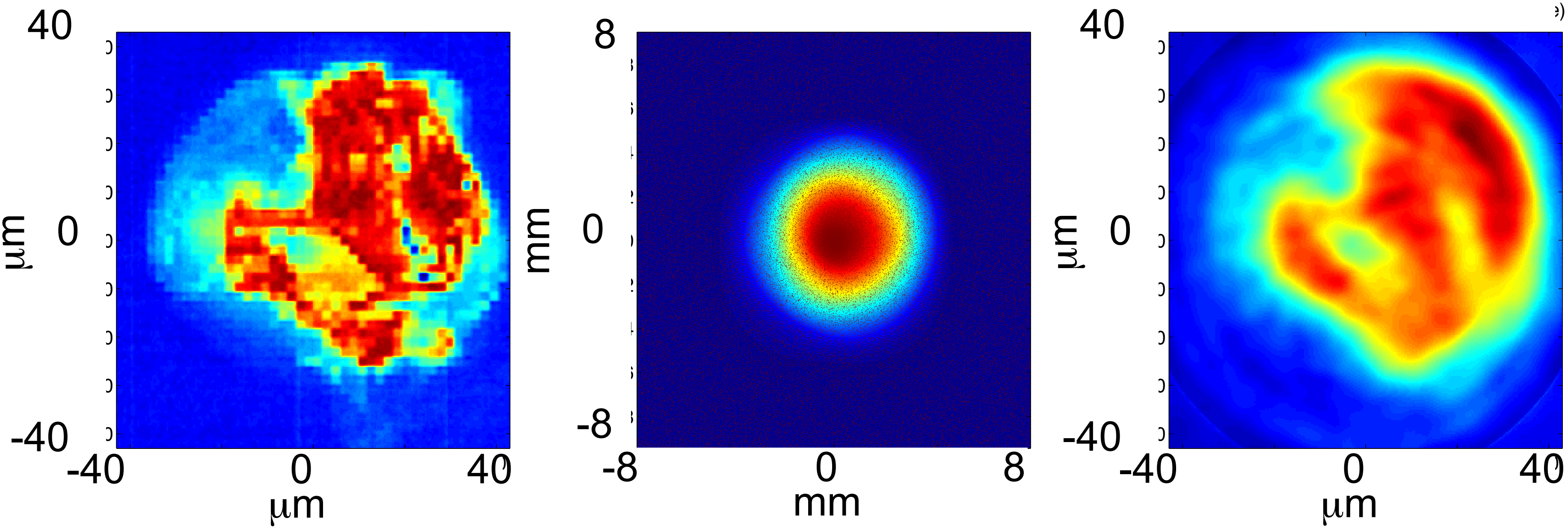


Penumbral imaging on DIXI could reveal detailed hotspot structure

Possible ICF setup w/ DIXI diagnostic:

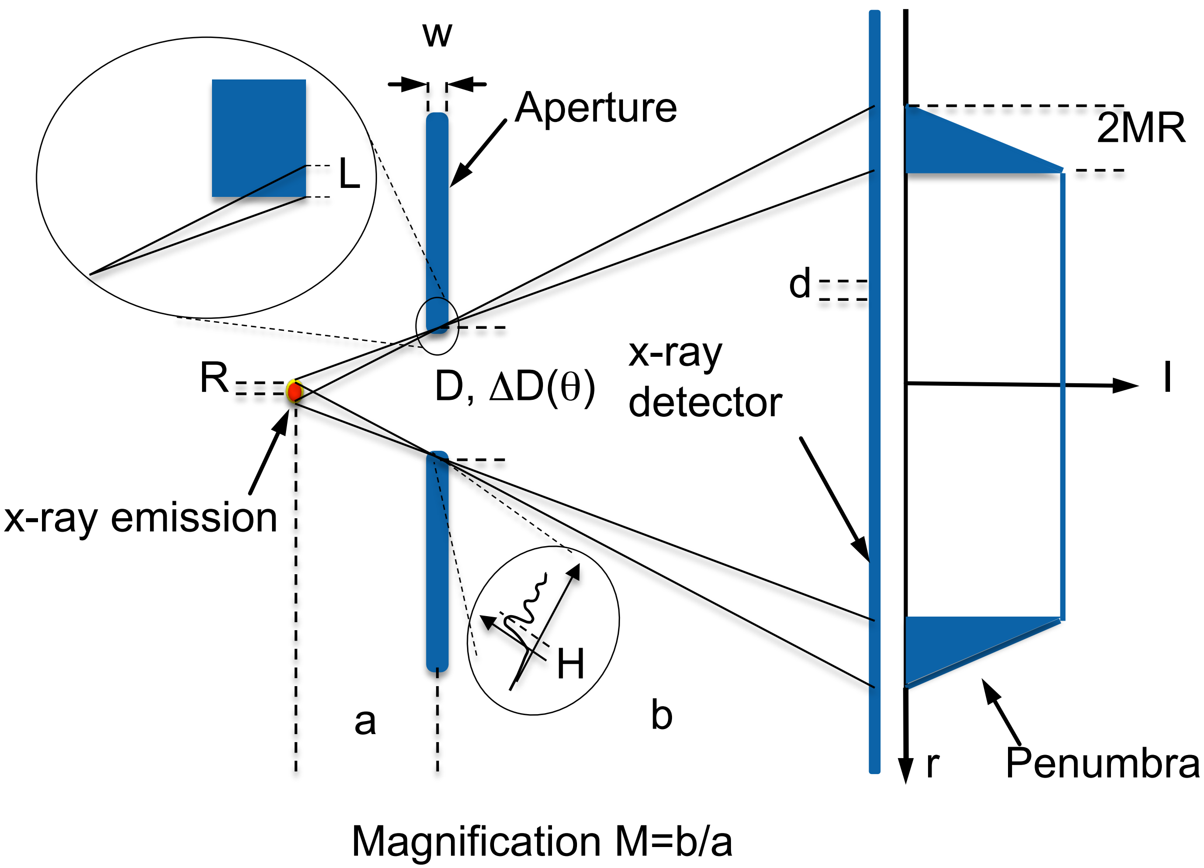
- Pinhole diameter: 100μm
- Magnification: M=64
- DIXI-Point Spread Function: 270μm FWHM Gauss
- 10% of pixels affected by neutron noise (10% dead pixels)

