U.S. DEPARTMENT OF ENERGY
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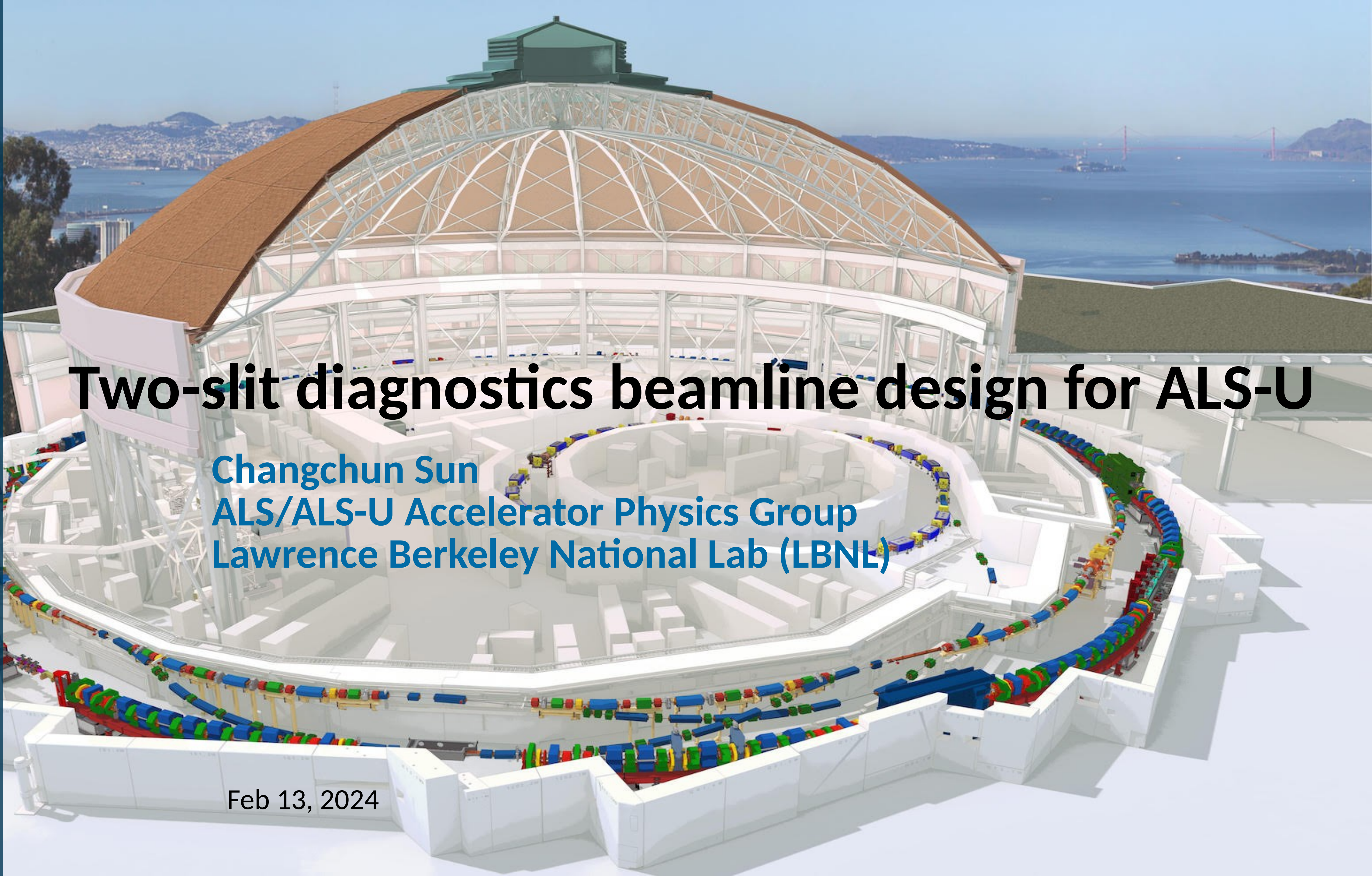
ALS-U
ADVANCED LIGHT SOURCE



