PLANNED X-RAY DIFFRACTION DIAGNOSTICS FOR APS-U EMITTANCE MEASUREMENTS

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Emittance Measurements for Light Sources and FELs
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Outline

- Emittance monitor specifications
- Right x-ray source is half the success
- Design of x-ray diffraction apertures
- Simulation of diffraction profiles and estimation of beam size monitor performance
- Key features of optical / mechanical design
- Summary

APS-U Storage Ring Emittance Monitor

Expected storage ring emittance*

Operating Mode	Horizontal Emittance	Vertical Emittance	Beam Current
Timing Mode	31.9 pm	31.7 pm	200 mA
Brightness Mode	44 pm	4.2 pm	200 mA
Initial Commissioning Mode			25 mA
Beam Instability?	1000 pm	500 pm	
Low emittance ratio study (1%)?		0.4 pm	

* Two planned operating modes for user operation

Emittance monitor operating requirements*

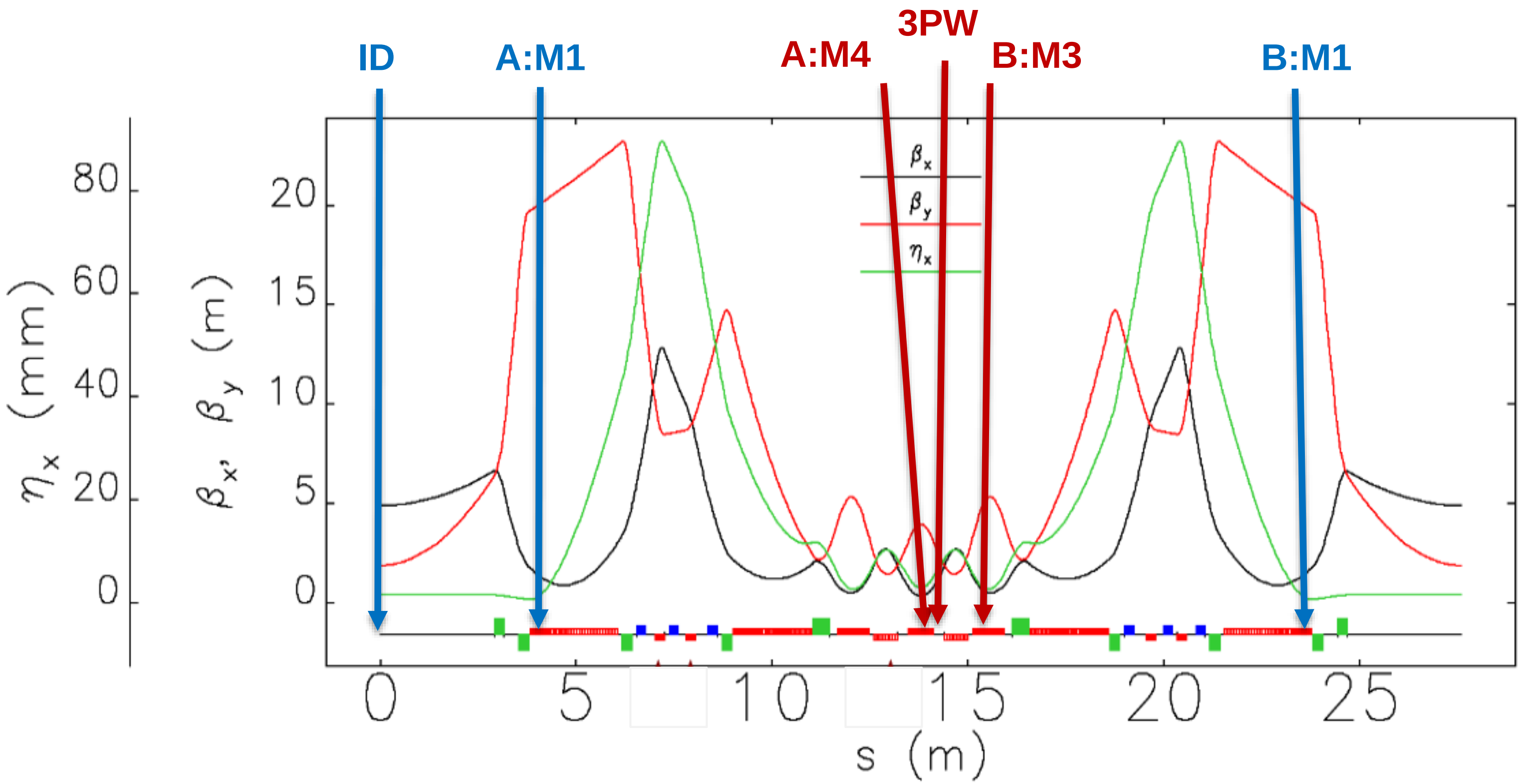
Horizontal Emittance	Vertical Emittance	Beam Current
25 – 1000 pm	0.4 – 500 pm	20 – 200 mA

* Planned bandwidths: 0.1 – 1 Hz for absolute beam size monitor; 1 – 10 Hz for relative beam size monitor.

X-ray Source for Beam Size Monitor

SR emittance will be calculated from measured beam sizes. Choosing proper x-ray source is a critical step to the successful emittance monitor! The APS-U storage ring chamber has **two light ports**, looking at 7 – 8 x-ray source points:

- **ID port**: insertion devices + bend magnet sources B:M1 and A:M1
- **BM port**: M4, Q8 (too weak), M3, and optional three-pole wiggler



APS-U storage ring lattice functions.

