Z-Beamlet: a multi-KJ, TW-class laser for backlit x-radiography applications on the Z-Accelerator

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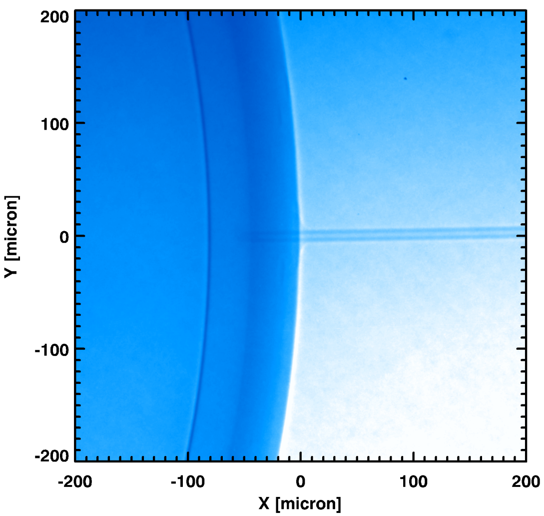

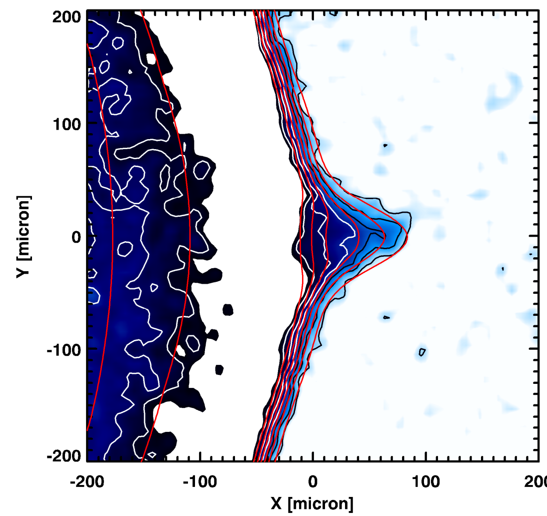

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Abstract

6.151-keV curved-bragg-crystal x-ray optics are routinely used to image inertial-confinement-fusion capsules, wire-array z-pinches, and other experiments on Sandia National Laboratories' Z-Accelerator [M. K. Matzen *et al*., Phys. Plasmas 12, 055503 (2005)]. Two temporally and spatially separated 6.151-keV x-rays sources are created by the terawatt-class, multikilojoule Z-Beamlet Laser (ZBL) [P. K. Rambo *et al*., Appl. Opt. 44, 2421 (2004)], allowing a two-frame history of an event to be recorded. Despite the size of Z, the world's most powerful pulsed soft x-ray source, the imaging system allows, for example, μg mass measurements to be made on a 1-mg capsule, with ns time resolution, 20+/-5 μm spatial resolution, and 4-8 ns between the frames. Z's imaging capabilities will soon be enhanced with the addition of a second laser; the 2-kJ, 0.5-1 ps Z-Petawatt Laser (ZPW). ZPW will permit higher energy x-ray imaging capabilities - for example, possibly 25-keV curved-bragg-crystal imaging in Laue mode - at higher temporal resolutions, which are required to diagnose the details of extremely dense, fast moving plasmas. Maximizing x-ray source brightness, optic collection efficiency, and detector sensitivity, as well as optimizing the spatial resolution and the number of frames, is a constant, ongoing activity. ZBL, ZPW, and the x-ray optics represent a large portion of the Z infrastructure; a diagnostic capability that allows the maximum scientific return to be obtained from physics performed on Z.

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The Z-Accelerator [1], the World's most powerful and energetic x-ray source, is used in various areas of high-energy-density-physics

An enhancement to the Z-Accelerator will soon provide a 26-MA peak current, nearly doubling the previously available energy

This enormous current can be used to either create soft x-rays, or drive a planar flyerplate for shockwave physics experiments

The soft x-ray flux can be used, for example, to uniformly compress inertial-confinement-fusion capsules

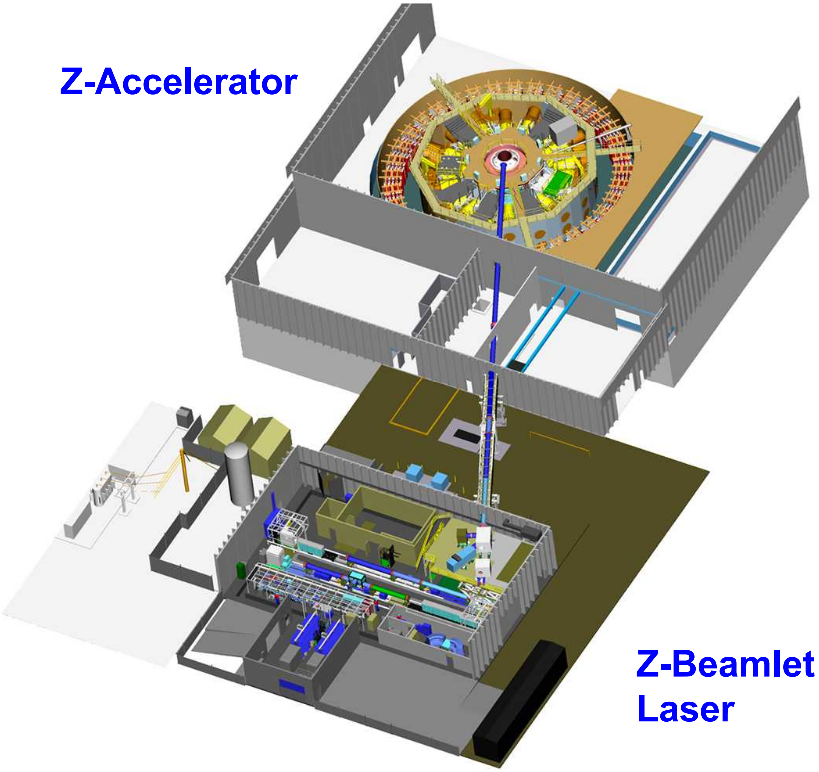
[1] M. K. Matzen *et al*. Phys. Plasmas. **12,** 055503 (2005)

Backlit x-ray imaging is often a critical requirement on Z

In 2001, the addition of the Z-Beamlet Laser (ZBL) [2] allowed an optic to be backlit with a bright, fast x-ray source on Z

ZBL is a TW-class, multi-kJ, 526.57 nm Nd:glass laser capable of generating four 0.2-1.8 ns pulses anywhere within a 20 ns window

The first Z/ZBL experiments used, in fact, ~6.7 keV point-projection imaging (the dental radiograph scheme), to study ICF capsule implosions [3,4]