# Two-slit diagnostics beamline design for ALS-U

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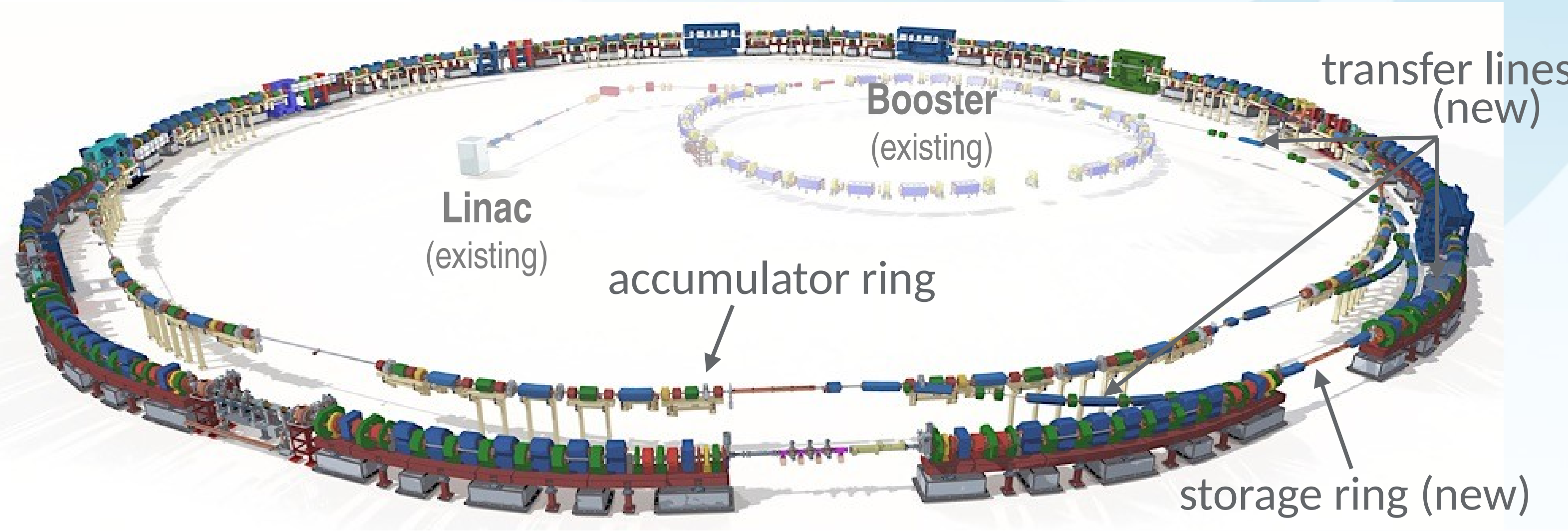
# Outline

- Introduction to ALS-U
- Physics aspects in ALS-U diagnostics beamline design
- Mechanical design

