SAND2008-3028C

2-Frame 6.151-keV X-ray Imaging on the Recently Upgraded Z-Accelerator: A Progress Report

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17th Topical Conference
High-Temperature Plasma Diagnostics
May 11-15, 2008
Albuquerque, NM, USA

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Abstract

When used for the production of an x-ray imaging backlighter source on Sandia National Laboratories' recently-upgraded 26 MA Z-Accelerator, the tewawatt-class, multikilojoule, 526.57 nm Z-Beamlet laser (ZBL) [Appl. Opt. **44**, 2421 (2005)], in conjunction with the 6.151-keV (Mn 1s^2 - 1s2p triplet) curved-crystal imager [Rev. Sci. Instrum. **75,** 3672 (2004), Rev. Sci. Instrum. **77,** 10E322 (2006)], is capable of providing a high quality x radiograph per Z shot for Inertial Confinement Fusion (ICF), Complex Hydrodynamics, and other high-energy-density physics experiments. For example, this diagnostic has recently afforded ng-scale mass perturbation measurements on an imploding ignition-scale 1-mg ICF capsule [Phys. Rev. Lett. **99,** 205003 (2007)], where the perturbation was initiated by a surrogate DT fuel fill tube. Using an angle-time multiplexing technique, ZBL now has the capability to provide two spatially and temporally foci in the Z chamber, allowing '2-Frame' imaging to be performed, with an interframe time range of 2 - 20 ns. This multiplexing technique allows the full area of the 4-pass amplifiers to be used for the two pulses, rather than split the amplifiers effectively into two rectangular sections, with one leg delayed with respect to the other, which would otherwise double the power imposed onto the various optics thereby halving the damage thresh hold for the same irradiance on target. The 6.151-keV '2-Frame' technique has recently been used to image imploding wire arrays, using a 7.3 ns interframe time; and it will soon be used to obtain two near simultaneous images (2 ns interframe time) at 6.151- and 1.8651-keV energies. This 'diagnostic' will soon be converted to operate with *p*- rather than *s*-polarized laser light for enhanced laser absorption in the Mn foil, plus other changes (e.g., operation at the brighter 6.181-keV Mn 1s^2 - 1s2p singlet line, etc.), to increase x-ray yields. Also, a highly sensitive, inline, multiframe ultrafast (1 ns gate time) digital x-ray camera is being developed to extend the system to '4-Frame' and markedly improve the signal-to-noise (S/N). [Presently, time-integrating Fuji BAS-TR2025 image plate (scanned with a Fuji BAS-5000 device) forms the image-plane detector.] New 2-Frame wire-array physics results from the upgraded 26-MA and planned S/N, 4-frame, and other improvements will be presented.

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"2-Frame" uses two temporally-separated pulses propagating through *full* amp area, thus allowing max energy extraction without exceeding damage threshold power levels

The technique is called angle/time-multiplexing

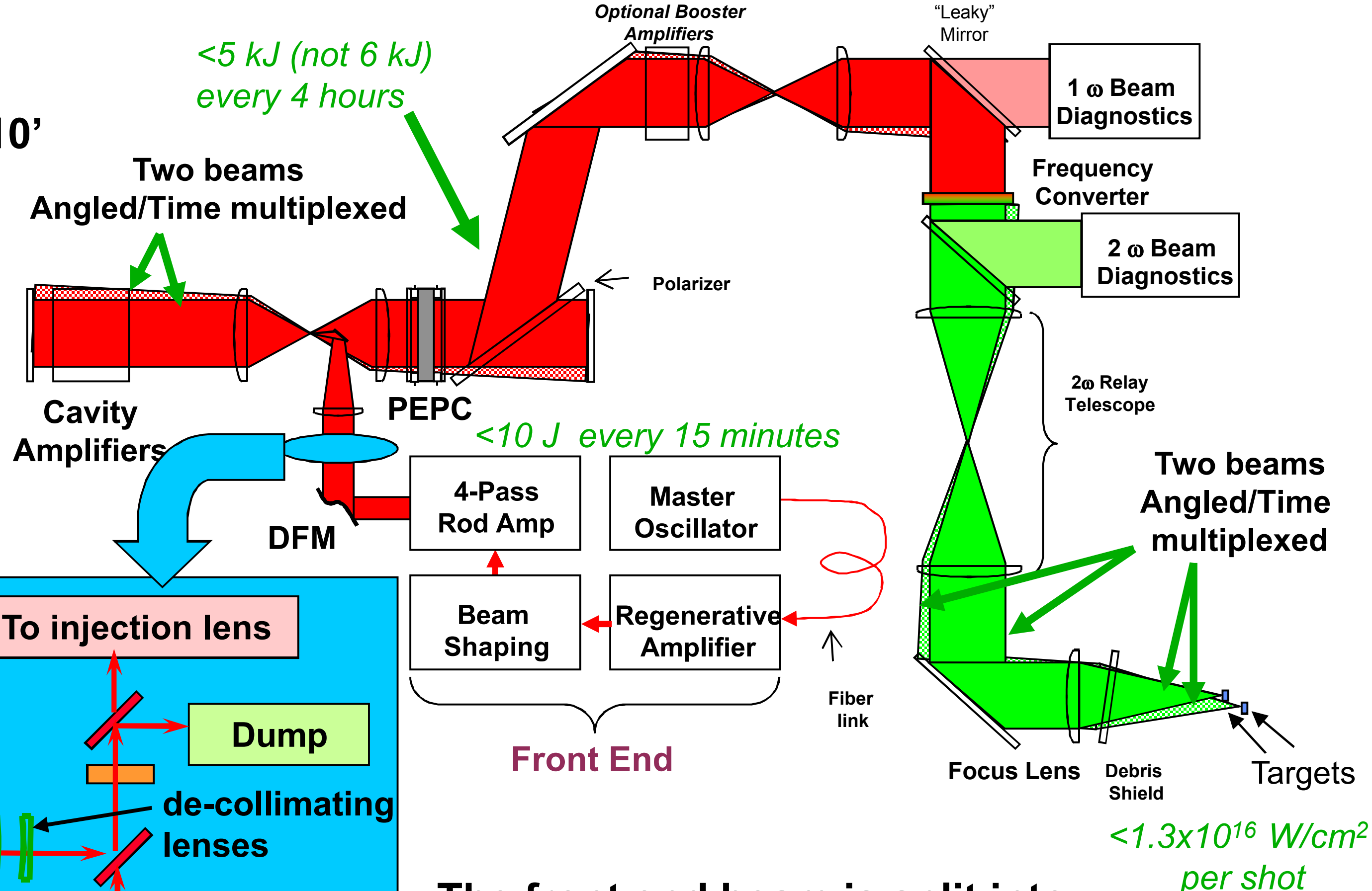
The key advantage over splitting the amps into otherwise rectangular sections (with an appropriate time split separation) is that the power levels (3-TW max red, 2-TW max green), for same irradiance on target, are halved

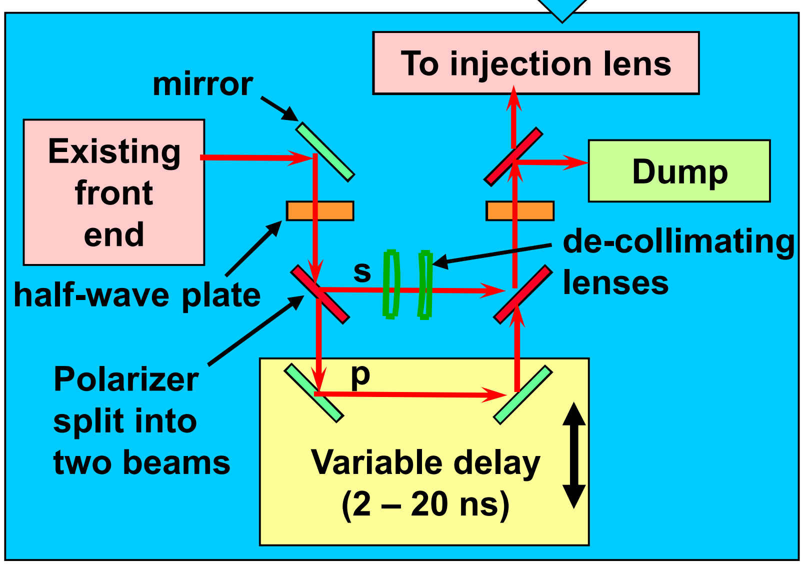
Assuming a 1 ns pulse-length, this *in principle* allows 6-kJ red and 4-kJ green in total

D. B. Sinars and G. R. Bennett used 2-Frame 6.151-keV imaging prior to Z shutdown in summer 2006

….Unfortunately, limited x-ray brightness of the "late" frame led both experimenters to revert to 1-Frame imaging

Injection Box with 10' trombone addition



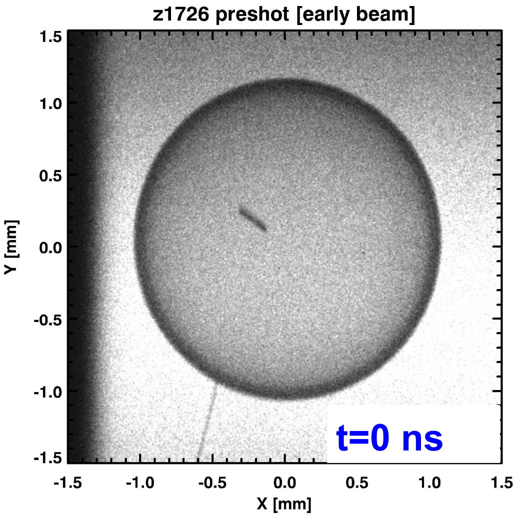


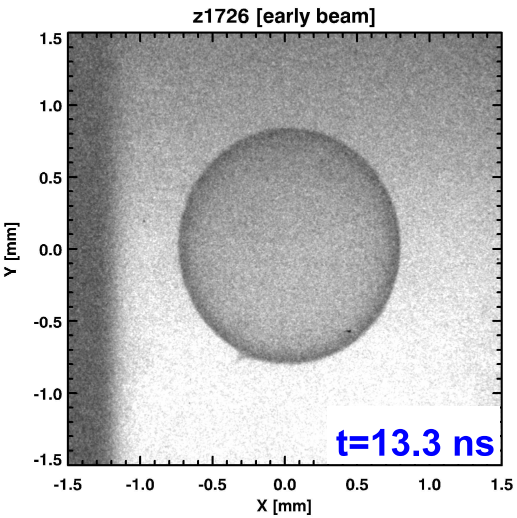
The front end beam is split into Two, with variable energy ratio