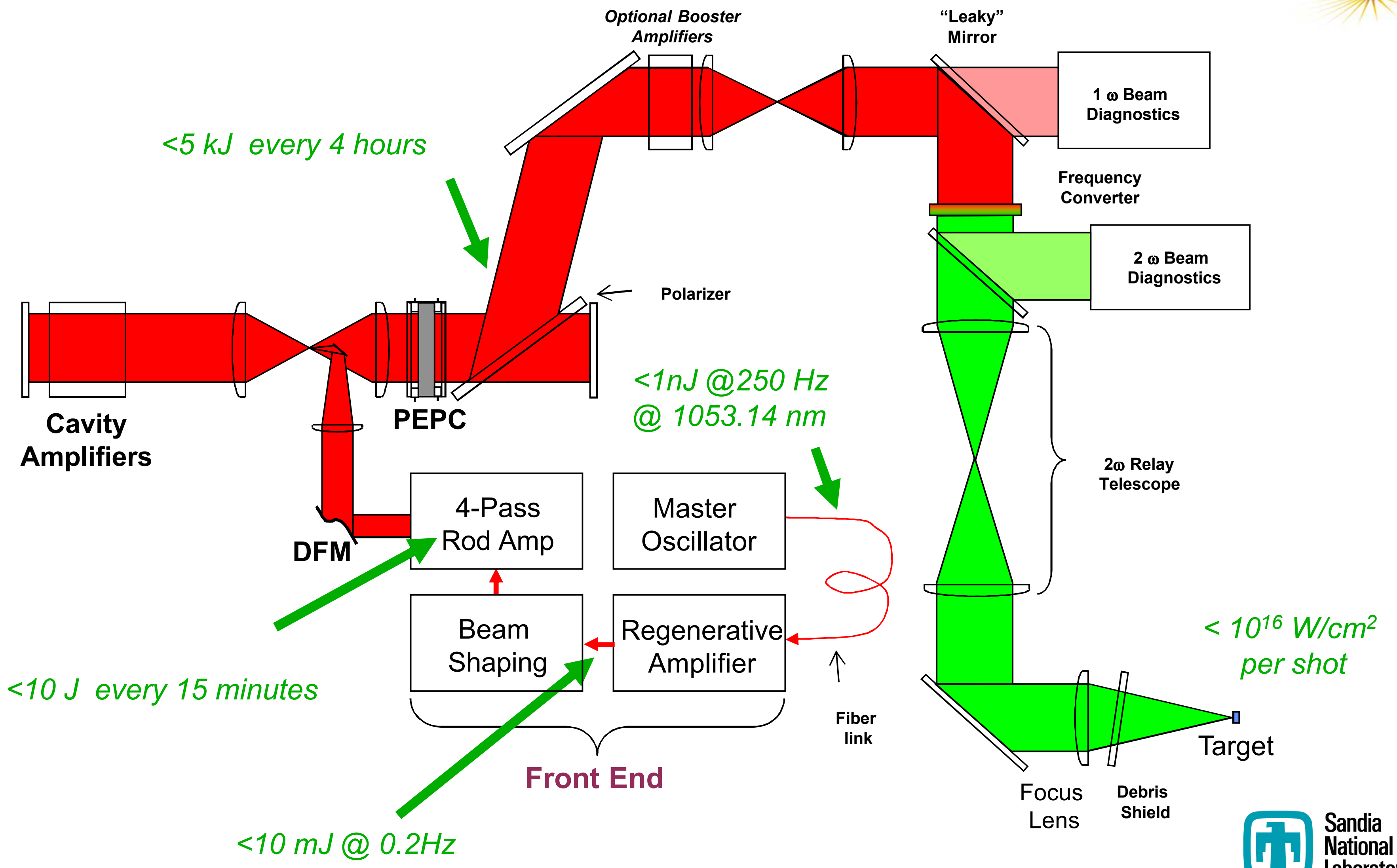
[2] P. K. Rambo *et al*. Appl. Opt. **44,** 2421 (2005)
[3] G. R Bennett *et al*. Phys. Rev. Lett. **89,** 245002 (2002)
[4] R. A. Vesey *et al*. Phys. Rev. Lett. **90,** 035005 (2003)

NIF scientific prototype now used for x-radiography on Z

2-Frame 6.151-keV or 1.8651-keV curved-bragg-crystal imaging
1200 +/- 120 J green per frame

Up to 4 shots/day

ZBL layout


Optional Booster Amplifiers
"Leaky" Mirror
1 ω Beam Diagnostics
<5 kJ every 4 hours
Frequency Converter
2 ω Beam Diagnostics
Polarizer
Cavity Amplifiers
PEPC
<1nJ @250 Hz @ 1053.14 nm
2ω Relay Telescope
DFM
4-Pass Rod Amp
Master Oscillator
Beam Shaping
Regenerative Amplifier
Fiber link
< 10^16 W/cm^2 per shot
<10 J every 15 minutes
Front End
Target
Focus Lens
Debris Shield
<10 mJ @ 0.2Hz

More recently, 6.151 keV curved-crystal (α-Quartz 22$\underline{4}$3) imaging [5,6] has replaced 6.7 keV point-projection

6.151-keV curved-crystal imaging advantages:

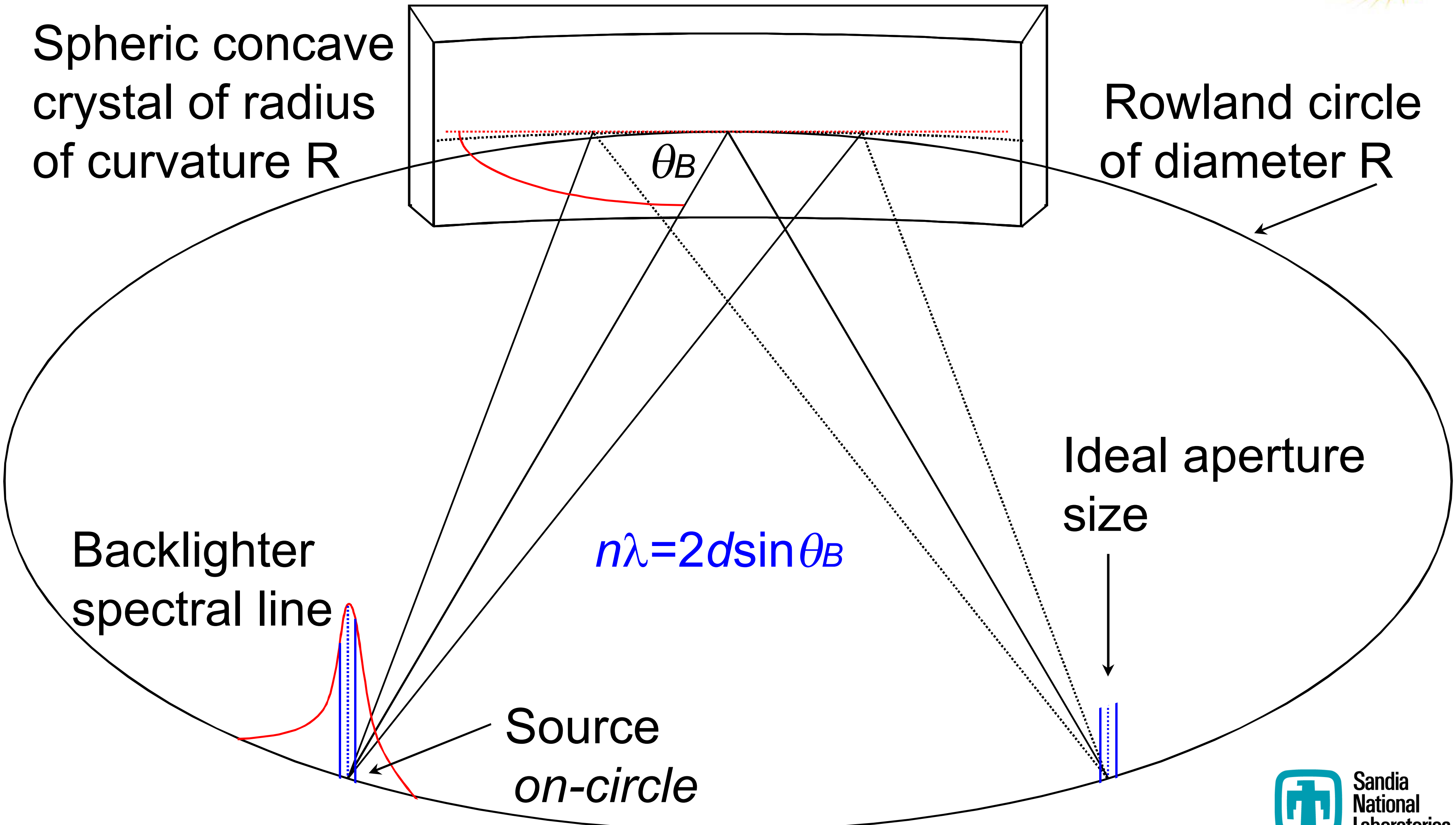
(1) Higher spatial resolution for a given ZBL spot size
(2) Highly monochromatic: The Bragg diffraction condition is satisfied
(3) Larger field of view
(4) Higher dynamic range: Image plate and other advanced detectors can be fielded

