# Beam coherence control and diffraction limited focusing for APS-U beamlines — layout design and optics requirements

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Thank Dr. Ruben Reininger for the many discussions.

# Outline

- Overview on beam coherence
- Beam coherence control and diffraction limited focusing with different layouts
- Beamline design examples – ISN

# Coherence length

- Longitudinal (Temporal) coherence
  - Determined by monochromaticity

$$l_c = \lambda^2/\Delta\lambda$$

For $\lambda/\Delta\lambda$ = 7000 (Si 111), $\lambda$ = 0.1 nm, $l_c$ = 0.7 µm

$l_c >> \mathit{max\ path\ difference}$ ($W\theta$) to ensure good contrast

- Transverse (Spatial) coherence
  - Determined by collimation
  - Quantitatively, the transverse coherence length is described as the distance between the two narrow slits in the Young's experiment which drops the interference fringes contrast to exp(-1/2) = 0.6.
  - For a Gaussian distributed source with the rms size of $\Sigma$

$$L_c = \frac{\lambda D}{2\pi\Sigma} \approx 0.16\frac{\lambda D}{\Sigma}$$

H. Onuki and P. Elleaume, *Undulators, Wigglers and Their Applications* (Taylor and Francis, London, 2003).

  - For a flat rectangular beam with size $\Delta$,

$$L_c = \frac{\lambda D}{2\Delta}$$

# Transverse coherence length (continue)

- Another way of defining $L_c$ comes from the phase space area. For a Gaussian laser mode with rms size and angle width of $\sigma$ and $\sigma'$, we have

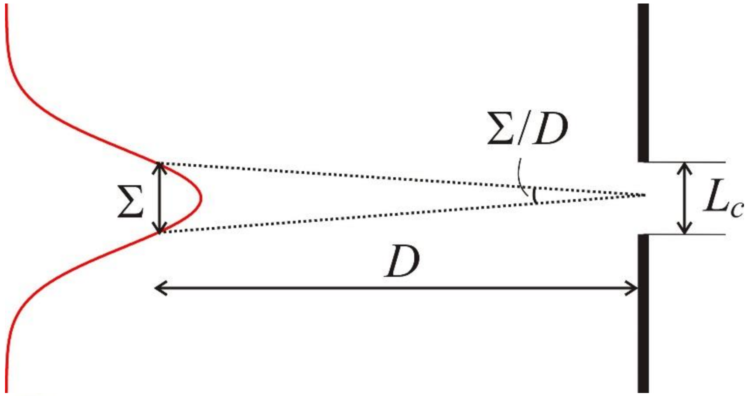
$$\sigma\sigma' = \lambda/4\pi$$

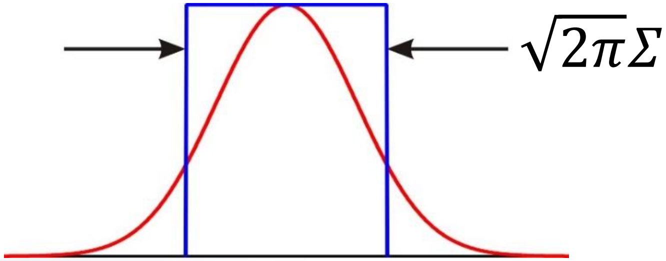
- Considering a rectangle of width $\Delta = \sqrt{2\pi}\Sigma$ and height 1 has the same area as a Gaussian of rms width $\Sigma$ and height 1, we have

$$\Delta\Delta' = \lambda/2$$

- Coherence by propagation (van Cittert-Zernike theorem) of a Gaussian beam

$$L_c \frac{\sqrt{2\pi}\Sigma}{D} = \frac{\lambda}{2} \Rightarrow L_c = \frac{\lambda D}{2\sqrt{2\pi}\Sigma} \approx 0.2\frac{\lambda D}{\Sigma}$$





# Coherence mode

- The number of coherence mode of the source is

$$m_x = \frac{\Sigma_x \Sigma'_x}{(\lambda/4\pi)}, \qquad m_y = \frac{\Sigma_y \Sigma'_y}{(\lambda/4\pi)}$$

Electron $\otimes$ photon = Total

$$\sigma_x = \sqrt{\varepsilon_x \beta_x}$$

$$\sigma_y = \sqrt{\varepsilon_y \beta_y}$$

$$\sigma'_x = \sqrt{\varepsilon_x / \beta_x}$$

$$\sigma'_y = \sqrt{\varepsilon_y / \beta_y}$$

$$\sigma_r = \frac{\sqrt{2\lambda L_u}}{2\pi}$$

$$\sigma'_r = \sqrt{\frac{\lambda}{2L_u}}$$

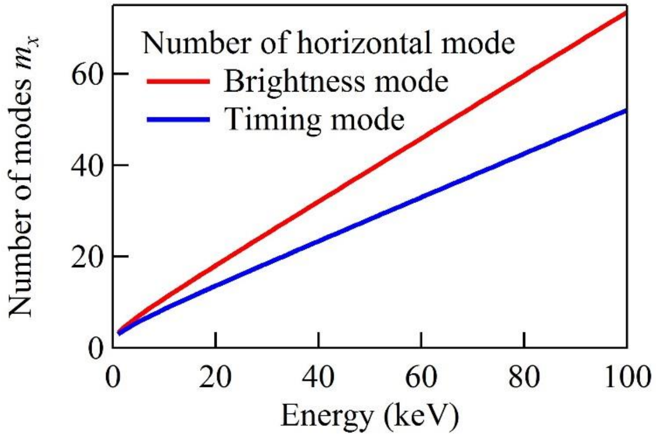
$$\Sigma_x = \sqrt{\sigma_x^2 + \sigma_r^2}$$