Expected SNR>10
Resolution: ~5μm
Fresnel limit (a=10cm): 3.6 μm



Simulated hotspot | Penumbral Image | RECONSTRUCTED

Penumbral Imaging uses the edge of an aperture to encode the image



- Source radius R
- Imaged through aperture D
- Yielding Penumbra 2MR on detector

Physical limits:

- Fresnel Diffraction
- Effective optical density length scale L of aperture (thickness w)

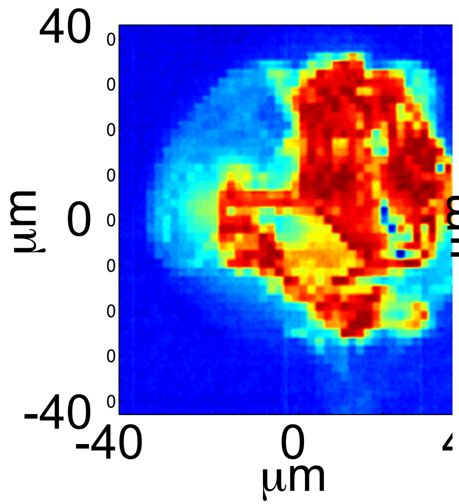
$$H \approx \sqrt{\lambda a}$$

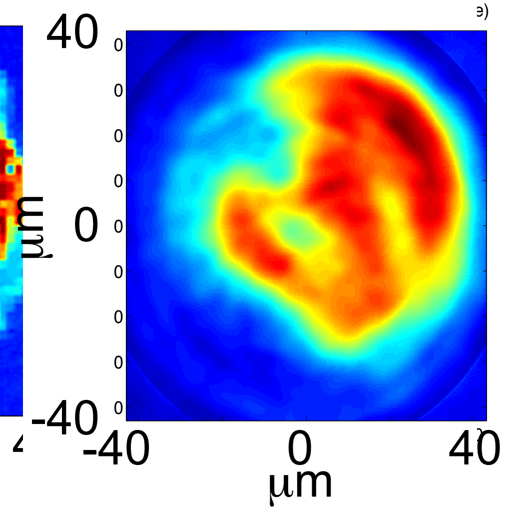
Technical limits:

- Det. Resolution d
- DQE
- SNR
- Aperture circularity ΔD(θ)

X-ray Penumbral Imaging can be a powerful technique to improve understanding of stagnated implosions

- Few μm resolution penumbral imaging has been successfully fielded on the NIF
- Manufacturing challenges of quality apertures have been overcome



