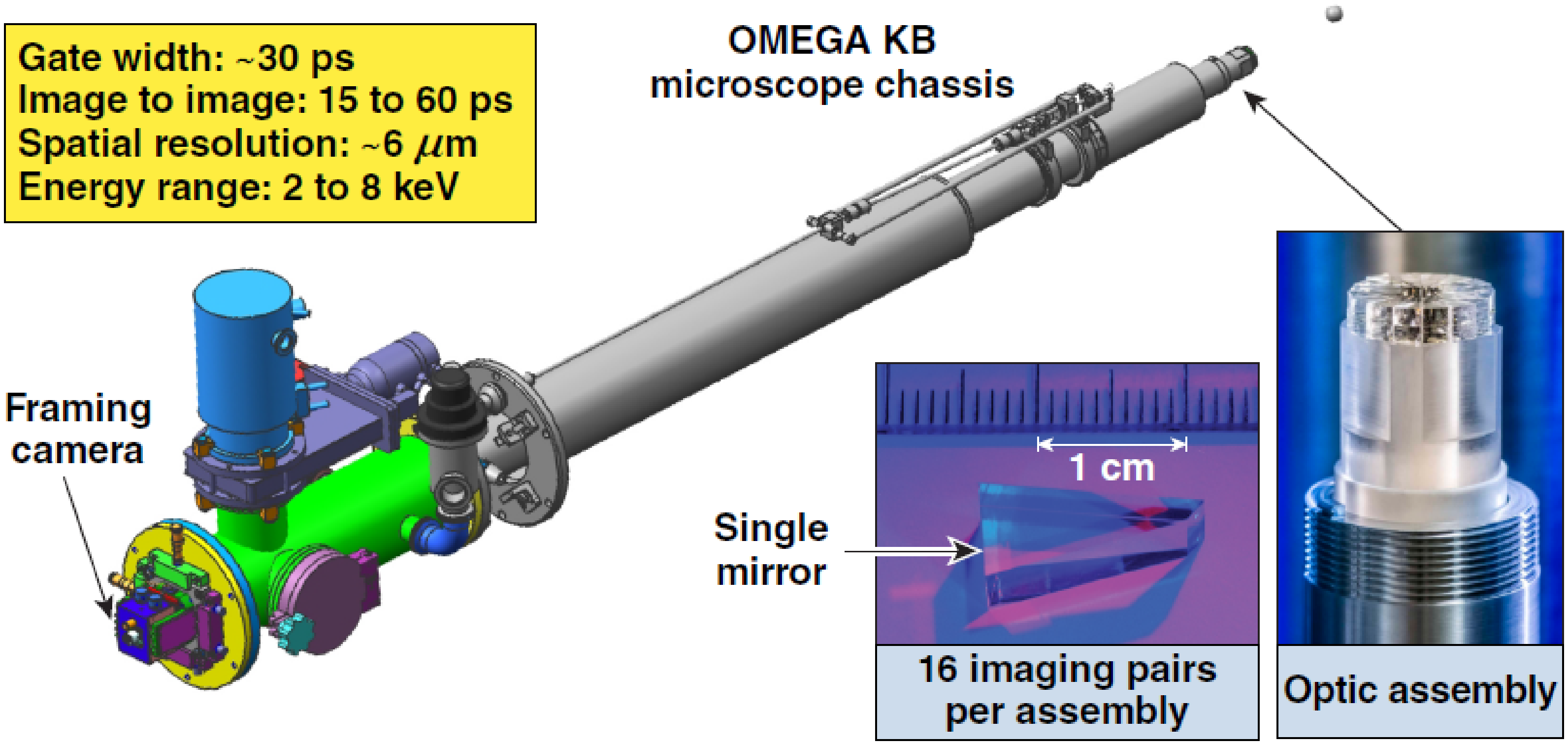
X-ray emission shape/size analysis at LLE
F. J. Marshall, LLE

Outline of talk:

- **Instruments used to image cryogenic target implosion cores:**
  - **Time integrated: GMXI, KB3**
  - **Time resolved: KBFRAMED, SFC3 w/pinhole array**
- **Method of determining core size**
- **Comparison of sizes from different directions:**
  - **Time integrated: GMXI, KB3, KBFRAMED(unframed mode)**
  - **Time resolved: KBFRAMED, SFC3**
- **Direct comparison of core size along common perpendicular lines of sight:**

KBFRAMED is a 16-channel Kirkpatrick–Baez (KB) x-ray microscope that provides time-resolved images of the core around stagnation

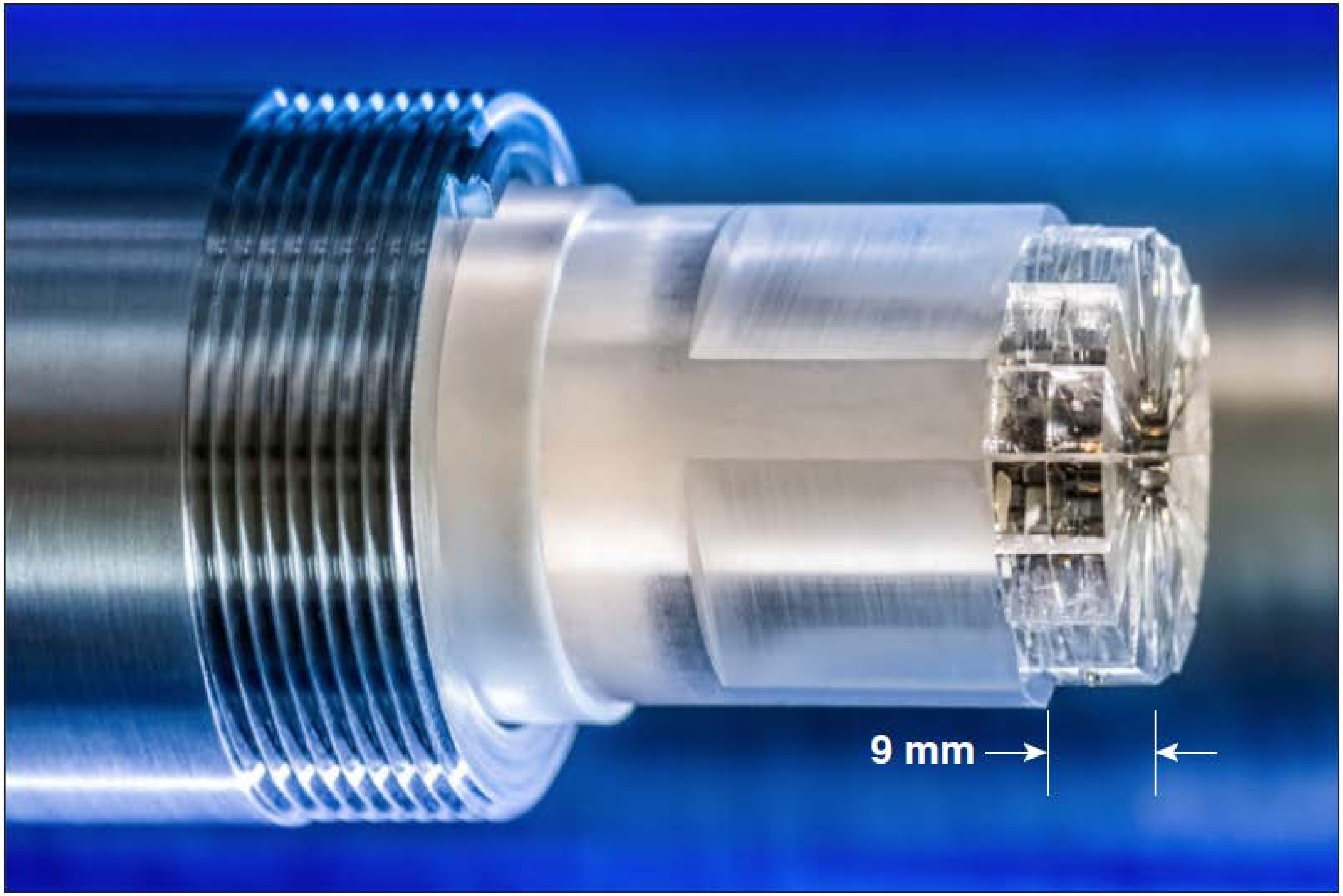
Gate width: ~30 ps
Image to image: 15 to 60 ps
Spatial resolution: ~6 μm
Energy range: 2 to 8 keV



E22996b

F. J. Marshall, J. A. Oertel, and P. J. Walsh, Rev. Sci. Instrum. 75, 4045 (2004).

The KBFRAMED x-ray optic consists of 16 mirror pairs with images aligned to a high-speed framing camera



E24419

The off-axis resolution of a KB microscope is limited by spherical aberration and diffraction

Single mirror focus*:

$$\frac{1}{p} + \frac{1}{q} = \frac{2}{R \sin i}$$

Primary spherical aberration and obliquity of field**:

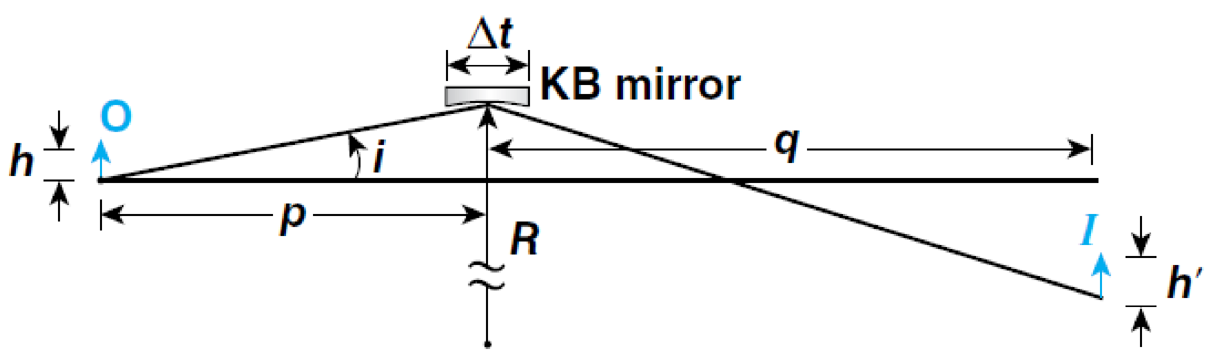
$$\delta_{ab} = \left(\frac{3M+7}{2M+2}\right)\frac{(\Delta t)^2}{R} + 2h\frac{\Delta t}{R \sin i}$$