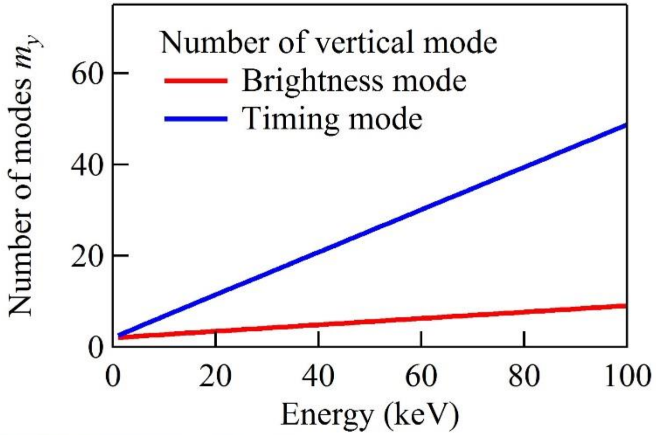
$$\Sigma_y = \sqrt{\sigma_y^2 + \sigma_r^2}$$

$$\Sigma'_x = \sqrt{\sigma_x'^2 + \sigma_r'^2}$$

$$\Sigma'_y = \sqrt{\sigma_y'^2 + \sigma_r'^2}$$

| APS-U | Brightness mode | | Timing mode | |
|---|---|---|---|---|
| ***E* (keV)** | 10 | 50 | 10 | 50 |
| $\Sigma_x$ (μm) | 22.5 | 21.9 | 18.9 | 18.3 |
| $\Sigma_x'$ (μrad) | 4.8 | 3.5 | 4.4 | 3.0 |
| $\Sigma_y$ (μm) | 6.8 | 4.7 | 11.8 | 10.8 |
| $\Sigma_y'$ (μrad) | 4.0 | 2.3 | 5.7 | 4.7 |





# Phase space arguments

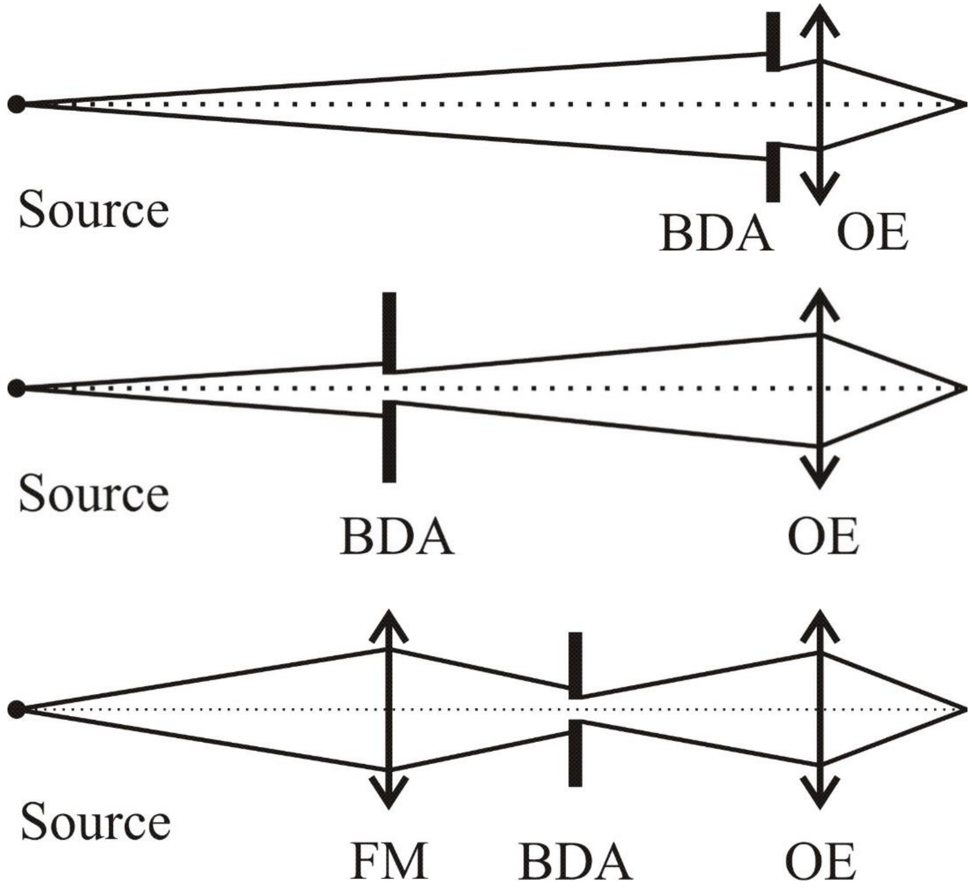
- If the acceptance of the experiment is greater than the beam emittance then 100% of the beam can be accepted — this is a **flux experiment**
- If the phase-space acceptance of the experiment is smaller than the phase-space area of the x-ray beam then light must be lost — in this case we say it is a **brightness experiment**
- If the acceptance of the experiment is for a beam of phase-space area $\lambda/2$ then this is a **coherence experiment** (STXM, Phase-contrast imaging, CDI, Ptychography, XPCS) and light must always be lost

Courtesy of Malcolm Howells

- The phase-space density of photons cannot be increased.
  - Geometric optics and aperture preserve the phase-space density but cut the phase space volume
  - Wave (diffraction) optics and aperture also reduce the phase-space density

# General beamline layout consideration

- Three cases to control beam coherence and focusing properties



Common parameters:

Source-to-sample *D* = 70 m

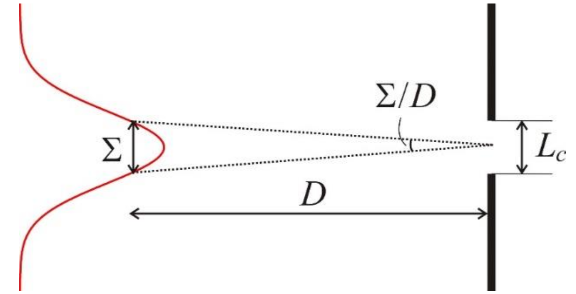
Working distance *W* = 100 mm

- To compare
  - Coherence control
  - Focusing capability
  - Vibration effects

# Some general equations

- Coherence length

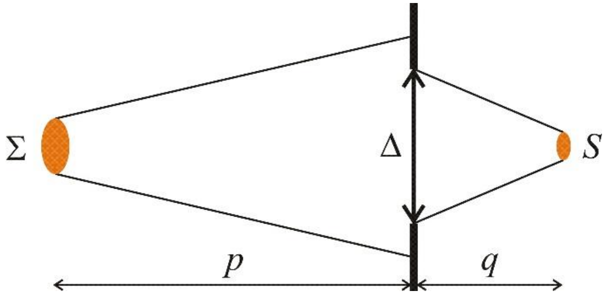
$$L_c = \frac{\lambda D}{2\sqrt{2\pi}\Sigma}$$