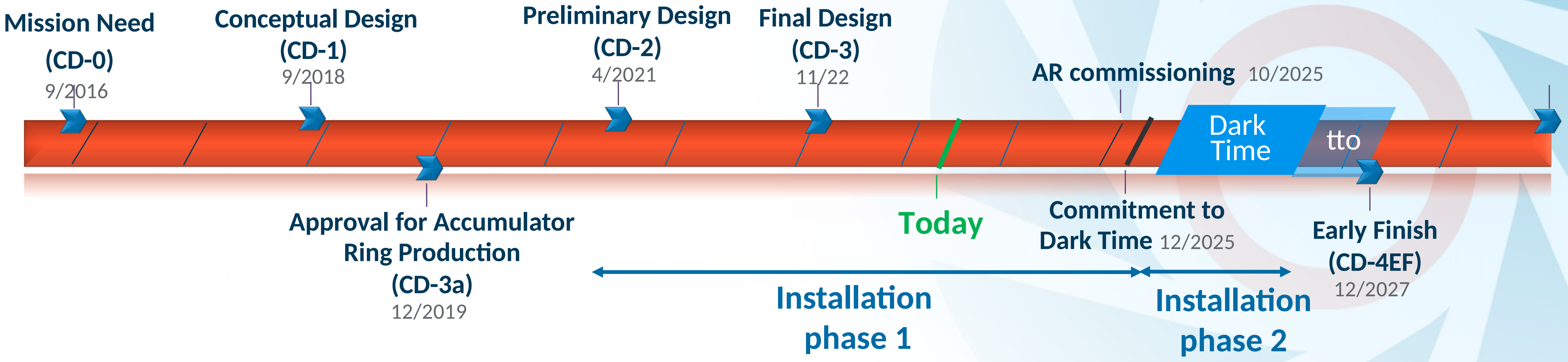
# ALS-U goal and accelerator scope

- ALS-U is an ongoing upgrade of the Advanced Light Source (ALS) at Berkeley Lab
- **Goal:** Deliver a word-leading light source that provides users with bright, high-coherent-flux soft x-rays
- New 2.0 GeV 9BA **storage ring** (SR) in existing tunnel optimized for low emittance and high soft x-ray brightness and coherent flux
- New 2.0 GeV **accumulator ring** (AR) for full-energy swap-out injection and recovery of bunch trains
- **Three transfer lines**
  - Booster to accumulator (BTA)
  - Accumulator to storage ring (ATS)
  - Storage ring to accumulator (STA)




Installing and commission the AR/BTA early to minimize the Dark Time

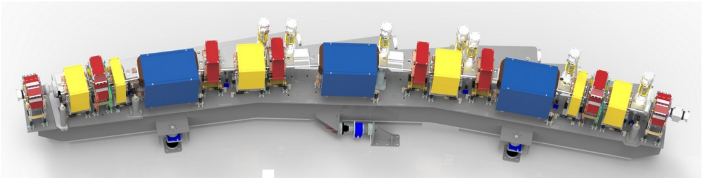
# ALS-U project timeline

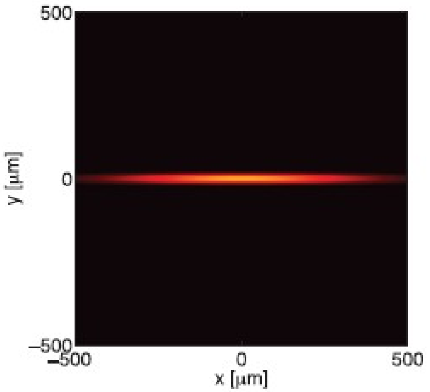



- Passed the US/DOE CD-3 milestone (Approve start of construction) in 11/2022
- Installation is separated into 2 phases to minimize the dark time
  - Tunnel prep and accumulator ring installation and testing conducted during ALS summer and winter shutdowns
- Integrated testing of accumulator ring will start in Oct 2025
- Dark Time is scheduled to be one year in duration starting in June 2026 followed by a 6-month transition to operations (tto) where beamlines are brought online

# ALS vs ALS-U

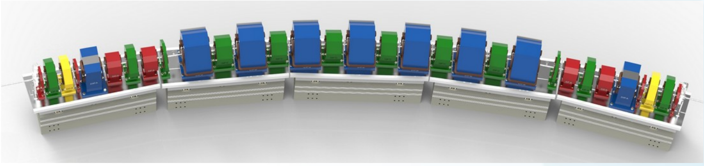
### ALS today : triple-bend achromat

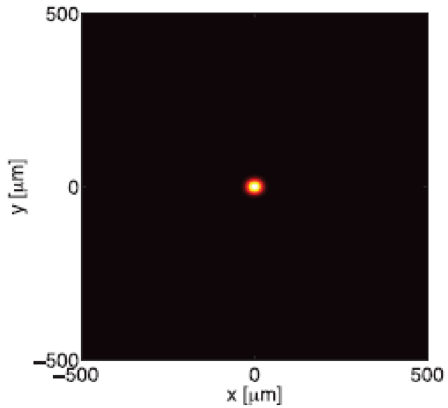





- Beam size is about 40umx7um
- Two diagnostic Bls at ALS
  - BL7.2 using x-ray pinhole
  - BL3.1 using KB mirror
- Resolution is about 30 um