Diffraction:

$$\delta_{diff} \approx \frac{\lambda p}{\Delta t \sin i}$$

Total aberration and diffraction:

$$\delta = \sqrt{\delta_{diff}^2 + \delta_{ab}^2(h)}$$

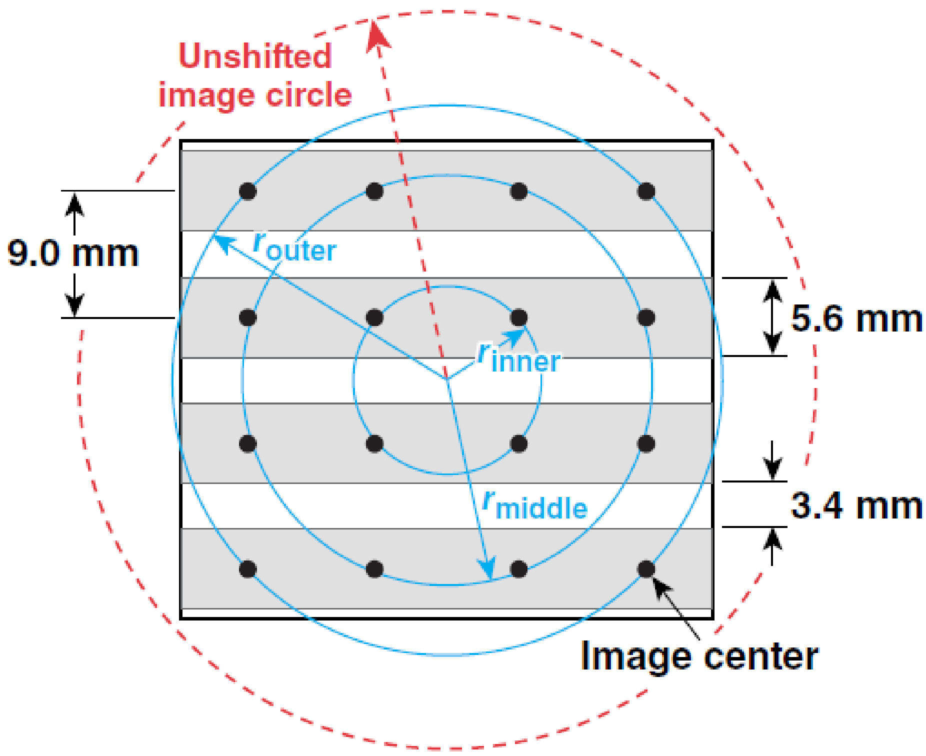


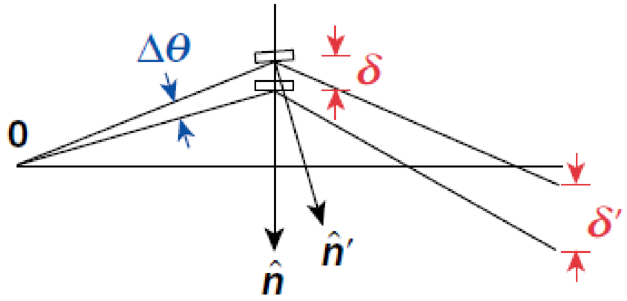
*P. Kirkpatrick and A. V. Baez, J. Opt. Soc. Am. 38, 766 (1948).
**J. F. McGee and J. W. Burrows, in *X-Ray Imaging*, edited by R. C. Chase and G. W. Kuswa (SPIE, Bellingham, WA, 1977), Vol. 106, pp. 107-112.

E21109

Mirror repositioning is required to make compact KB mirrors compatible with the four-strip framing camera

Four-strip framing camera schematic





For M = 12

Mirror pair	ϕ (°)	r (mm)	$\Delta\theta_{pitch}$ (°)	$\Delta\theta_{roll}$ (°)
r_{outer}	45	4.27	0.417	0
r_{middle}	±22.5	4.63	0.481	0
r_{inner}	0	5.40	0.724	0.059

Positions accurate to 10 μm
Tilts accurate to 10 arcsec

E21102a

F. J. Marshall, Rev. Sci. Instrum. 83, 10E518 (2012).

KBFRAMED has a known response to soft x rays

KBFRAMED (unframed) has the following sensitivity:

$$f = s(E) * \varepsilon_{KB}(E) * \Delta\Omega / M^2$$

where f is the flux density at the image plane in keV/keV/cm^2/s
and s = surface flux density in keV/keV/cm^2/s/sr
ε_{KB} = KB microscope efficiency (reflectivity * filter transmission)
$\Delta\Omega$ = solid angle of the microscope
M = magnification.

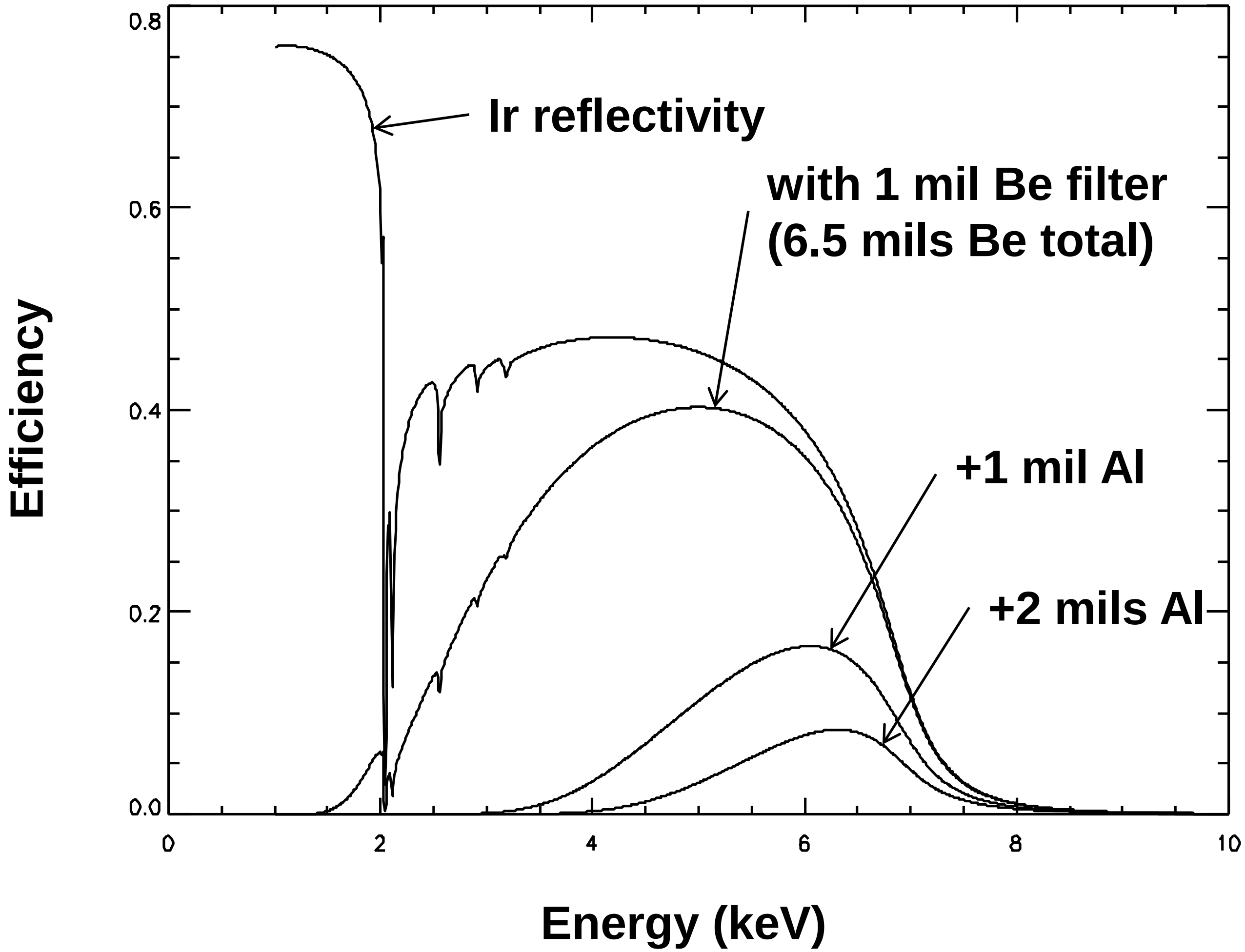
For KBFRAMED:
$\Delta\Omega = 9 \times 10^{-8}$ sr
M = 12.0

The counts seen in a particular image are given by:

$$C = \int dE * s(E) * \varepsilon_{KB}(E) * \Delta\Omega / M^2$$

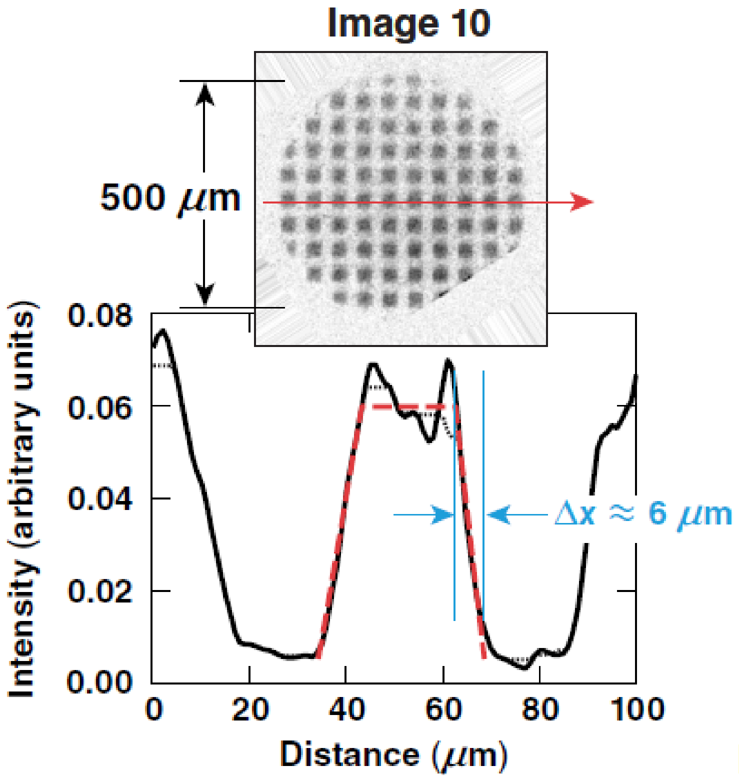
where ε_{KB} is the reflection efficiency times the filter transmission.

KBFRAMED (unframed response)

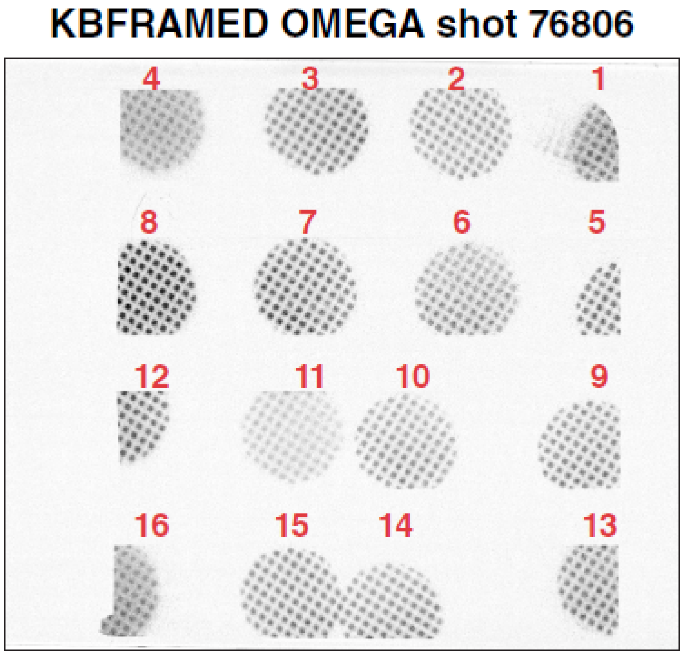


Note: Blast shield = 4 mils Be, vacuum Be window = 1 mil Be
secondary debris shield = 0.5 mils Be
(total filtration = 5.5 mils Be + filter at image plane, 6.5 mils Be in example above)