- Focal size (FWHM)

$$S = \sqrt{S_{\text{geo}}^2 + S_{\text{dif}}^2}$$

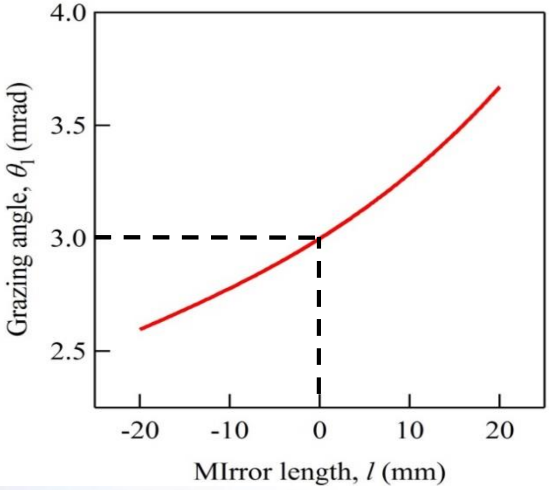
$$S_{\text{geo}} = \frac{2.355 q\Sigma}{p}, \qquad S_{\text{dif}} = \frac{0.88\lambda q}{\Delta}$$



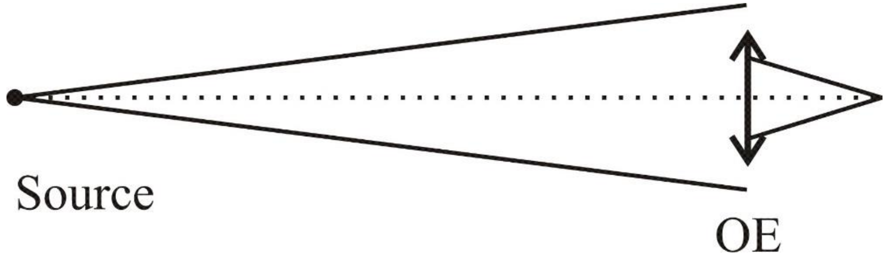
- Mirror aperture

$$\Delta \approx L \sin\theta$$

$\theta$ — grazing angle at the mirror center

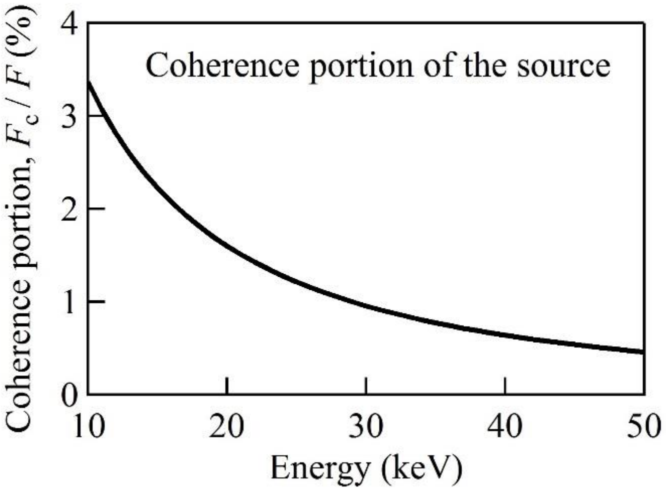


# Direct focusing approach



Source-to-sample $D$ = 70 m
Working distance $W$ = 100 mm

- Exploits the source size
- Coherence controlled by OE aperture (OE size)
- Overall stability



| **$E$ (keV)** | 10 |
|---:|:---:|
| **$L_c$, H (μm)** | 77 |
| **$L_c$, V (μm)** | 254 |
| **$\theta$ (mrad)** | 4 |
| **$L_{\text{mirror}}$, H (mm)** | **19** |
| **$L_{\text{mirror}}$, V (mm)** | **63** |
| **focal size, H (nm)** | 176 |
| **focal size, V (nm)** | 74 |
| **Total transmission** | 2.7% |
| **# of Coherence mode** | 1 |

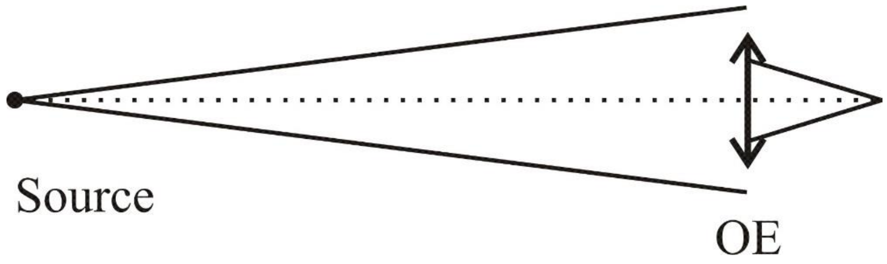
$$L_c = \frac{\lambda D}{2\sqrt{2\pi}\Sigma}$$

$$L = \frac{L_c}{\sin\theta}$$

$$S = \sqrt{S_{\text{geo}}^2 + S_{\text{dif}}^2}$$

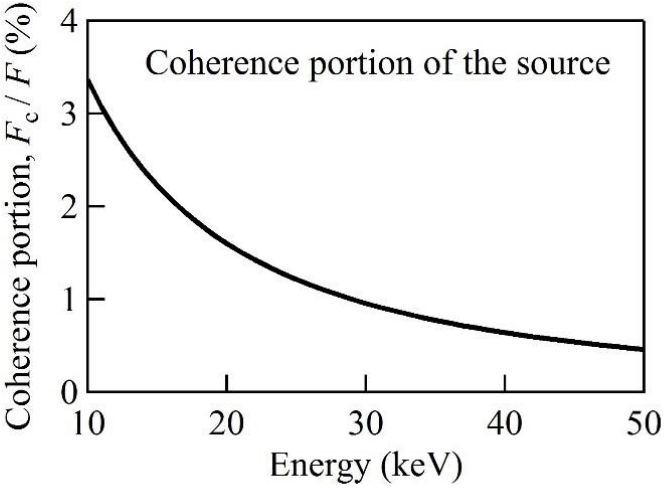
Mirror acceptance
Mirror reflectivity×2

# Direct focusing approach



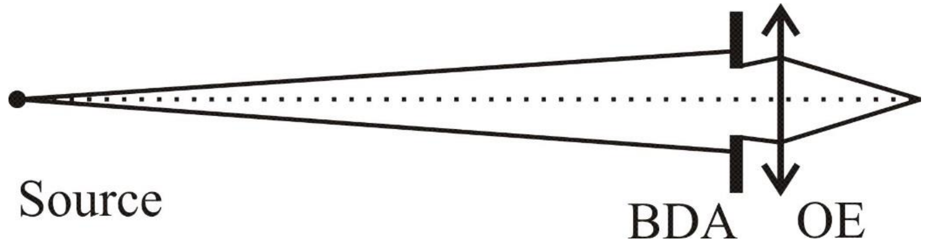
Source-to-sample $D$ = 70 m
Working distance $W$ = 100 mm

