Novel X-Ray Beam Position Monitor for Coherent Soft X-Ray Beamlines

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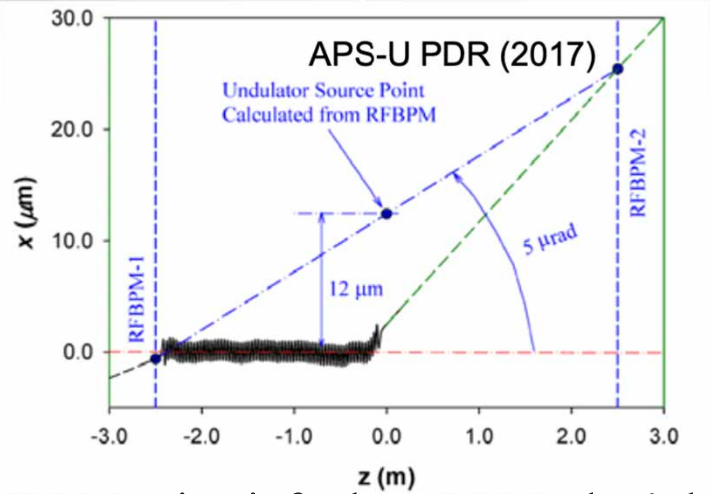
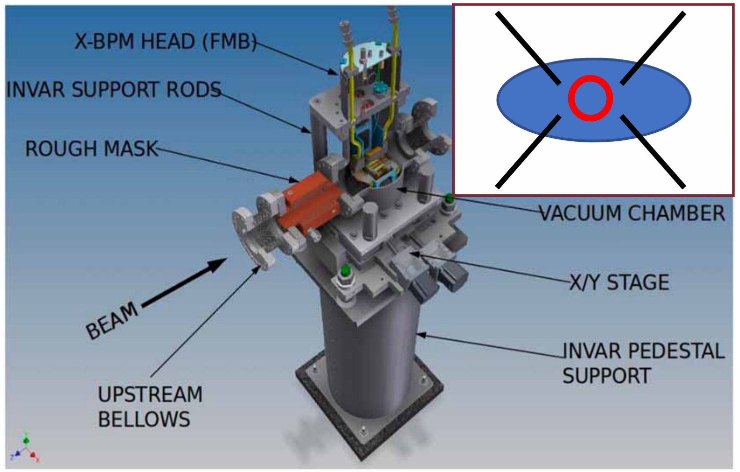
Motivation for Novel X-Ray BPMs

- Modern synchrotron light sources are all about photon beam brightness and stability
- X-ray beam must be stable at the user sample (position, wavefront, intensity)
- Need stability of e-beam, and of all beamline elements, starting from the undulator source
- Real-time diagnostics & feedbacks must rely on XBPMs, both white beam and mono
- White-beam XBPMs are especially important, being upstream of any beamline optics
- Standard solution (blade photoemission XBPMs) does not work for coherent soft X-ray beamlines
- Non-invasive XBPMs which preserve the coherence of the beam are still needed



XBPMs give info that eBPMs don't have



"standard solution": doesn't work for coherent soft X-ray beamlines

Soft X-ray BPM (sXBPM) R&D Project at NSLS-II

Approach

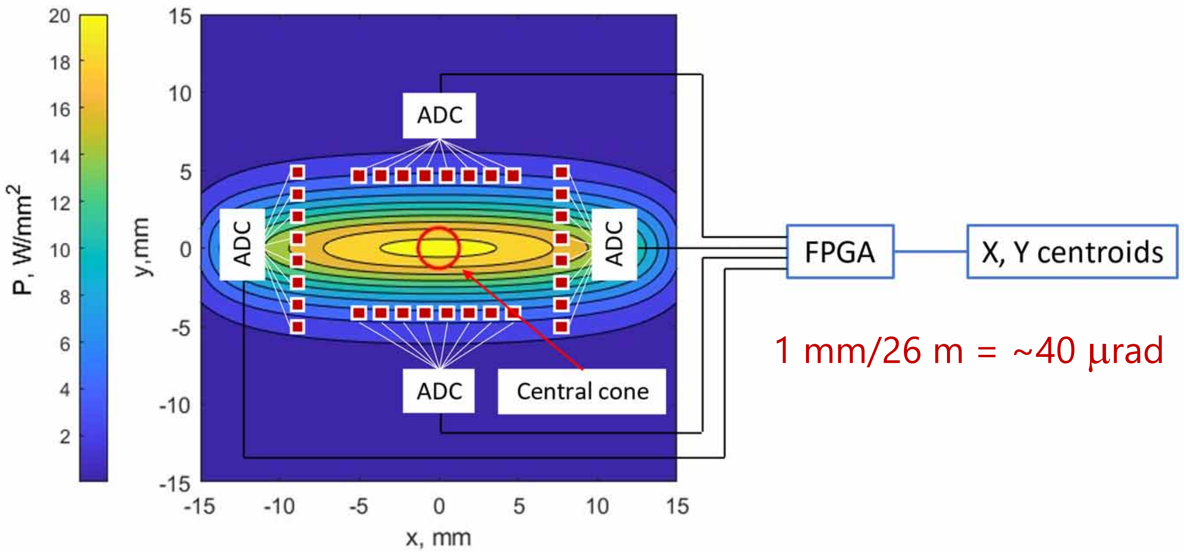
- Place custom-made GaAs photodiode arrays into outer portions of X-ray beam and calculate beam position from pixel photocurrents

Potential advantages

- High sensitivity: E=1 keV photon yields E/(4eV)~250 photoelectrons in GaAs, vs. ~1 in metal blades
- Multi-pixel arrays: better positional resolution, spatial feature resolution, ability to discriminate stray light from bend magnets and other sources

Goals and constraints

- Prototype to be installed and tested in C23-ID NSLS-II canted soft X-ray undulator beamline FOE (white beam, 26 m from EPU source)
- ~1 micron positional resolution @ 10 Hz sampling, all undulator K parameter values, linear polarization
- Coherence preservation, no interference with beamline operations



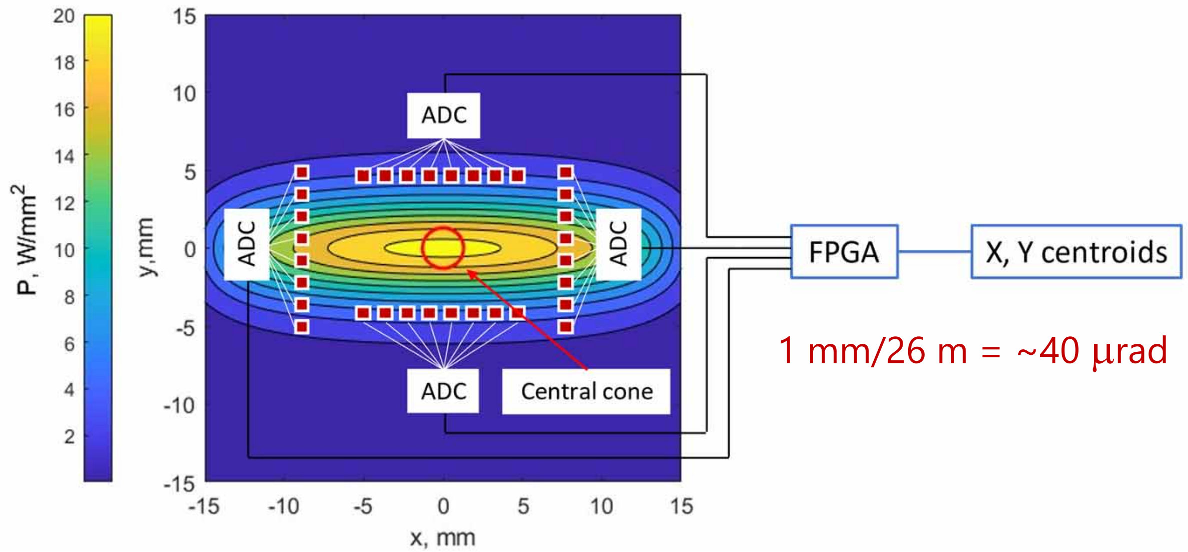
sXBPM concept

J. Liu et al., MOPAB121, proc. IPAC'21

Soft X-ray BPM (sXBPM) R&D Project at NSLS-II

Challenges

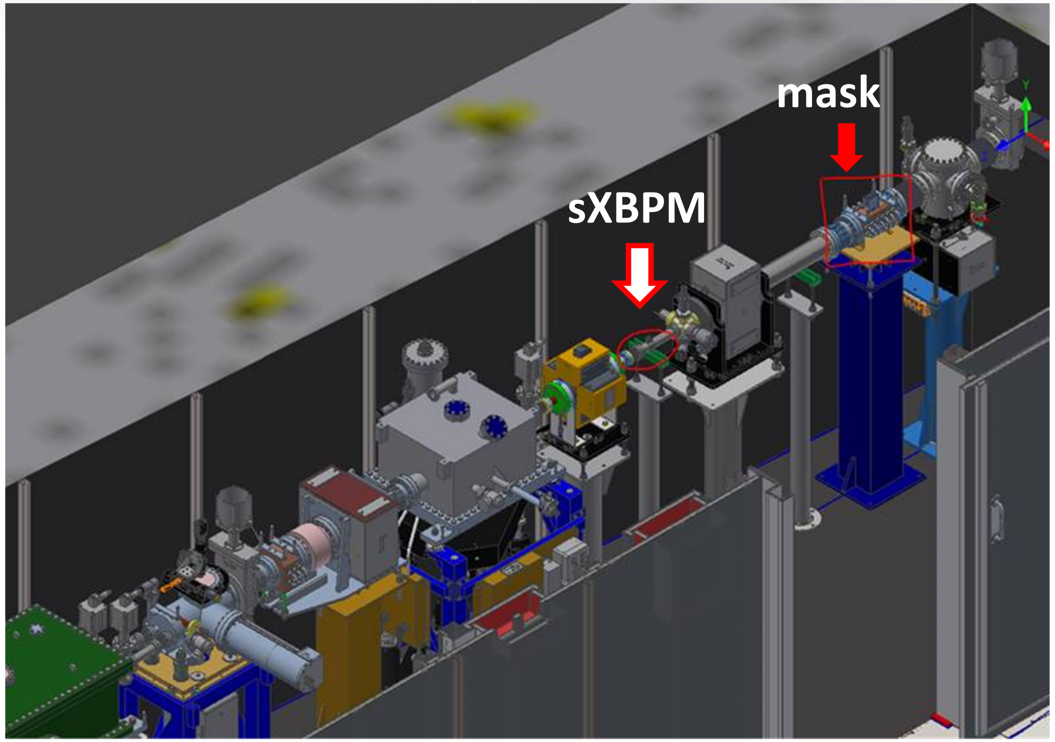
- High power density (at high K) => potentially high heat load and detector photocurrents
- Detectors must operate in UHV
- Compatibility with existing beamline operations
- sXBPM mechanical stability
- Systematic errors due to widely varying beam profile with changes of ID gap and phase
- Contamination of ID radiation with that from the closest dipole and other magnets