KBFRAMED optic magnification and framed resolution have been measured using an x-ray backlit grid on OMEGA



M = 12 with 6-μm resolution



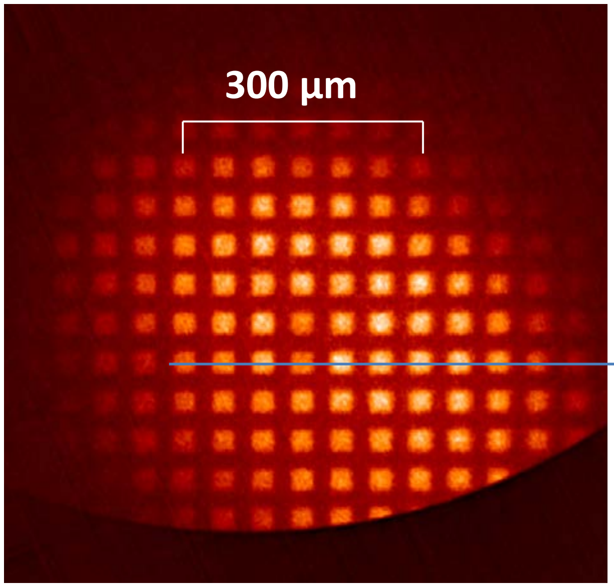
M = 12.0 within 1%
Resolution (FWHM* of the PSF**) $\approx$ 6 μm varies from image to image

*FWHM: full width at half maximum
**PSF: point spread function

E23991

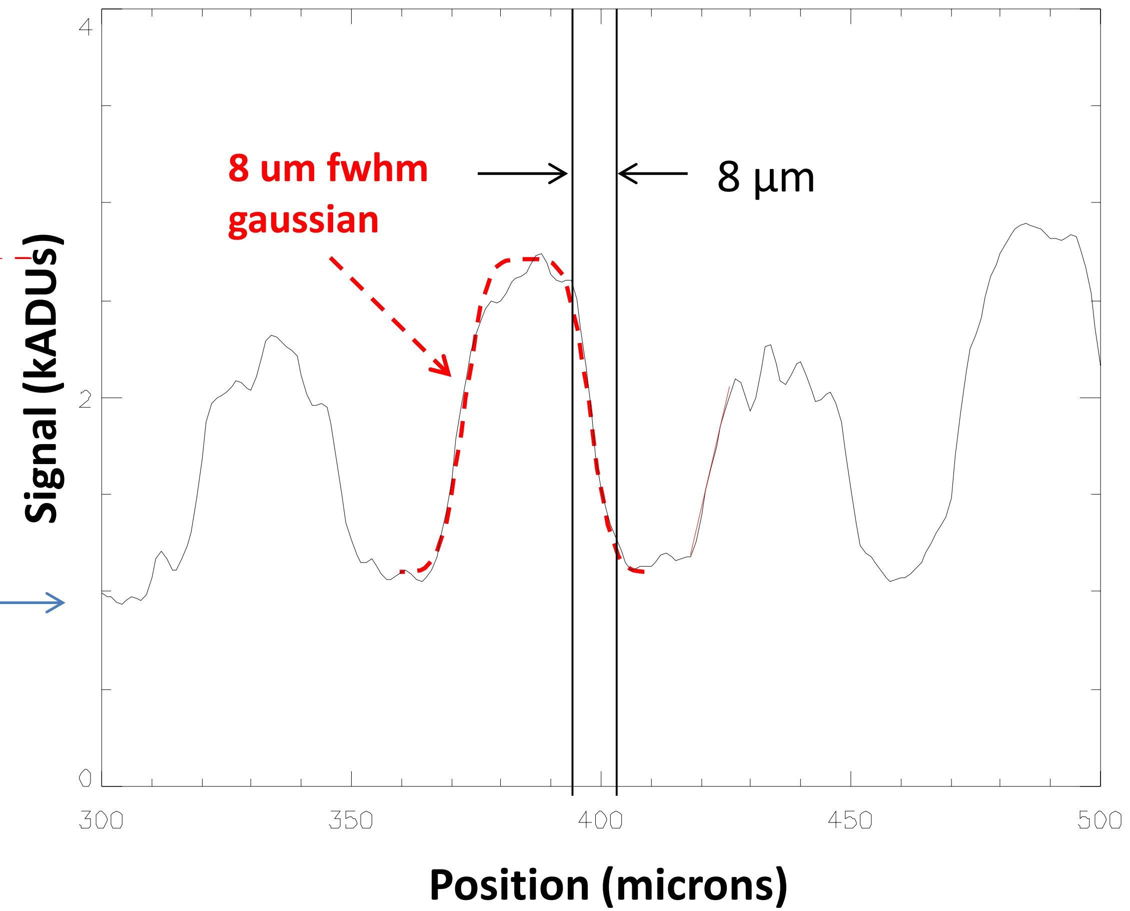
The GMXI has a resolution of ~8 µm at best focus when images are recorded by CID cameras

Backlit 500 mesh Cu grid image corrected to target plane



Magnification: 13.64 ave
14.01 horizontal
13.28 vertical
verified to better than 1%

OMEGA shot 80301



F. J. Marshall and J. A. Oertel, Rev. Sci. Instrum. 68 (1), January 1997

The detailed cryogenic core hot-spot evolution is seen every ~15 ps with KBFRAMED

UR LLE

OMEGA shot 77064
KBFRAMED x-ray images

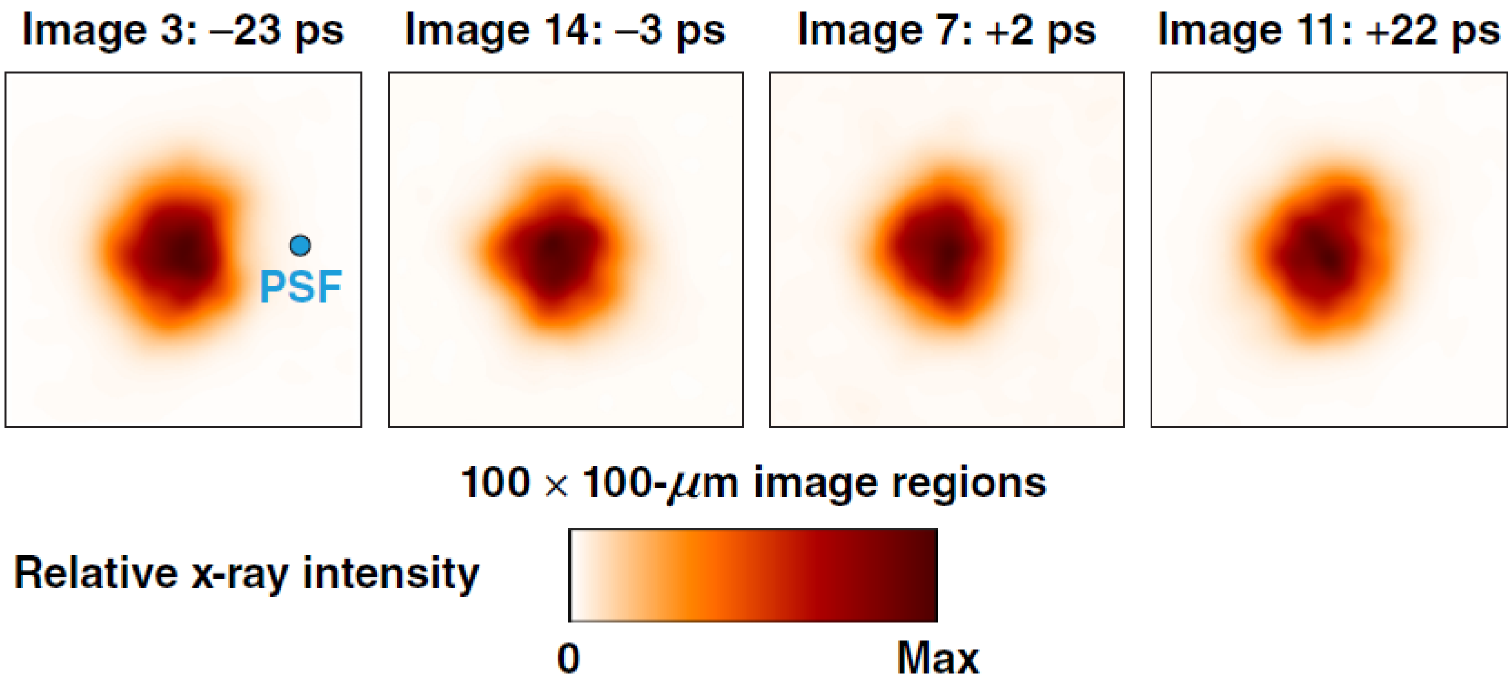
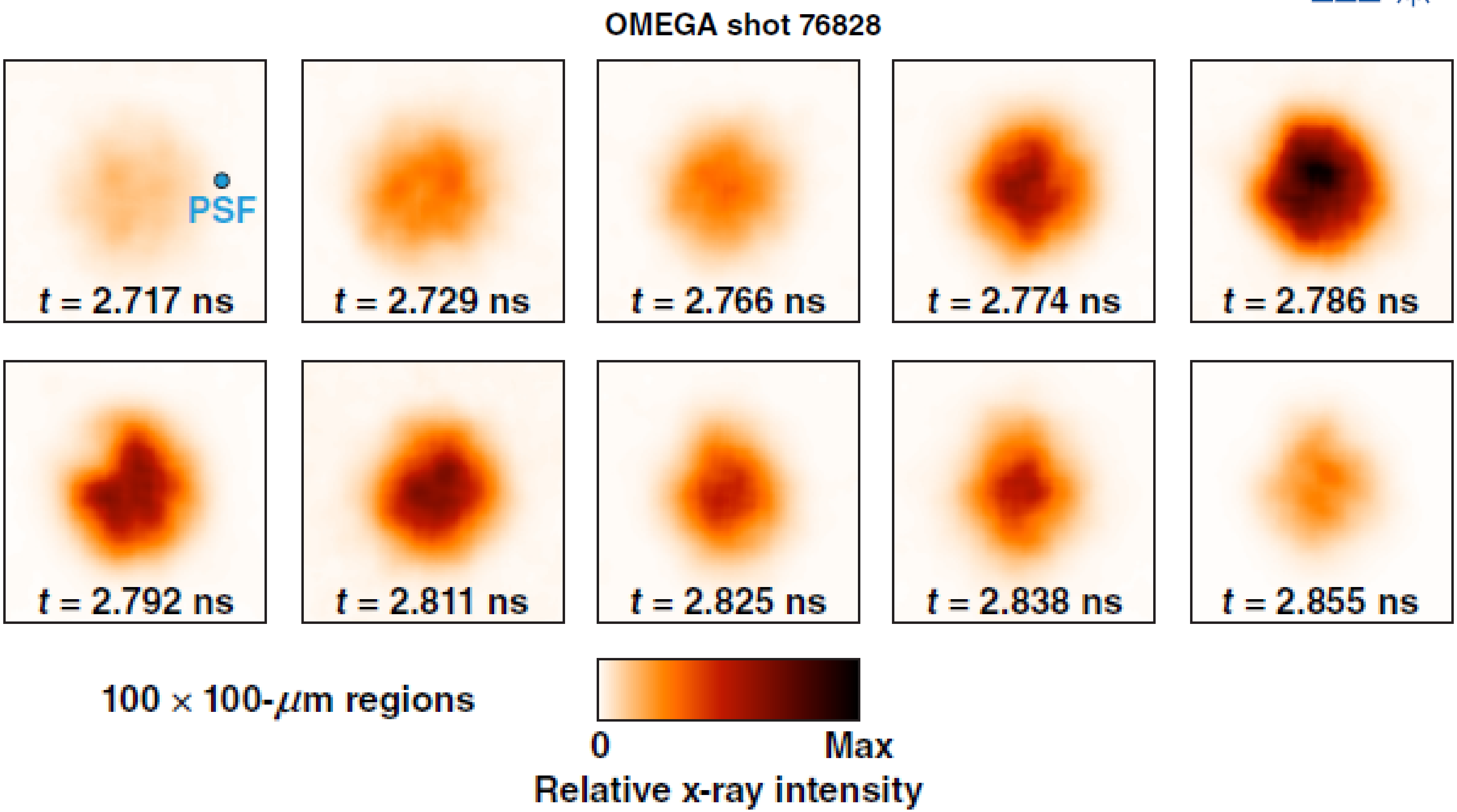


Image-to-image timing is precisely determined from position and the use of measured cables (±2 ps).