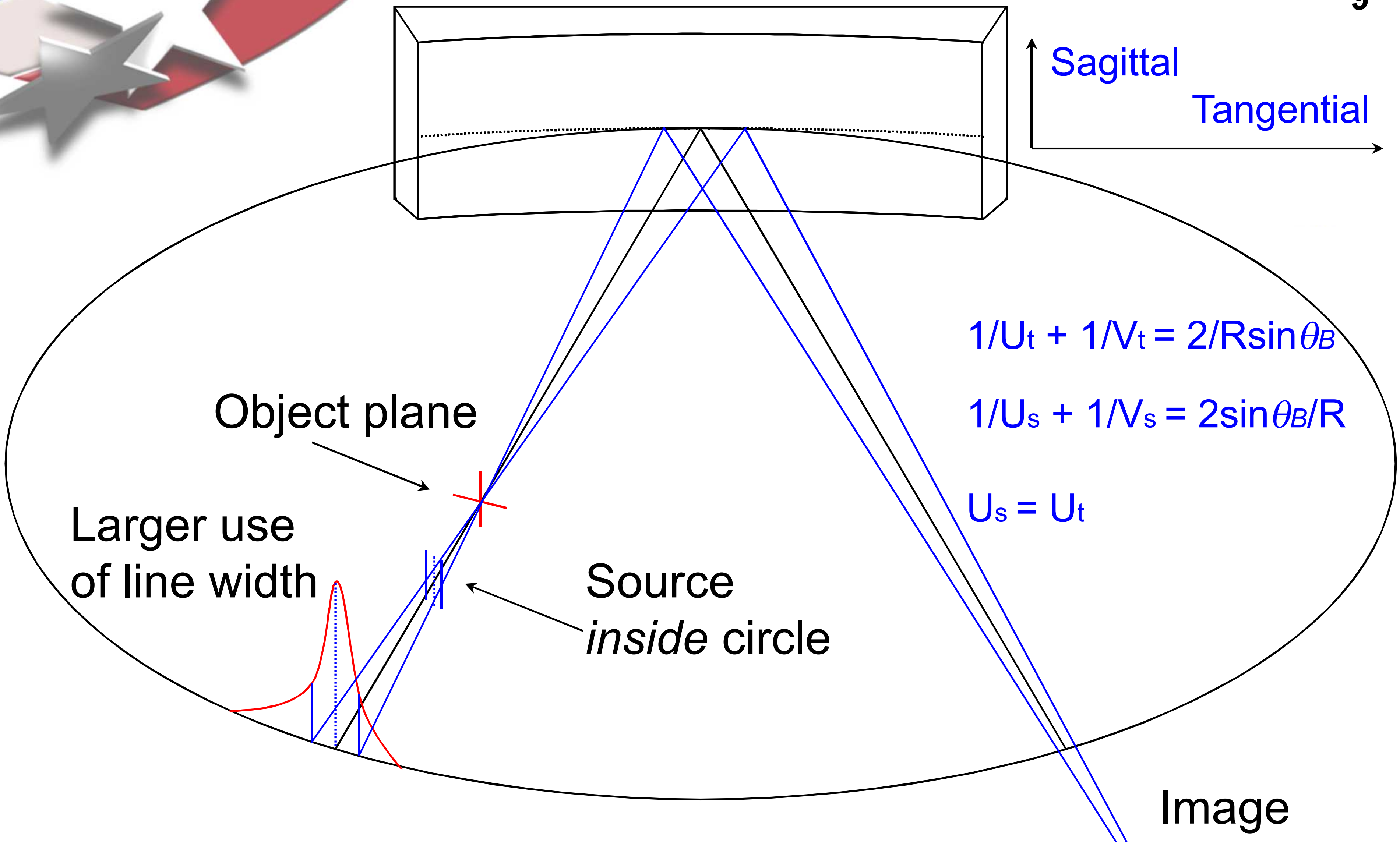
Point-projection imaging advantage:

(1) Simpler

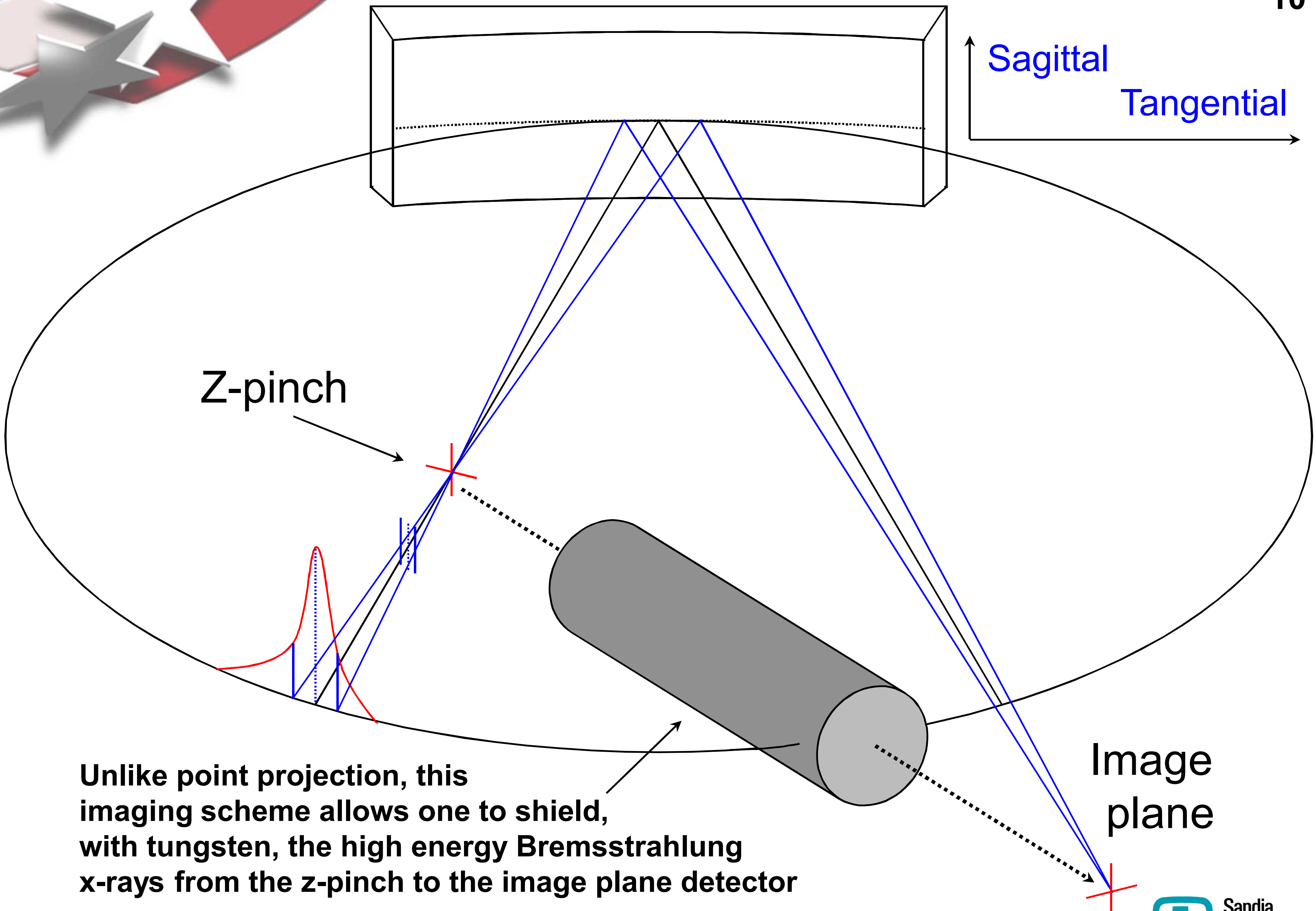
[5] D. B. Sinars *et al*. Rev. Sci. Instrum. **75,** 3672 (2004)
[6] G. R. Bennett *et al*. Rev. Sci. Instrum. **77,** 10E322 (2006)