- Exploits the source size
- Coherence controlled by OE aperture (OE size)
- Overall stability



| ***E* (keV)** | 10 | 30 | 50 |
|---:|:---:|:---:|:---:|
| **$L_c$, H (μm)** | 77 | 26 | 16 |
| **$L_c$, V (μm)** | 254 | 112 | 73 |
| **$\theta$ (mrad)** | 4 | 2 | 1.5 |
| **$L_{mirror}$, H (mm)** | 19 | 13 | 11 |
| **$L_{mirror}$, V (mm)** | 63 | 56 | 49 |
| **focal size, H (nm)** | 176 | 168 | 165 |
| **focal size, V (nm)** | 74 | 52 | 46 |
| **Total transmission** | **2.7%** | **0.8%** | **0.4%** |
| **# of Coherence mode** | 1 | 1 | 1 |

# Direct focusing approach



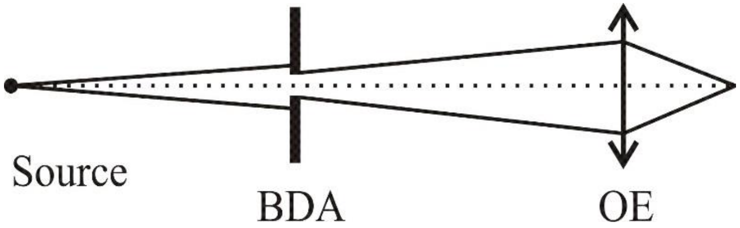
Source-to-sample $D$ = 70 m
Working distance $W$ = 100 mm

- Exploits the source size
- Coherence controlled by BDA size in front of OE

- Overall stability
- Larger size with smaller aperture
- Trade off between coherence and spot size and transmission.

| **$E$ (keV)** | 10 | | |
|---|---|---|---|
| **$L_c$, H×V (µm)** | 77×254 | | |
| **$\theta$ (mrad)** | 4 | | |
| **$L_{\mathrm{mirror}}$, H (mm)** | **200** | | |
| **$L_{\mathrm{mirror}}$, V (mm)** | **200** | | |
| **BDA size, H×V (µm)** | 77×254 | 154×508 | Open |
| **focal size, H×V (nm)** | 320×195 | 208×126 | 150×107 |
| **Total transmission** | 2.7% | 25.6% | 55% |
| **# of Coherence mode** | 1 | 4 | 30 |

# Slits as secondary source



Source-to-sample *D* = 70 m
Working distance *W* = 100 mm
Source-to-BDA distance: 30 m

Widely used at current APS in the horizontal direction

Same transmission for the coherence beam as the direct focusing approach

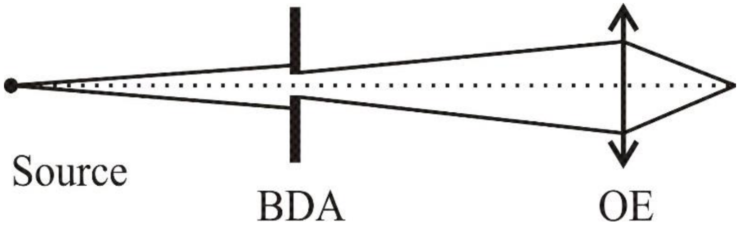
| **$E$ (keV)** | 10 |
|---|---|
| **$L_c$, H (µm) @ BDA** | 33 |
| **$L_c$, V (µm) @ BDA** | 109 |
| **$\theta$ (mrad)** | 4 |
| **BDA size H (µm)** | 33 |
| **BDA size V (µm)** | 109 |
| **$L_{mirror}$, H (mm)** | 200 |
| **$L_{mirror}$, V (mm)** | 200 |
| **focal size, H (nm)** | 339 |
| **focal size, V (nm)** | 515 |
| **Total transmission** | 2.7% |
| **Coherence mode** | 1 |

$$L_c = \frac{\lambda D}{2\sqrt{2\pi}\Sigma}$$

$$S = \sqrt{S_{\text{geo}}^2 + S_{\text{dif}}^2}$$

BDA acceptance
Mirror reflectivity×2

# Slits as secondary source



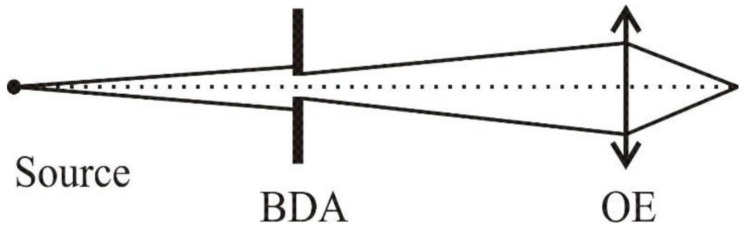
Source-to-sample *D* = 70 m
Working distance *W* = 100 mm
Source-to-BDA distance: 30 m

- BDA control focal size
- BDA control coherence
- Isolate source and mono vibration