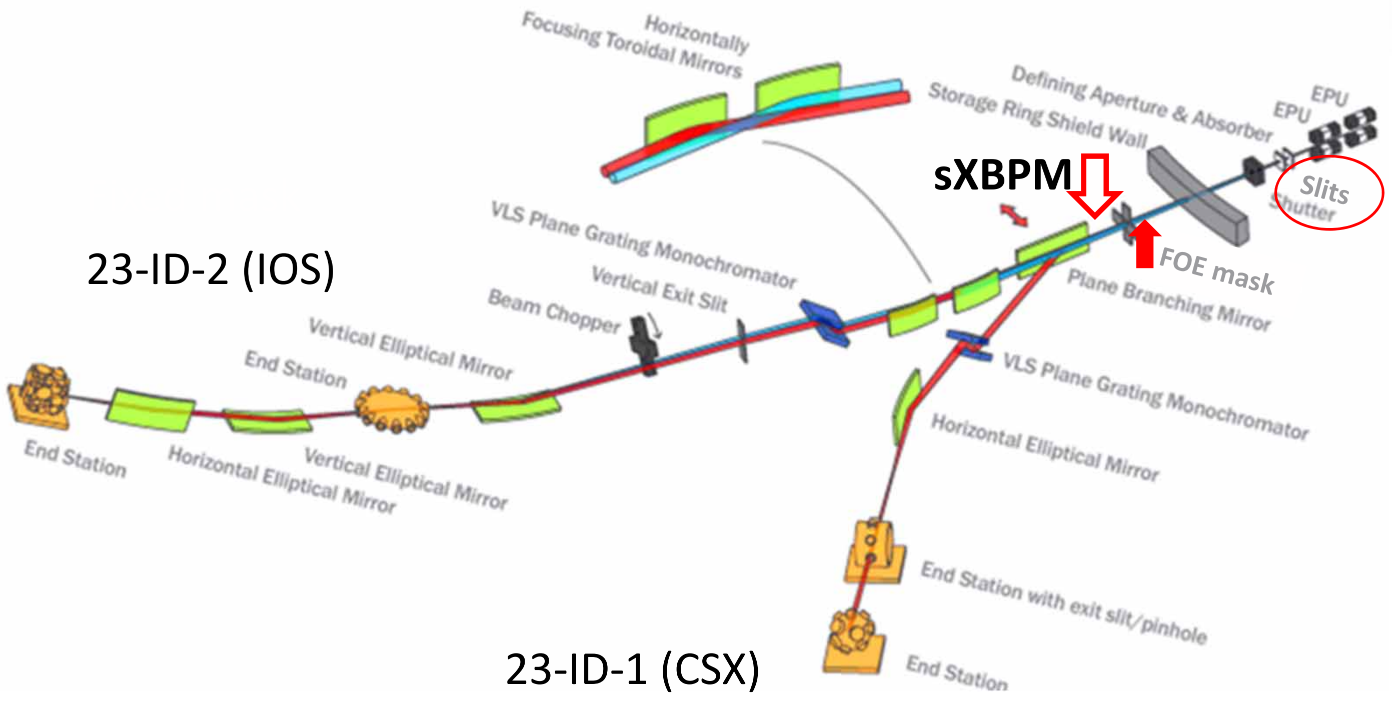


sXBPM concept

J. Liu et al., MOPAB121, proc. IPAC'21

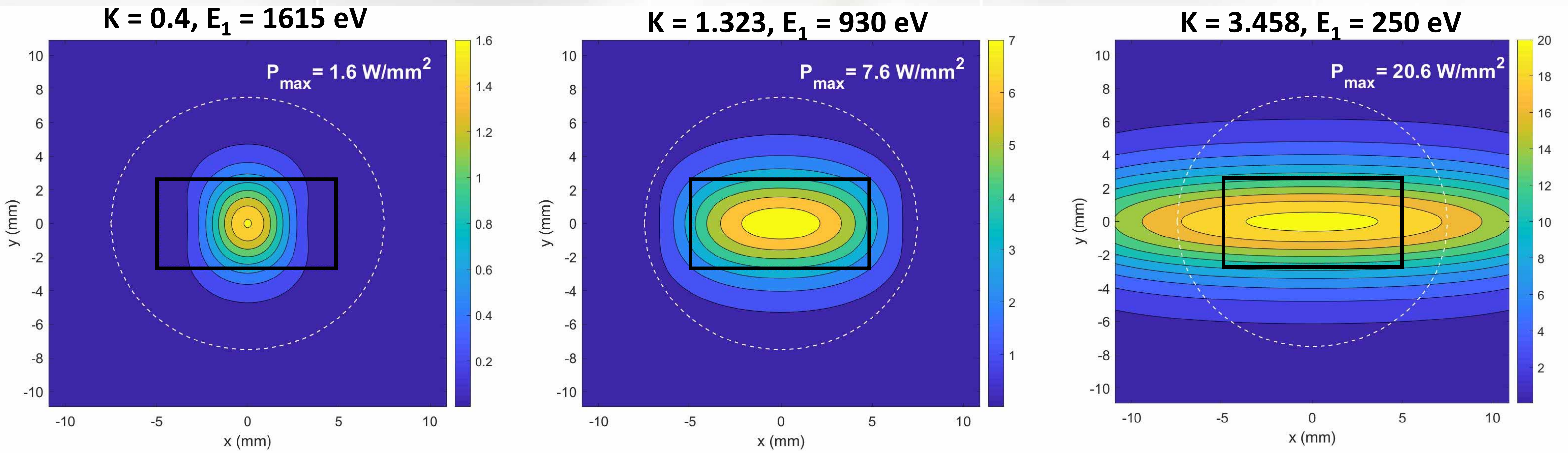
sXBPM Location at 23-ID FOE





- White X-ray beam, right outside of the ring tunnel at the First Optics Enclosure (FOE)
- Two operating soft X-ray beamlines, 0.25 keV to 2 keV: IOS and CSX
- Two identical 2 m long EPUs, 49 mm period, nominally canted at 0.16 mrad
- sXBPM is ~28 m downstream from the center of the EPU pair
- sXBPM is ~1 m downstream of the FOE mask (~10x5 mm^2 water-cooled aperture)

X-ray Beam Power Density at sXBPM Location

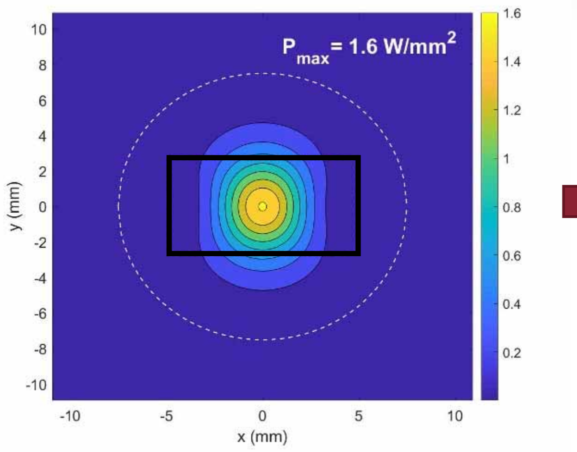


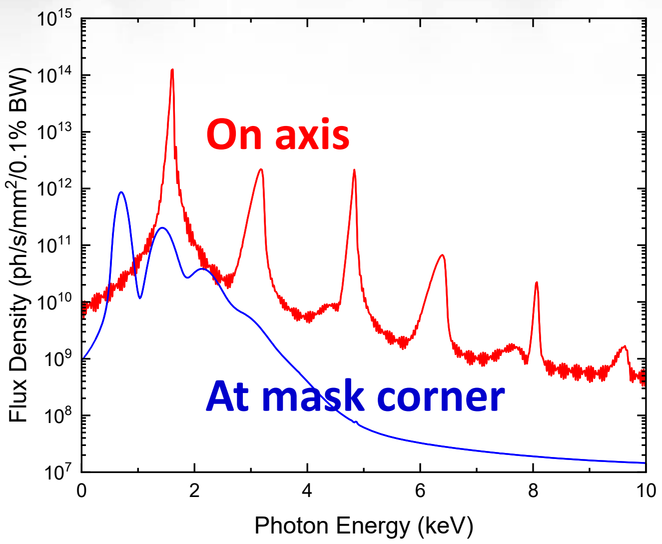
- Power density of undulator radiation 26 m downstream of the CSX undulator (λ_u = 49 mm, L = 2 m) at different magnetic strength settings in linear horizontal polarization
- Photons outside the rectangle (=fixed mask projection) do not reach the sXBPM
- The aperture can be additionally limited by upstream slits
- Photodiodes should be able to operate at power densities up to 20 W/mm^2