Bragg diffraction & Rowland circle are key to backlit monochromatic operation and rejection of near-Planckian (T<300 eV) z-pinch-emitted x-rays



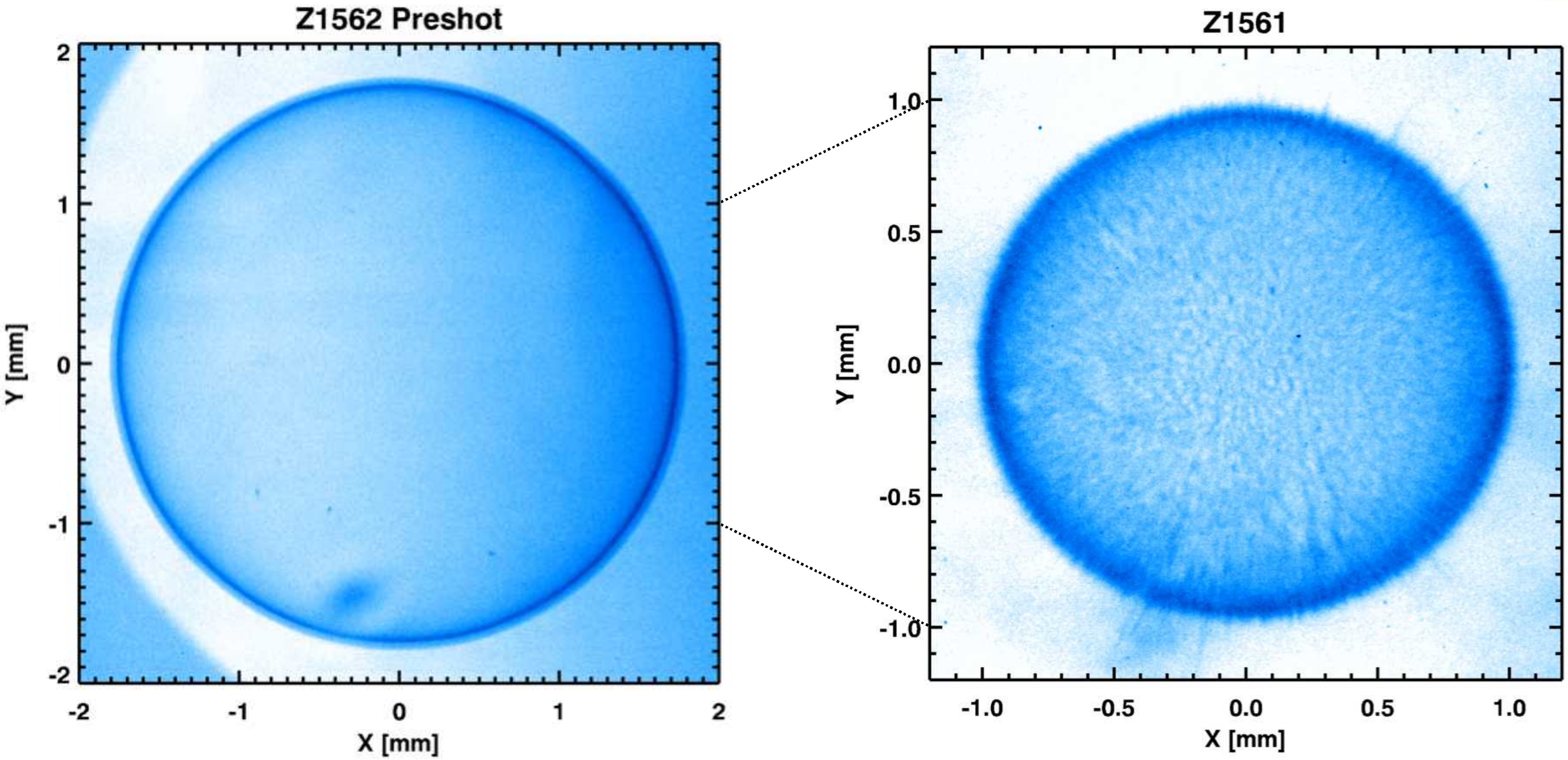


~1.5 mm line width of Mn Heα (triplet) 6.151 keV line indicates that source can be moved inside Rowland circle to increase collection solid angle



Unlike point projection, this imaging scheme allows one to shield, with tungsten, the high energy Bremsstrahlung x-rays from the z-pinch to the image plane detector