- Focal position changes
- BDA need to be as close to the source as possible

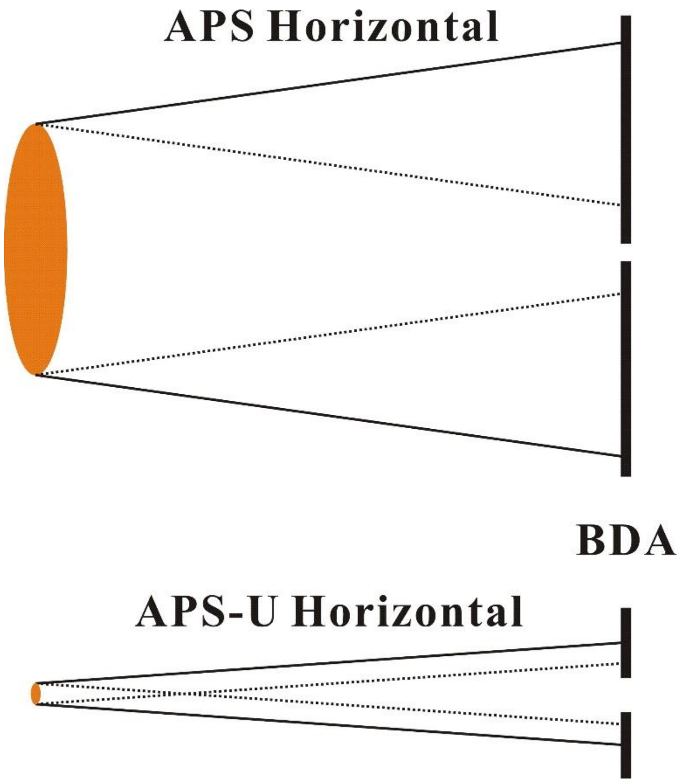
| ***E*** **(keV)** | 10 | 30 | 50 |
|---:|:---:|:---:|:---:|
| $L_c$, **H (μm) @ BDA** | 33 | 11 | 7 |
| $L_c$, **V (μm) @ BDA** | 109 | 48 | 31 |
| $\theta$ **(mrad)** | 4 | 2 | 1.5 |
| **BDA size H (μm)** | 33 | 11 | 7 |
| **BDA size V (μm)** | 109 | 48 | 31 |
| $L_{mirror}$, **H (mm)** | 200 | 200 | 200 |
| $L_{mirror}$, **V (mm)** | 200 | 200 | 200 |
| **focal size, H (nm)** | 339 | 116 | 70 |
| **focal size, V (nm)** | 515 | 230 | 152 |
| **Total transmission** | **2.7%** | **0.8%** | **0.4%** |
| **Coherence mode** | 1 | 1 | 1 |

# Focusing the source or the BDA?



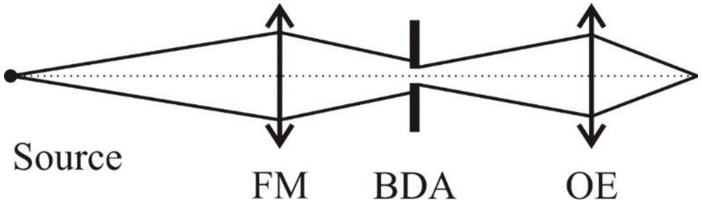
- Where is the source

| $E$ (keV) | 10 | |
|---|---|---|
| | **APS** | **APS-U** |
| $\Sigma_x$ (μm) | 273 | 22.5 |
| $L_c$, H (μm) @ 30 m | 2.7 | 33 |



Since the BDA cannot be placed too close to the source, this geometry is not recommended for APS-U.

# Secondary focusing approach

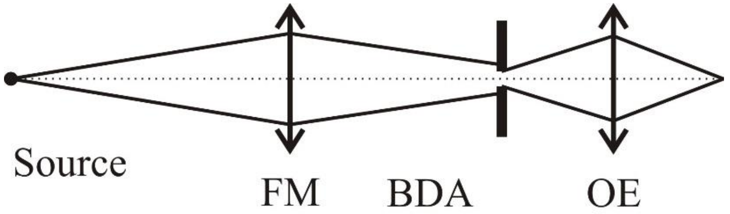


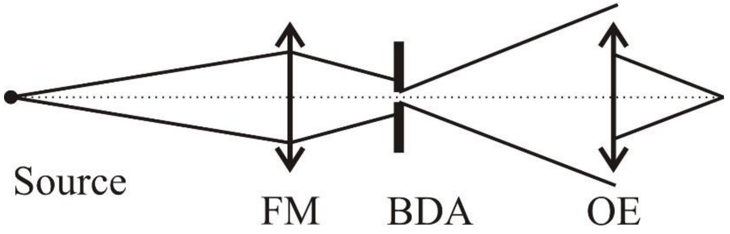
- Compact and stable instrument
- Overfilling of the slits makes the beamline less sensitive to drifts and vibrations
- Optical optimization is possible
- The secondary slit can be used to clean-up the beam (speckles from upstream components)
- Trade-off flux vs. resolution is tunable
- Small slit size hard to achieve

| | | | | |
|---|---|---|---|---|
| **$E$ (keV)** | 10 | | | |
| **$\theta$ (mrad)** | 4 | | | |
| **FM demag, H** | **1:1** | | | |
| **FM demag, V** | **1:1** | | | |
| **$L_c$, H (μm) @ BDA** | 5.2 | | | |
| **$L_c$, V (μm) @ BDA** | 6.3 | | | |
| **BDA size H (μm)** | 5.2 | 10 | 21 | Open |
| **BDA size V (μm)** | 6.3 | | | |
| **$L_{\text{mirror}}$, H (mm)** | 200 | | | |
| **$L_{\text{mirror}}$, V (mm)** | 200 | | | |
| **focal size, H (nm)** | 215 | 413 | 796 | 2100 |
| **focal size, V (nm)** | 130 | | | |
| **Total transmission** | 2.3% | 4.6% | 9% | 25% |
| **# of Coherence mode** | 1 | 2 | 4 | 30 |

Not diffraction limited by OE

# Secondary focusing approach





- Larger FM demagnification gives smaller beam size
- Need even smaller BDA size
- Larger beam size at OE