E24420

KBFRAMED records an image (Δt = 30 ps) of the stagnating core every ~15 ps in the 4- to 8-keV photon-energy range



E24014a

The cryogenic-target implosion, hot-spot size is determined from an elliptical super-Gaussian fit

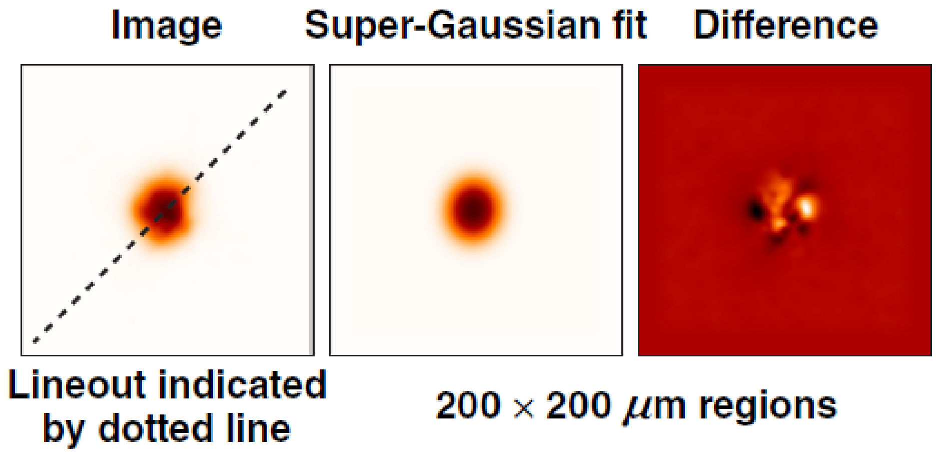
OMEGA shot 77064 KBFRAMED core image near peak compression

$$I = I_0 \times \exp\left[-\frac{(x - x_c)^2}{a^2} - \frac{(y - y_c)^2}{b^2}\right]^{n/2}$$

$$I^* = I \otimes PSF\,(x, y)$$

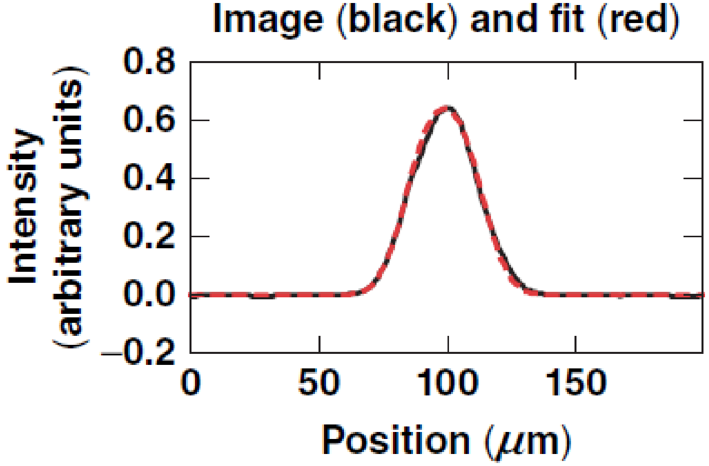
$$R_{1/e} = \sqrt{ab}$$

$$R_{17} = (1.77)^{1/n} \times R_{1/e}$$



- Fit is to super-Gaussian Convolved with PSF (I^*)
- For KBFRAMED: PSF ≈ 6 μm FWHM Gaussian

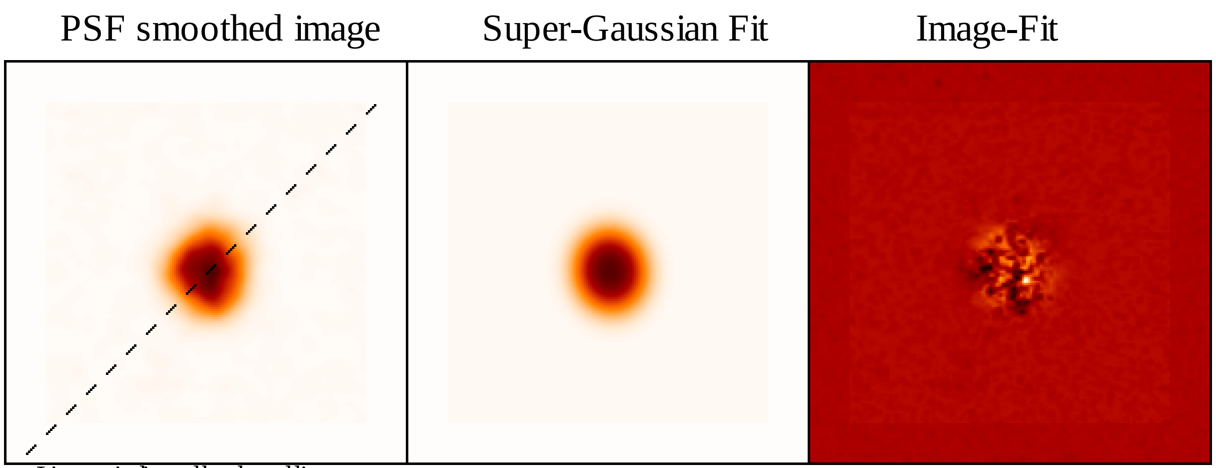
  (SFC3 PSF ≈ 12 μm)



E24509

03/04/2016

OMEGA shot 77064: KBF image 7

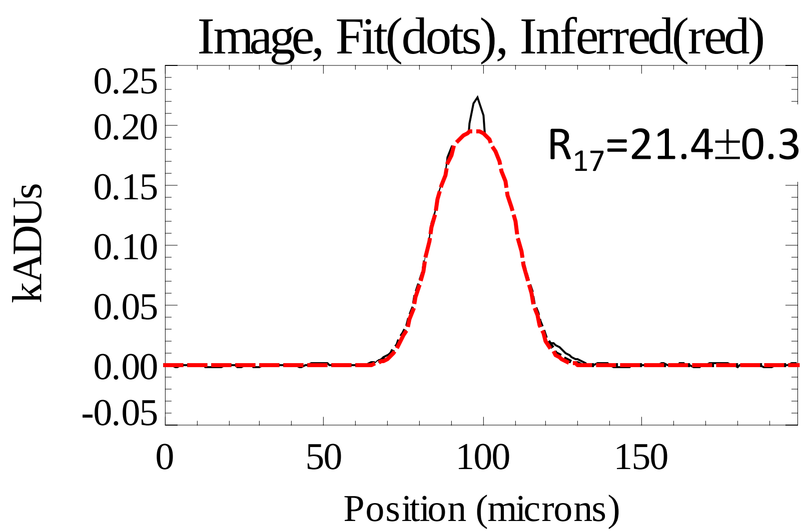


Lineout indicated by dotted line

Inferred fit

Ro (microns):	17.24+/- 0.00
maximum:	0.196+/- 0.000
exponent:	2.66+/- 0.00
a/b:	1.144+/- 0.000
phi (deg):	98.1+/- 0.0
background:	0.002+/- 0.000

6.5 mils Be, 2 mils Al
200. by 200. micron region
psf(fwhm) = 6.0 microns

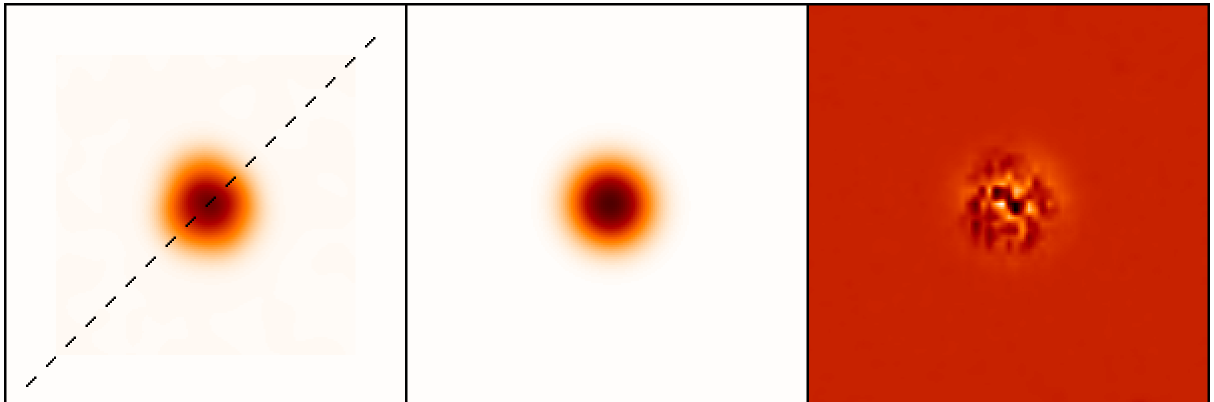


Output of aq_gaussfit1.pro

05/06/2015

OMEGA shot 77064: SFC3T5, IMAGE 35

PSF smoothed image | Super-Gaussian Fit | Image-Fit



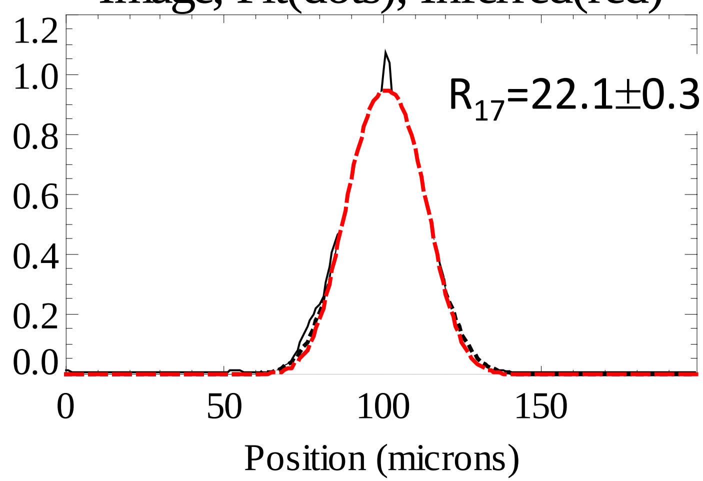
Lineout indicated by dotted line

Inferred fit

Ro (microns):	17.23+/- 0.13
maximum:	0.948+/- 0.032
exponent:	2.30+/- 0.17
a/b:	1.029+/- 0.001
phi (deg):	120.0+/- 0.9
background:	0.001+/- 0.008