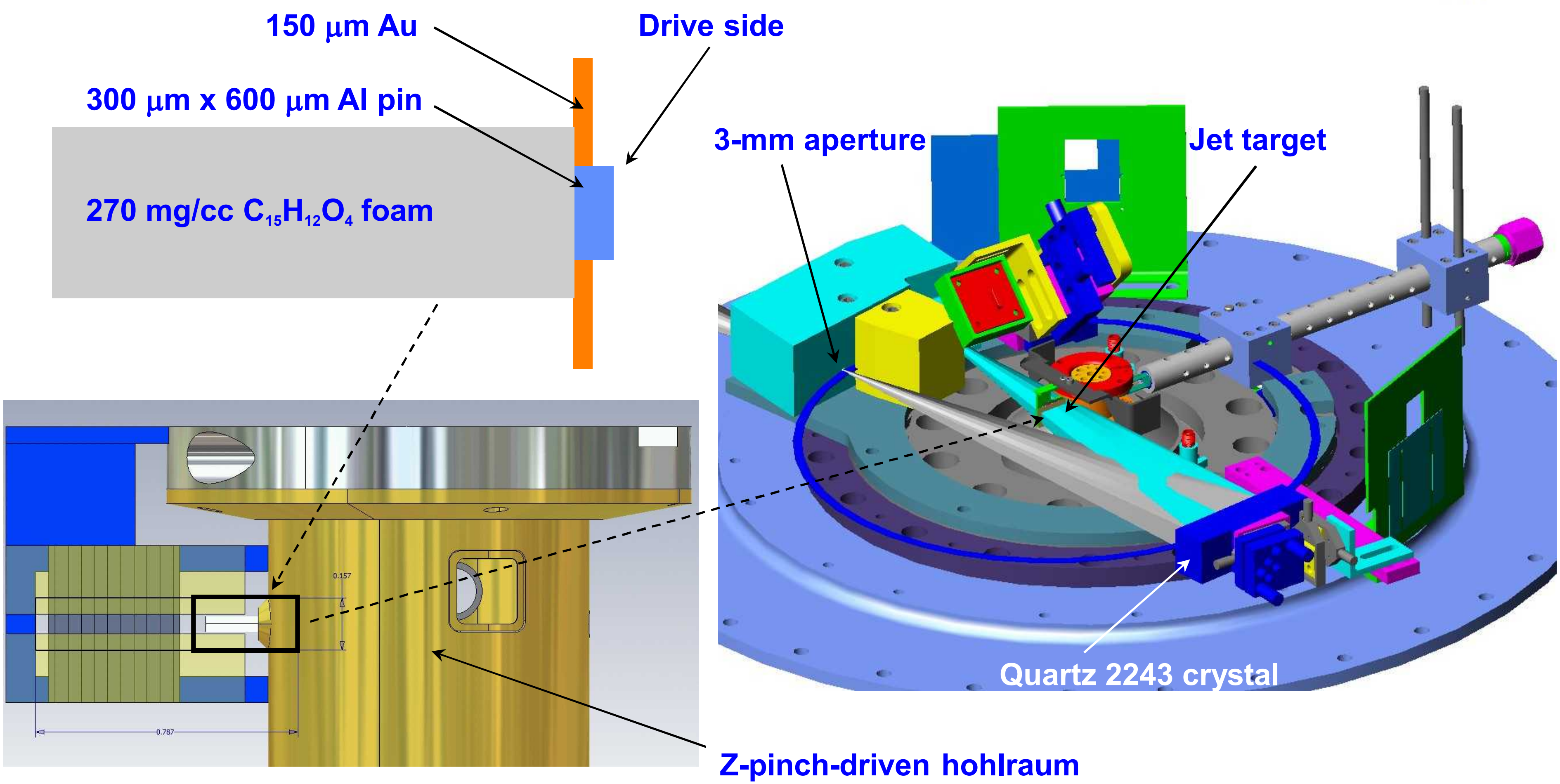
A curved-bragg-crystal x-ray optic backlit by ZBL has revealed good scientific images [5,6] on Z experiments



ICF capsule implosion in Sandia's Double-Ended Hohlraum

[5] D. B. Sinars *et al.* Rev. Sci. Instrum. **75,** 3672 (2004)
[6] G. R. Bennett *et al.* Rev. Sci. Instrum. **77,** 10E322 (2006)

Supersonic jet examples



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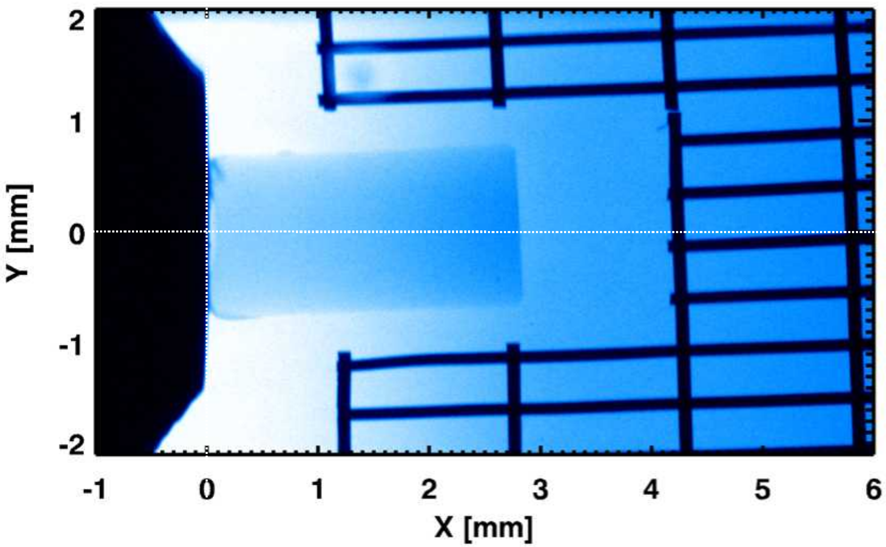
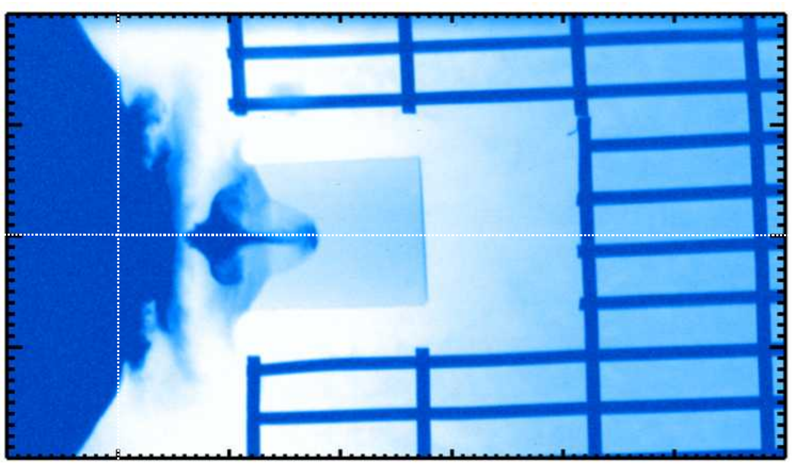
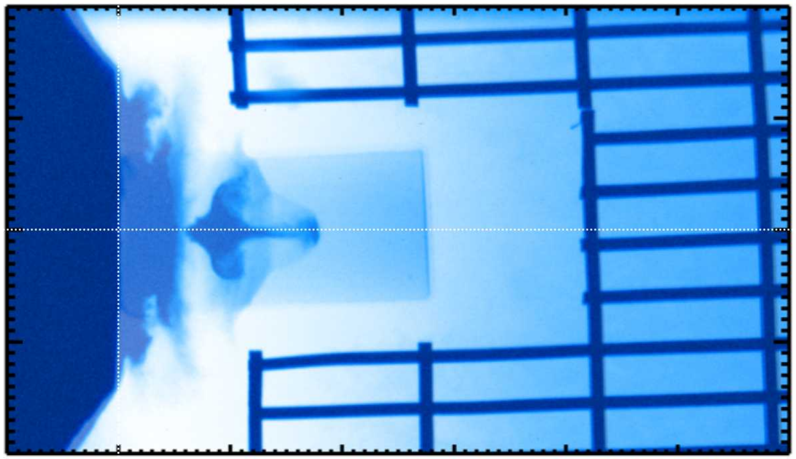
In-situ pre-shot radiograph allows one to determine exact x=y=0 ref point and correct rotation