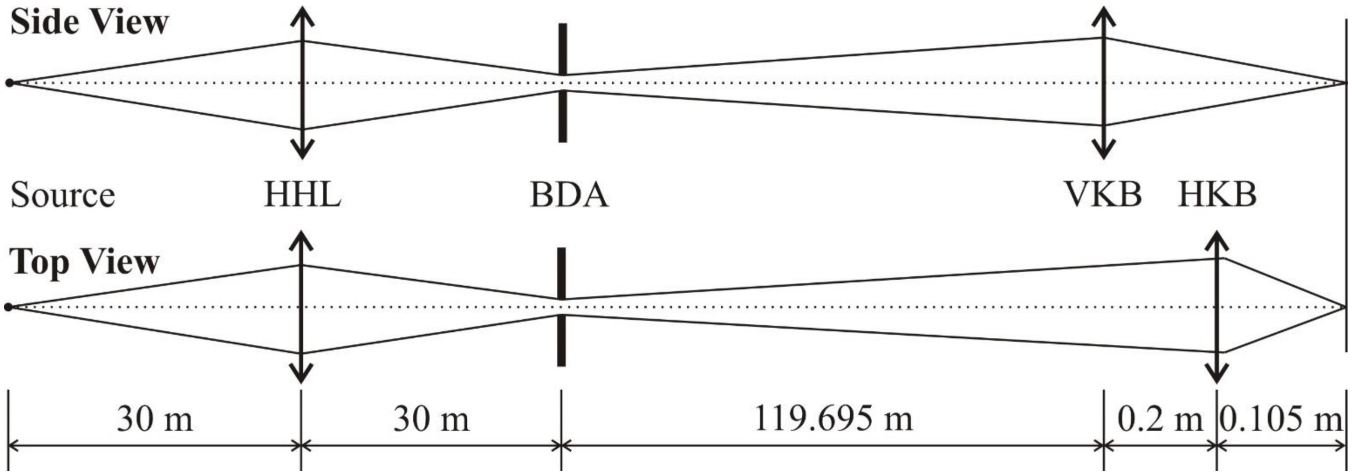
- Optical optimization required to match the BDA size and OE acceptance

Diffraction-limited Focusing by OE

| **$E$ (keV)** | **10** | **10** |
|---:|:---:|:---:|
| **$\theta$ (mrad)** | 4 | 4 |
| **FM demag, H** | **1:1** | **3:1** |
| **FM demag, V** | **1:1** | **3:1** |
| **$L_c$, H (μm) @ BDA** | 5.2 | 1.7 |
| **$L_c$, V (μm) @ BDA** | 6.3 | 2.1 |
| **BDA size H (μm)** | 5.2 | 1.7 |
| **BDA size V (μm)** | 6.3 | 2.1 |
| **$L_{mirror}$, H (mm)** | 200 | 200 |
| **$L_{mirror}$, V (mm)** | 200 | 200 |
| **focal size, H (nm)** | 215 | 59 |
| **focal size, V (nm)** | 130 | 30 |
| **Total transmission** | 2.3% | 0.32% |
| **# of Coherence mode** | 1 | 1 |

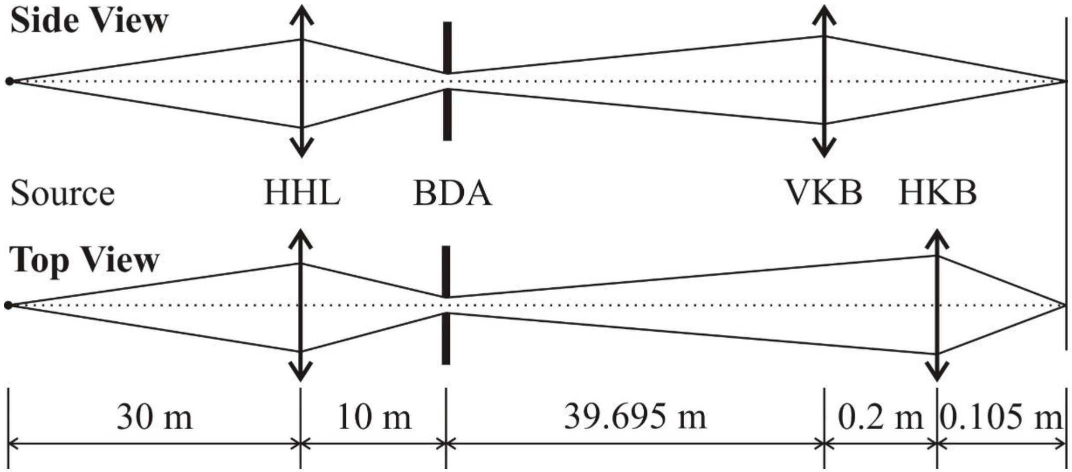
# In situ Nanoprobe (ISN) beamline

180 m long



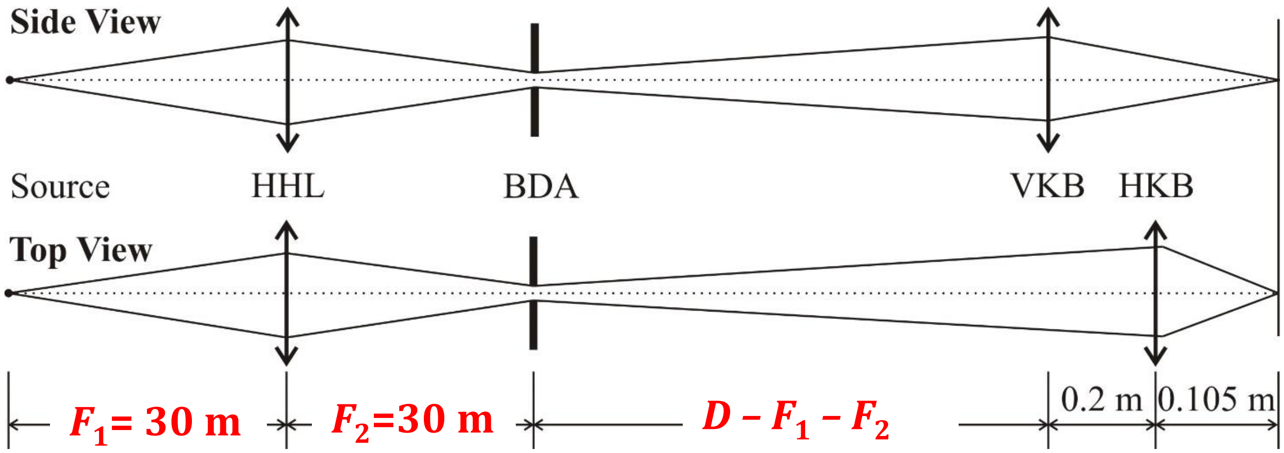
With different BDA size and Mono acceptance

80 m long



# In situ Nanoprobe (ISN) beamline

$D$ = 180 m



- Mirror length determined by the designed focal size of $S$ = 20 nm at 25 keV and a working distance of W = 55 mm.

$$\frac{0.88\lambda(L_H/2+W)}{L_H\sin\theta}=S, \qquad \frac{0.88\lambda(L_V/2+L_H+W)}{L_V\sin\theta}=S$$