1 mils Be, 1.5 mils Al
200 by 200 micron region
psf(fwhm) = 12.0 microns

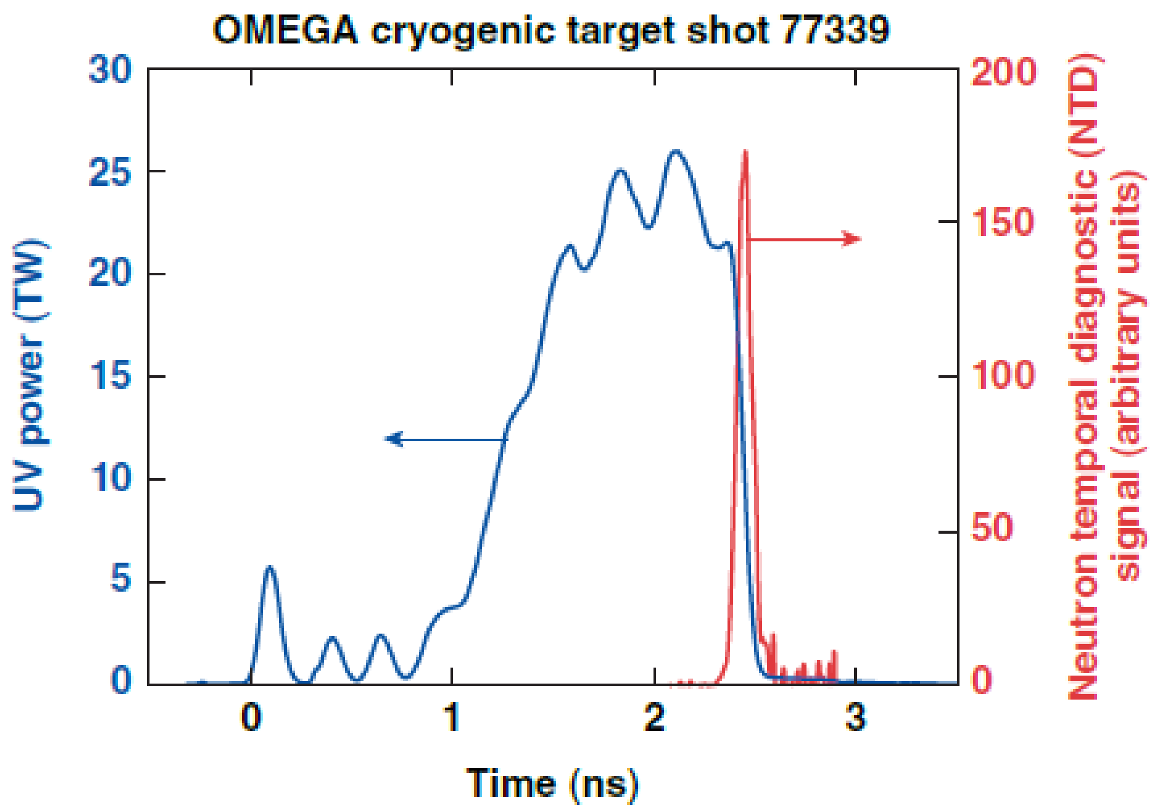
Image, Fit(dots), Inferred(red)

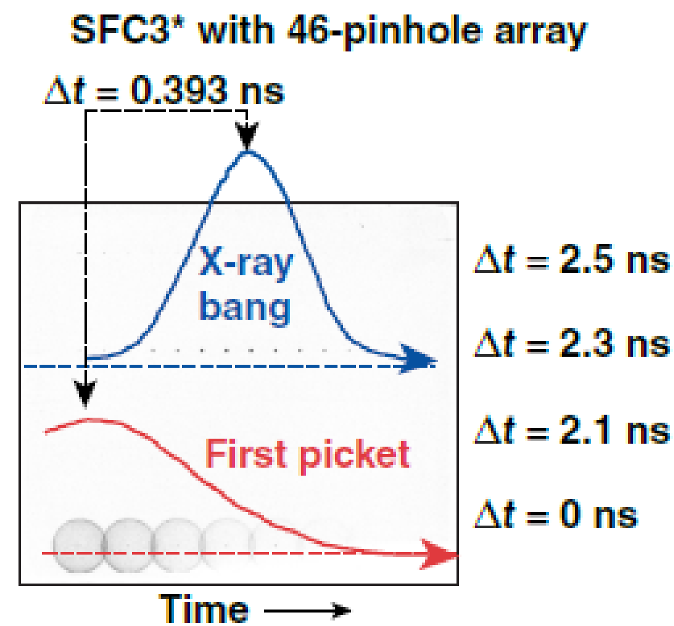


Output of aq_gaussfit1.pro

The x-ray "bang time" is independently determined by measuring the time from the first picket peak to the stagnation peak

UR LLE

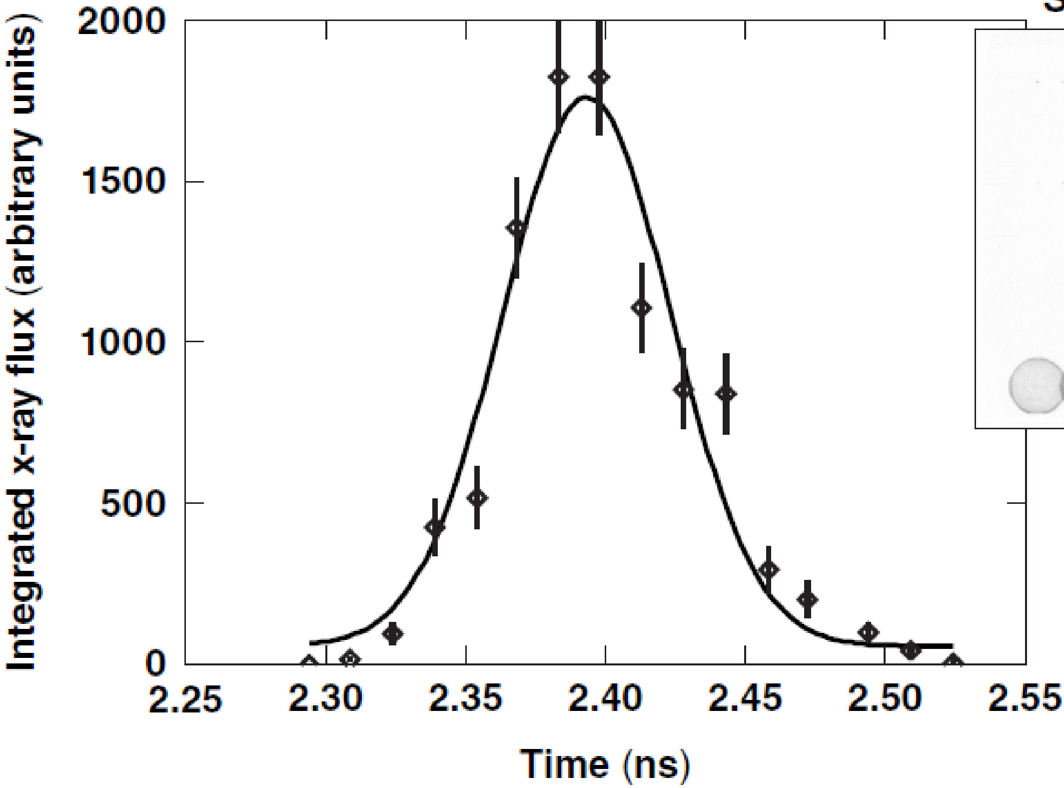




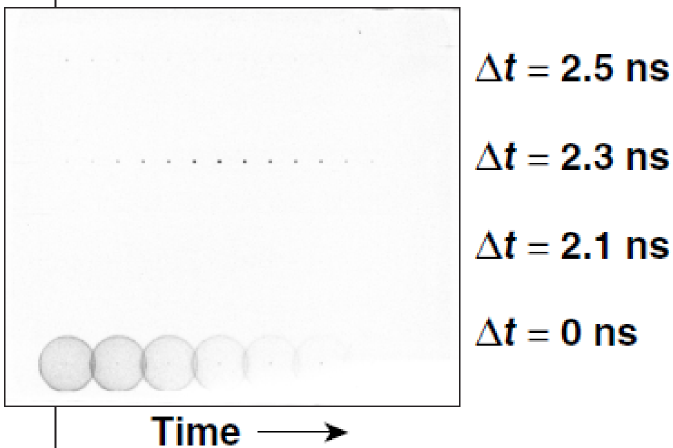
T_{bang} = 2.3 ns + Δt = 2.393 ns

The pinhole array framing-camera images determine the absolute x-ray bang time and burnwidth

Core x-ray emission, OMEGA shot 77339



SFC3* with 46-pinhole array



Best fit:
I_0 = 1710
t_{bang} (exp) = 2.393±0.005 ns
t_{bang} (1-D) = 2.38 ns
} From first picket
FWHM (exp) = 64±5 ps
FWHM (1-D) = 64 ps

Flat fielded by framing constant-emission x rays.

E24421

*SFC3: Sydor framing camera

The hot-spot pressure and volume are inferred from the neutron yield, burnwidth, ion temperature, and core size

$$\langle P \rangle^* = \sqrt{\frac{Y_n / 10^{16}}{\xi(T) V_{hs} \tau}}, \text{ where } \xi(T) \equiv \frac{1}{V_{hs}} \int V_{hs} \frac{\langle \sigma v \rangle}{T^2} dV \text{ and } V_{hs} \approx \frac{4\pi}{3} R_{17\%}^3$$