More complicated picture during ops with 2 EPUs

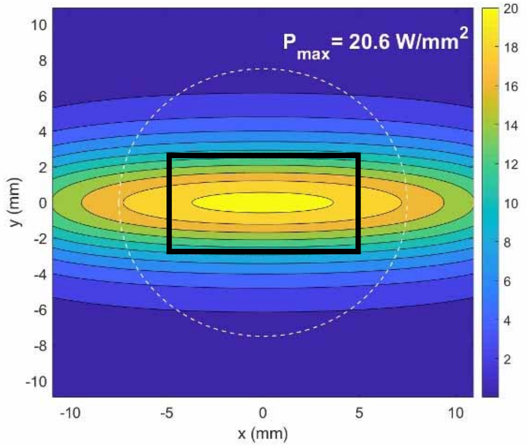
Desired Detector Spectral Responsivity

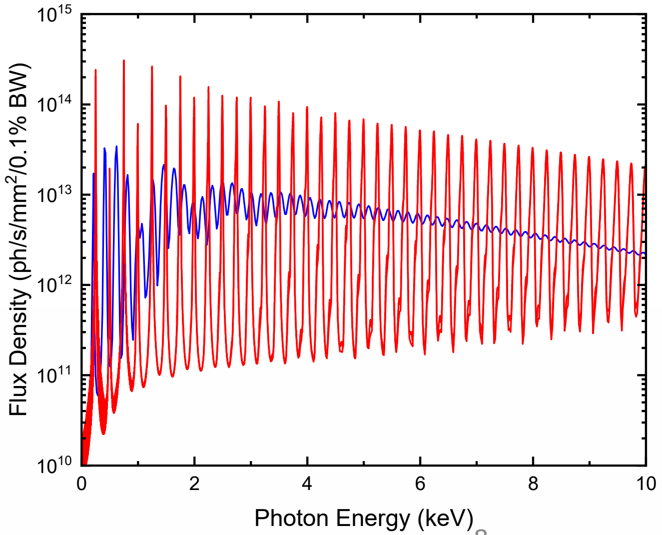
$K = 0.4, E_1 = 1615$ eV





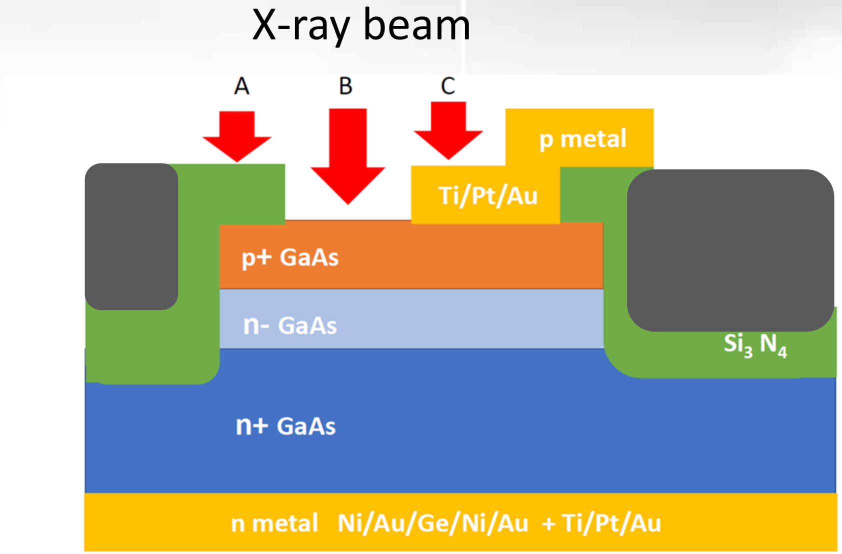
$K = 3.458, E_1 = 250$ eV



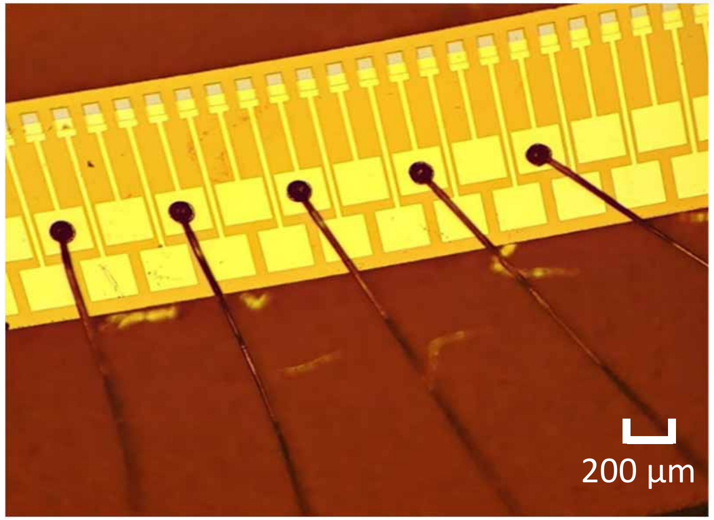


- Must have spectral coverage (high responsivity) from ~650 eV to at least 2 keV, as defined by low-K operation
- At high K, high power is mainly coming from hard X-ray (i.e. on-axis, 80% @ 2-16 keV)
- => Need low hard X-ray responsivity to keep manageable photocurrent density

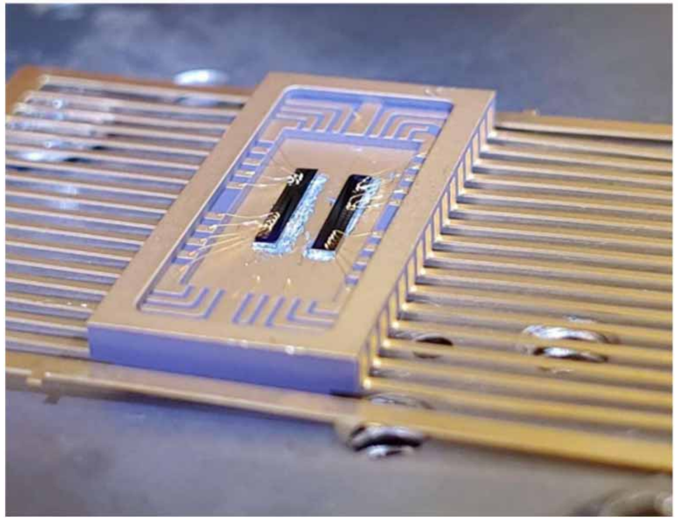
Detector Design, Fabrication, and Testing



The schematic cross-section of the prototype (not in scale) for measurements of the responsivity spectra at the end station: A, B, C three configurations studied



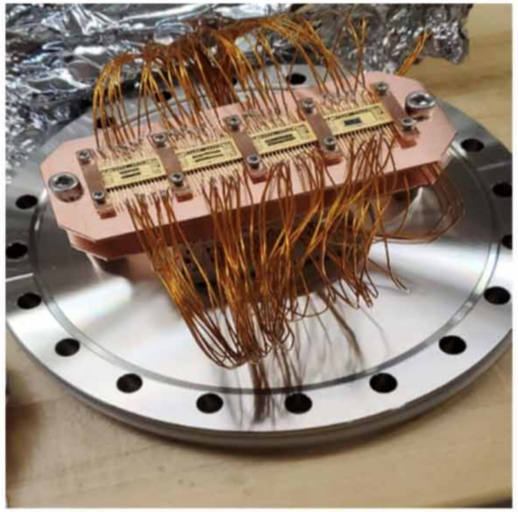
Photodiode array with 64 pixels



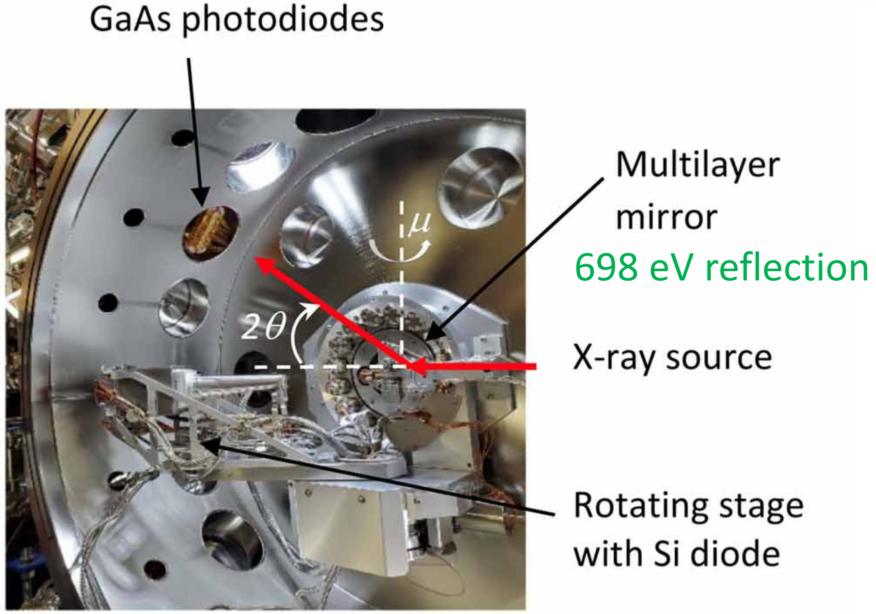
Leaded ceramic carrier with two photodiode arrays

- GaAs selected due to mature technology, ability to operate at high current density, and wide energy gap for temperature stability
- Devices with shallow p-n junctions for enhanced sensitivity in soft X-ray region were designed
- Wafers were grown by solid-source Molecular Beam Epitaxy for high quality of the top p-doped layer
- Photodiode arrays with 32 and 64 pixels were fabricated with pixels sizes from 2 x 6 to 60 x 50 µm^2
- Responsivity was measured with Ar-ion laser at 514 nm with power density up to 200 W/cm^2

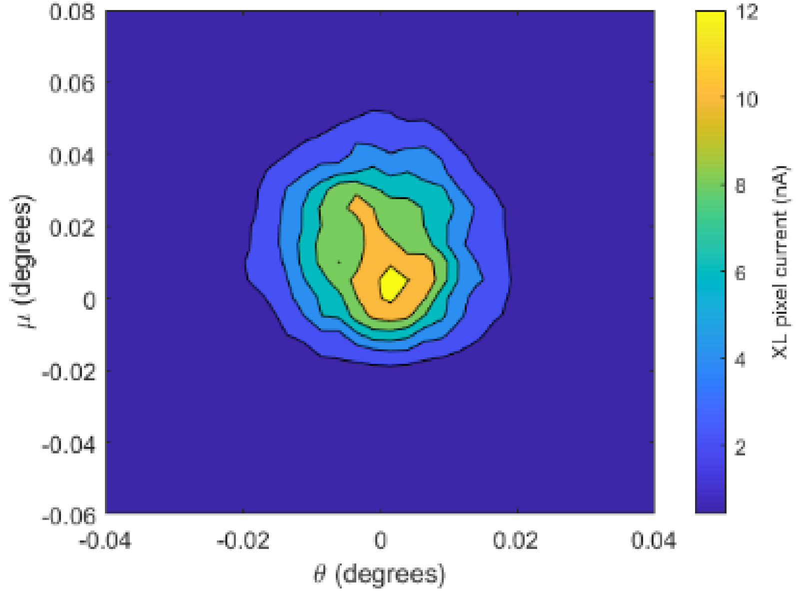
Responsivity Measurements in Soft X-ray at 23-ID-1 (CSX) Beamline