X-ray Source for the Emittance Monitor

Minimum source sizes for APS-U user operations*

Port	ID		BM		
Source	**A:M1/B:M1**	**ID**	**M4**	**3PW**	**M3**
X-size from emittance	7.2	12.5	5.0	6.4	4.7
X-size from energy-spread**	0.4	0.9	8.0	11.0	4.9
Horizontal beam size (X)	**7.2**	12.6	9.4	12.8	6.8
Vertical beam size (Y)*	**9.1**	2.8	4.3	3.2	4.5

* Minimum emittances in user operations are 31.9pm / 4.2pm in horizontal / vertical planes.

** Nominal electron beam energy spread is 0.136%.

[Observations]

- At the BM port, the source sizes are dominated by contributions from beam energy spread, making pure emittance measurement difficult!
- At the ID port, the vertical ID source size is small, difficult to measure!
- The B:M1 is 7.7 m upstream of A:M1, farther away from the x-ray optics!
- **The A:M1 source is ideal for emittance measurement!**

APS-U Storage Ring Beam Size Monitor

Expected electron beam sizes at A:M1 source point*

Operating Mode	Horizontal Beam Size	Vertical Beam Size	Beam Current
Timing Mode (User Op)	7.3 μm	25.1 μm	200 mA
Brightness Mode (User Op)	8.5 μm	9.1 μm	200 mA
Initial Commissioning Mode			25 mA
Beam Instability?	41 μm?	100 μm	
Low emittance ratio study (1%?)		3 μm	

* Two planned modes for user operation

Beam size monitor operating range requirements*

Horizontal Beam Size	Vertical Beam Size	Beam Current
6.5 – 41+ μm	3 – 100+ μm	20 – 200 mA

* Planned bandwidths: 0.1 – 1 Hz for absolute beam size monitor; 1 – 10 Hz for relative beam size monitor.

X-ray Diffraction Optics

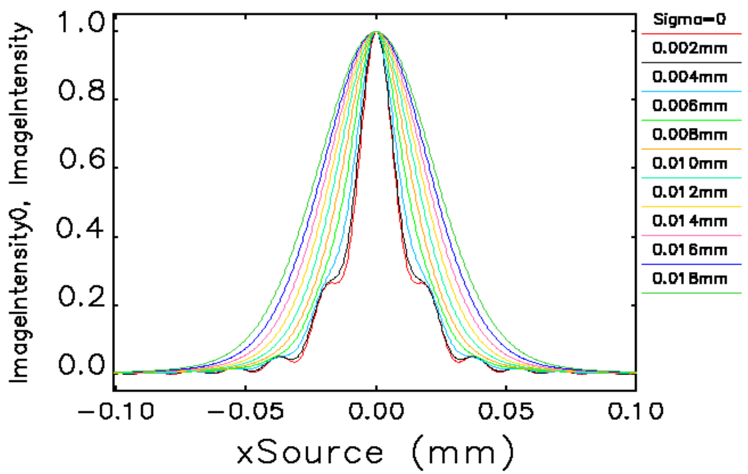
- The x-ray optics is a 0.1-mm tungsten foil with **six apertures**:
  - Aperture spacing is 0.5 mrad (3.3 mm), making separate images at detector
  - The apertures are located 6.56 m from the source
  - Apertures may be put into **two function groups.**
- **Absolute beam size monitor (ABSM)**: obtain beam sizes by analyzing x-ray diffraction profiles, operating in 0.1 – 1 Hz range. Three apertures cover different beam size ranges:
  - Monochromatic x-ray pinhole camera (15 keV): for 8 – 100+ μm beam sizes.
  - Wide-aperture Fresnel diffractometer (8 keV): 4 – 14 μm
  - Young's double slits interferometer (8 keV): 2 – 6 μm
- **Relative beam size monitor (RBSM)**: obtain beam size information by monitoring x-ray diffraction peak intensities, operating at 1 – 10+ Hz:
  - Double-slits collimator for horizontal beam size (15 keV): 4 – 100 μm
  - Double-slits collimator for vertical beam size (15 keV): 4 – 100 μm
  - X-ray beam position monitor (15 keV) for maintaining collimator alignment

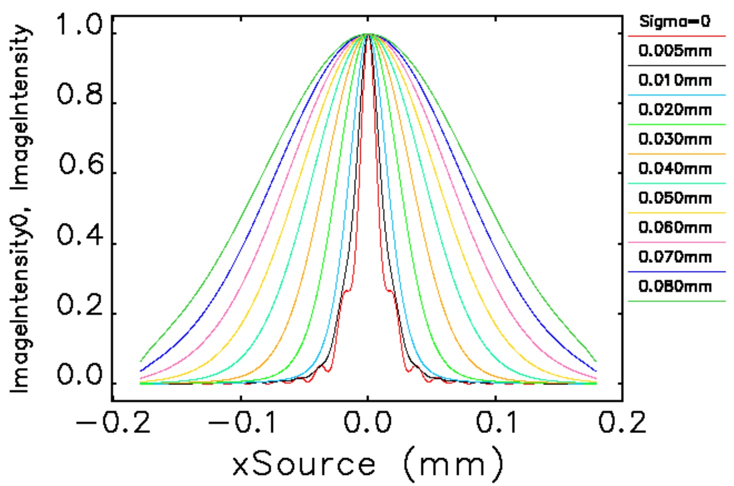
15-keV X-ray Pinhole Camera: Geometry

Today, most x-ray pinhole-camera emittance monitors use white beams. But the monochromatic beam has several unique advantages:

- Diffraction profiles can be more precisely modelled, resulting in more accurate beam size data.
- Photon energy can be chosen in a opaque region for tungsten, making the pinhole slits easier to make, and with a better optical quality.