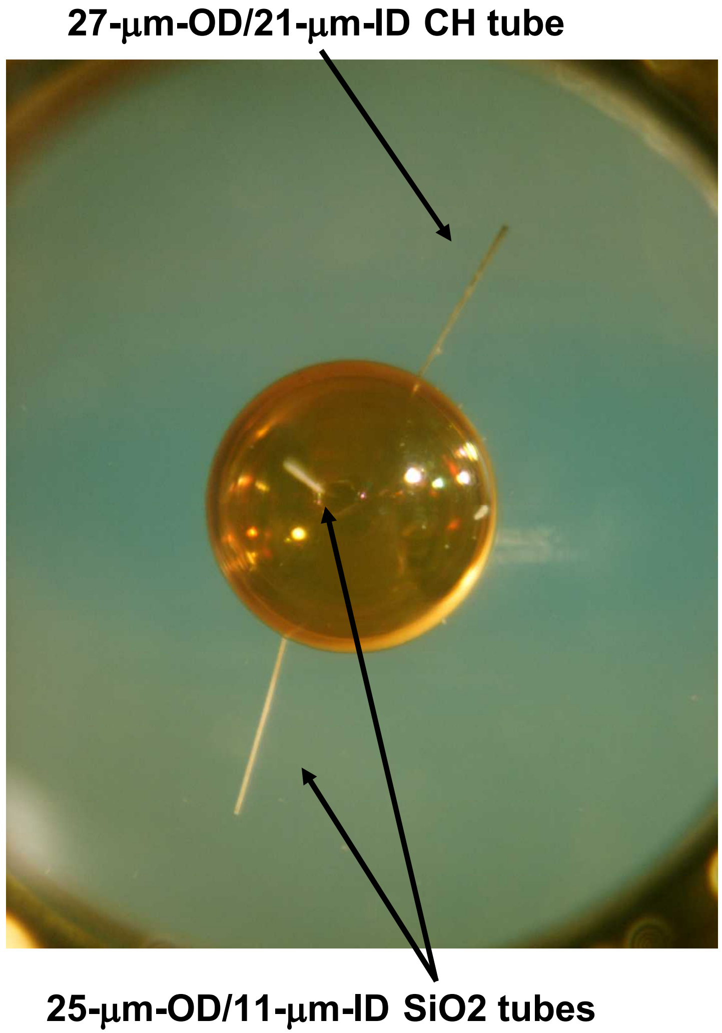
1st beam: unchanged

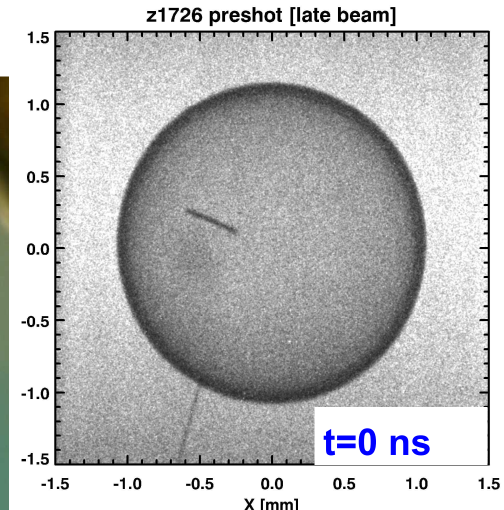
2nd beam: delayed 2-20 ns, 1.3 mrad change in angle & focus

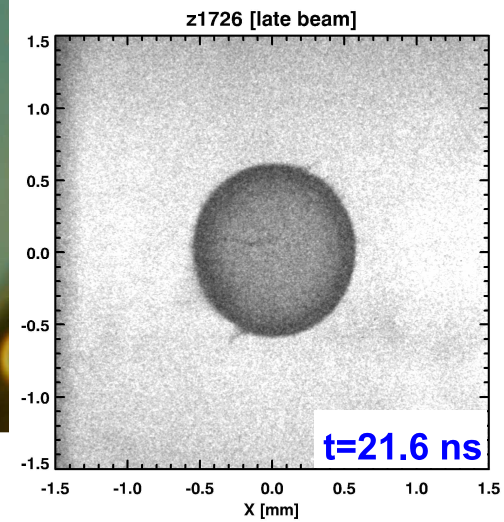
Example 2-Frame, 6.151-keV x-ray imaging applied to 2006 Fill-Tube Hydro Z experiments; note poor S/N





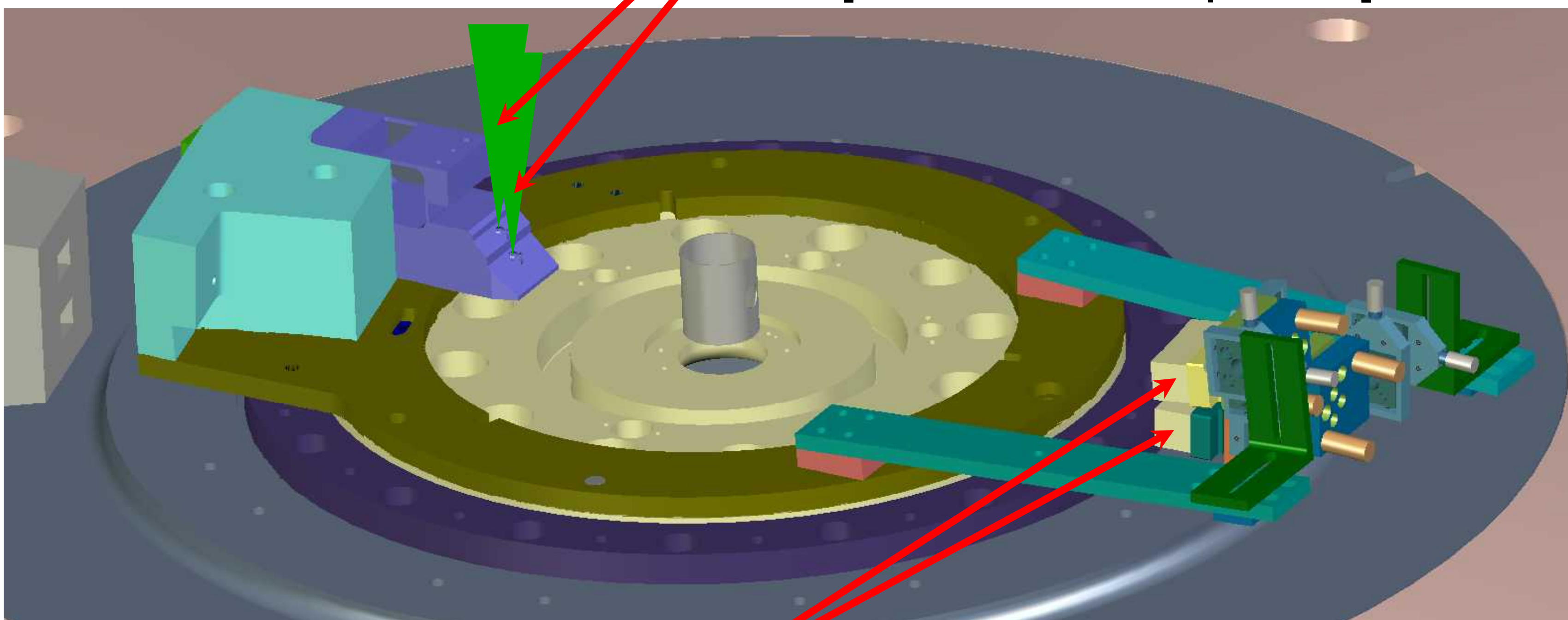






Two temporally and spatially separated ZBL beams irradiating Mn foils

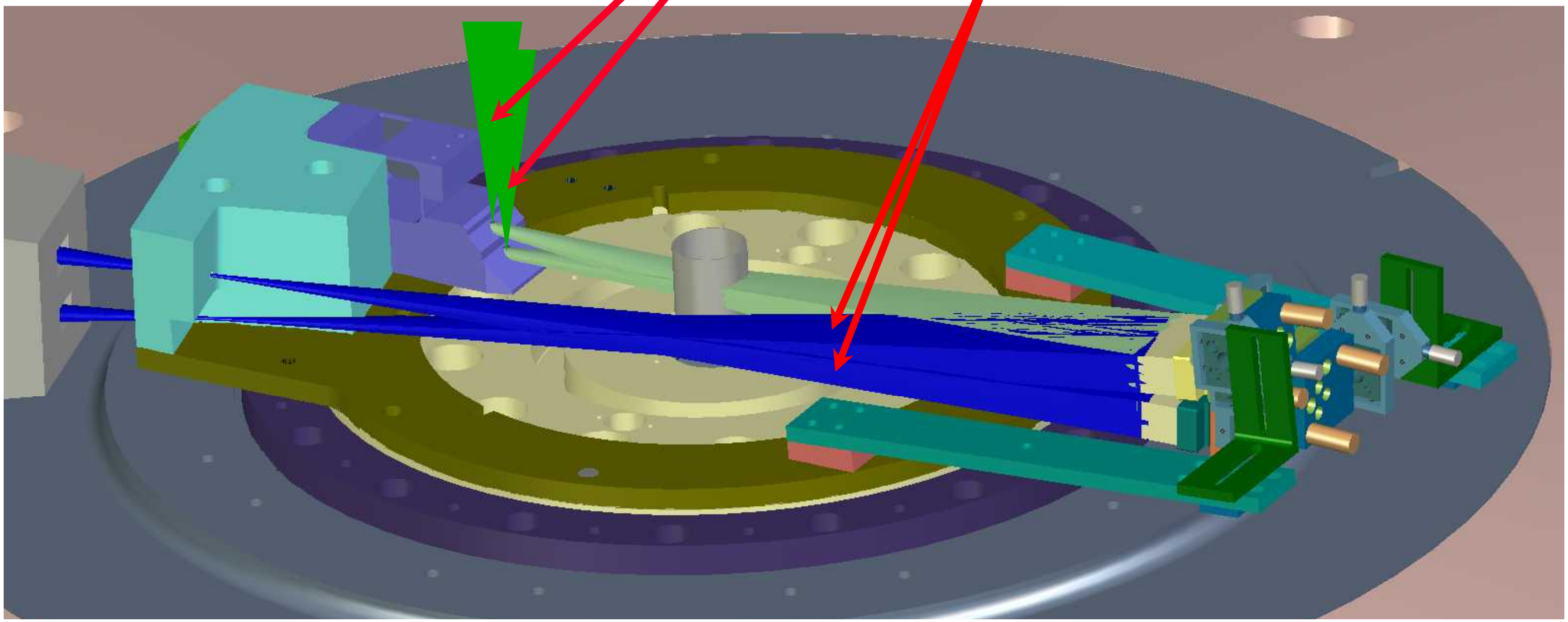
[10.196 mm vertical separation]
[3.783 mm radial separation]