### ALS-U: 9-bend achromat with reverse bends



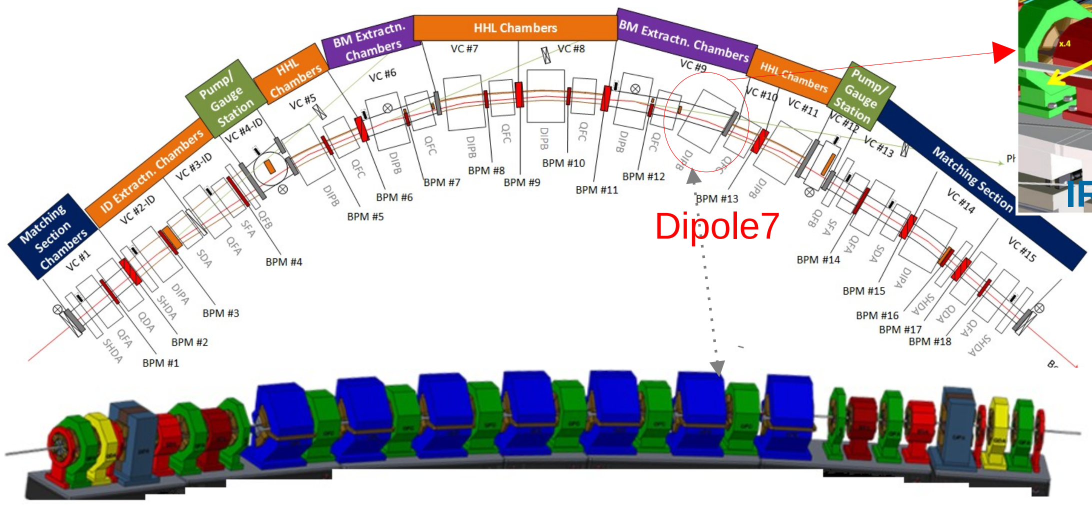


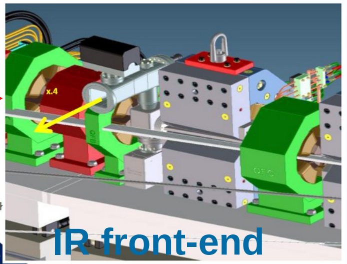

- Beam size is about 7umx10 um
- Need to a new BL with a higher resolution of

### ALS to ALS-U

| Parameter | Units | ALS | ALS-U |
|---|---|---|---|
| Electron energy | GeV | 1.9 | 2.0 |
| Beam current | mA | 500 | 500 |
| Horiz. emittance | pm-rad | 2000 | <75 |
| Vert. emittance | pm-rad | 30 | <75 |
| Beamsize @ ID center ($\sigma_x/\sigma_y$) | μm | 251 / 9 → | <14 / <14 |
| Beamsize @ bend ($\sigma_x/\sigma_y$) | μm | 40 / 7 → | <7 / <10 |
| bunch length (FWHM) | ps | 60-70 (harmonic cavity) | 120-200 (harmonic cavity) |
| Circumference | m | 196.8 | ~196.5 |