<u>OMEGA cryogenic target shot 77066</u>

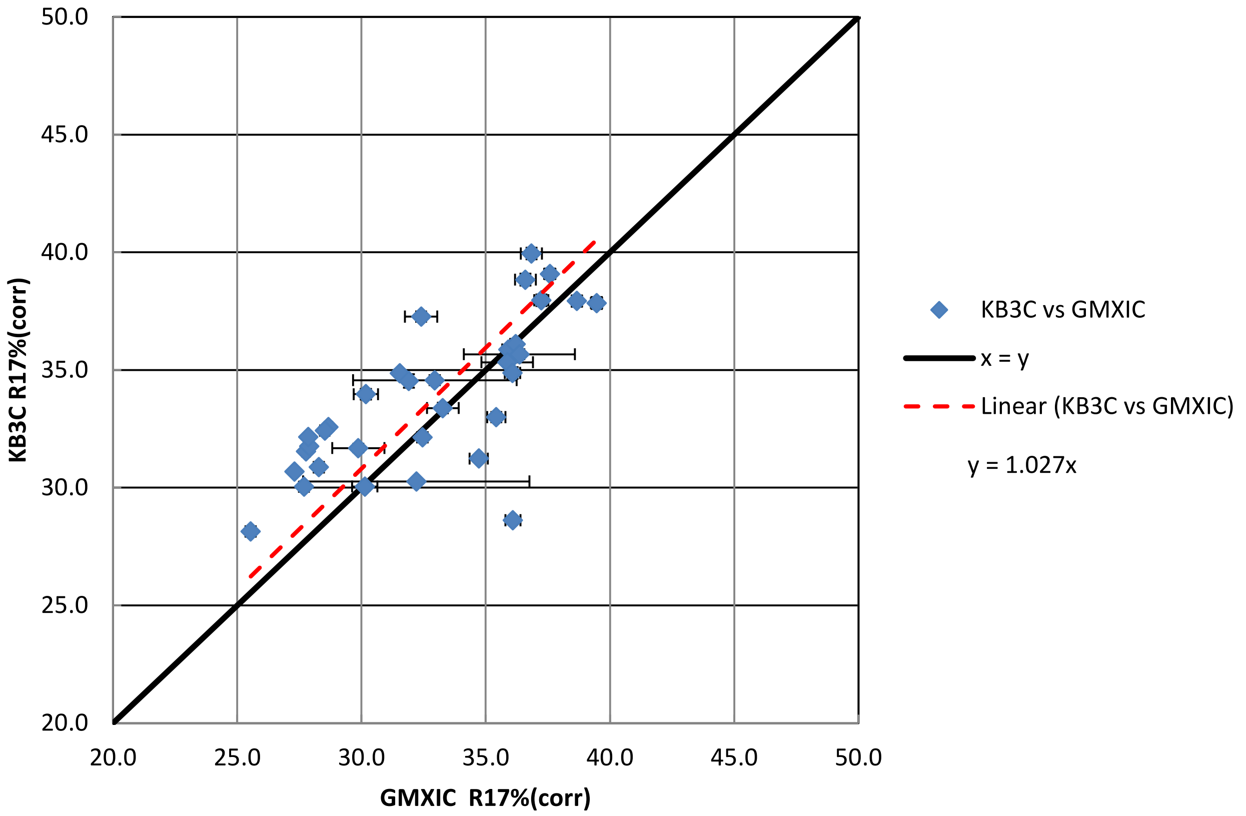
R_{17} = 22.0±0.4 μm (framed images + KB microscope images)
$Y_n = 4.0 \times 10^{13}$
τ = 63±5 ps (x rays), 67±5 ps (neutrons), 66 ps (1-D)
T_i = 3.2±0.4 keV
$\langle P \rangle$ = 56±7 Gbar
$\langle P \rangle_{1\text{-D}}$ = 90 Gbar

*C. Cerjan, P. T. Springer, and S. M. Sepke, Phys. Plasmas 20, 056319 (2013); R. Betti *et al*., Phys. Plasmas 17, 058102 (2010).

E23702a

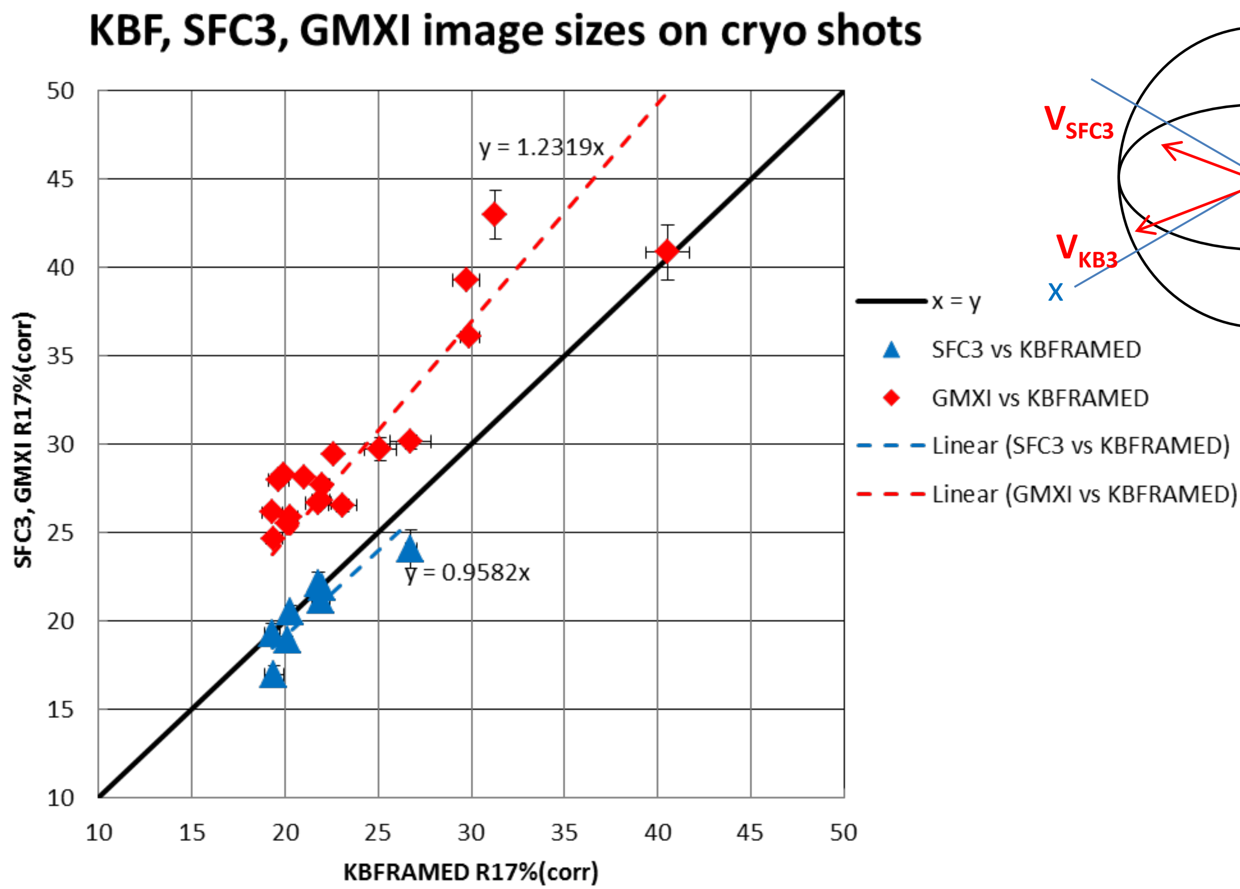
The cryogenic target implosion cores have been measured with two KB microscopes in time integrated mode

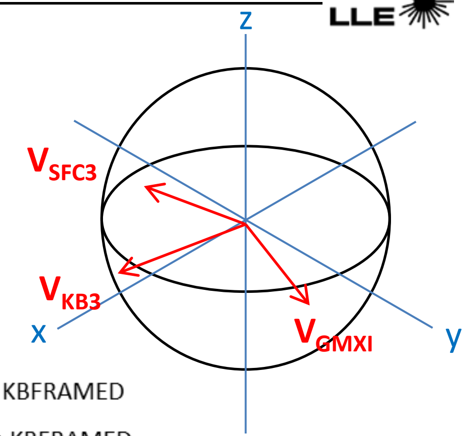
KB3c vs GMXIc image sizes on cryo shots



The two measurements infer a core size that agree within a few percent of each other from quasi-orthogonal views

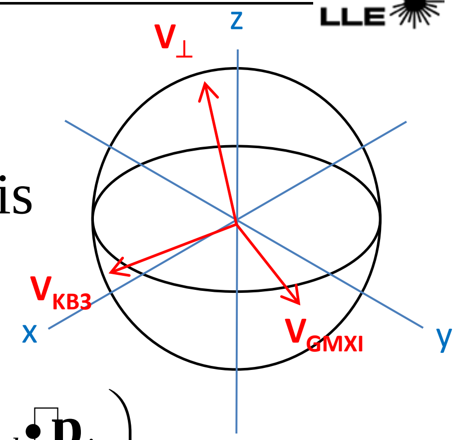
Cryogenic target implosion cores have been measured with KBFRAMED, a framed pinhole array, and a time integrated KB





The larger time integrated core sizes place an upper limit on "emission-region-size" evolution of ~ 5 μm

The flux along common perpendicular lines of sight can be compared exactly by rotation and integration



$$\mathbf{v}_{ab\perp} = \frac{\mathbf{v}_a \times \mathbf{v}_b}{|\mathbf{v}_a \times \mathbf{v}_b|}, \quad \text{where } \mathbf{v}_{ab} \text{ is the common axis}$$

In coordinates of image:

$$\mathbf{q}_i = \frac{\mathbf{z} \times \mathbf{v}_i}{|\mathbf{z} \times \mathbf{v}_i|}, \quad \mathbf{p}_i = \frac{\mathbf{v}_i \times \mathbf{q}_i}{|\mathbf{v}_i \times \mathbf{q}_i|}, \quad \alpha_i = \arctan\left(\frac{\mathbf{v}_{ab} \cdot \mathbf{p}_i}{\mathbf{v}_{ab} \cdot \mathbf{q}_i}\right), \quad i = a, b$$

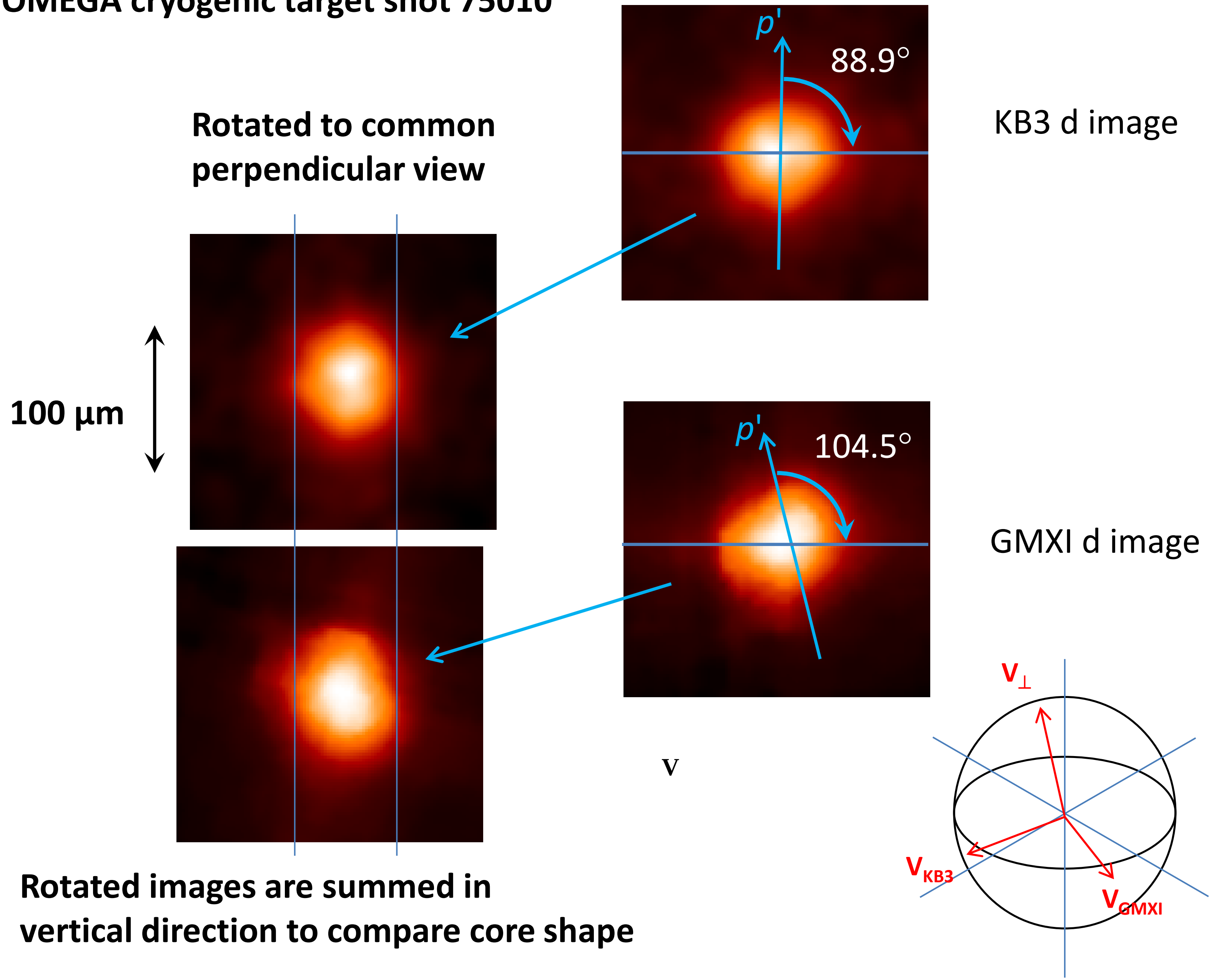
Flux along common line of sight:

$$F_i(p'_i) = \int_{\mathbf{v}_{ab\perp}} f(q'_i, p'_i)\,dq'_i, \quad \text{where } \mathbf{v}_{ab} = \mathbf{q}'_a = \mathbf{q}'_b$$