Two independent 6.151-keV systems; 2.9307° off horizontal

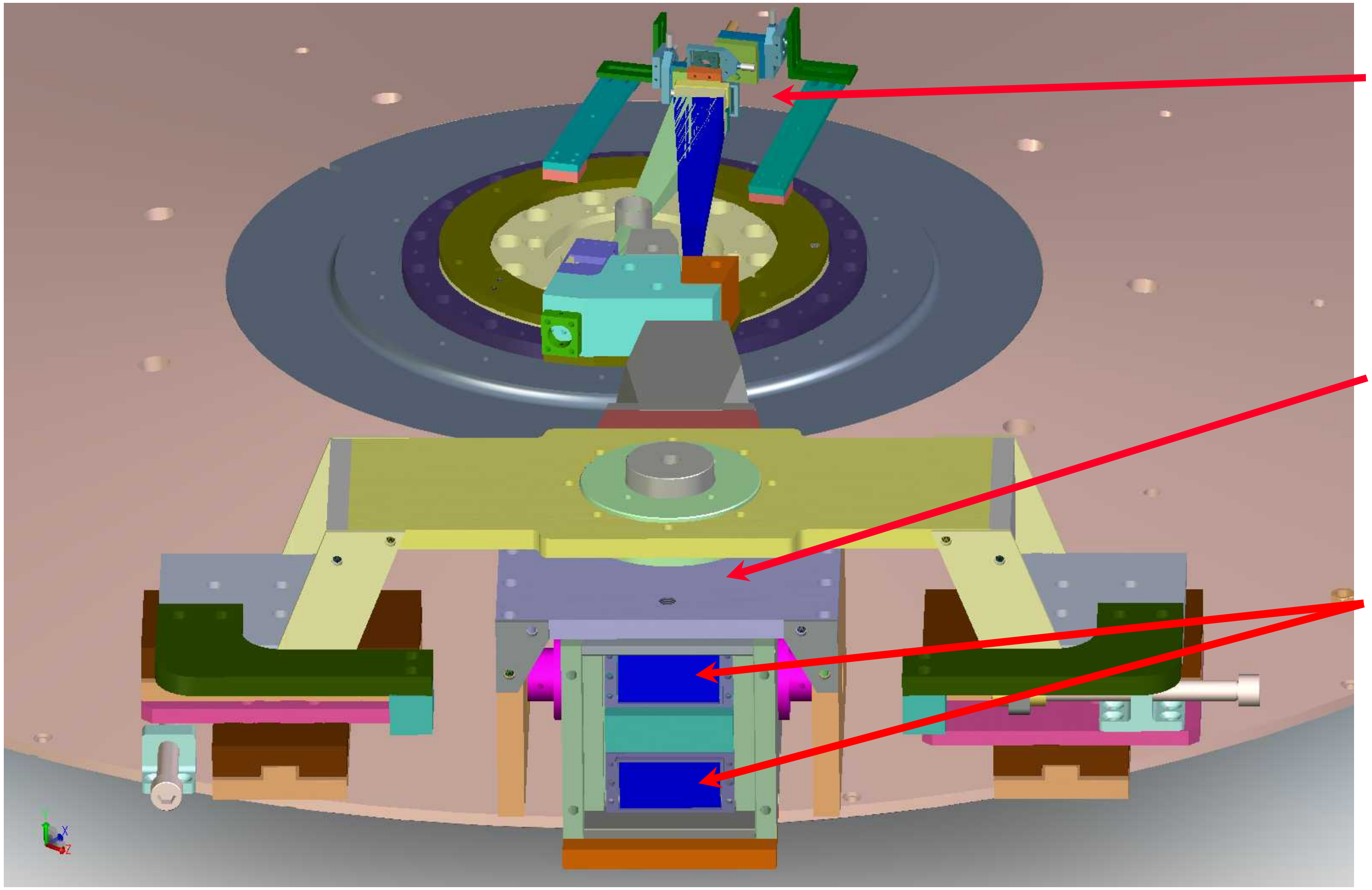
Two temporally and spatially separated ZBL beams irradiating Mn foils

Focused 6.151-keV x-ray beams



Each of the two image-plane detectors (*Image Plate*) capture one time-integrated image

Full 2-Frame system showing housing unit for the twin image-plane detectors



The poor 2-Frame S/N in 2006 was attributed to spatial filter pinhole clipping of the late beam

The 2-Frame pinholes in the Cavity Spatial Filter (CSF) and Transport Spatial Filter (TSF) were in fact manufactured incorrectly

The outcome: Instead of placing the laser spots 244° CW of N, we had to field at 64°

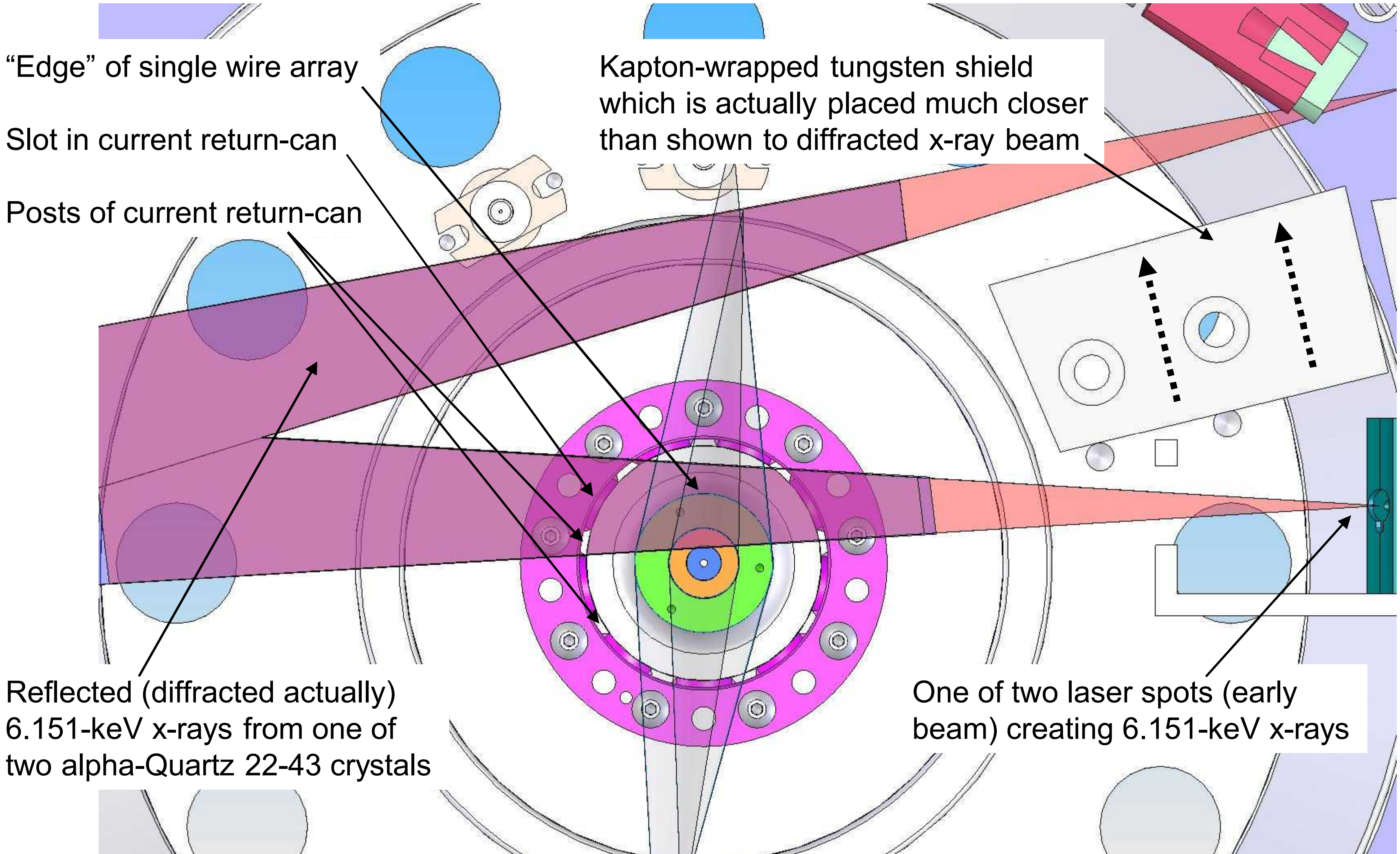
The result: The DCID blocked LOS 5/6 and 10% of the ZBL beam area was clipped in the On-Axis FOA

The former could have easily been corrected, but the latter would require an FOA modification

We chose to install correctly-fabricated pinholes, thus the laser spots are now at 244°

A new optimized frequency-doubling crystal was also installed: The overall outcome was success on z1787

z1787 2-Frame 6.151-keV imaging results (Thursday, Feb 7th), led by Michael Jones, Mike Lopez, & Mike Cuneo



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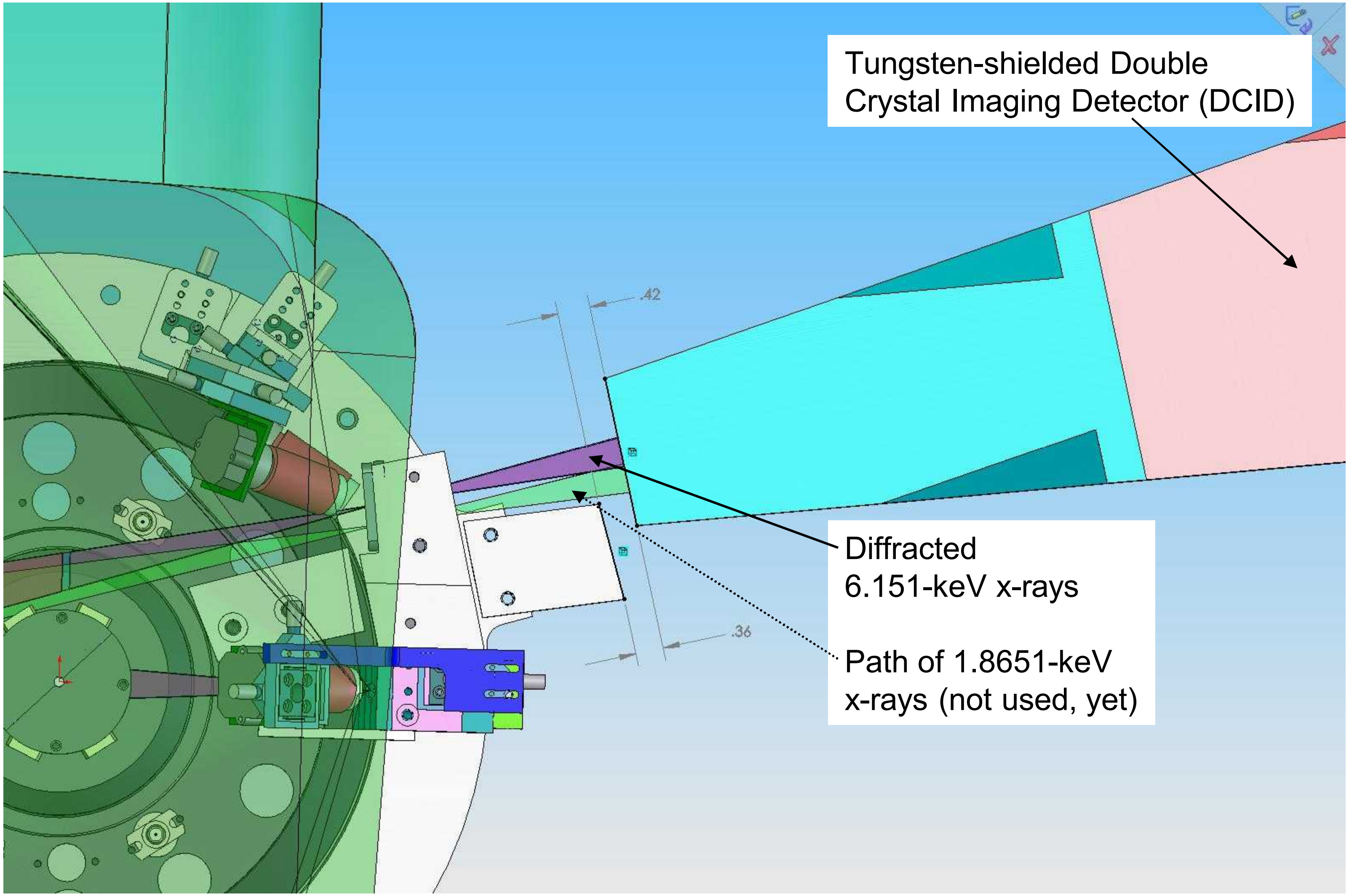