# A single diagnostic beamline based on 2-slit interferometer technique

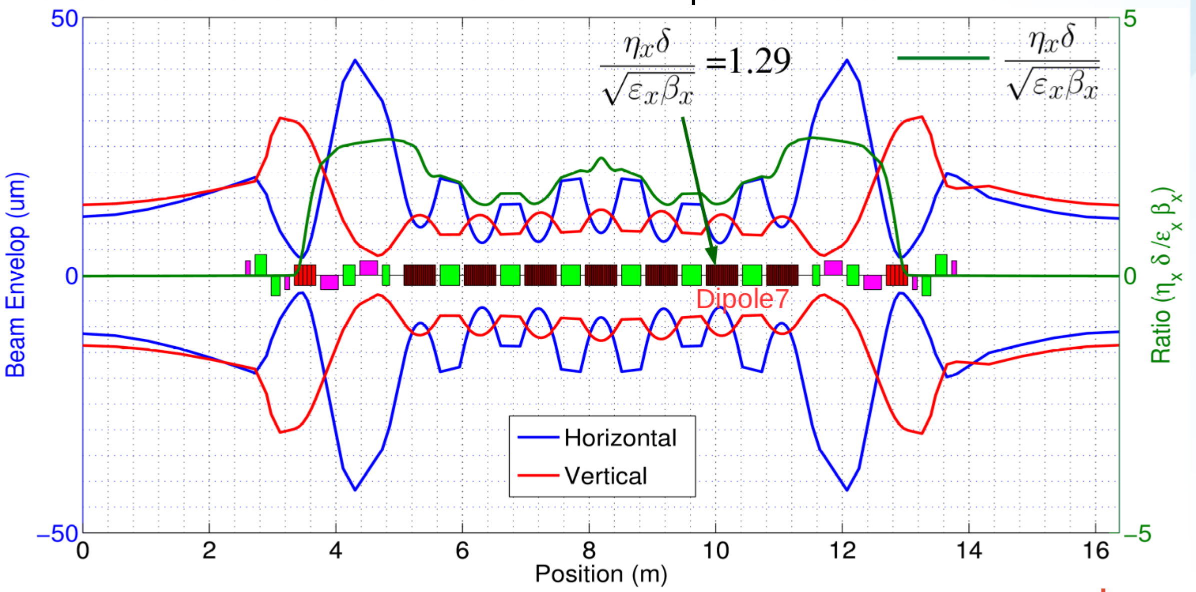



Design requirement

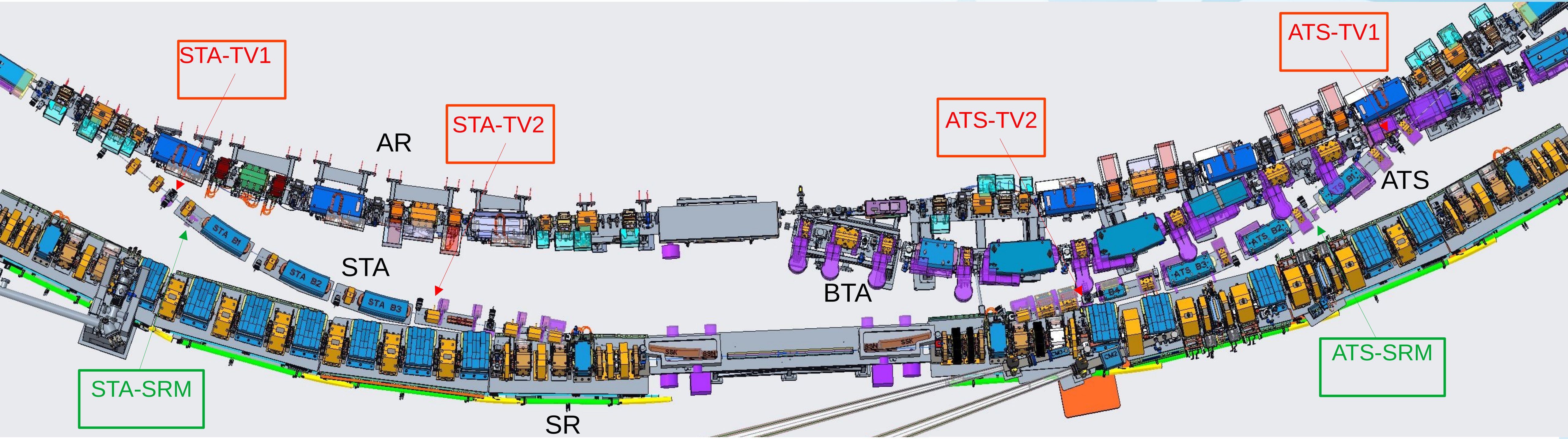
| | | | | | |
|---|---|---|---|---|---|
| 005307 | Shall | H Beam size measurement resolution | ≤ 0.5 | µm | Beam Physics |
| 005310 | May | H Beam size measurement resolution | ≤ 0.3 | µm | Beam Physics |
| 005311 | Shall | V Beam size measurement resolution | ≤ 0.5 | µm | Beam Physics |
| 005312 | May | V Beam size measurement resolution | ≤ 0.3 | µm | Beam Physics |
| 005308 | Shall | Vertical beam size range at measurement location | 4.5 - 25 | µm | Beam Physics (flat beam, 10% cpl-4x full cpl emit) |
| 005308.1 | Should | Vertical beam size range at measurement location | 1.5 - 25 | µm | Beam Physics (flat beam, 1% cpl-4x full cpl emit) |
| 005309 | Shall | Horizontal beam size range at measurement location | 3 - 13 | µm | Beam Physics |
| 005312 | Shall | H and V Emittance measurement accuracy at nominal round beam emittance | ≤20 | % | Beam Physics |
| 005314 | Shall | H and V Emittance measurement resolution at nominal round beam emittance | ≤10 | % | Beam Physics |