Diode arrays in leaded ceramic carriers on customized 8’’ flange



CSX TARDIS chamber with diode arrays



Photocurrent map when scanning X-ray beam across detector pixel

Responsivity Measurements in Hard X-ray at 4-ID (ISR)

6-Circle Diffractometer

1710 XL Mounted in Diffractometer

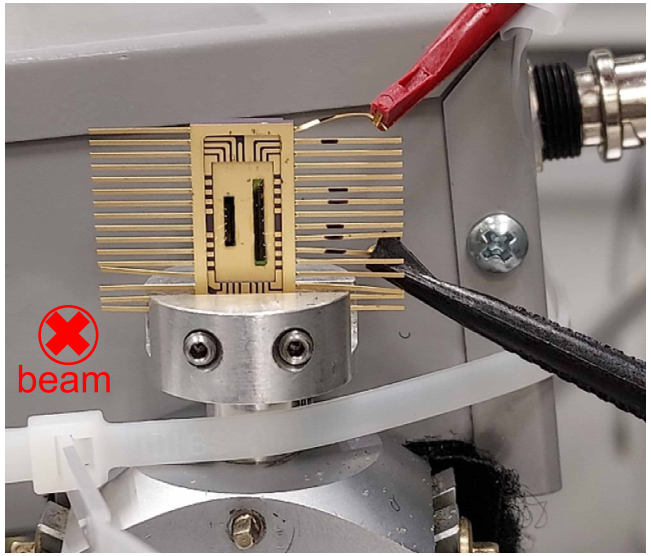
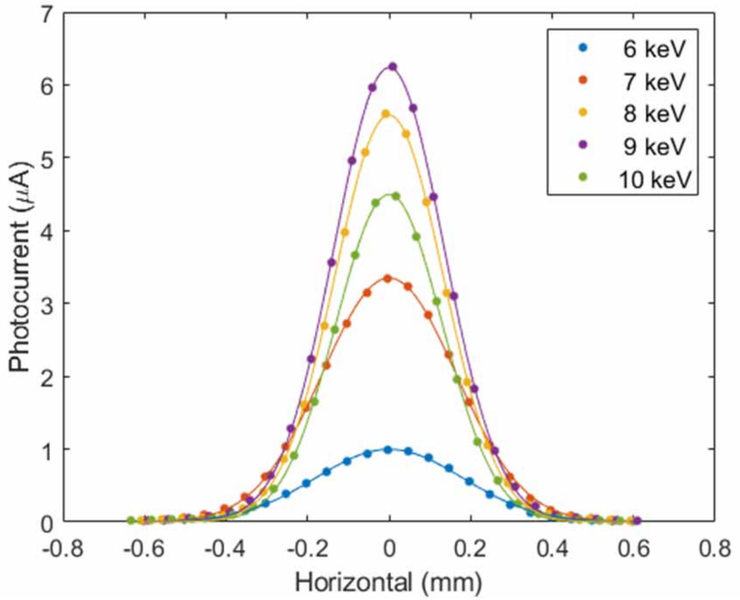
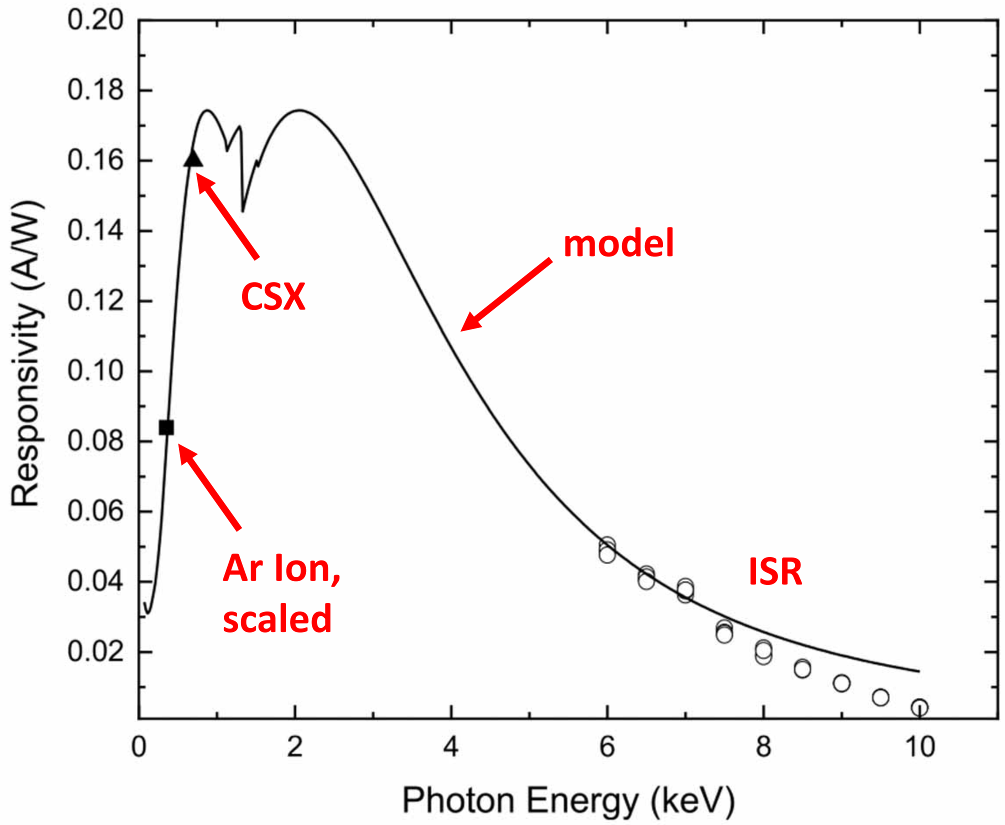


Photo-current vs. x-position scans



Measurement Parameters	
energy range	6-10 keV
incident beam intensity	6 x 10^{10} – 1 x 10^{12} photons/s
horizontal beam size	320 – 490 μm (FWHM)
vertical beam size	45 – 60 μm (FWHM)

Measured Detector Spectral Responsivity



- Good responsivity in soft X-ray, rapid fall-off in hard X-ray, as needed for sXBPM
- Pixel-to-pixel uniformity
- Good device model

IOP Publishing

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High power density soft x-ray GaAs photodiodes with tailored spectral response

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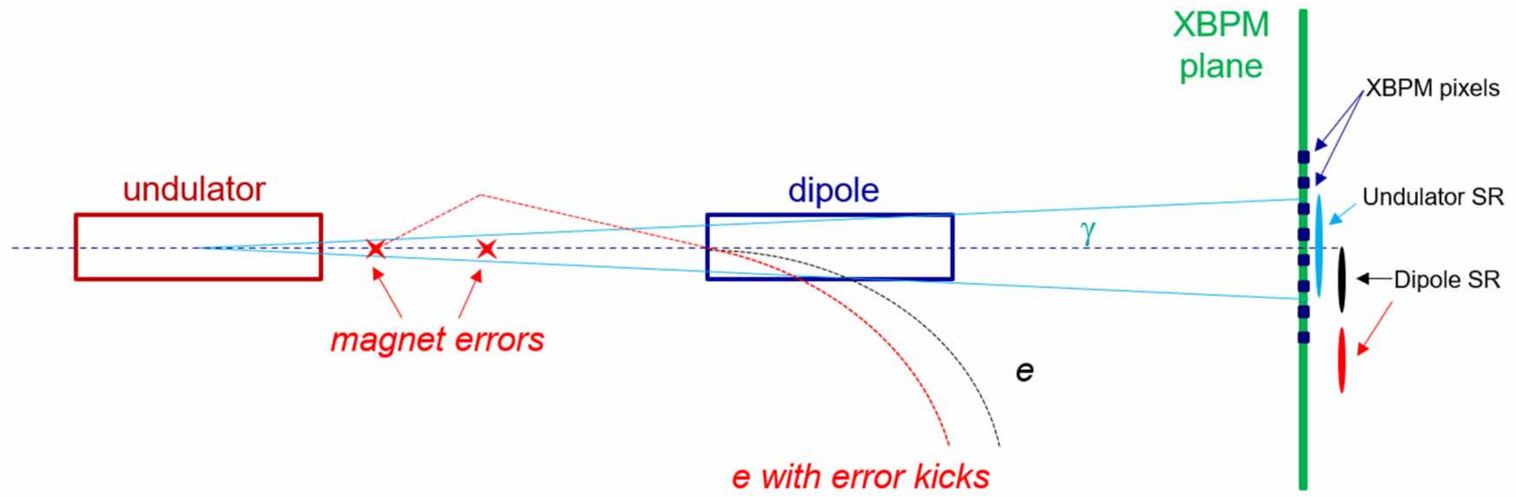
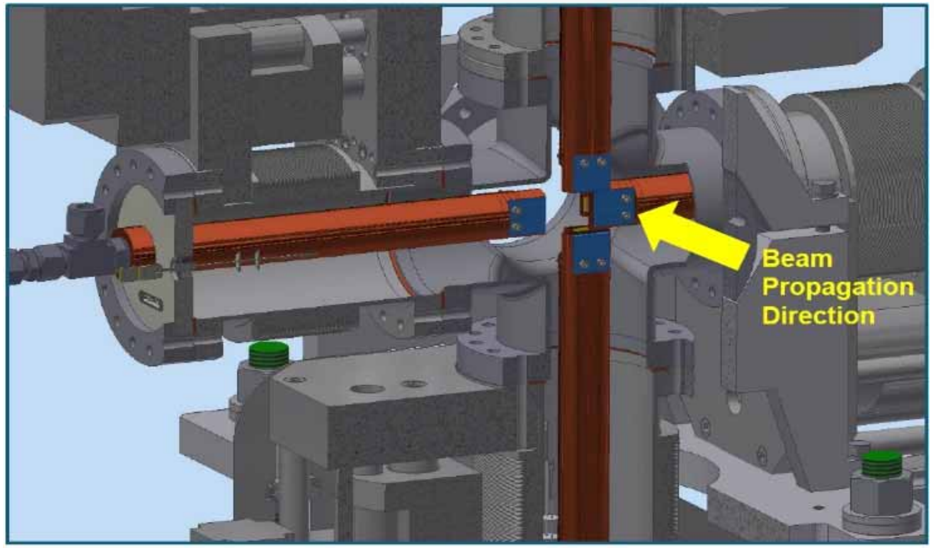
Advantages of Pixelated Detectors for White X-ray Beams

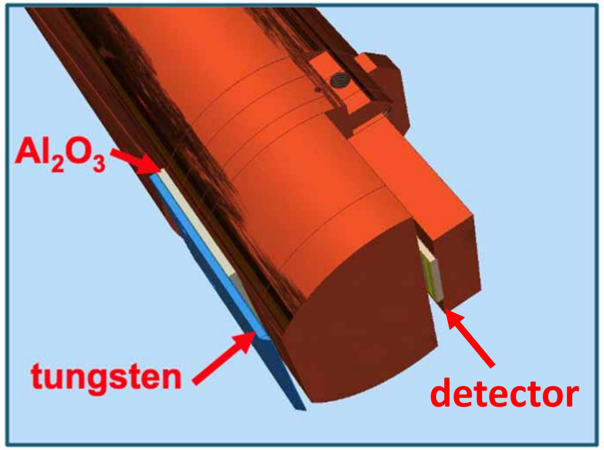
- Provide useful information on top of the beam centroid position (e.g. beam cross-sectional shapes)
- Especially useful for canted beamlines
- Can discriminate between the undulator-sourced X-rays and stray light from the dipoles, etc.