Source distance	Pinhole	Image distance	M	Source sizes
6.6 m	34 μm × 34 μm	13.4 m	2.6	**8 – 100 μm**





Pinhole camera profiles for source size 2 – 18 μm (left panel) and 5 – 80 μm (right panel)

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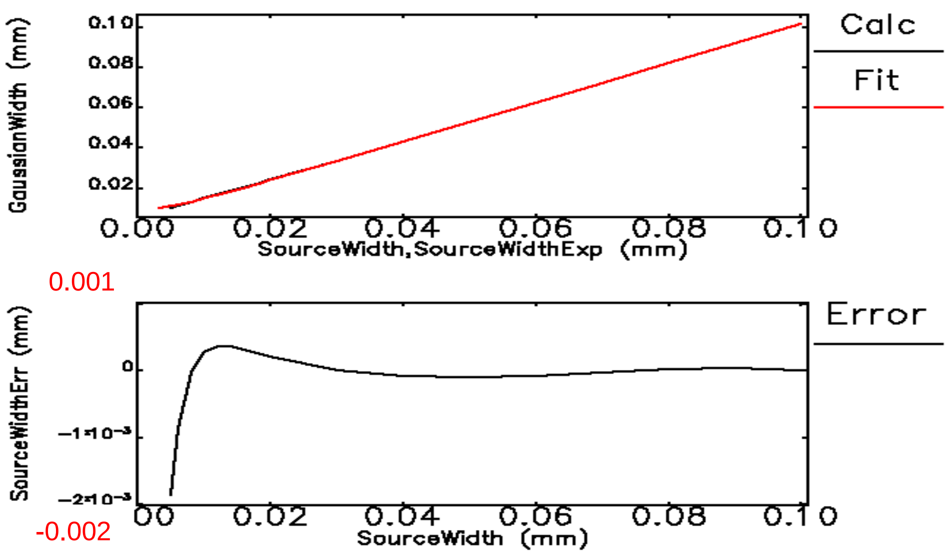
15-keV X-ray Pinhole Camera: Data Analysis

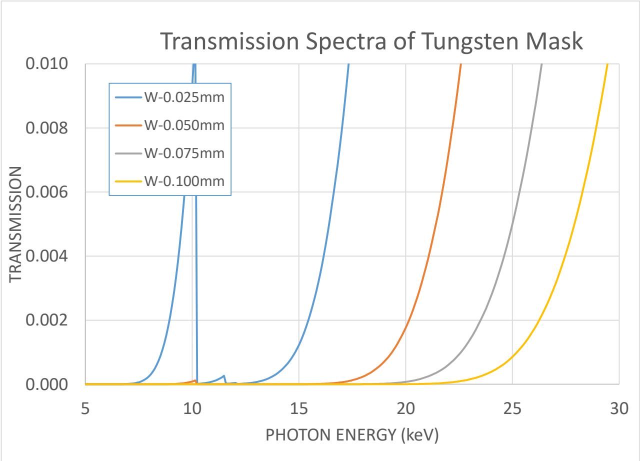
- For small sources, full diffraction profiles get best curve-fitting results.
- Shortcut for larger beam sizes (> 8 μm): Fit 60% of the peak data to a Gaussian curve. The resulting peak width σ_G can be "corrected for resolution effect" using the following expression:

$$\sigma_{exp} = \sqrt{a\sigma_G{}^2 - 2b\sigma_G - \sigma_0{}^2}$$

with $a = 1.041,\ \ b = 3.591\ (\mu m)$ and $\sigma_0 = 4.601\ (\mu m)$



The resolution-corrected source sizes carry an error below 1 μm for source size < 8 μm

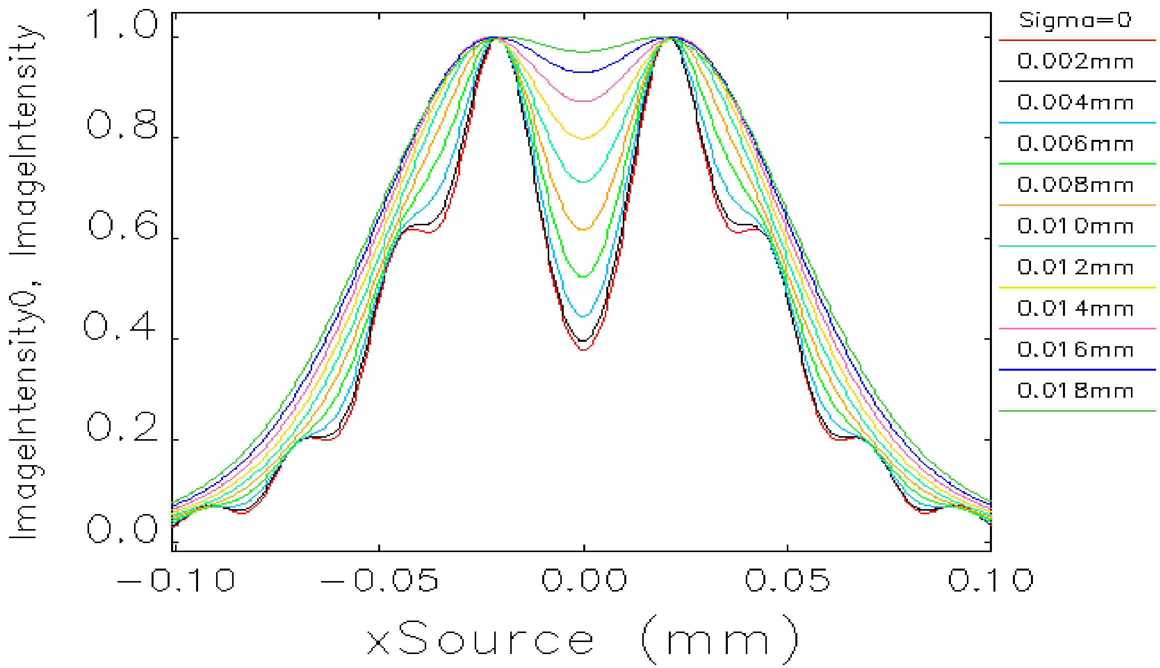


X-ray absorption by tungsten is strong at 15 keV. A 50-μm foil has less than 0.01% transmission.