Beam size and dispersion



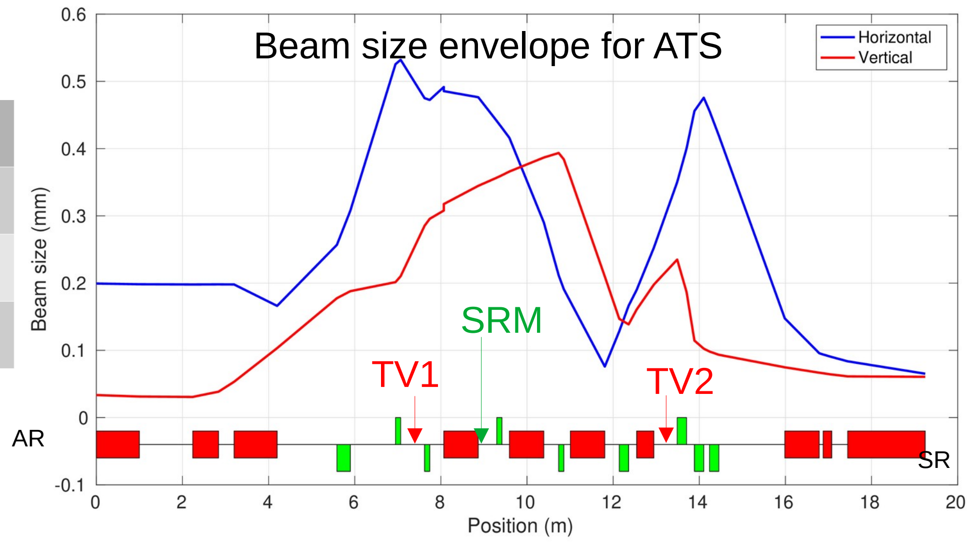

- A single diagnostics BL for SR based on 2-slit interferometer technique
  - Sharing the same front-end vacuum system design as the IR user beamline to save the project cost
  - Achieve horizontal resolution of 0.5 um and vertical resolution of 0.3 um
- The energy spread is independently measured at STA with less than 5% resolution

# Energy spread is measured at ATS/STA transferlines with TV screens




- 4 retractable scintillator screen (TV) and 2 synchrotron radiation profile monitors (SRM) for online measurement
- The beam size is dominated by energy spread due to small beta and large dispersion functions
- Less than 5% resolution can be achieved for energy spread measurement given <15 um resolution at TV2 screen

| | σx (um) | σy (um) |
|---|---|---|
| TV1 | 493 | 261 |
| TV2 | 319 | 223 |
| SRM | 492 | 321 |

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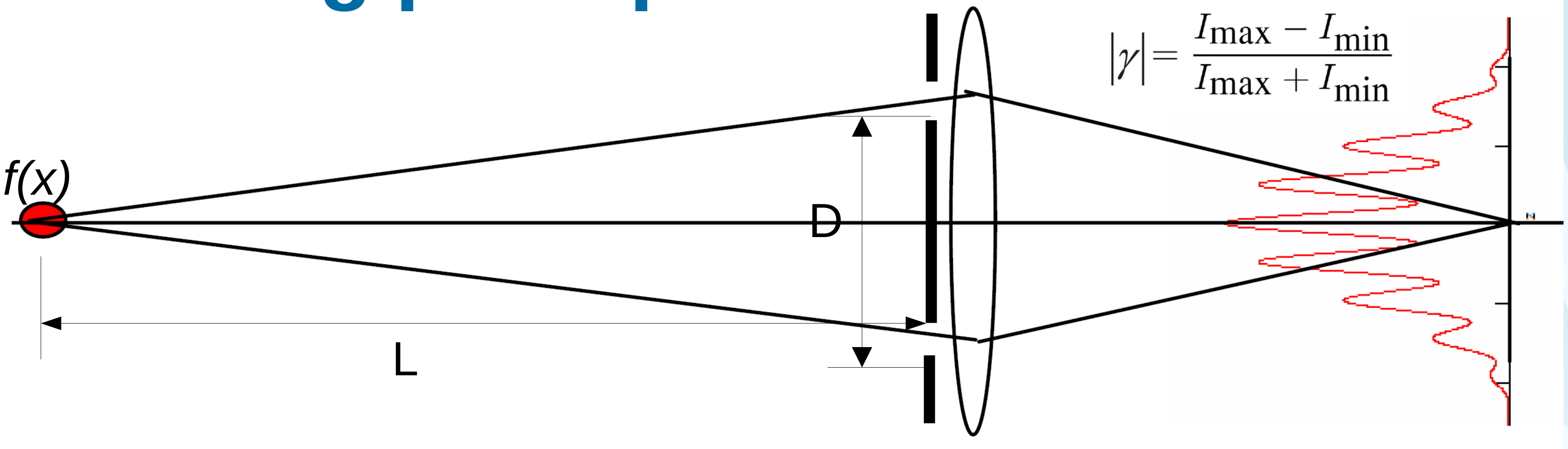
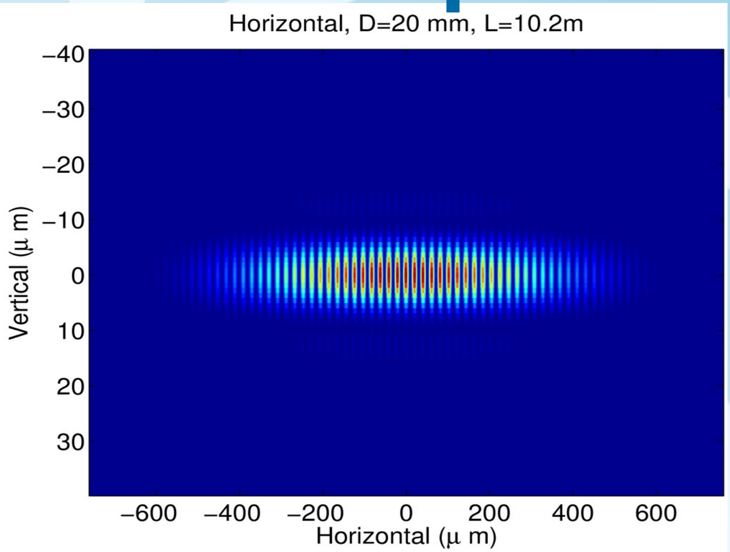
# Working principle of 2-slit interferometer technique