Frames separated by 7.3 ns

Early beam: 138-J pre-pulse, 1016-J main pulse, 1154-J total

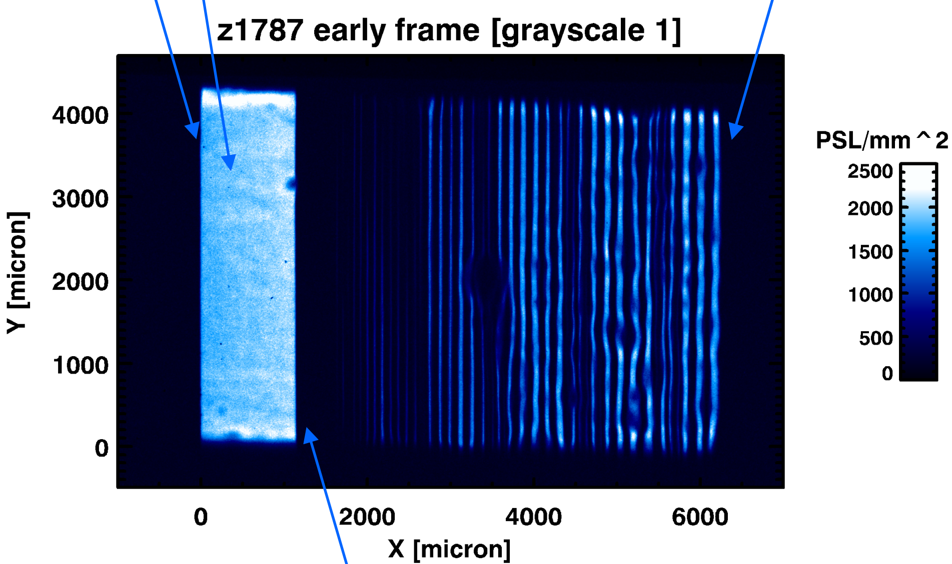
Late beam: 125-J pre-pulse, 861-J main pulse, 986-J total

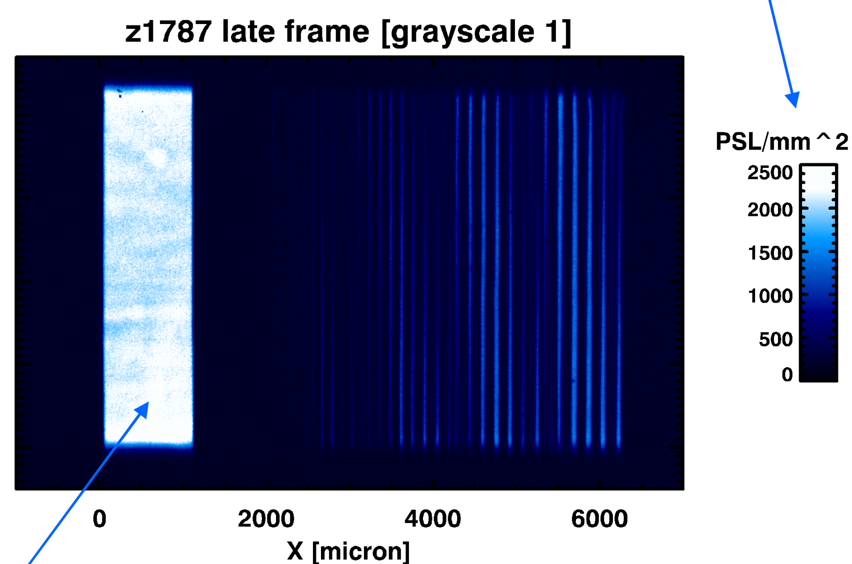
Hard edge of slot (out of focus)

Transmission (T) T=1 region

Hard edge of slot (out of focus)

PSL, Photo-Stimulated-Luminescence, is proportional to x-ray dose





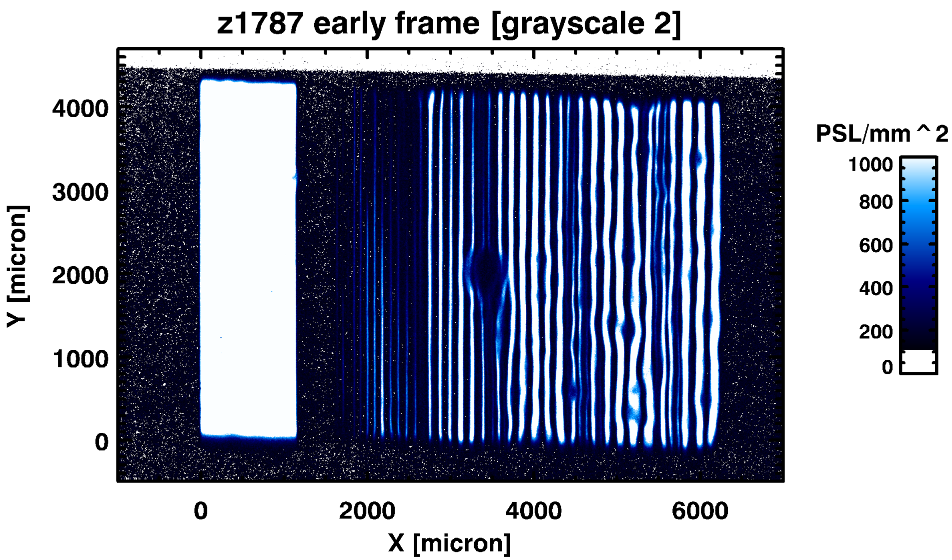
Edge of array?

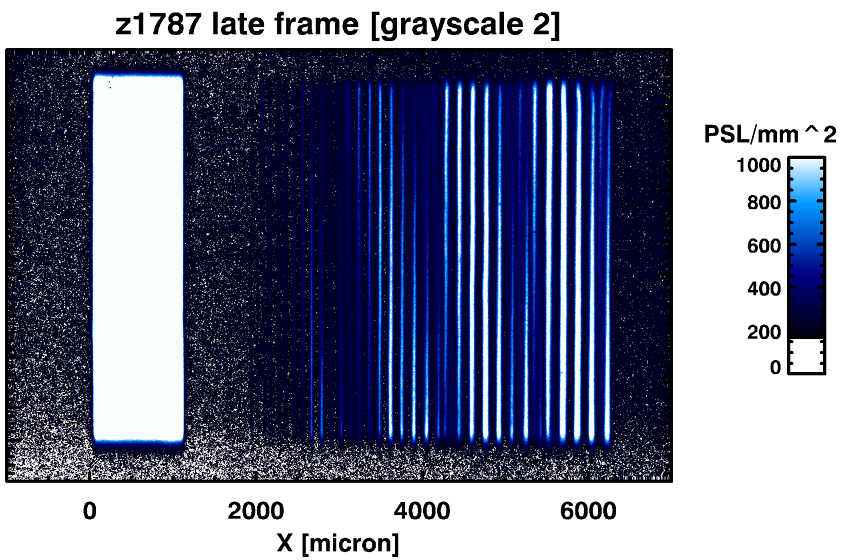
Stronger signal at lower irradiance?