8-keV X-ray Fresnel Diffractometer

If we widen the diffraction aperture to include the second Fresnel zones, the diffraction profile will have a center minimum. The entire profiles can be used for image analyses to extract beam size information.

Source distance	Pinhole	Image distance	M	Source sizes
6.6 m	70 μm × 70 μm	13.4 m	2.6	**4 – 14 μm**



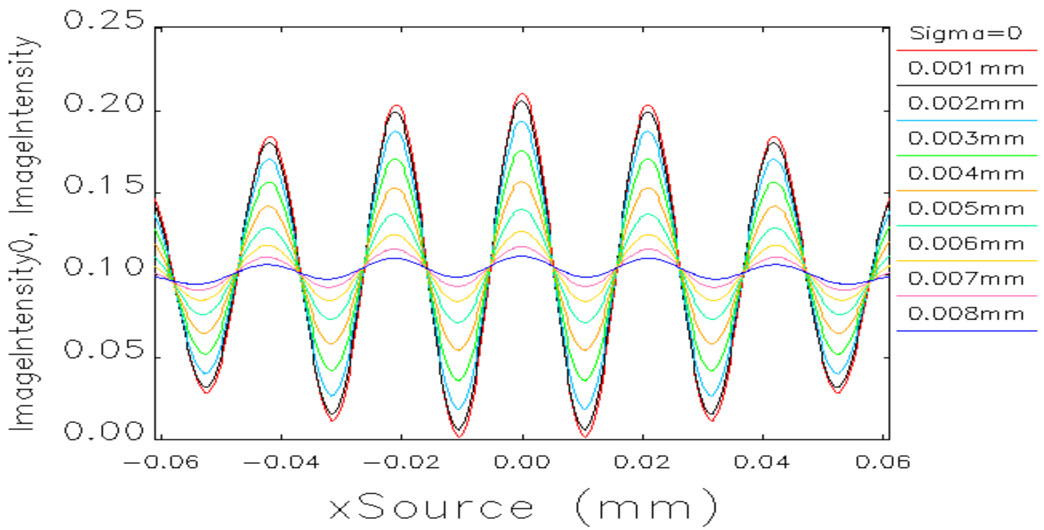
Fresnel diffractometer profiles for source size 2 – 18 μm

8-keV Young's Interferometer (Vertical)

For very small beam sizes, a pair of double slits will be used to make a Young's Interferometer, which produces sinusoidal interference fringes.

- Full diffraction profiles will be used for image analyses.
- Expect longer integration time
- If necessary, a larger slit spacing can be used for even smaller beam sizes

Source distance	Slits	Image distance	M	Y-Beam sizes
6.6 m	2 × 8 μm 80 μm spacing	13.4 m	2.6	**2 – 6 μm** (0.2 – 1.8 pm)



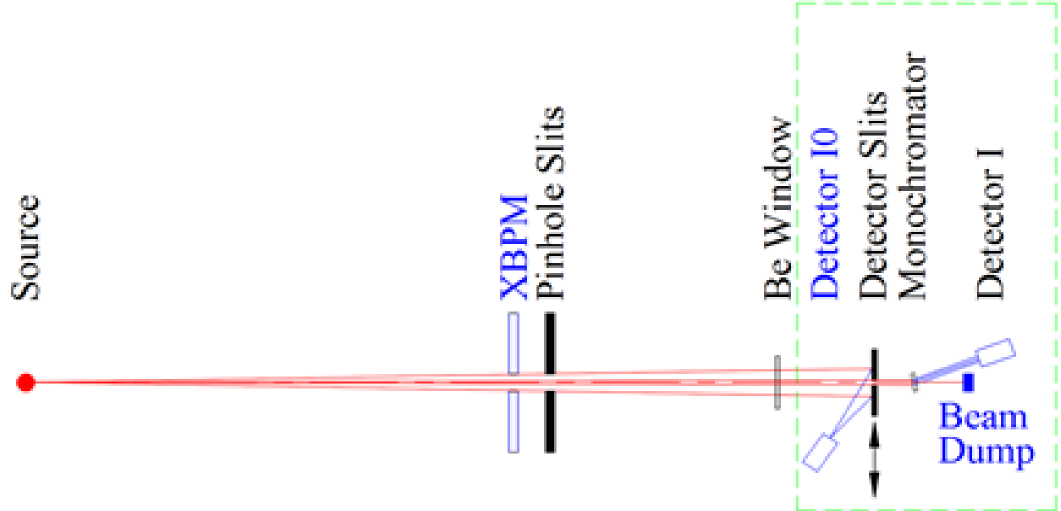
Young's interference pattern from two 8-μm slits with 80-μm spacing

Relative BSM: Double-Slits Collimator

One-dimensional 15-keV x-ray pinhole camera:

- Pinhole-slit width is chosen to maximize the peak intensity at the detector.
- The slits' length increases the x-ray flux by five fold (relative to a pinhole).
- Detector slits width is chosen to balance good resolution and good signal level.