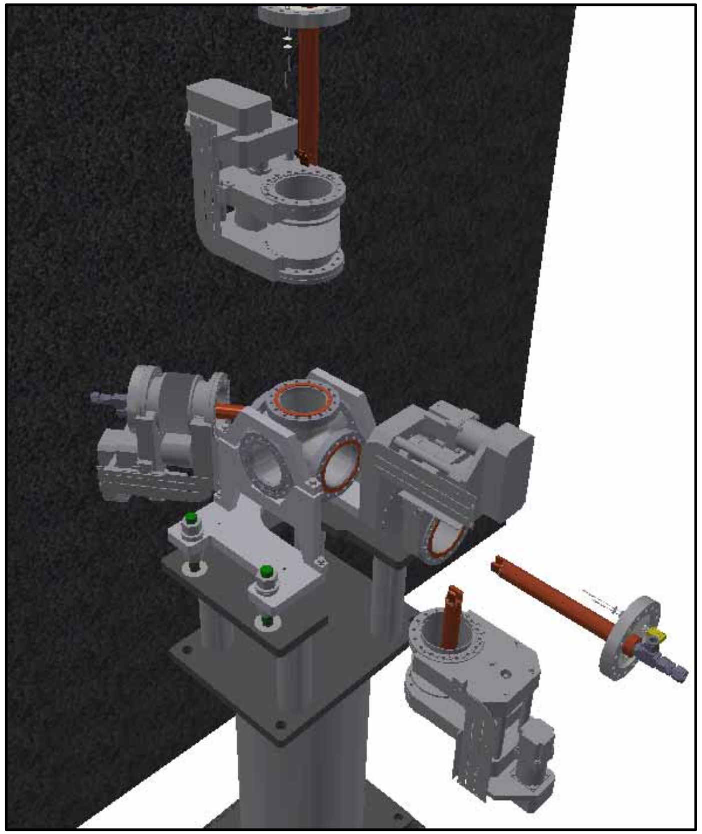
Schematic of dynamic e-beam trajectory and the dipole stray radiation



Mechanical Design, Assembly, and Installation





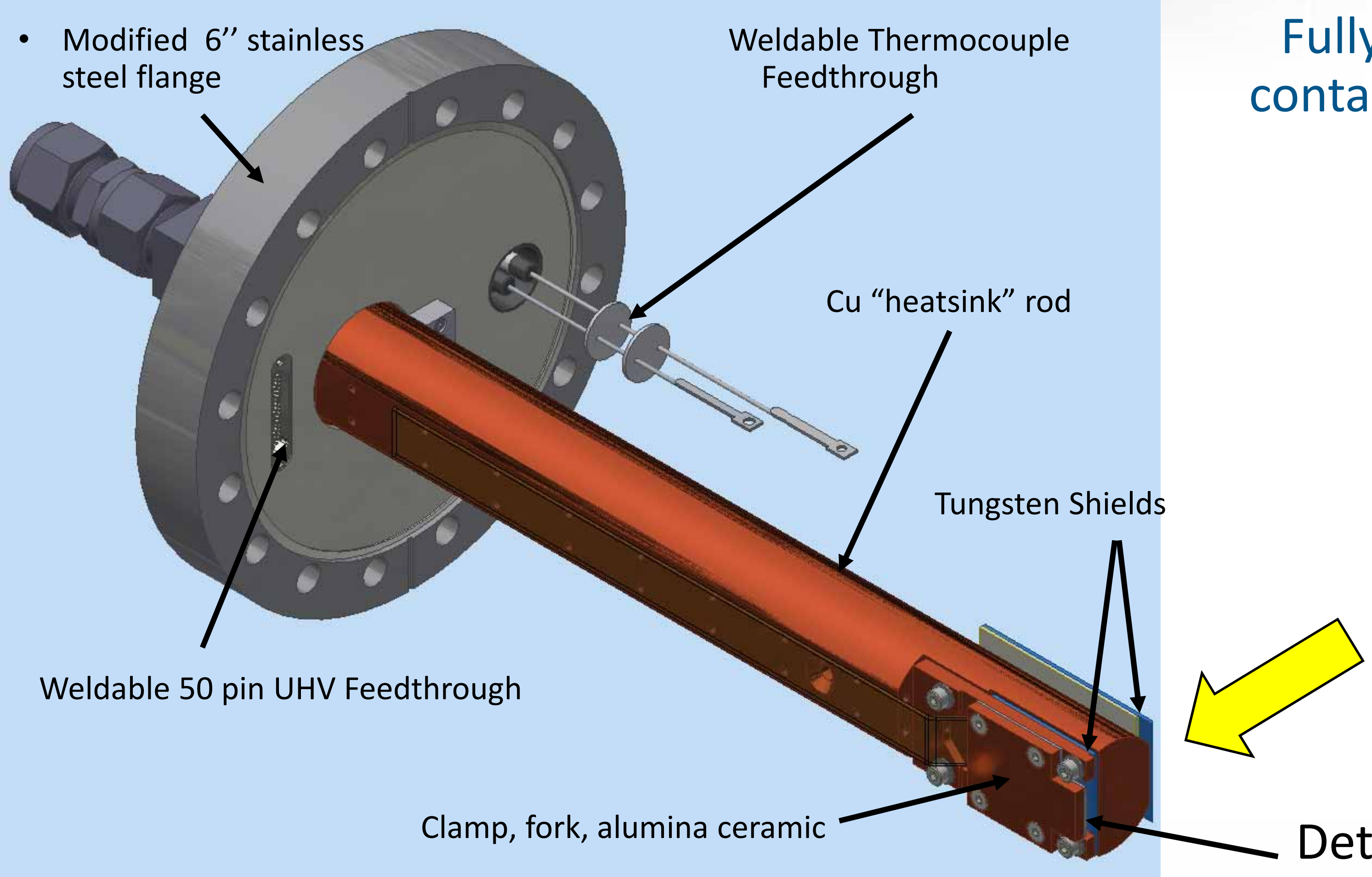


- Features: 4 water-cooled blade (a.k.a. heatsink) assemblies, single-axis translatable blades, tungsten shields to reduce heat flux to the detector
- Challenges: stability, heat load management, compactness to fit the FOE, accessibility for modifications, alignment
- Status: design, fabrication, and installation (1 out of 4 blades) completed. Top blade with detector in-place for 2 months this summer providing first data, two blades are being installed now