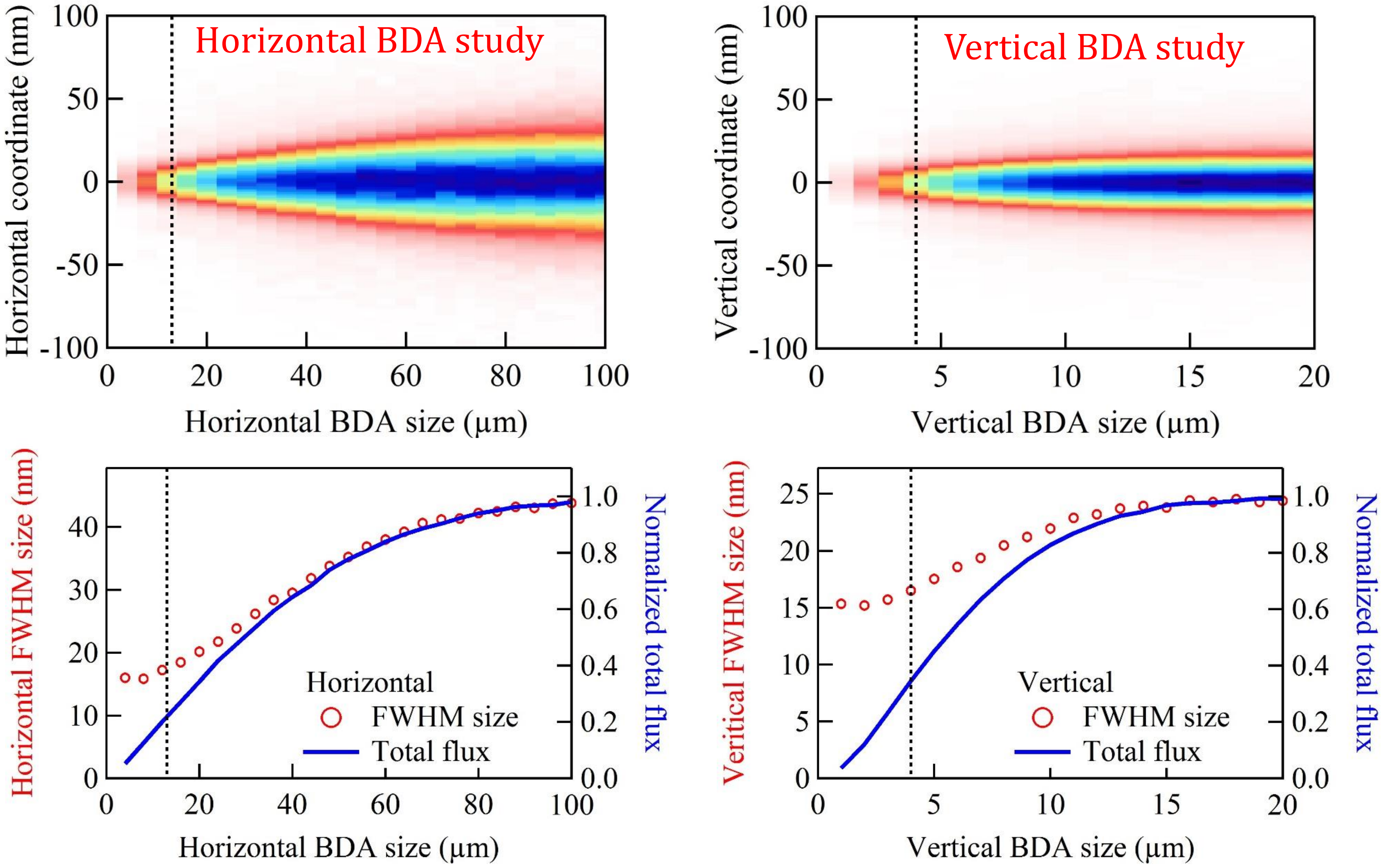
$L_H$ = 100 mm, $L_V$ = 300 mm

- BDA size determined by the coherent illumination of the mirrors.