Z1526 Preshot



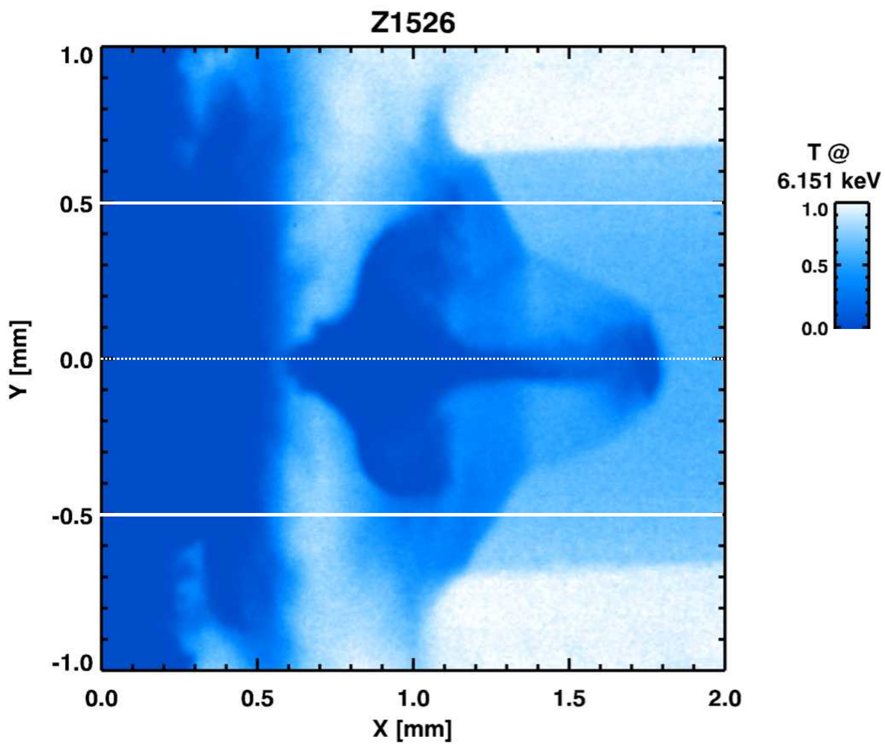


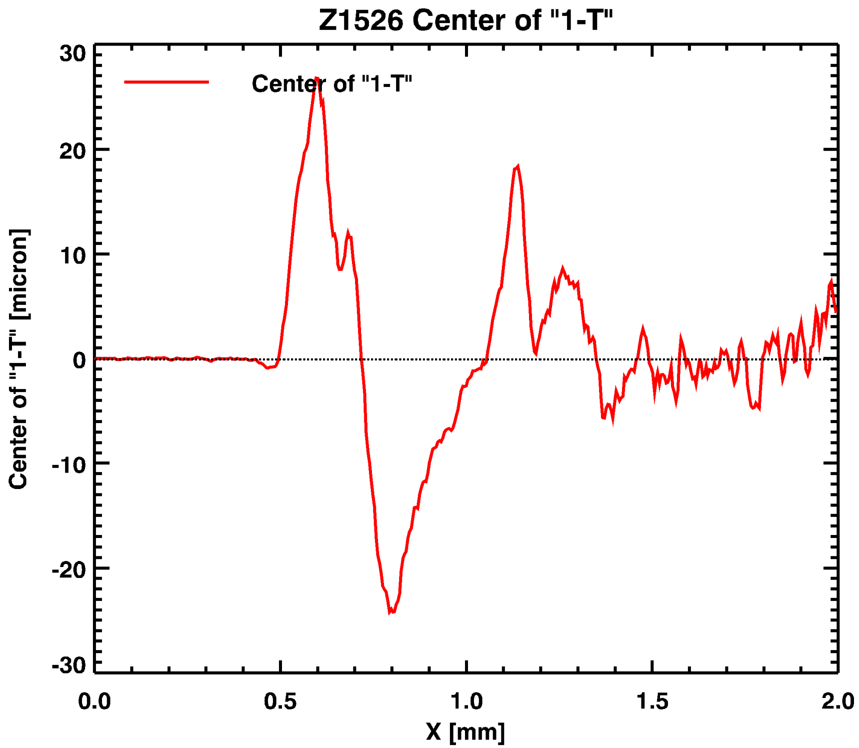
Z1526 pre-shot and down-line images overlaid



Analysis of “1-T” center for Z1526 between y=-0.5 and +0.5 mm indicates a very symmetric jet

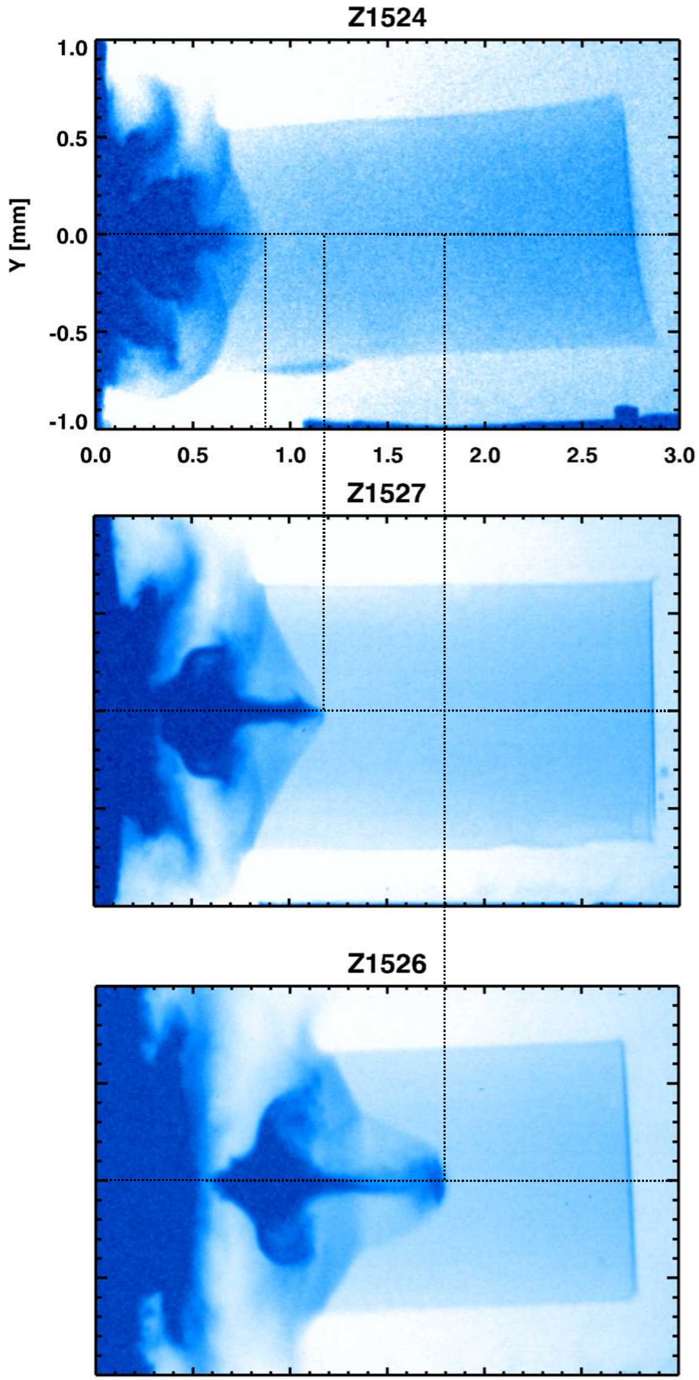
T=T(x,y)=transmission at 6.151 keV. Center of “1-T” is a metric that allows one to quantify a jet’s symmetry





In this case, the Center of “1-T” deviates by <+/-30 micron over a 2 mm extent

Time sequence of most symmetric jets



t=31 ns
328.1 mg/cc

t=40 ns
285.2 mg/cc

t=73 ns
270.1 mg/cc

Each image requires one Z shot (presently one a day)

Intent was to study early time jet evolution (before symmetry was broken) under reproducible conditions

Slight differences in drive and foam densities, shot-to-shot, makes such a study difficult

Developing a Multiframe Ultrafast Digital X-ray Cameras (MUDXC) to obtain 4 images per shot at 6.151 keV with ZBL….