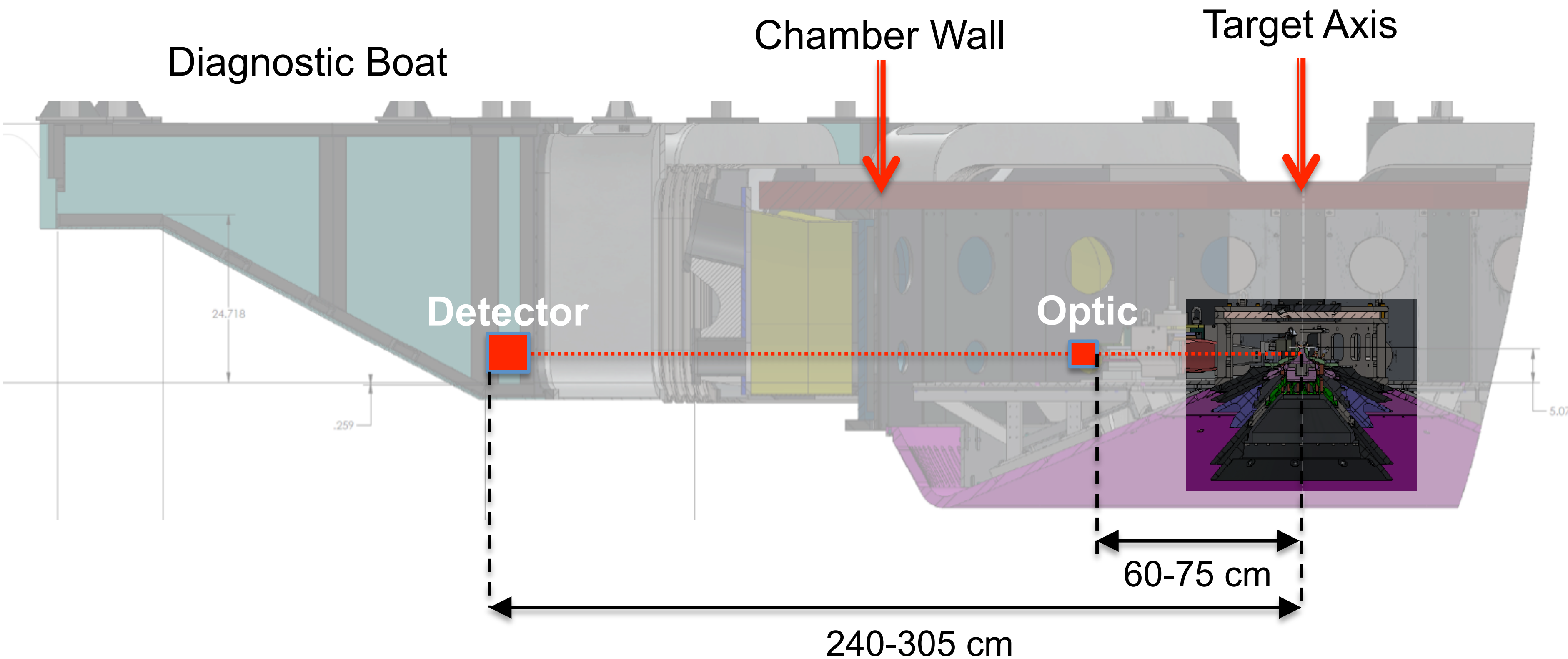


- Challenges of Penumbral imaging:
  - Aperture characterization and build for high energy
  - Energy selection
  - Fielding in NIF (close in?)

Wolters and multilayers

- Wolter optics promise large solid
  - Current technology achieves ~30μm spatial resolution
  - Waiting on advancement of the technology achive ~5μm resolution
  - 3+years and a R&D project to do this, so there is risk
- Multilayer coatings that operate at grazing incidence allow the possibility of pseudo monochromatic or band-like energy response (implemented in NIF KBO1 at 10.2keV)
  - Multilayer with higher reflectivity are of great interest…

Wolter for Z at Sandia

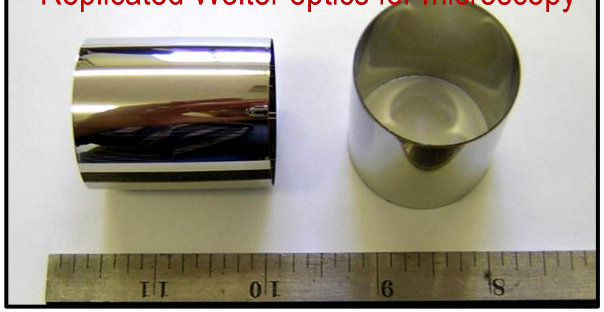


- Imaging K_α emission to diagnose stagnation conditions
- Wolter microscope (M= 3.5) on the Z target chamber with optic ~70 cm from the pinch
- Geometry similar to what has been previously demonstrated with multi-layer Wolters