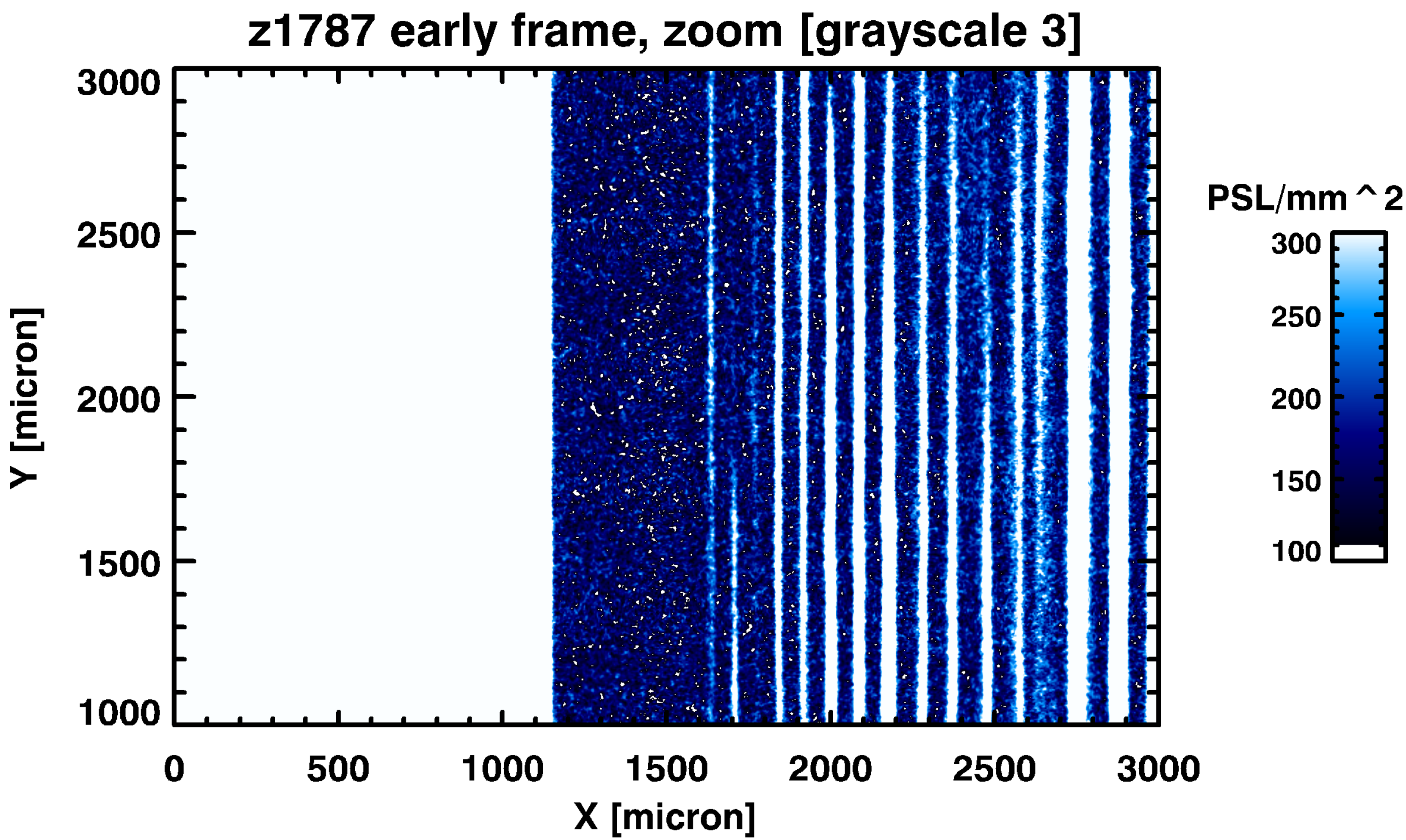
Frames separated by 7.3 ns

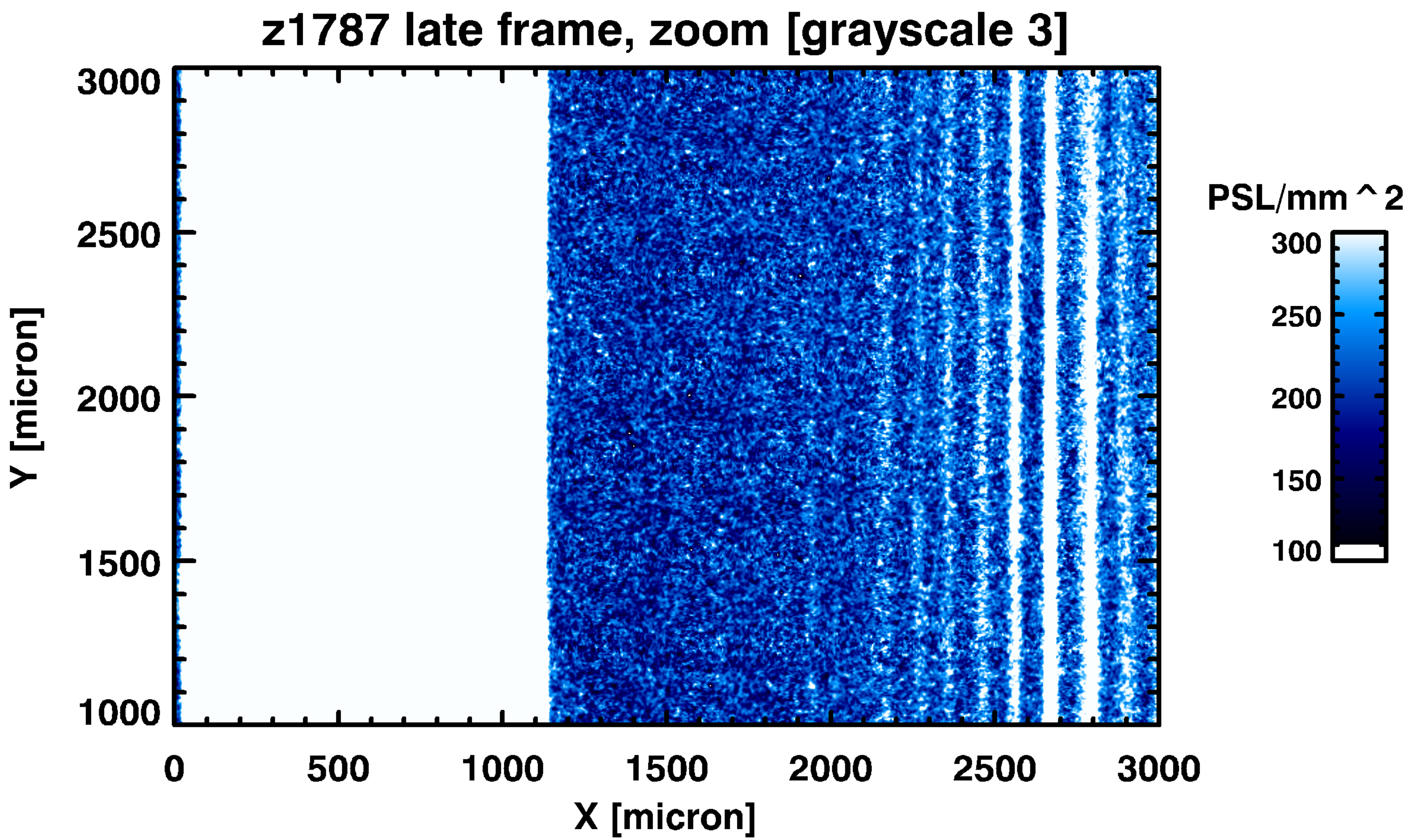
Early beam: 138-J pre-pulse, 1016-J main pulse, 1154-J total

Late beam: 125-J pre-pulse, 861-J main pulse, 986-J total



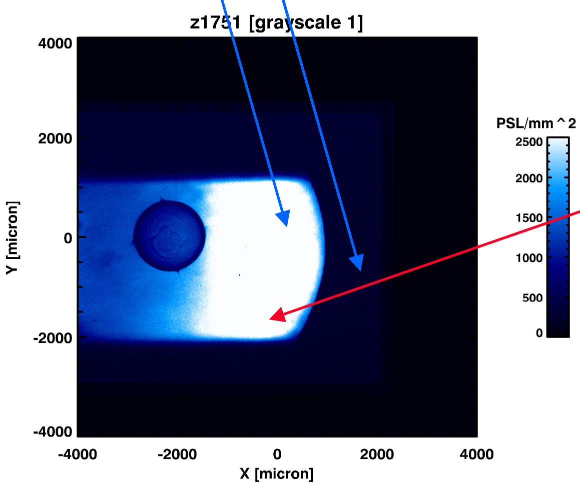



z1787 early frame, zoom [grayscale 3]
Y [micron]
3000
2500
2000
1500
1000
0
500
1000
1500
2000
2500
3000
X [micron]
PSL/mm ^ 2
300
250
200
150
100


z1787 late frame, zoom [grayscale 3]
3000
2500
2000
1500
1000
0
500
1000
1500
2000
2500
3000
X [micron]
Y [micron]
PSL/mm ^ 2
300
250
200
150
100

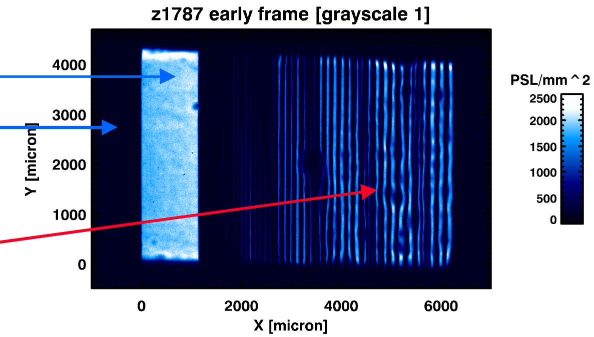
PSL/mm^2 signal and background comparisons between z1787 (2-Frame *on* Rowland circle) and z1751 (1-Frame *inside* Rowland circle)

Signal = 3800
Background = 250
[800-J]

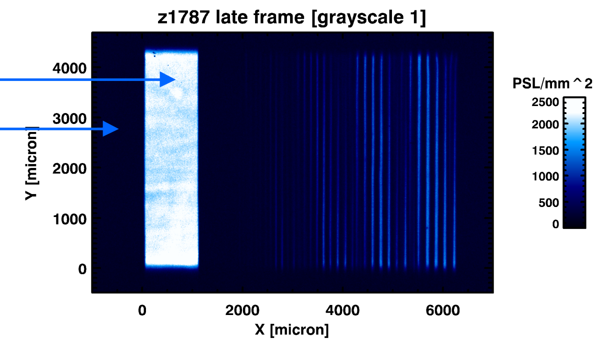


Disappointing “2-Frame” crystal performance

Signal = 1900
Background = 150
[1150-J]



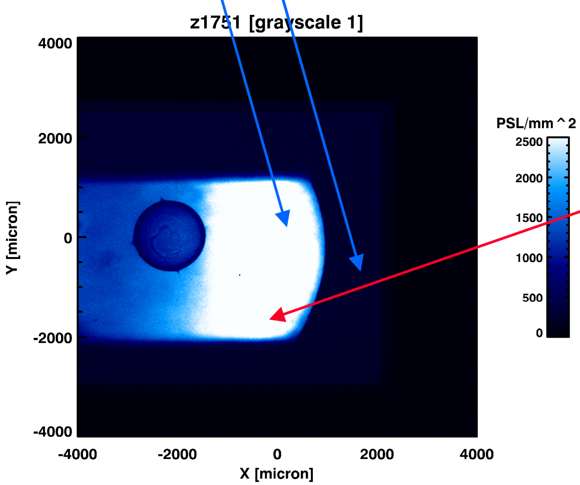
Signal = 2100
Background = 200
[1000-J]



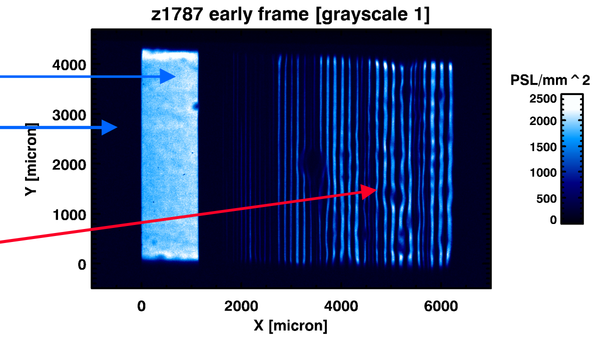
May be some evidence that the irradiance is too high on z1787 early frame; if so, will correctly defocus in future

PSL/mm^2 signal and background comparisons between z1787 (2-Frame *on* Rowland circle) and z1751 (1-Frame *inside* Rowland circle)

Signal = 3800
Background = 250
[800-J]



Signal = 1900
Background = 150
[1150-J]