C. Eng et al., MOPC01, proc. MEDSI'2020

Heatsink Assemblies with Detectors

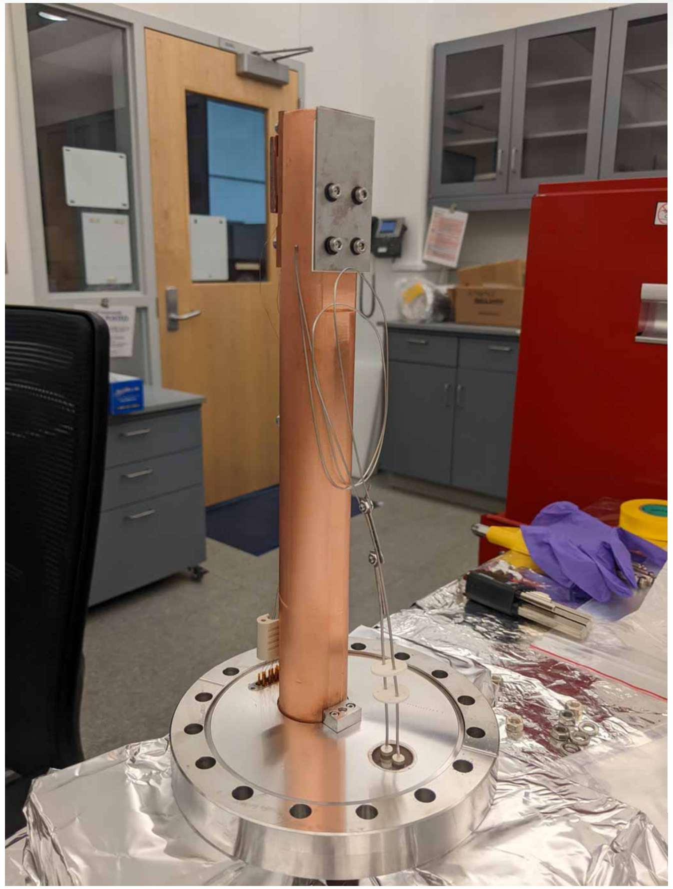
Fully built sXBPM contains 4 assemblies



X-ray direction

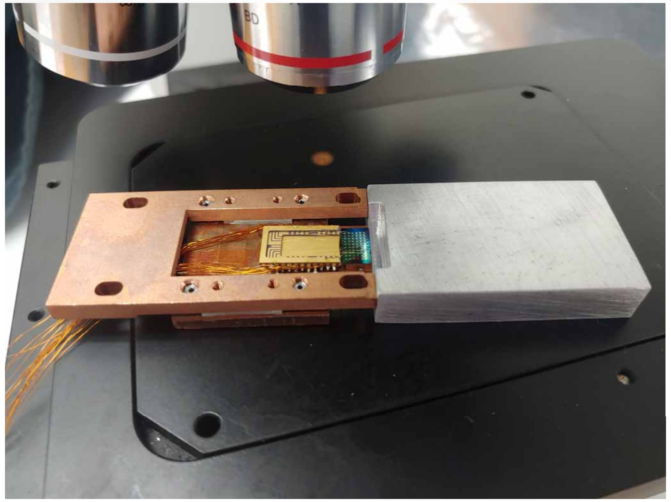
Detector assembly

Heatsink and Detector Assembly Cont'd

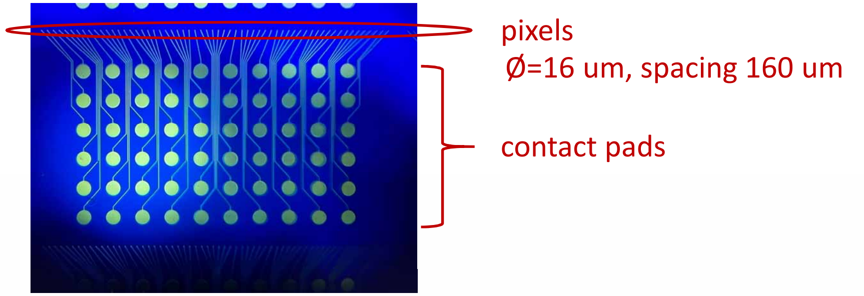


Heatsink assembly

Detector assembly

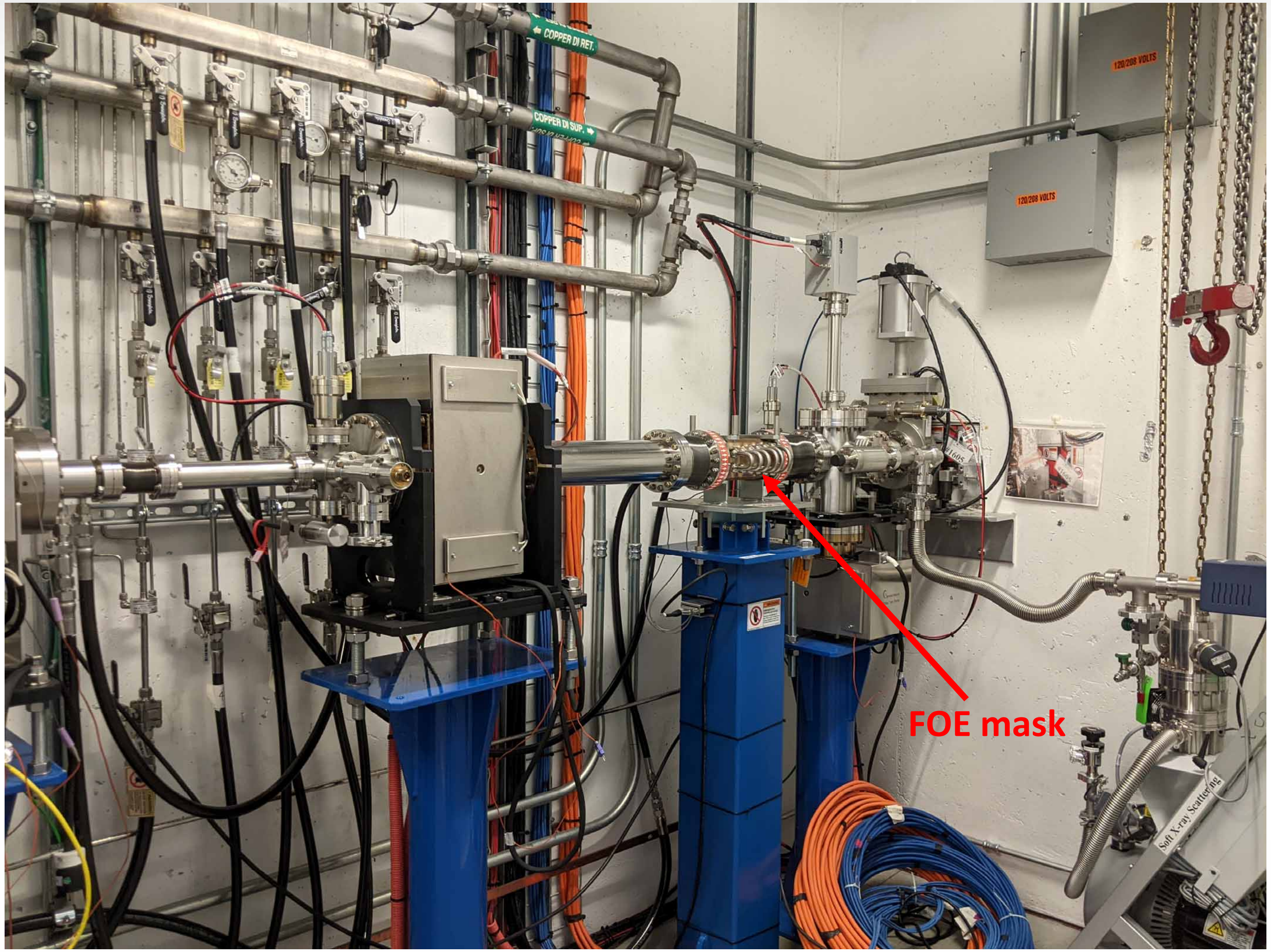


Detector assembly
pre-alignment



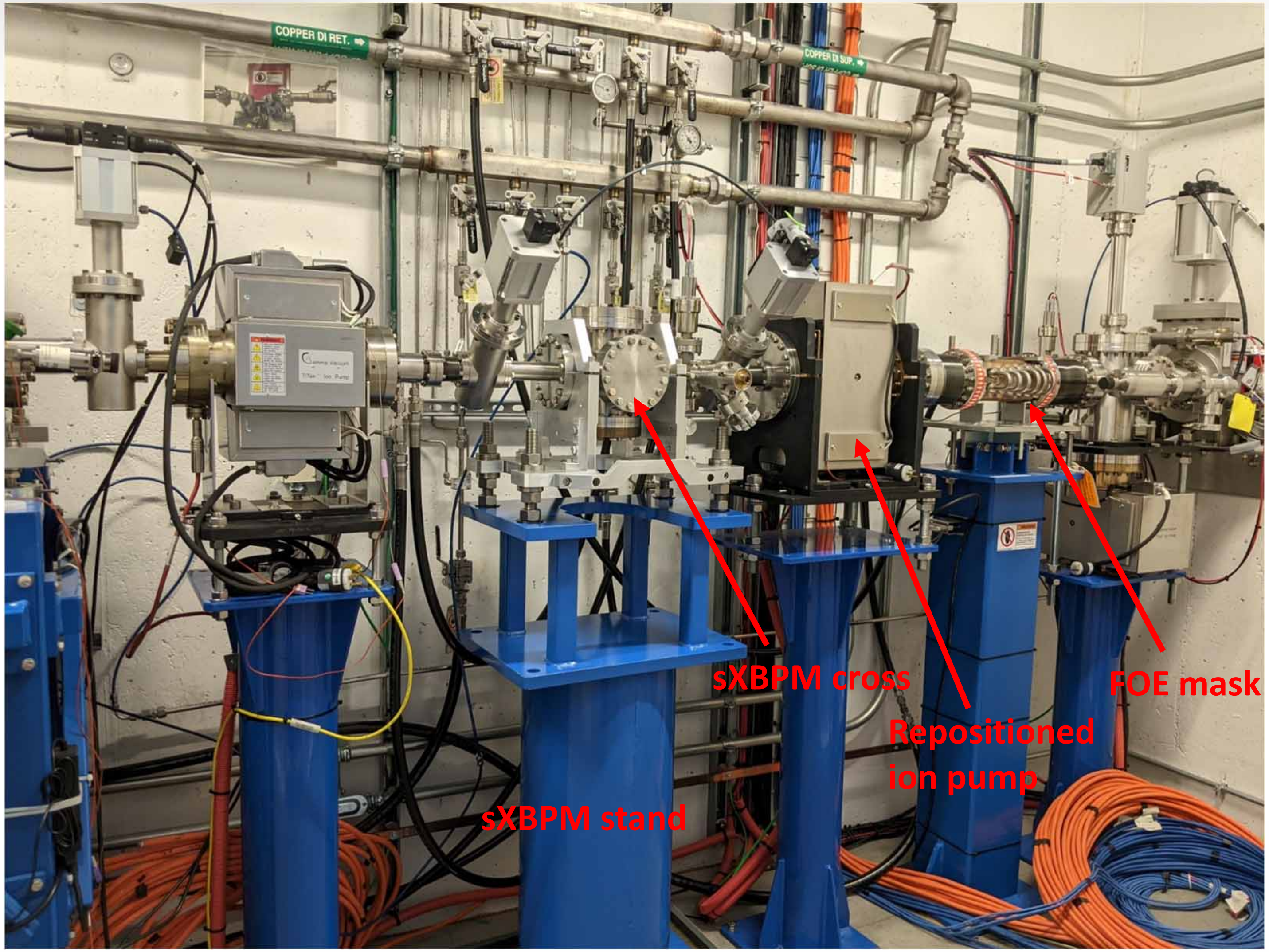
GaAs detector array
(before cleaving)