$$\frac{0.44\lambda(D-F_1-F_2)}{\Delta}\geq L\sin\theta$$

$\Delta_H \leq$ 12 μm, $\Delta_V \leq$ 4 μm

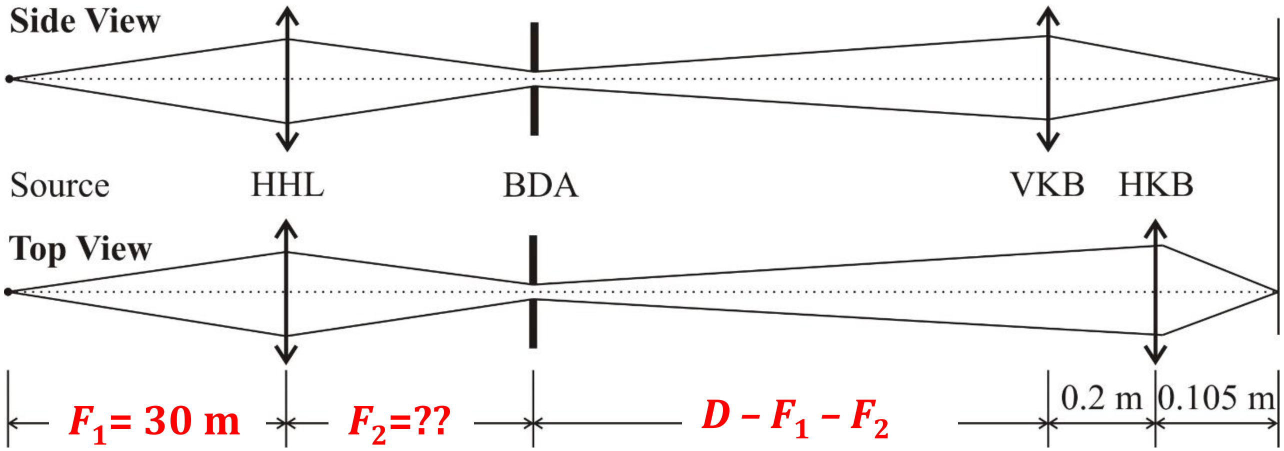
# ISN beamline



Required BDA size: H < 12 μm, V < 4 μm

# BDA size and location

***$D$* = 180 m**
***$E$* = 25 keV**



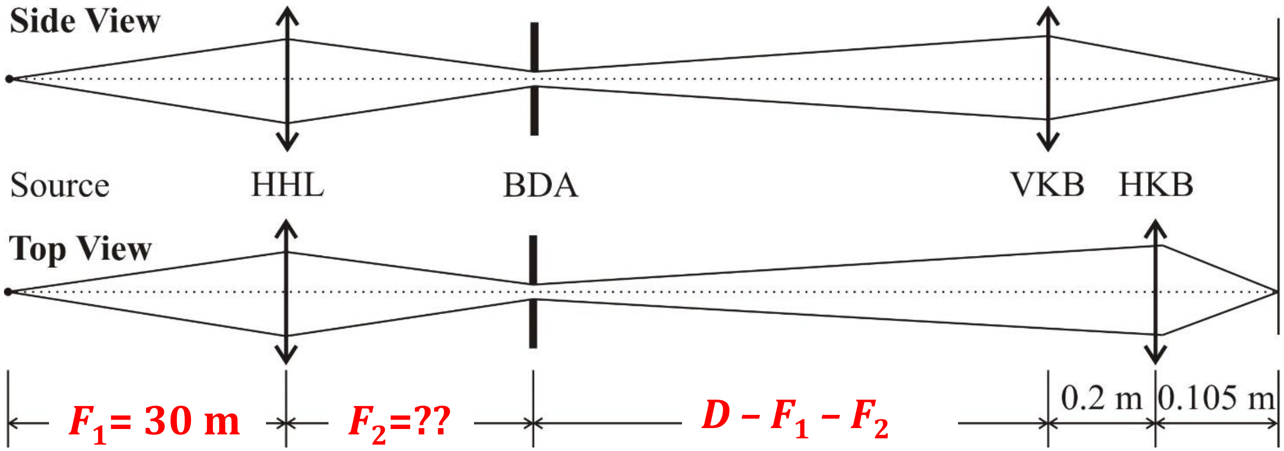
| HHL-to-BDA distance, $F_2$ | **30 m** |
|---|---|
| Horizontal | |
| RMS beam size at BDA (μm)(H) | 22 |
| BDA size to match HKB (μm)(H) | 12 |
| # of coherence mode at BDA(H) | 5.3 |
| Vertical | |
| RMS beam size at BDA (μm)(V) | 4.7 |
| BDA size to match VKB (μm)(V) | 4.0 |
| # of coherence mode at BDA(V) | 1.5 |

$\Sigma \frac{F_2}{F_1}$

Beam is coherent due to mirror acceptance

# BDA size and location

**$D$ = 180 m**
**$E$ = 25 keV**

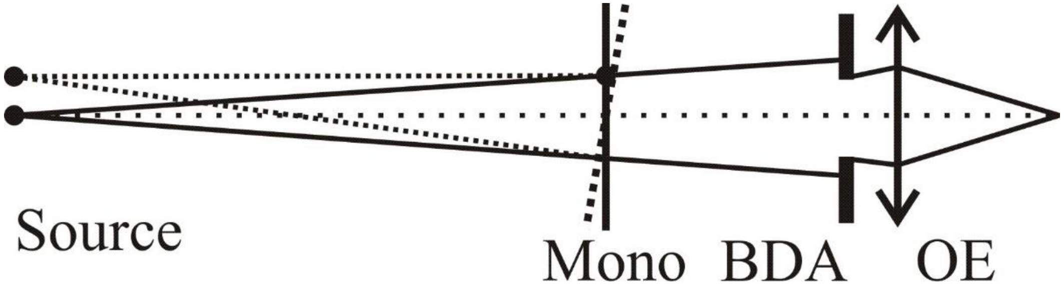


| HHL-to-BDA distance, $F_2$ | **20 m** | **30 m** | **40 m** |
|---|---|---|---|
| Horizontal | | | |
| RMS beam size at BDA (μm)(H) | 15 | 22 | 30 |
| BDA size to match HKB (μm)(H) | 24 | 12 | 11 |
| # of coherence mode at BDA(H) | 8.5 | 5.3 | 3.7 |
| Vertical | | | |
| RMS beam size at BDA (μm)(V) | 3.1 | 4.7 | 6.3 |
| BDA size to match VKB (μm)(V) | 7.3 | 4.0 | 3.6 |
| # of coherence mode at BDA(V) | 2.4 | 1.5 | 1.0 |
| **Total transmission** | 0.35% | 0.28% | 0.20% |

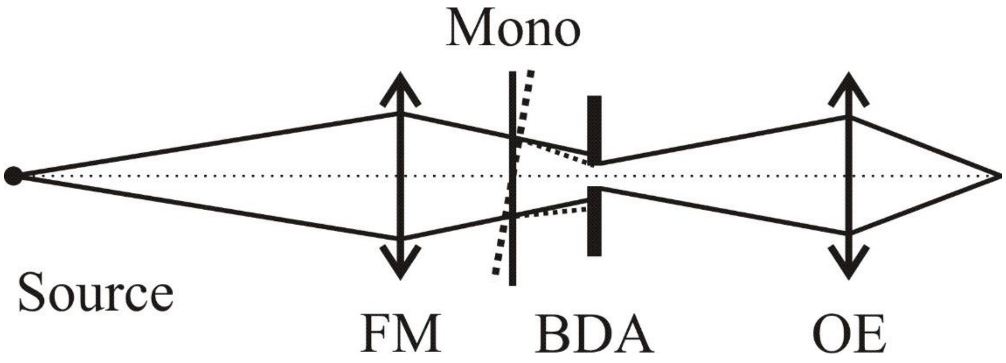
Small $F_2$:
Larger flux,
but no beam
size control

# Vibration effects on coherence beamline

- Mono vibration enlarges the virtual source and reduces the coherence length, therefore, smaller BDA sizes are needed to select the coherent portion of the beam.



- Larger source vibration effect
- Larger mono vibration effect
- Same OE vibration effect



- BDA serves as the new source, isolates the source, FM and Mono vibration.
- Same OE vibration effect

# Summary

- The direct focusing and the secondary focusing geometries are both suitable to the APS-U. The use of slit directly as the secondary source is not recommended.
- The direct focusing case gives the simple optical layout, but requires low vibration optics. Beam sizes cannot be controlled easily by the BDA size.
- The secondary focusing case provides the best focusing control and vibration isolation. The BDA position and size need to be optimized. Long beamline is necessary for the precise control of beam size and coherence.
- Beamline simulation is important for the beamline design optimization.
- R&D needed for coherence/wavefront preserving optics and high heat load optics.

# References

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Thank you!