….and two 25.2713 keV frames per shot with ZPW

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Utilizing ZBL's multipulse capability for "2-Frame" 6.151-keV x-ray imaging

[1] Front-end output is now split into two paths; one beam is delayed in a trombone periscope to incur a 4-20 ns delay

[2] Delayed beam is also slightly de-collimated by a positive-negative lens pair

[3] Delayed beam is injected into the *full* aperture of the main 4-pass amplification system at a slightly offset angle; "*angle multiplexed*"

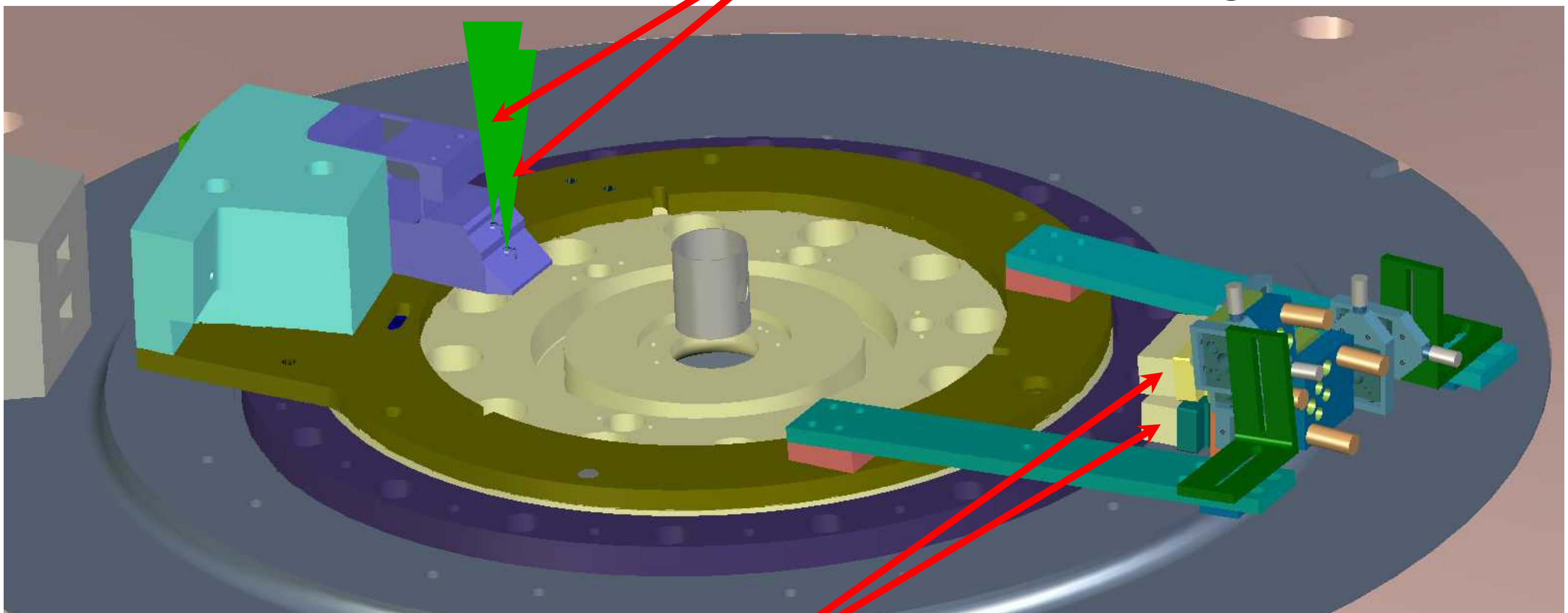
[4] "Early" and "late" beams are focused by the same 3.2 m lens, but focus at slightly different locations because of item [2]

This method is superior to beam separation & delay after full amplification since:

(A) Energy extraction is essentially doubled without changing B-integral level
(B) No need for a segmented focusing lens, etc.

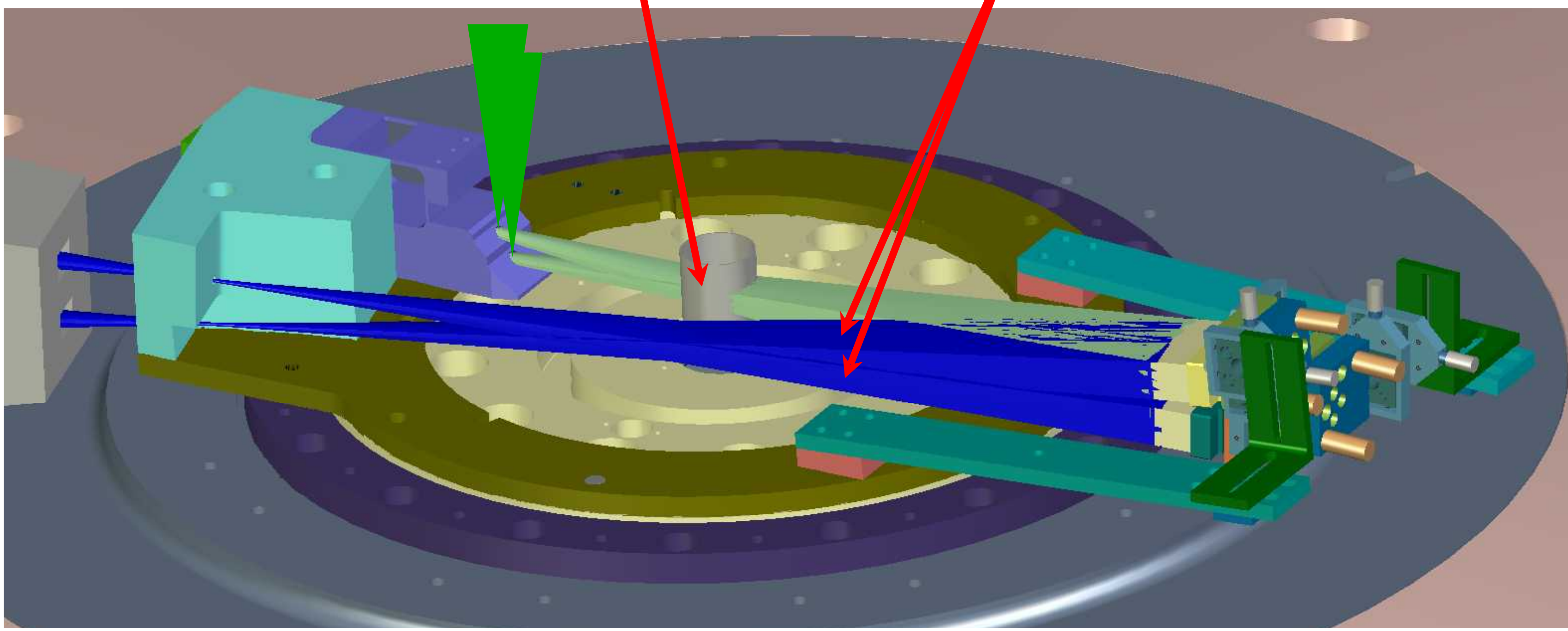
"2-Frame" 6.151-keV imaging capability on Z