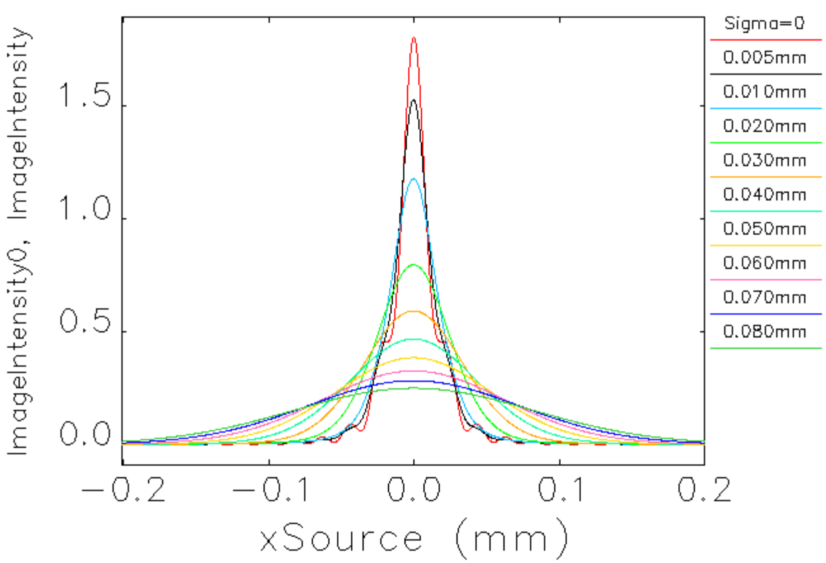
Source distance	Pinhole slits	Detector distance	Detector slits	M	Source sizes
6.6 m	34 μm × 150 μm	13.4 m	10 μm × 400 μm	2.6	4 – 100 μm

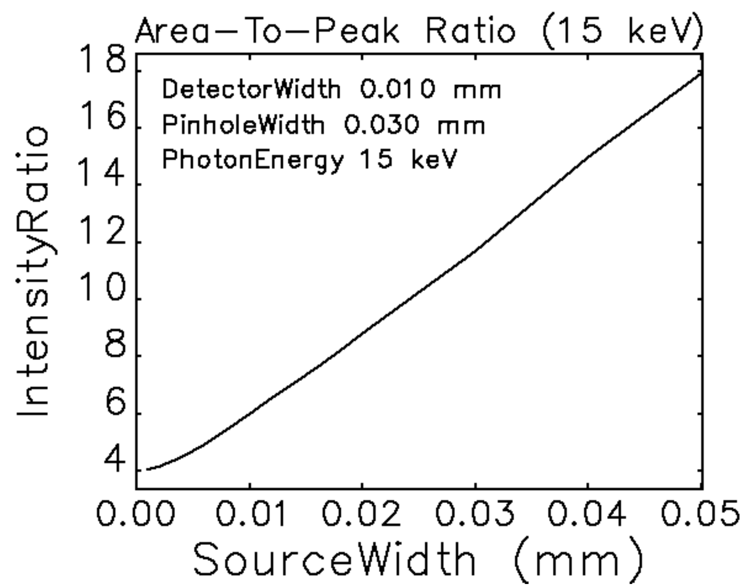


Concept of the APS-U relative beam size monitor

Relative BSM: Two Modes of Operations

- **Scanning mode**: scanning a narrow slit across the pinhole image
  - A slow, but accurate absolute beam size monitor, free from degradation by x-ray imaging detectors
  - Beam size obtained by fitting the entire intensity profile ➔ Reliable calibration
- **Intensity mode**: measure area and peak signal intensities
  - In user operations, the area-to-peak intensity ratio will be used to monitor beam size /emittance variations for emittance feedback system.

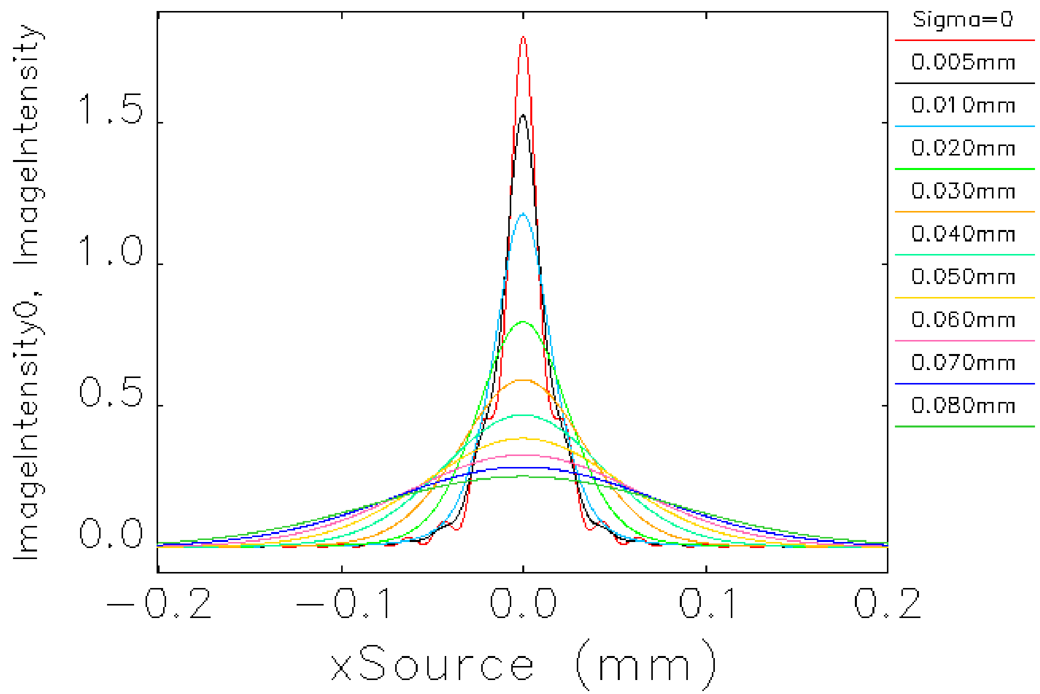




Relative Beam Size Monitor detector slits scanning profiles and peak intensity depends on source sizes.