Wolter for Z at Sandia

Need	Goals	Driver
Photon energies (Kα's)	**Mo: 17.479 keV** **Ag: 22.163 keV** W: 59.318 keV	**Study K-shell radiators from Ag to W**
Spectral window	~1 keV	Simultaneously view Kα 1 & 2 from cold and low-ioniziation states
Field of View	**2 cm in each direction**	**Collect all emission from 2 cm pinch. Kα emission comes from large diameter**
Spatial Resolution	**~100 μm**	**Resolve length-scale of structures emitting Kα**
Time resolution	Time integrated initially ~1 ns in 3-5 years	Resolve evolution over pulse
Sensitivity	100 J from ~cm^3 source with good S/N	Able to record 100 J over full source area

Replicated Wolter optics for microscopy



Other considerations

- Survivable (optic at >40 cm from source)
- Hard x-ray background (1-inch W in LOS)

Julia Vogel

Advancing Wolter optics to 5µm resolution for NIF

- Ability to focus is limited by low-spatial frequency errors (i.e. "figure")
- Resolution degrades off-axis even for perfect mirrors (i.e. $\Delta\alpha=0$):
- To first order, the angular resolution of the optic is driven by angular resolution of the master mandrel

Main Challenge: Achieving small figure errors on small mandrels

Additional challenges: Minimizing electric-field edge effects in tuning the electro-plating processes for small-radius, "stubby" optics (those, in theory, ideal for NIF)

→ Results in difficulties to achieve the same figure quality in replicated optic as in mandrel

Current best performance for NASA MSFC replicated optics from optics with L = 300 mm ×2 and radius of 35−60 mm (larger than what is needed for NIF)

Path to high resolution Wolter optics for NIF

Preliminary NIF design: Total throw 8.0 m, grazing angle ≥ 0.4°

Spatial resolution, R (μm)

Mag \ Δα	1"	2"	3"	4"	5"	6"
10	5	10	15	20	25	30
12	4	8	13	17	21	25

2-3 years (challenging)

1-2 years (comfortable with R&D)

Current

Comparison of hard X-ray microscope systems for hotspot imaging

	Multiple 5µm Pinholes mounted on target	Penumbra mounted on target	CBI	Wolter
Approx. Solid angle/ through put	1e-7	1e-7*filter	2e-6	1e-6*R^2*efficiency
Number of images	10	1	1	1
	*5µm , 5mm from TCC	*100µm, 8cm from TCC, Mag 16	*60eV band,	

Summary: Hard x-ray imaging at NIF

- We are implementing several imaging systems on NIF to image (spatially and temporally resolved) hard X-rays
- Penumbral imaging and Wolter optics are the two technologies we have focused our efforts on
- Wolter optics with the desired resolution (5um) are years away (2020)
- Can we apply a different technology in the mean time?

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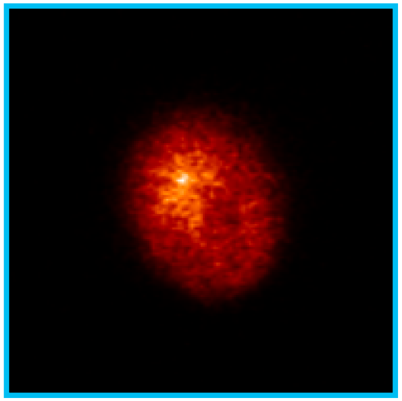
KBFRAMED results: LANL-HED 18-Feb-2015

OMEGA shot 76276



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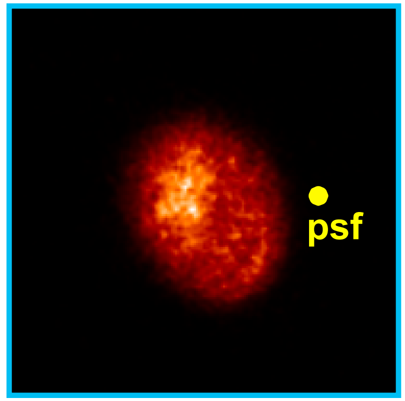

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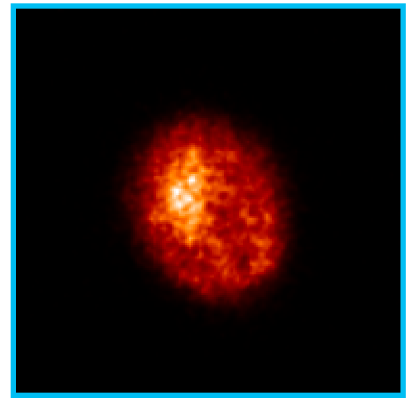

image 8

KBFRAMED time integrated images
Filter: 5 mils Be, 4 mils Al
200 x 200 μm region

F. J. Marshall
26 Feb 2015

Crystal backlight imager

- Primarily designed for backlight application for "close in imaging" at ~16keV
- We could adapt the system for self emission
- A good amount of R&D is needed to test making and using crystals at 20 keV
- Promises large solid angle, but very narrow energy band (~60eV)