Assuming omnidirectional, optically-thin emission

$$F_a(p'_a) = F_b(p'_b)$$

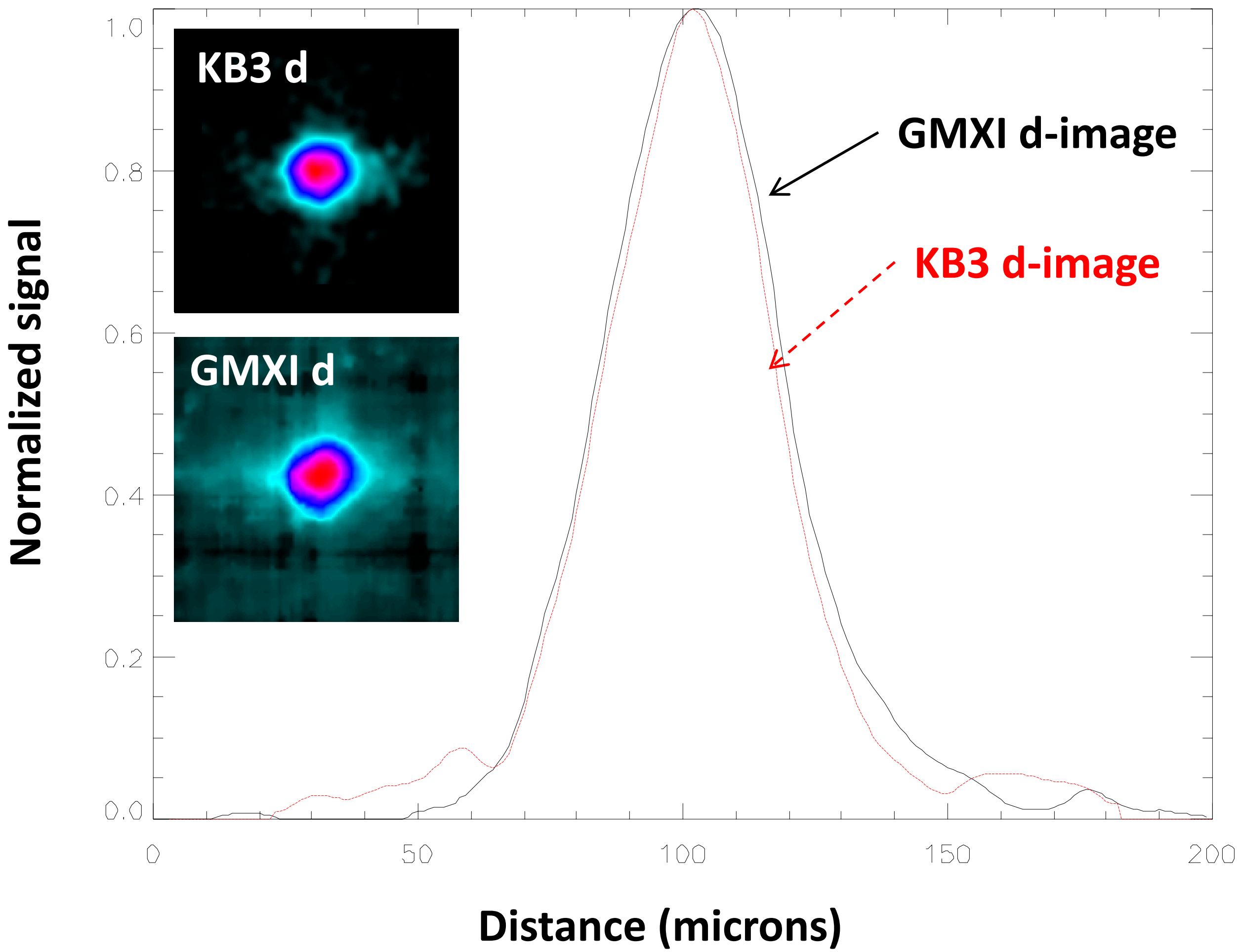
OMEGA cryogenic target shot 75010



Rotated images are summed in vertical direction to compare core shape

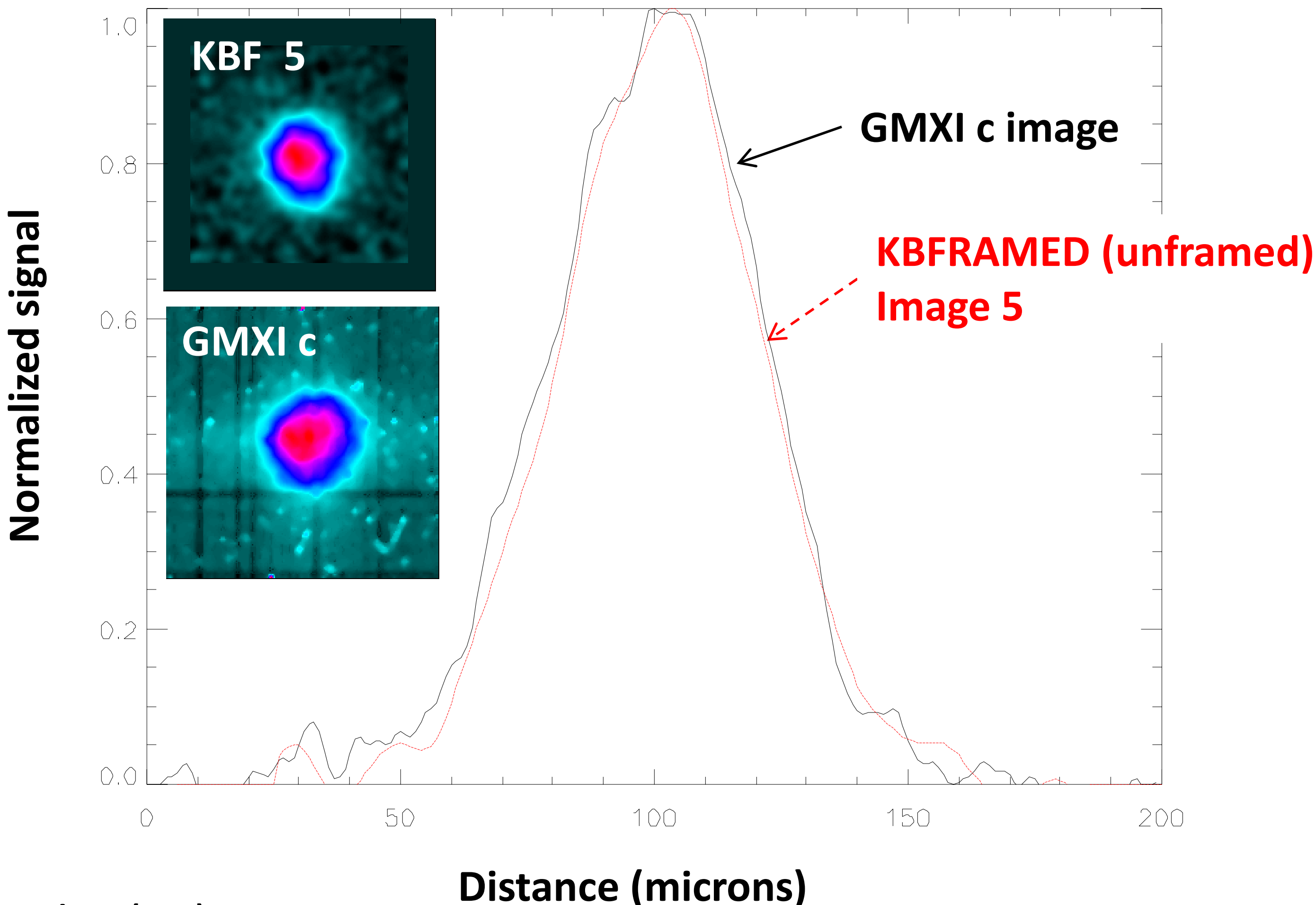
OMEGA cryogenic target shot 75010

Summations along common perpendicular lines of sight



OMEGA cryogenic target shot 80552

Summations along common perpendicular lines of sight



Flux at image plane (KBF)
was ~4000 photons/res el
at peak of image from calibrated Biomax response assuming 5 keV

CONCLUSIONS

X-ray emission shape/size analysis at LLE
F. J. Marshall, LLE

The size and shape of the cryogenic target implosion cores are being measured by multiple x-ray imaging diagnostics on OMEGA

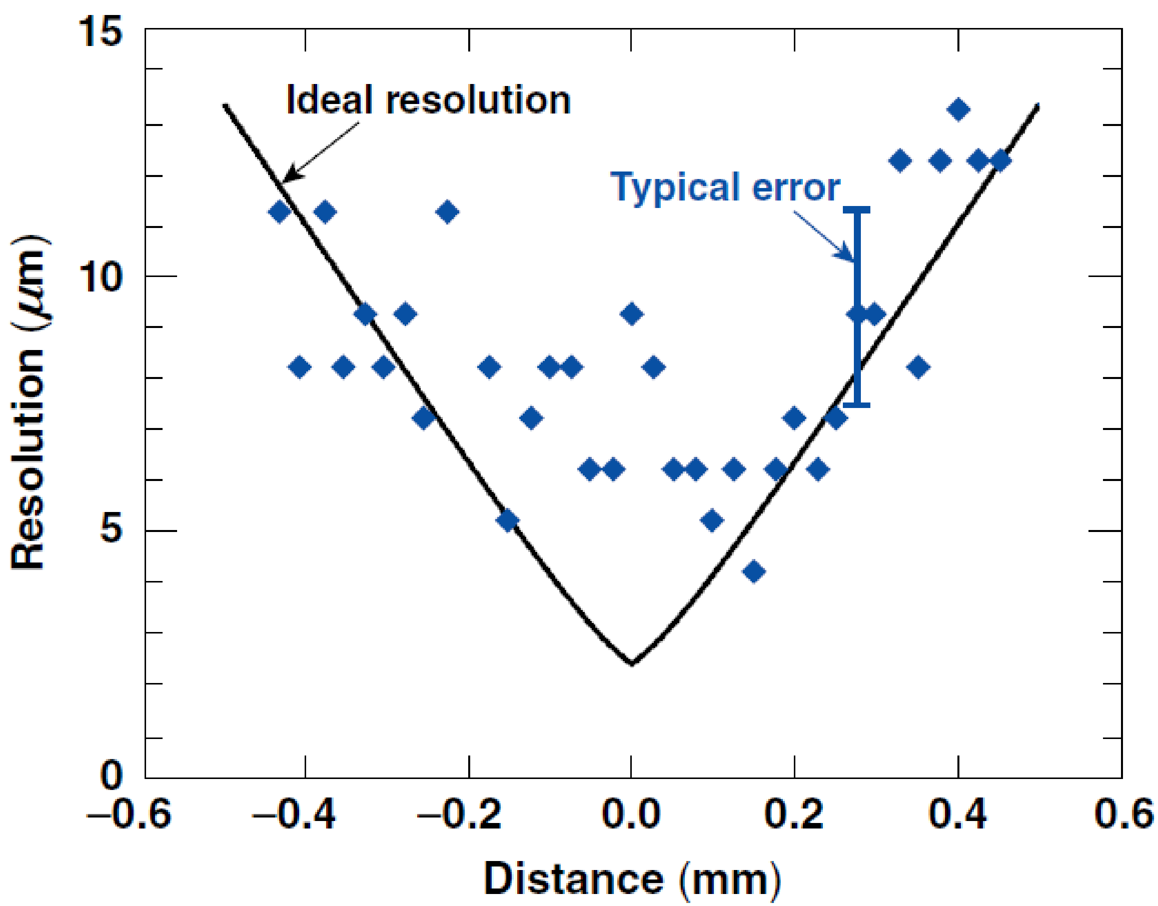
Simultaneous time-integrated images shown agreement within ~3% on average with large directional deviations on individual shots