RBSM: Alignment Requirements

- In the vertical plane, the pinhole slits needs to be centered in the BM x-ray fan.
- In both horizontal and vertical planes, the two-slit collimators need to be aimed precisely at the source. Any misalignment will cause detector signal drop, which may be misinterpreted as source size increase.
- To keep detector centered within top 2% of the peak intensity, we need to center the collimator within **1 μm** from the source center.

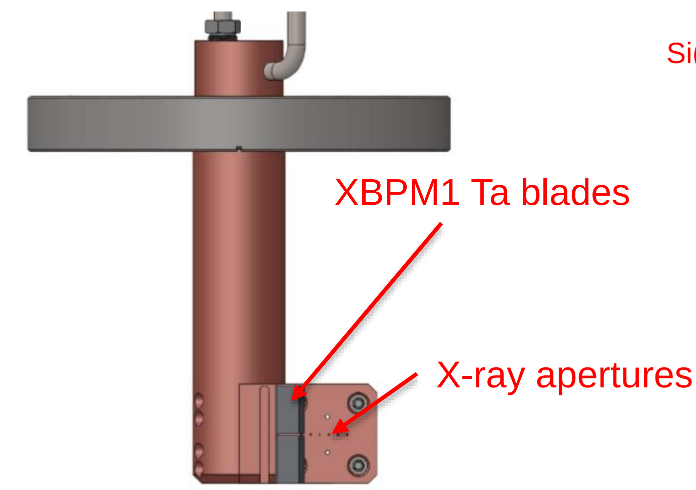


Relative Beam Size Monitor detector slits scanning profiles indicate alignment requirements.

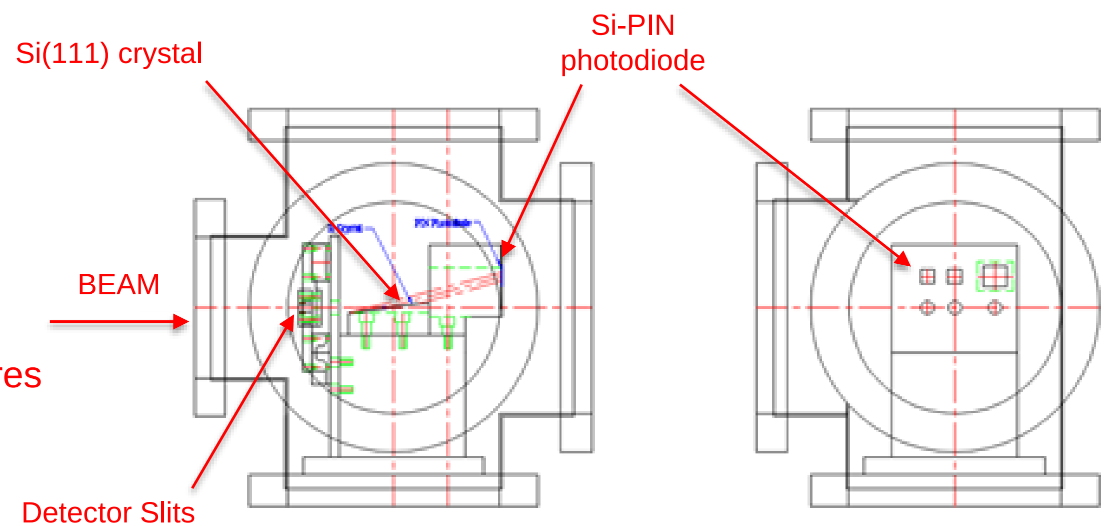
X-ray Beam Position Monitors

- XBPM1 is for centering the bend magnet fan vertically on the aperture array
  - Photoemission XBPM design integrated with the aperture holder (@6.56 m)
  - Resolution of several microns is more than adequate for BM fan height of 500 microns.
- XBPM2 is for aligning the source, pinhole slits, and the detector slits on the same straight line.
  - Large pinhole (300 μm × 200 μm) between XBPM1 blades
  - 15-keV mono and 2-D position-sensitive detector to readout source point position

Centering beam in the XBPMs centers the beam in the relative beam size monitors!