Two temporally and spatially separated ZBL beams irradiating Mn foils

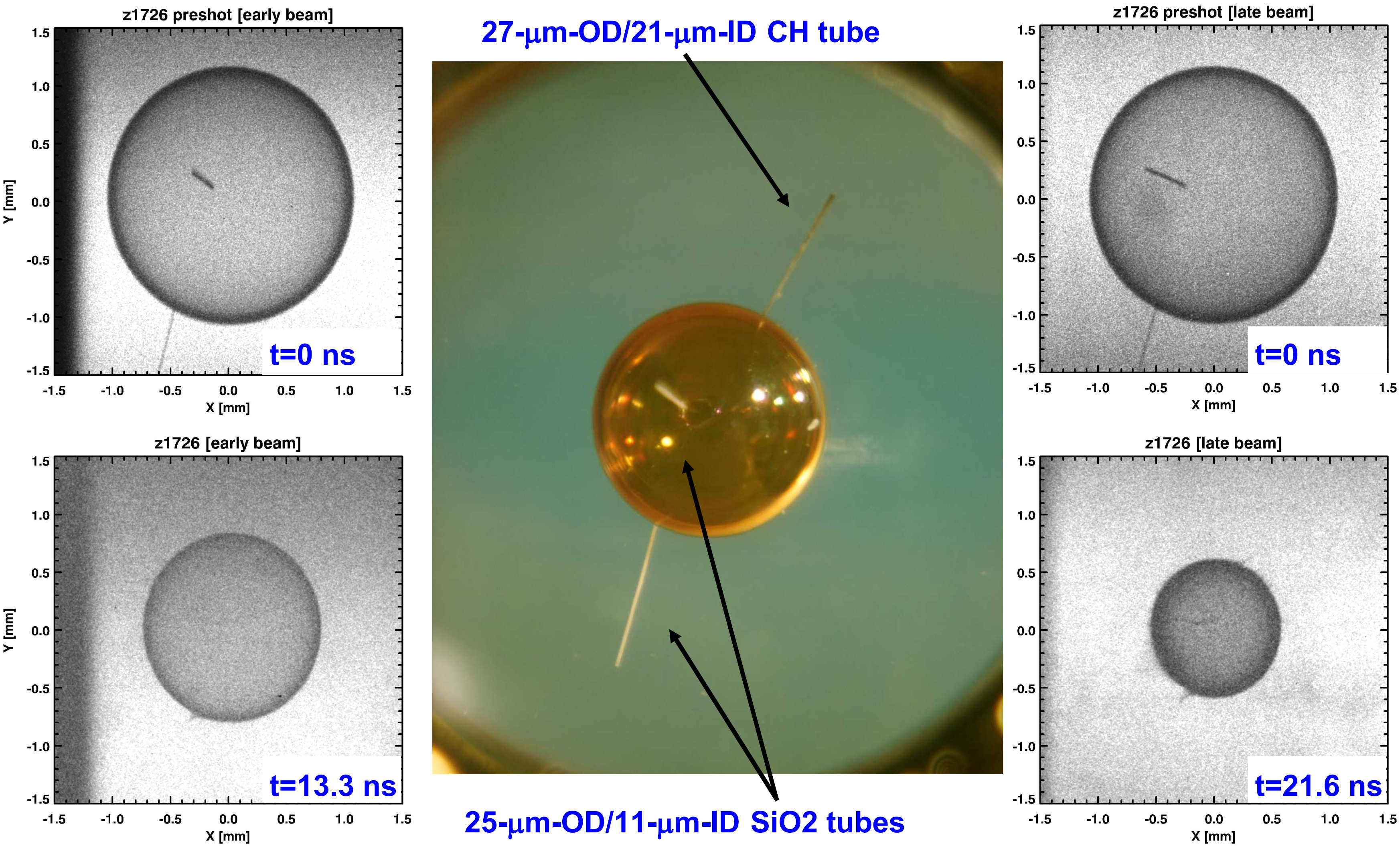


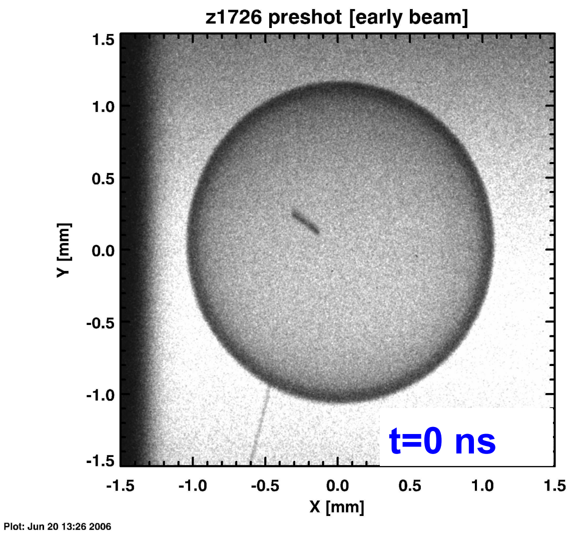
Two independent 6.151-keV systems

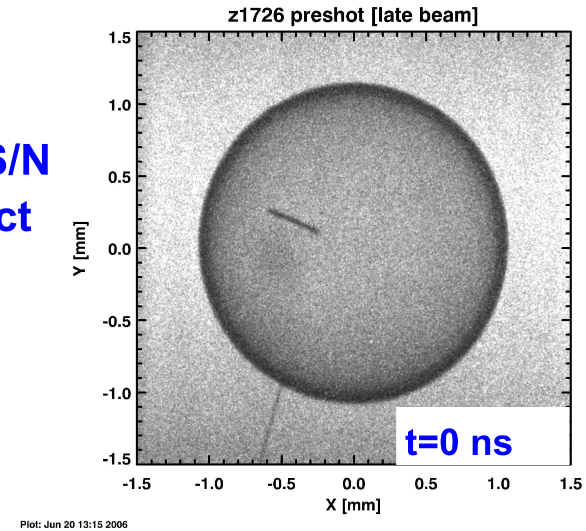
Z-pinch Double-Ended-Hohlraum **Focused 6.151-keV x-ray beams**



2-Frame, 6.151-keV x-ray imaging was successfully demonstrated on Z soon before the accelerator upgrade program began







"2-Frame" on Z had a lower S/N compared to 1-Frame, an effect that ultimately degraded the spatial resolution

To this end, ZBL is being upgraded in terms of the energy output

Independent of testing 2-Frame with the ZBL enhancements, the imaging system requires a thorough characterization in 1-Frame mode anyway