Vacuum Envelope Installation: pre-install



23-ID FOE
Apr. 21, 2022

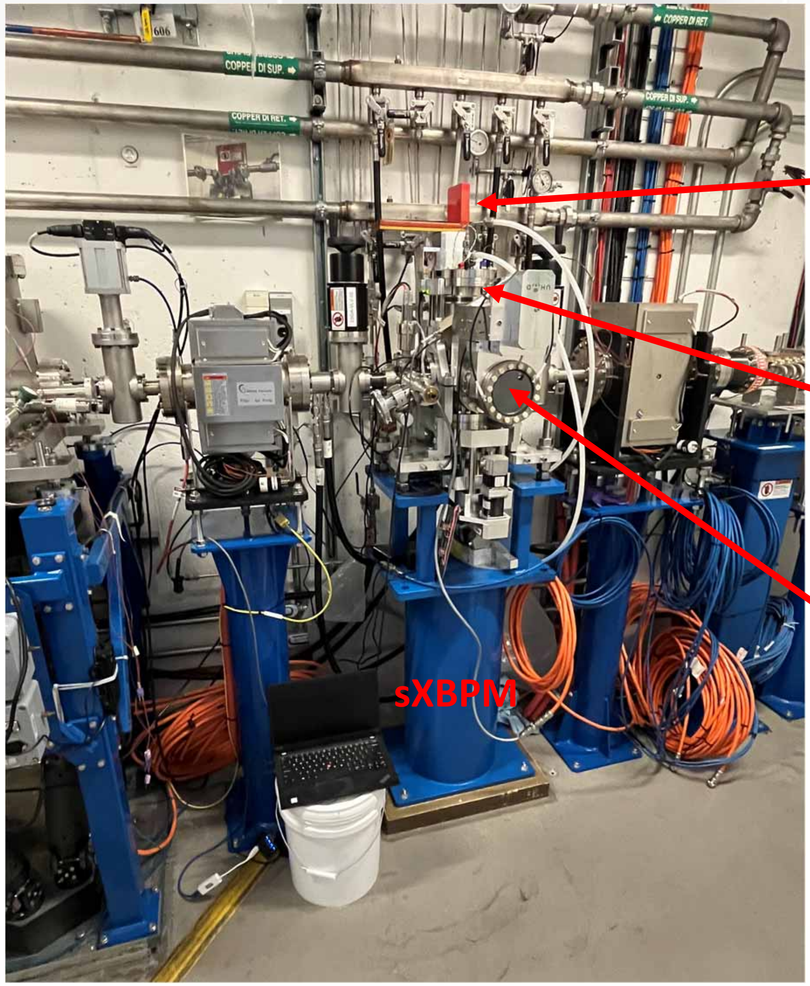
Vacuum Envelope Installation: completion



23-ID FOE
Apr. 26, 2022

Normal beamline ops resumed in May, 2022

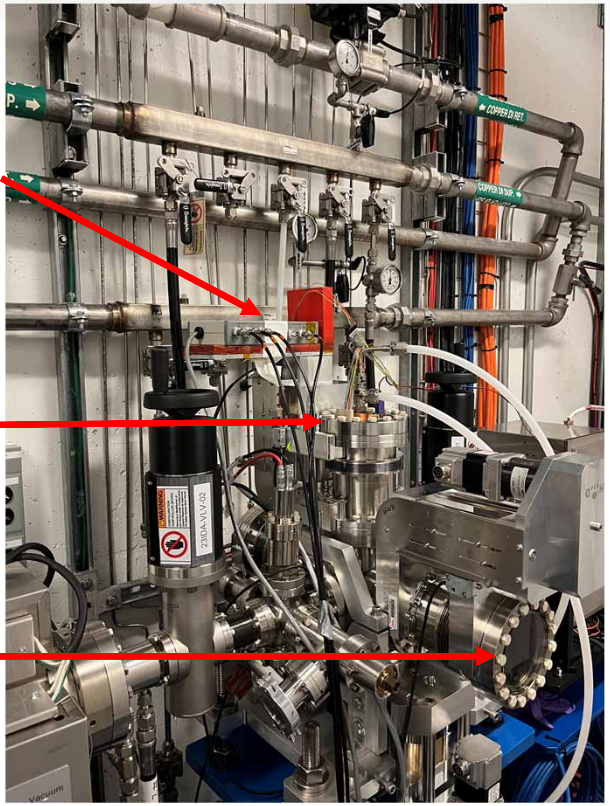
FOE View in Summer 2023



Electronics box with rad. shield

Flange with top blade with detector array

Temporary viewport

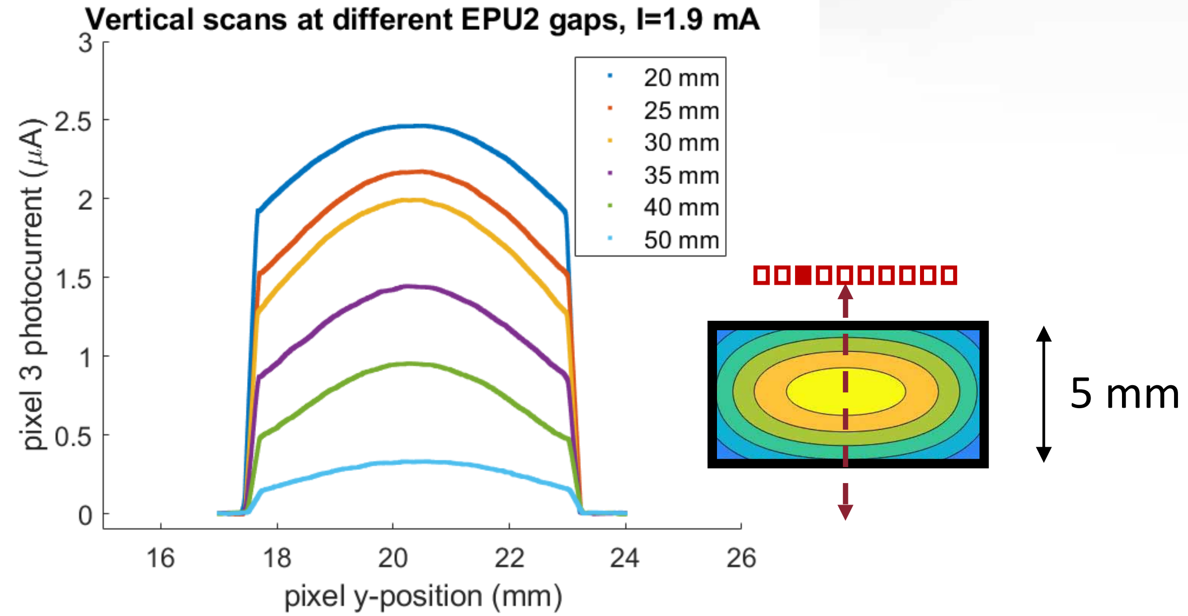


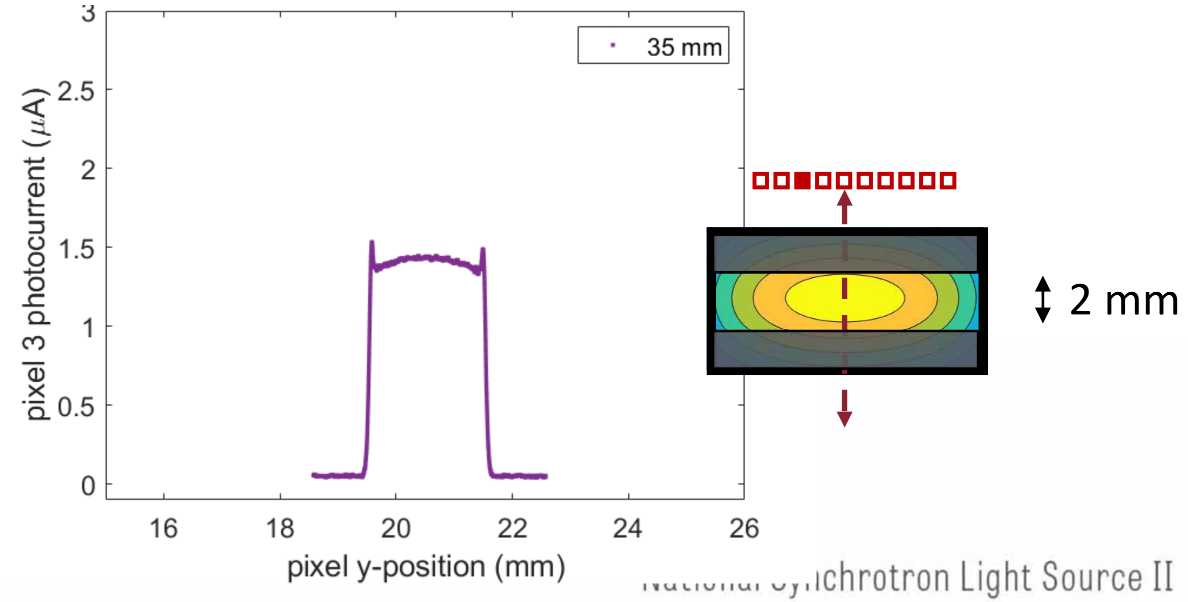
23-ID FOE
Aug. 2, 2023

- Only the top vertical blade with detector array was installed
- Temporary viewport was mounted on another sXBPM flange
- A pair of blades to be installed during on-going machine shutdown

Low-current Measurements

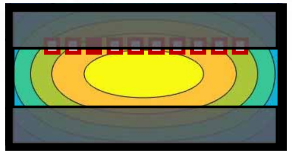
- Current-limited by vacuum conditions
- sXBPM detector array moved vertically across the X-ray beam at I=1.9 mA
- Varied EPU2 gap 20 to 50 mm (K=2.6 to 0.4)
- Intercepted beam height of 5 mm is due to FOE mask
- Detector pixel signals traced the expected X-ray beam shapes, decreasing in intensity and narrowing with larger ID gap
- No noise or parasitic signals when the detector is shaded by the mask
- Diffraction "lobes" seen when further limiting the aperture by upstream slits
- Detailed comparison with the model is in progress