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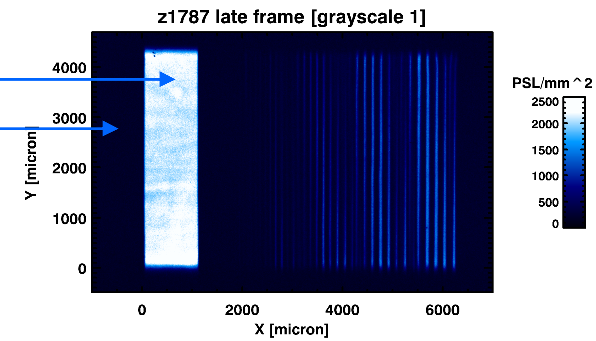
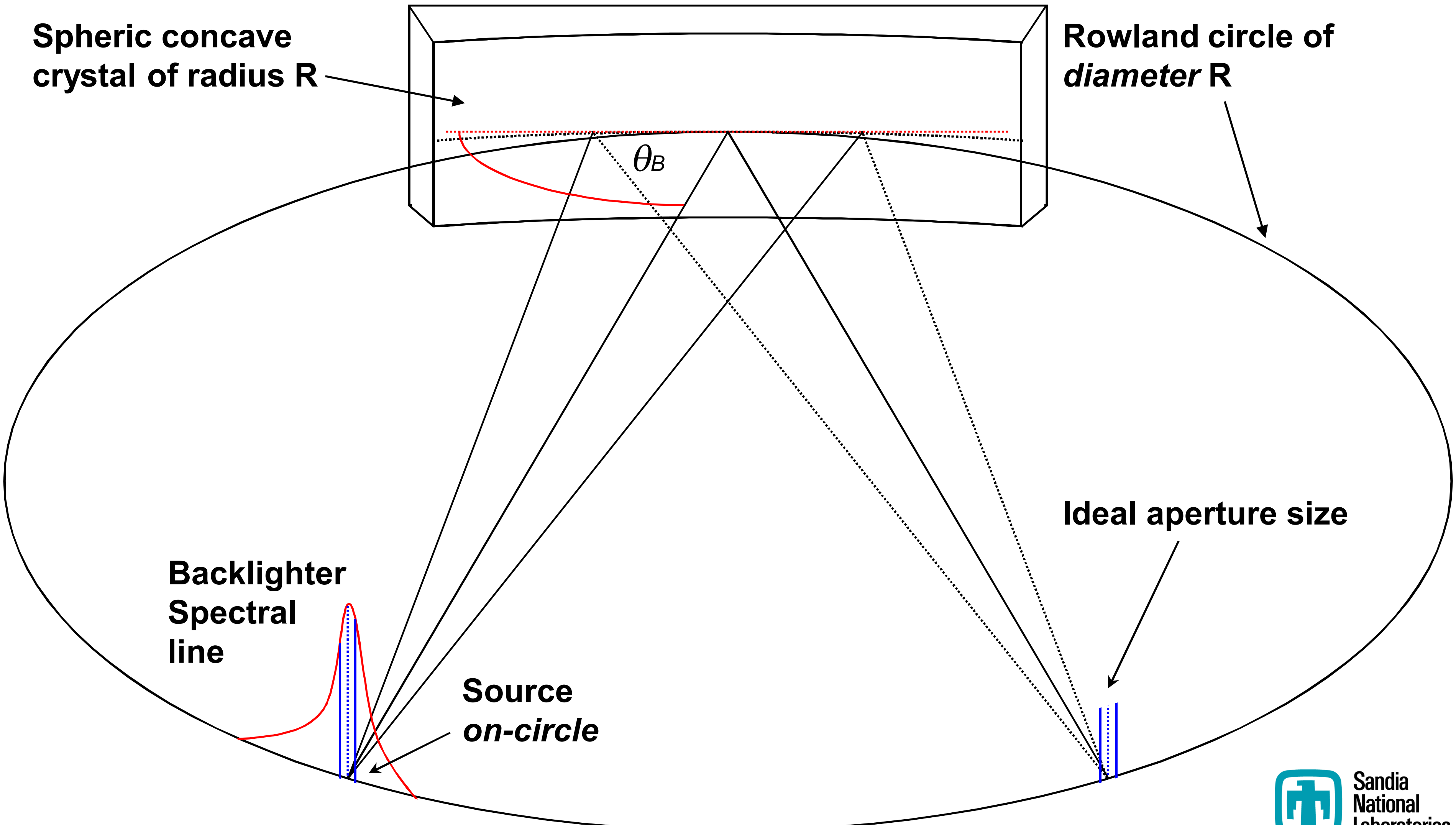


May be some evidence that the irradiance is too high on z1787 early frame; if so, will correctly defocus in future

Will test this with a M=6x 1D spatially-resolving spectrometer centered around 6151 [triplet] and 6181 [singlet] eV lines, in ZBL cal chamber

Bragg diffraction and a small entrance aperture on Rowland circle are key to near-monochromatic operation



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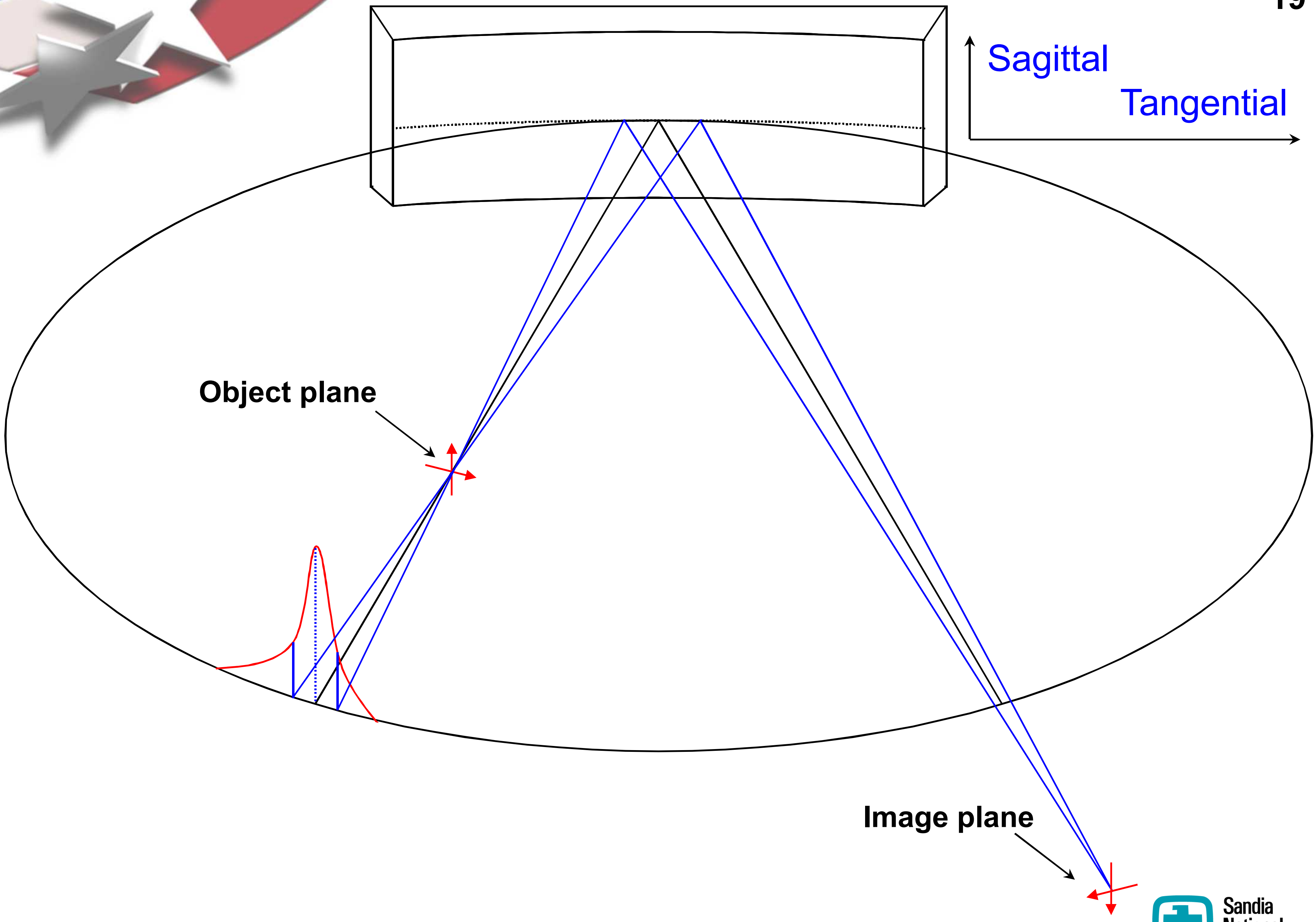
Sagittal
Tangential
Object plane
Image plane

But monochromatic to what level?

Given ΔE = cotangent$\theta_B$cosecantθ_B(100-200 μm)E/R, where:

E = 6151 eV

R = 250.0 +/- 0.1 mm

θ_B = 83.15° (2*d* = 2.030 Angstrom)

100-200 μm is the ZBL x-ray source size

….then in the absence of any background radiation ΔE = 0.3-0.6 eV

In the case of a brightly emitting z-pinch and a 3-mm entrance aperture, *background* x-rays of ΔE ~ 9 eV can reach the image plane detector

Successfully fielded 1-mm aperture on z1787 early frame. Should imply 1/9 reduction in Z100 self-emission centered at 6151 eV