Time-resolved images at the peak of the stagnation agree closely as to the size of the core (within ~5%)

Comparison of images along mutually perpendicular lines-of-sight confirm that only directional differences affect the measurements

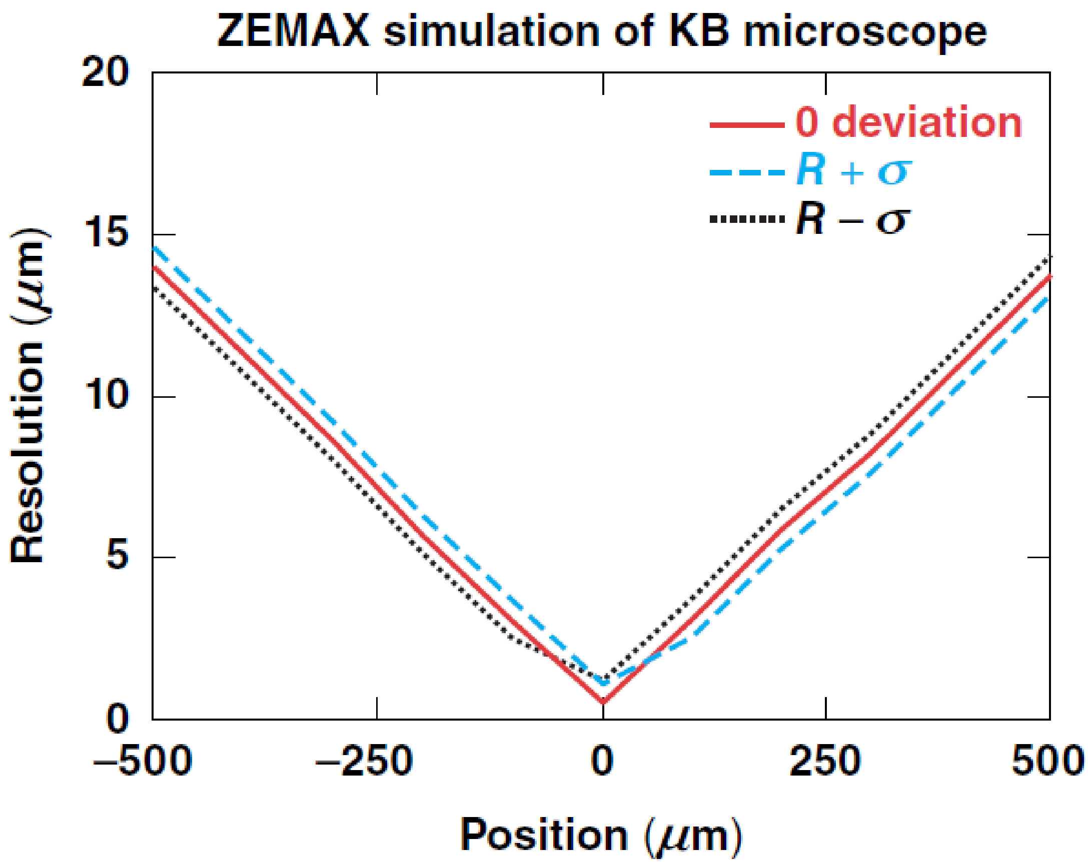
The new KB optic has a best resolution of ~5 μm with better than 10 μm over a 1-mm field of view

UR LLE



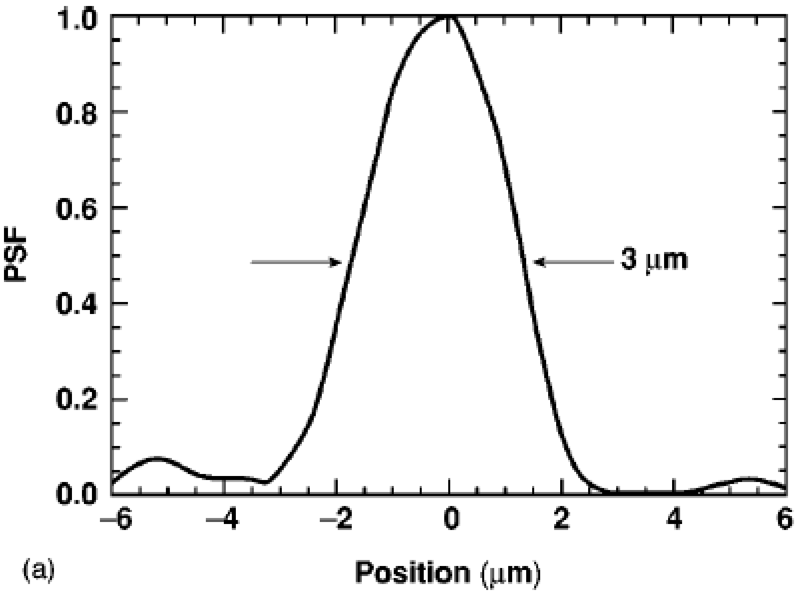
E8626b

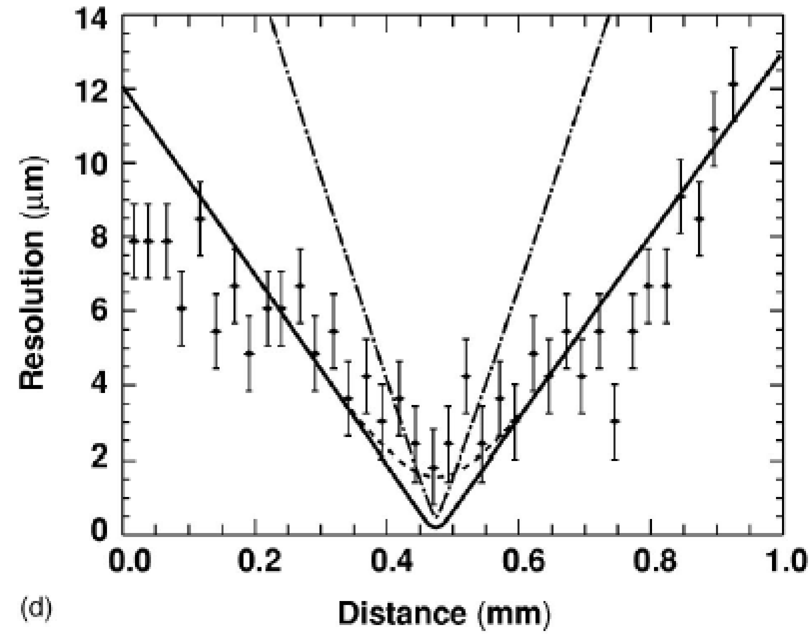
Ray tracing indicates that curvature variation will have a small effect on the spatial resolution

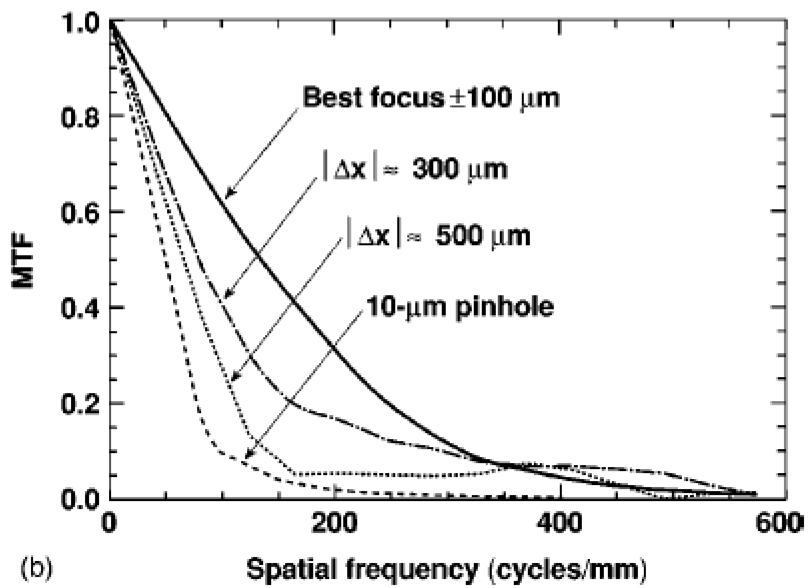


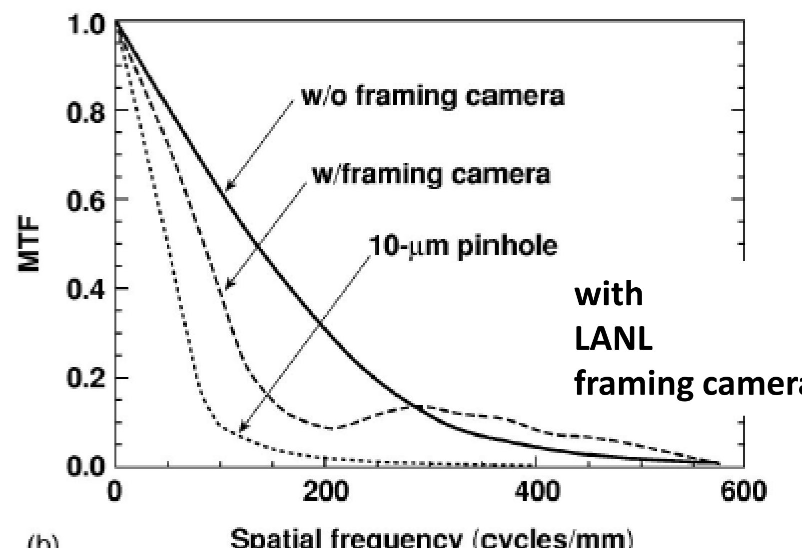
R_{ideal} = 25.6 m
M = 13.6
σ_R = 0.3 m
(measured variation of four mirrors)

E12934a









F. J. Marshall, et al., POP vol.4, 1118 (1998).