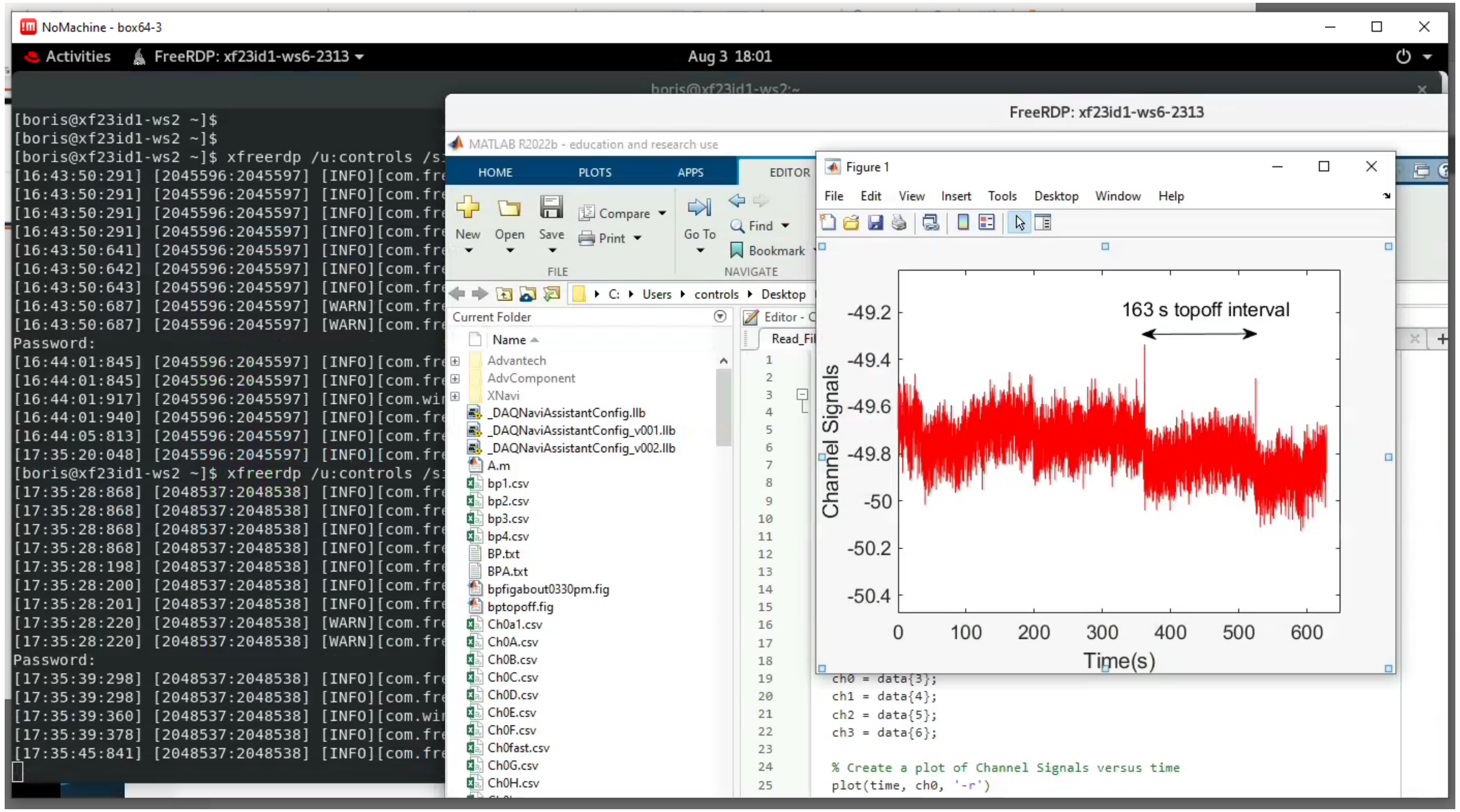




High-current Measurements

- Limited by vacuum conditions, esp. at small ID gaps
- Detector parked in the slit "shade"
- Observe injection transients during 500 mA user ops

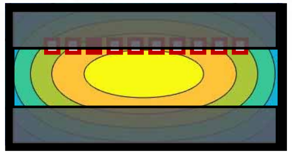


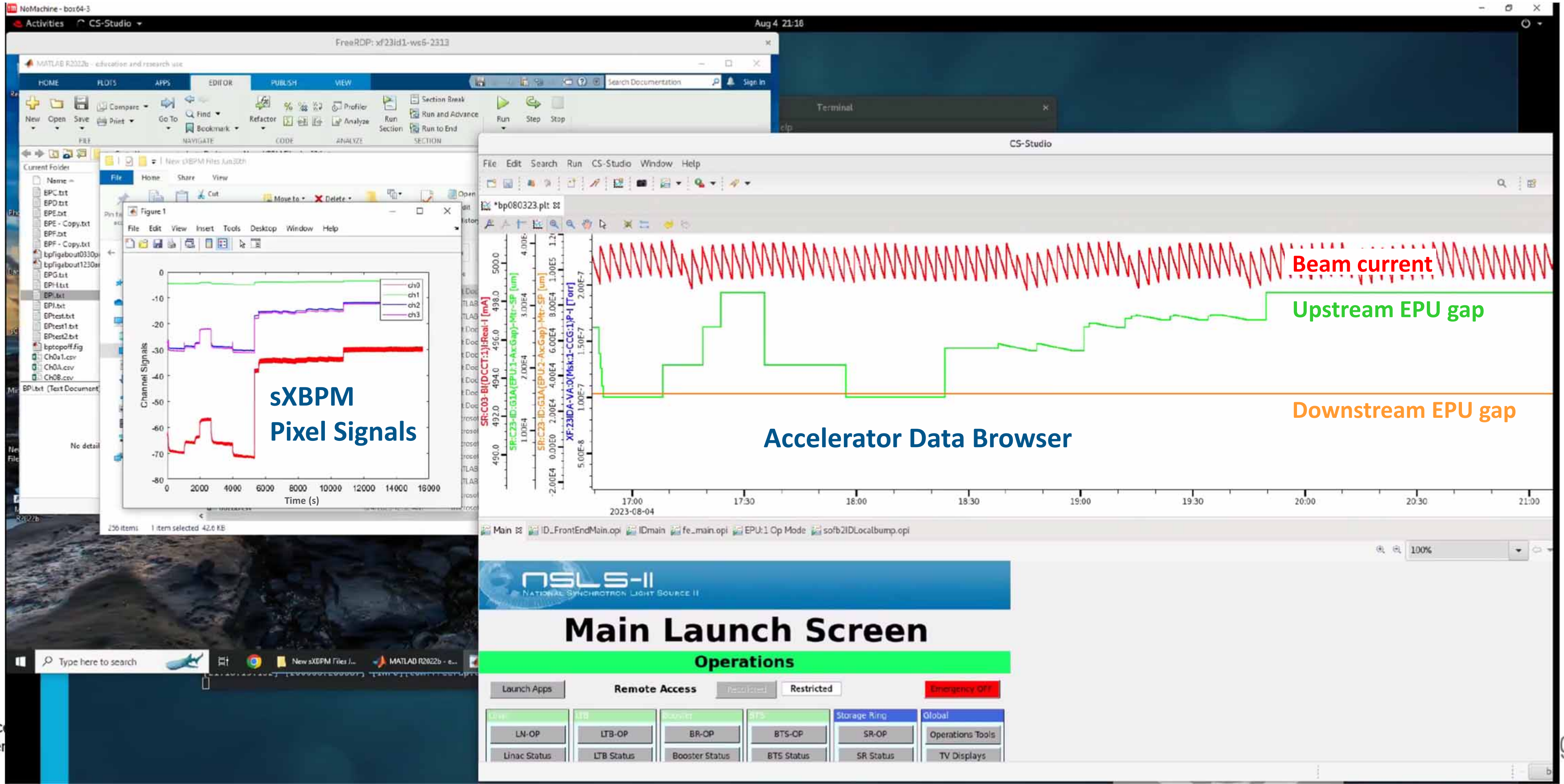


- Signal from one of the pixels in Volts/512
- R=10 kΩ
- => I≈50/512/10k ≈ 10 uA

High-current Measurements Cont'd

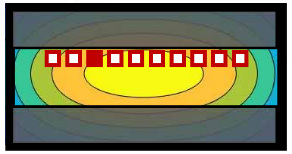
- Detector in the slit shade
- Observe sXBPM detector pixels respond to ID gap changes



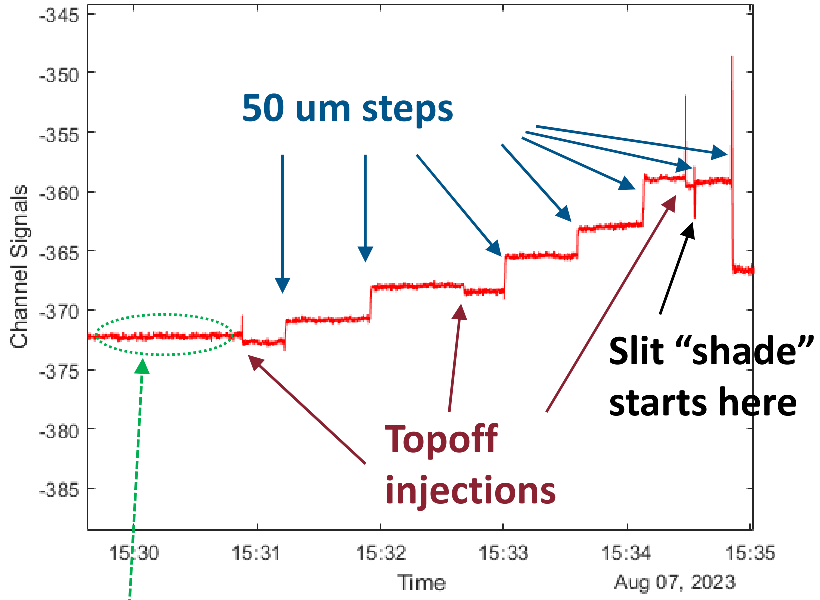


High-current Measurements Cont'd

- Started with fully illuminated detector
- Moved up in 50-micron steps
- Resolve the steps (and topoff injections)
- Detector noise is much smaller than the step change
- Noise standard deviation (between the steps) is equivalent to 2-4 microns
- Confident in achieving micron-scale resolution in the future with optimized electronics and multi-pixel position-calculation algorithms



Pixel 3 signal



500 mA Ops, EPU2 gap 30 mm

standard deviation 0.15 counts, equivalent to ~2-4 microns

Summary

- Non-invasive soft X-ray BPMs (sXBPMs) do not exist yet, but are greatly desired for coherent soft X-ray beamlines. We are working to develop such sXBPM for high-power, white X-ray beams
- In our approach, multi-pixel GaAs detector arrays are placed into the outer portions of X-ray beam. Beam position (+ other info) is inferred from the pixel photocurrents.
- Tailored detector responsivity from sub-keV to a few keV photon energies was accomplished with shallow p-on-n junction design
- Detector array prototypes have been manufactured and extensively characterized with high-power Ar-ion laser, and then tested in soft- and hard X-ray beamlines of NSLS-II
- sXBPM prototype with a single detector array was recently installed in high-power X-ray beam from two canted EPUs in C23-ID straight of NSLS-II
- The device successfully resolved small beam motions and gap-change-induced variations of X-ray beam shape during 500 mA user operations
- Immediate future steps: install symmetric top-bottom sXBPM configuration with 25 wired pixels per blade and optimized electronics. Studies of resolution, multi-pixel algorithm optimization, etc.
- We believe our innovative approach holds significant promise for enhancing synchrotron beamline and accelerator diagnostics, especially for highly coherent beams in future light sources

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