Believe that 0.67-mm can be routinely fielded, for a 20x reduction

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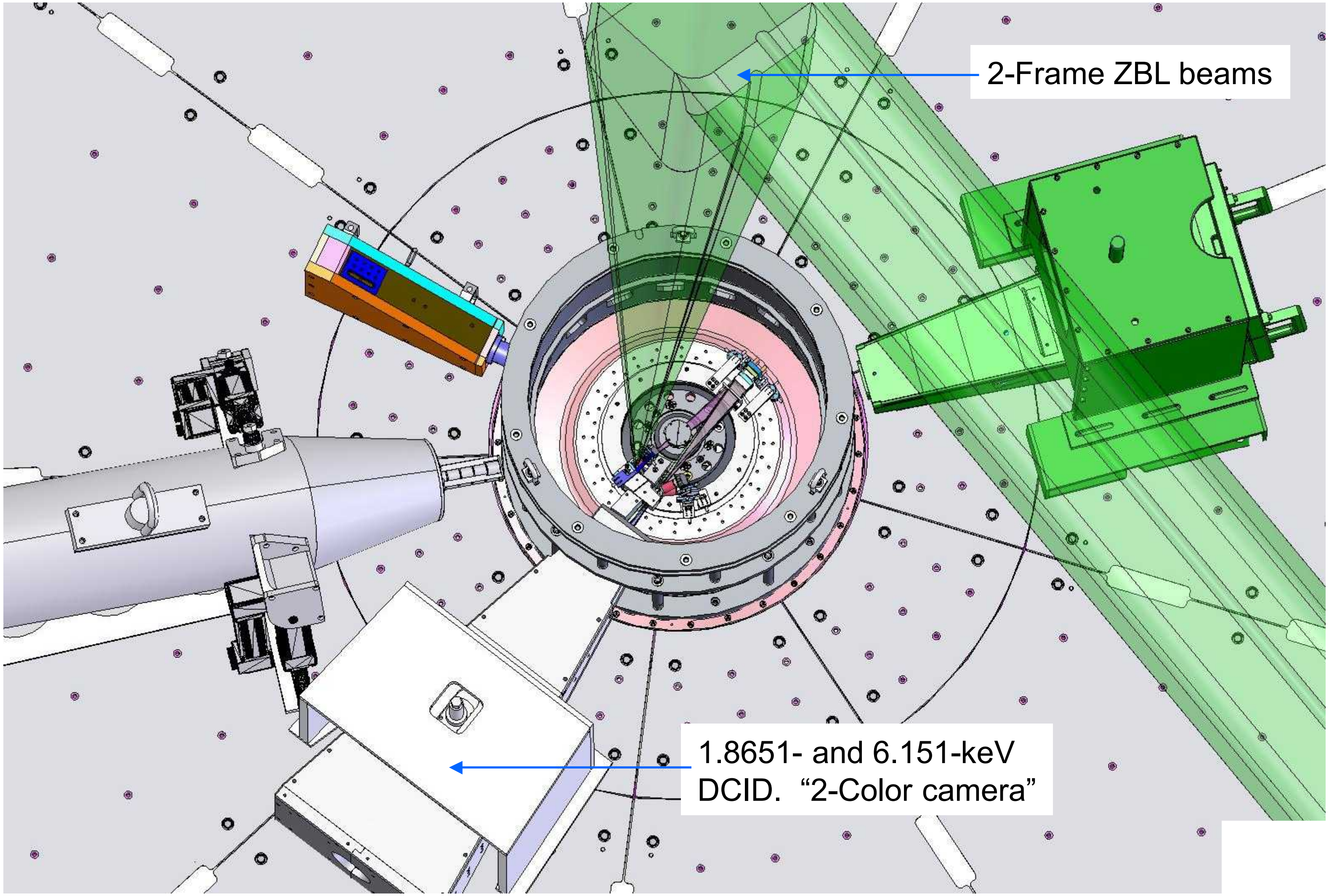
Near-term plans: Capture near-simultaneous 6.151- and 1.8651-keV images



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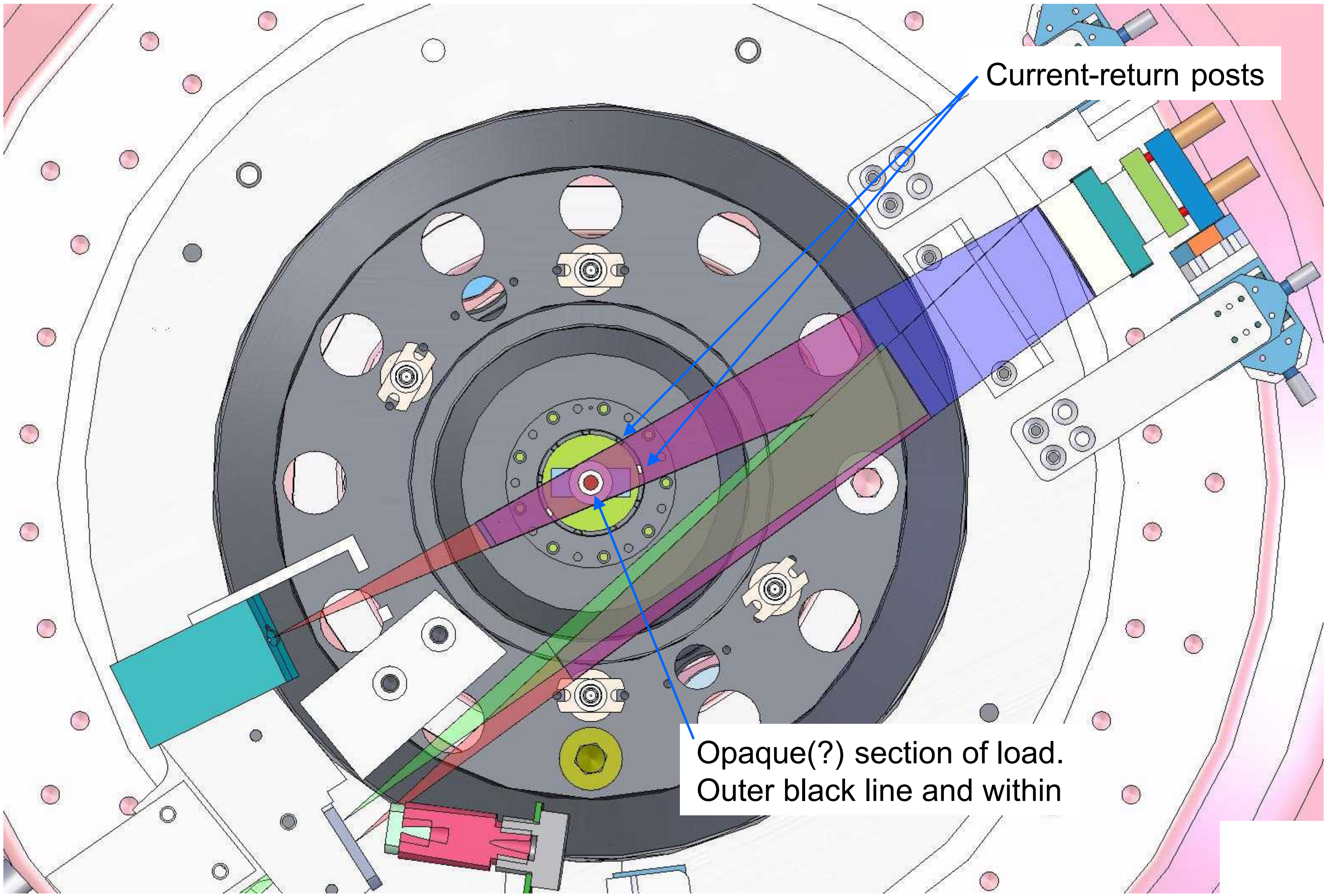


Near-term plans: *p* rather than *s* polarization; 6.181-keV singlet (brighter?); etc.

The polarization on target has always been *s*; *p* will be implemented ASAP

With *p*, the ideal laser-to-foil angle of incidence may be 25°, say (using 45° at present)

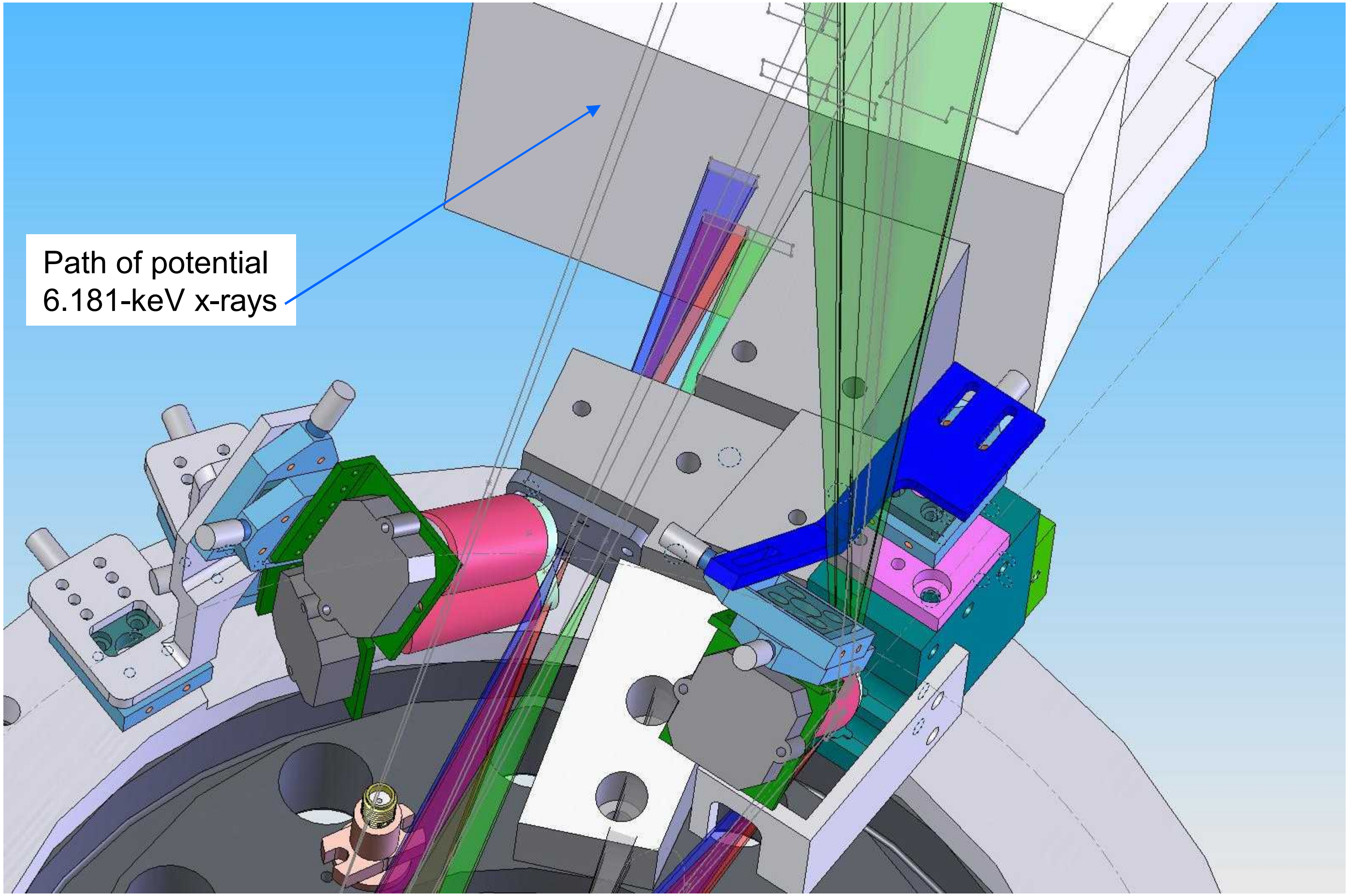
Ideal irradiance and optimum angle at *p* will be studied with the 1D spatially-resolving spectrometer

May chose to use the 6.181-keV singlet line as it could be brighter; again, spectrometer will determine this