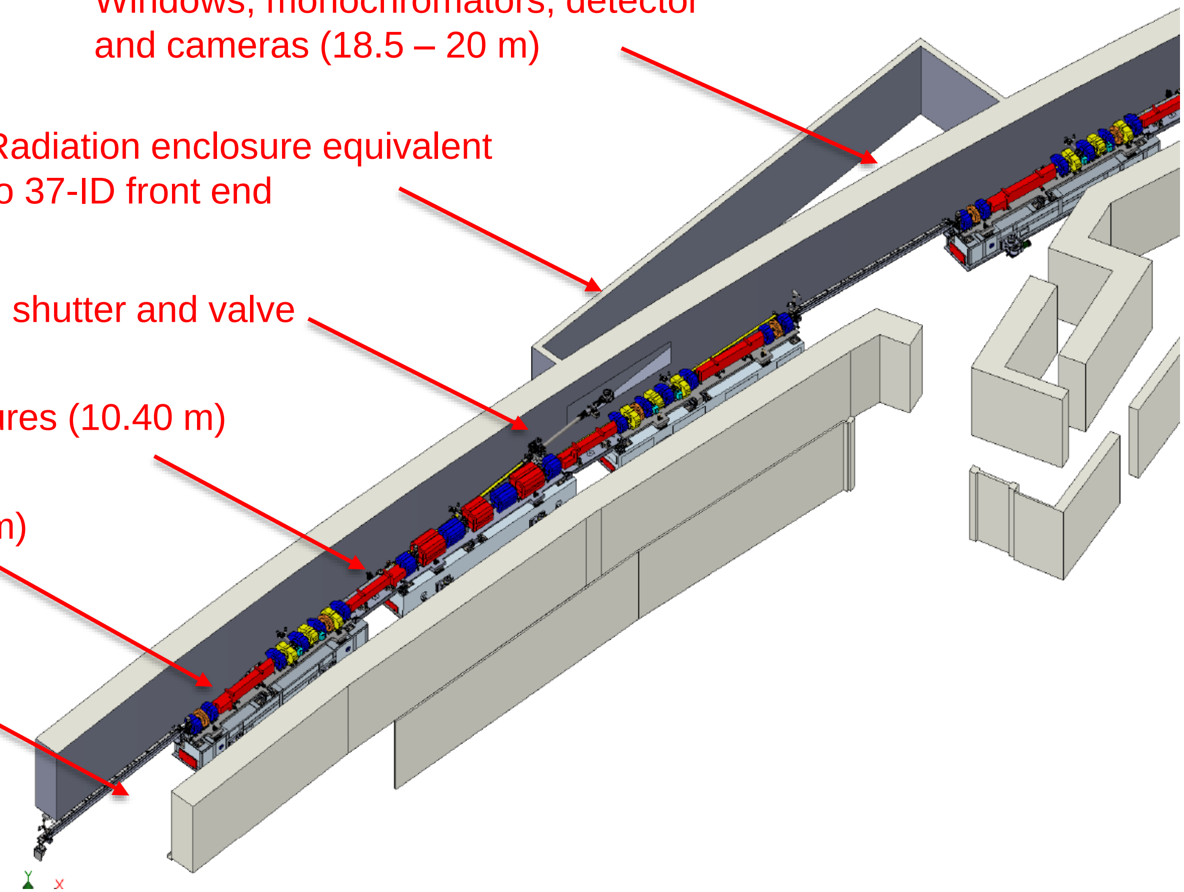
XBPM1 (for beam angle) is mounted on the x-ray aperture holder.



XBPM2 (for source point) shares the same mono and support with the RBSM detectors.

Implementation: Optics & Mechanics

- Beam Size Monitor will use S38A:M1 as the source, sharing the same straight section with the RF cavities in S37ID.
- Enclosure's radiation shielding managed 37-ID Front End.

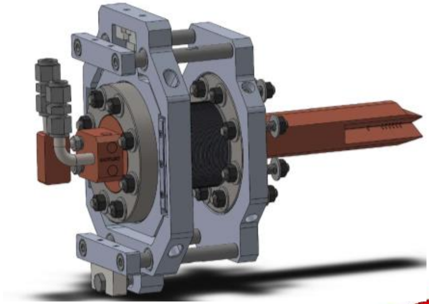


Mechanical Design: Vibration Control

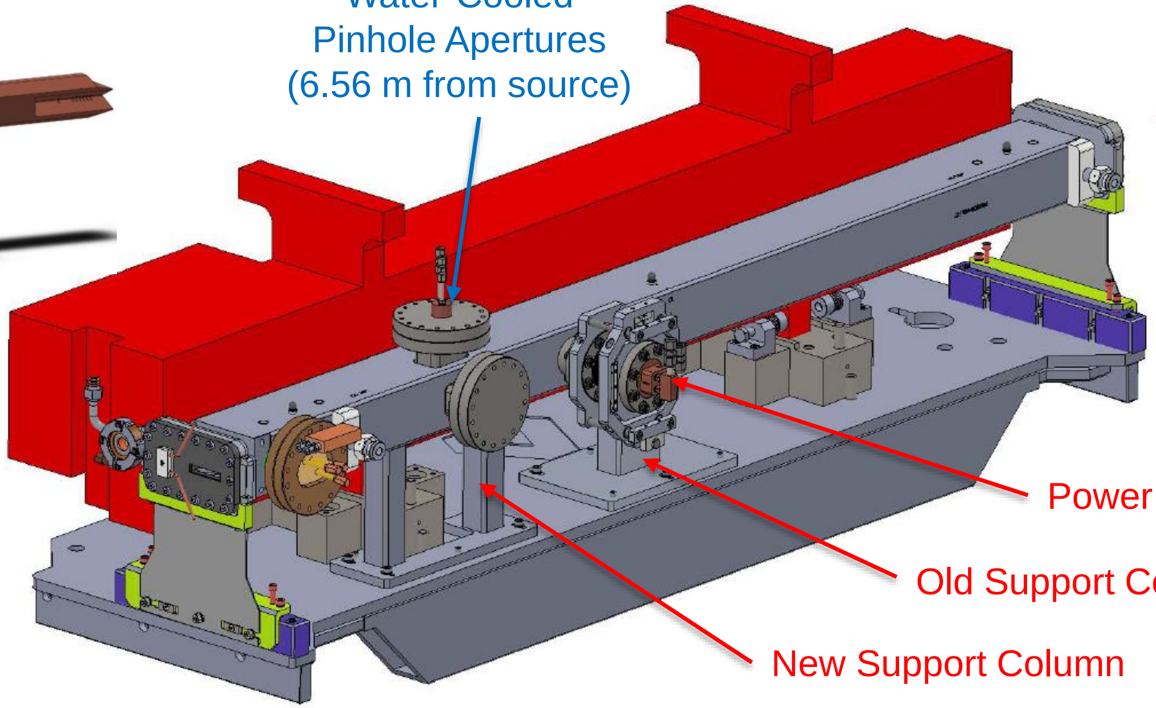
"Vibration-free" mounting for the pinhole apertures:

- Water-cooled absorber incepts ~75% beam power, lowers aperture flow req.
- Water-cooled x-ray apertures are mounted rigidly on the storage ring chamber.
- Reduce chamber flexing by placing support column under the apertures.

Estimated RMS vibration amplitude < 0.1 μm. XBPM handles slow motion.



Water-Cooled GlidCop absorber

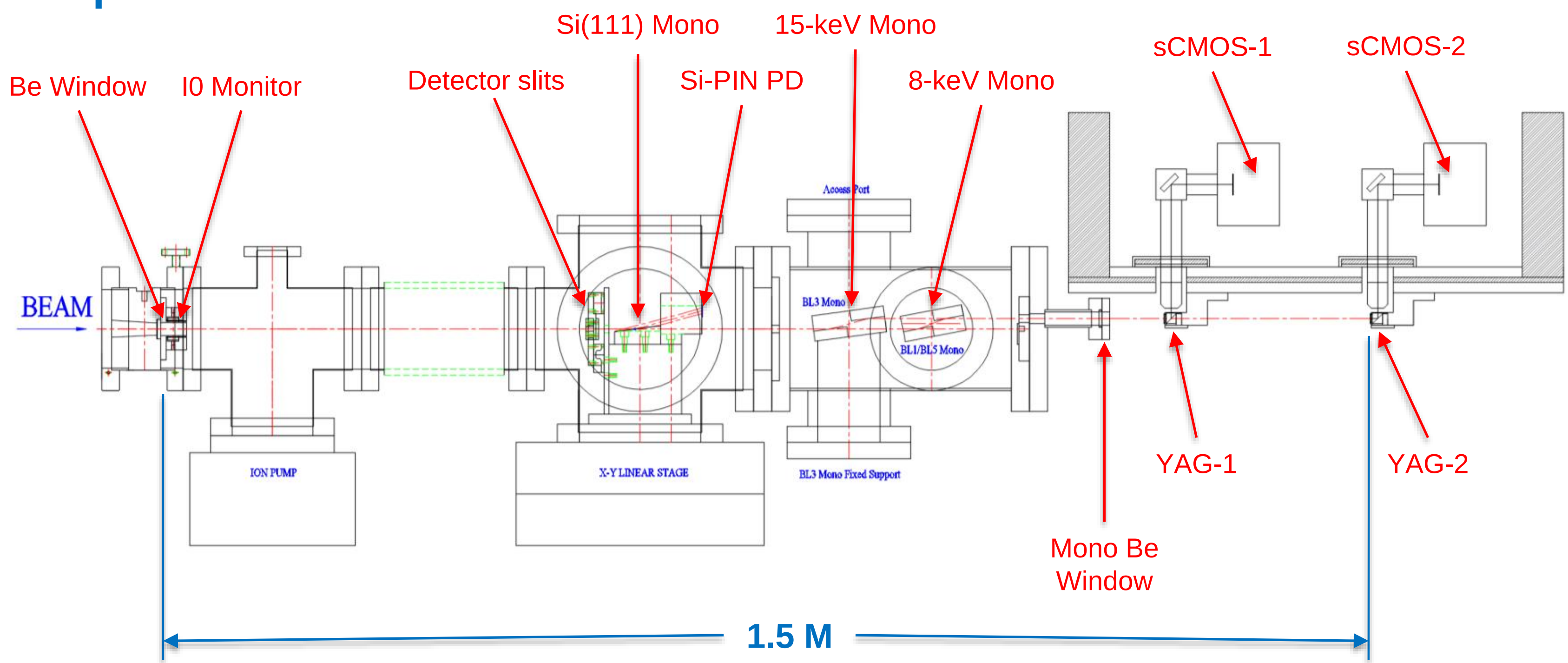


X-ray Optics Design

Coherence preservation is the most important consideration:

- Place transmission optics (window, lens, filters,…) at the very end.
- Place reflective optics (mirrors, monochromators,…) at the very end.

X-ray photons travel in vacuum in the first 92% of the beamline. Its wavefront only disturbed by diffraction apertures. Aperture edge perfection is important.



To preserve coherence, the first window is placed 1.5 M upstream of the last YAG screen

Summary

- The A:M1 source is very important to successful APS-U storage ring emittance diagnostics:
  - Low dispersion allows for clean emittance measurements
  - Larger beam sizes relax resolution requirements (>2x)
- An array of six x-ray diffraction apertures will be used:
  - For absolute beam size measurements, we will use a pinhole camera, a wide aperture Fresnel diffractometer and a Young's double-slit interferometer.
  - For relative beam size changes, 1-D double-slit collimator will be used to monitor normalized peak intensities.
- Coherence preservation is the most important concern.

The diagnostics cover all expected storage ring beam conditions, including extremely small vertical beam emittance (< 0.4 pm). Upgrade to 0.1-pm is possible with different set of double slits.