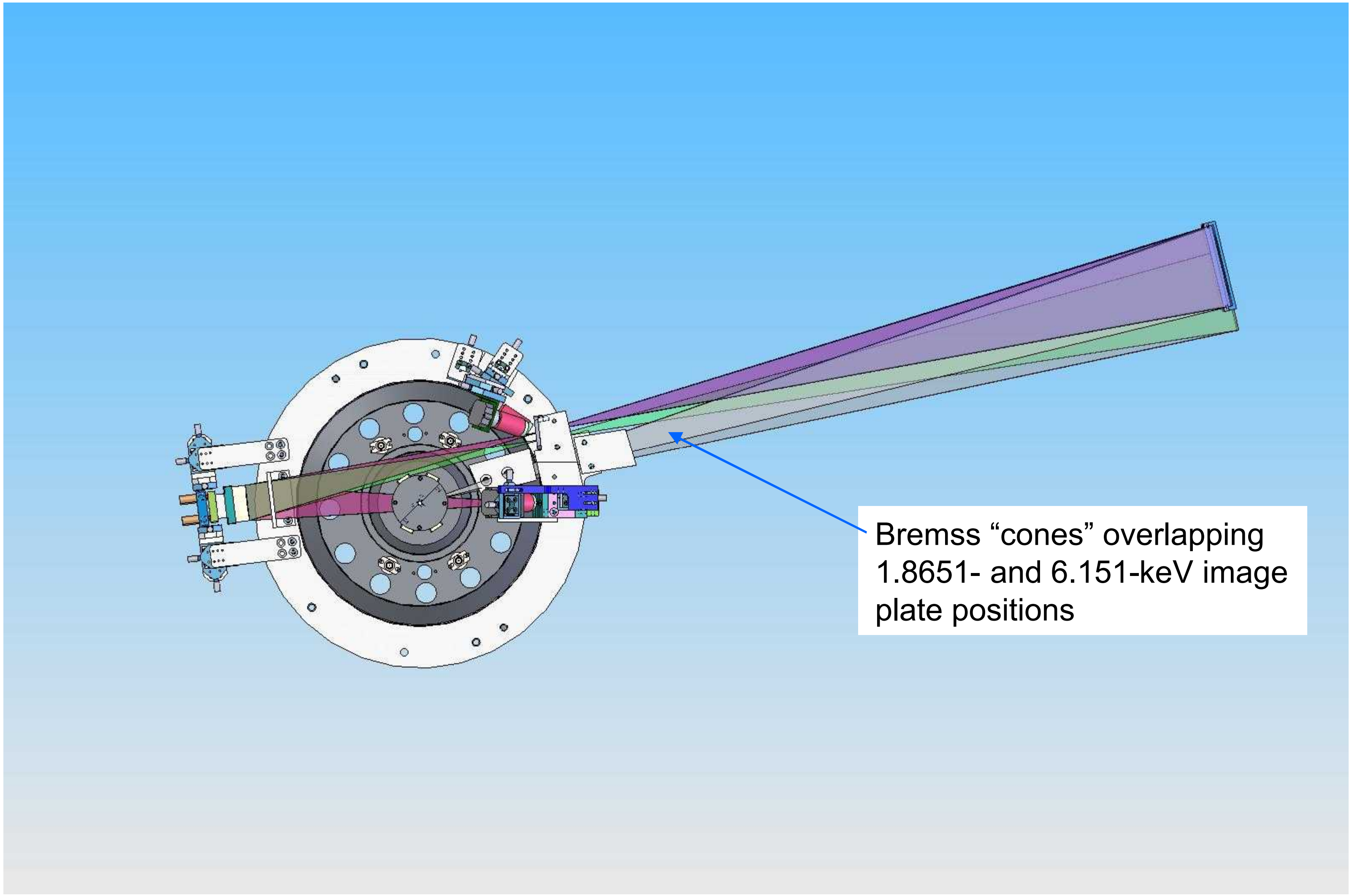
Will be investigating a custom-upgraded image plate scanner to suit our low-dose applications; that is, a system which extracts the maximum PSL signal on the first scan without degrading spatial resolution

Field high-resolution, time-integrated pinhole cameras behind each of the two Mn foils

Near-term plans: *p* rather than *s* polarization; 6.181-keV singlet (brighter?); etc.



Top view showing the ideal position of twin pinhole cameras behind each Mn foil



Near-term plans

Will be investigating a custom-upgraded image plate scanner to suit our low-dose applications; that is, a system which stimulates the maximum PSL signal on the first scan without degrading spatial resolution

Field high-resolution, time-integrated pinhole cameras behind each of the two Mn foils

Perform D.C. x-ray imaging test of each crystal prior to fielding on Z to check for defects

Measure R of each crystal using an interferometer (can also extract the so-called Zernike coefficients for feedback into our trace model)

In the much longer term: Field twin, inline multiframe ultrafast digital x-ray cameras (MUDXC) for 4-Frame imaging

What limits spatial resolution (and is excellent S/N with poor resolution sometimes more useful)?

X-ray spot size!

But, a very small spot may have poor x-ray conversion efficiency, in which case cannot talk about spatial resolution without discussing S/N

For, say, a 150-μm-diam ZBL x-ray source size, M=5.80x, and 25 x 25 μm^2 image plate pixel size, there is only one pixel per resolution-element; not 2.5

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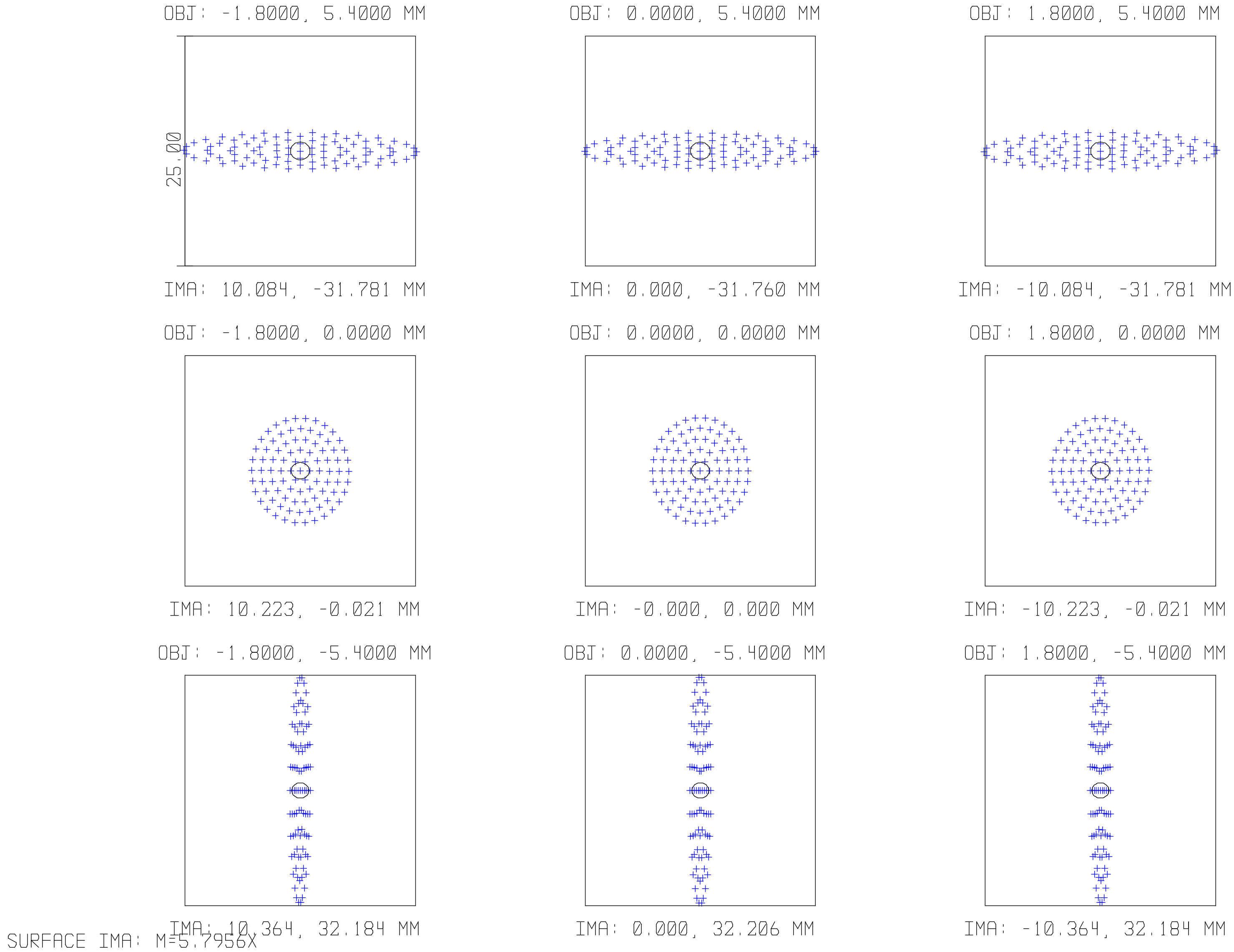
OBJ: -1.8000, 5.4000 MM
OBJ: 0.0000, 5.4000 MM
OBJ: 1.8000, 5.4000 MM
25.00
IMA: 10.084, -31.781 MM
IMA: 0.000, -31.760 MM
IMA: -10.084, -31.781 MM
OBJ: -1.8000, 0.0000 MM
OBJ: 0.0000, 0.0000 MM
OBJ: 1.8000, 0.0000 MM
IMA: 10.223, -0.021 MM
IMA: -0.000, 0.000 MM
IMA: -10.223, -0.021 MM
OBJ: -1.8000, -5.4000 MM
OBJ: 0.0000, -5.4000 MM
OBJ: 1.8000, -5.4000 MM
IMA: 10.364, 32.184 MM
IMA: 0.000, 32.206 MM
IMA: -10.364, 32.184 MM
SURFACE IMA: M=5.7956X

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Alternatives:

Increase M by 2.5 factor to 14.5x (but a results in a 2.5^2 = 6.25x reduction in image-plane brightness)

Obtain custom-upgraded scanner with 10 x 10 μm^2 pixel and high sensitivity

Use multi-megapixel MUDXC with, say, 25 x 25 μm^2 pixel but *exquisite* sensitivity and M=14.5x

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Summary

6.151-keV (or 6.181-keV) 2-Frame imaging is expected to be one of the most important Z diagnostics for several years

To this end, every aspect of system is being optimized

- Laser
- Switching to *p*- instead of *s*-polarization, laser angle of incidence onto foil, optimum irradiance
- Image plate scanner to stimulate maximum PSL signal in one scan (working directly with DITABIS in Germany)
- Operating energy: 6.181- vs. 6.151-keV
- Eventually replace Image Plate with MUDXC for higher S/N, but with 4 frames

Z also will have the 2 kJ Z-Petawatt laser for higher energy x-ray imaging. Looking at 25-keV to begin with, employing a germanium-based MUDXC for 2 frames