- The interference fringe is formed on the screen using two slits and lens
- The visibility |ɣ| (i.e., contrast) of the interference fringe is related to the beam size:

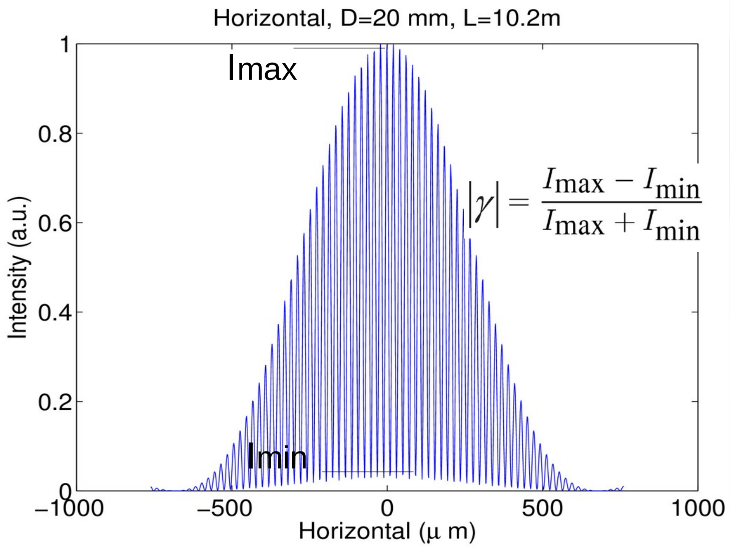
$$|\gamma| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \quad \begin{cases} |\gamma|=1 \text{ for a point source} \\ |\gamma|<1 \text{ for a finite source} \end{cases}$$

- ɣ is the complex degree of spatial coherence of the source given by the Fourier transform of the source profile f(x):

$$\gamma = \int dx f(x) \exp\left(-i\frac{2\pi D}{\lambda L}x\right)$$

- For a Gaussian Beam:

$$\sigma_x = \frac{\lambda L}{\pi D}\sqrt{\frac{1}{2}\ln\frac{1}{|\gamma|}}$$



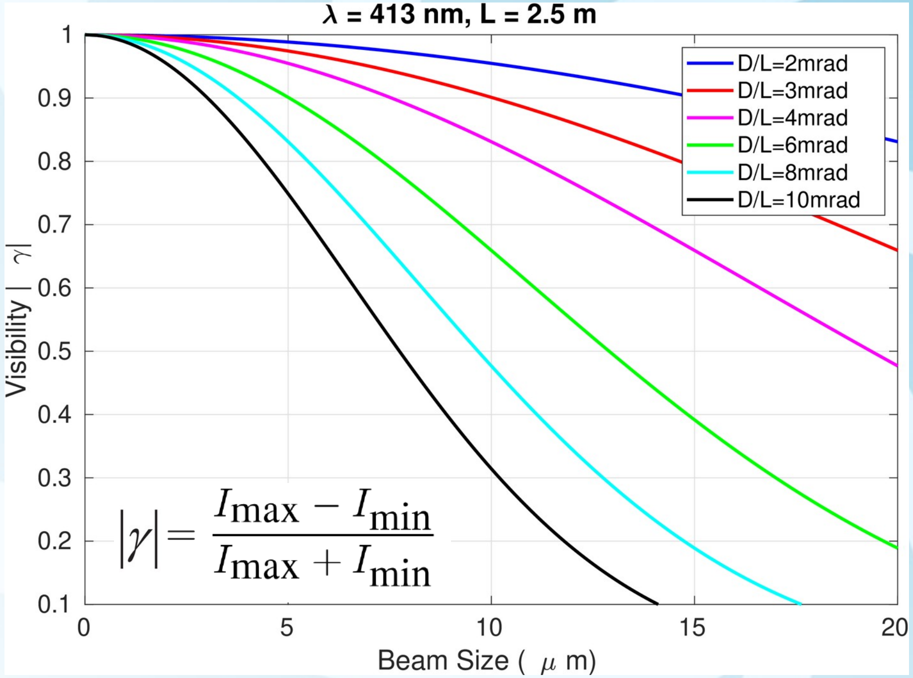

- For a given slit acceptance D/L, the beam size is derived from the measured visibility |ɣ| of interference fringes

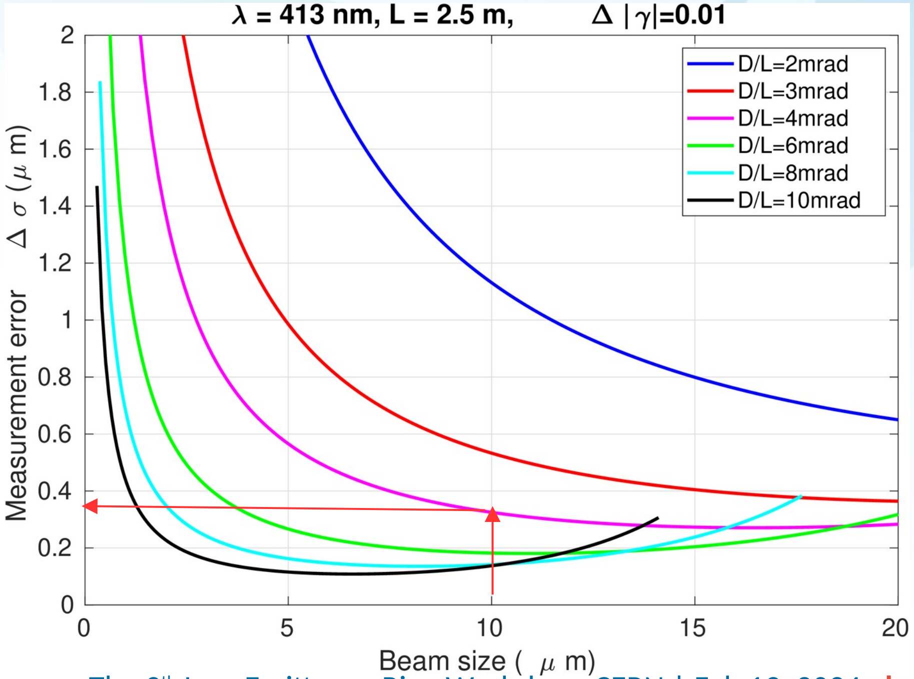
# Beam size measurement resolution

$$\sigma_x = \frac{\lambda L}{\pi D}\sqrt{\frac{1}{2}\ln\frac{1}{|\gamma|}} \quad \Longrightarrow \quad \Delta\sigma_x = -\frac{1}{\sqrt{8}}\frac{\lambda L}{\pi D}\frac{1}{|\gamma|\sqrt{ln\frac{1}{|\gamma|}}}\Delta|\gamma|$$

- The beam size measurement resolution is determined by the |ɣ| measurement error for given setup:
  - About 1% measurement errors can be achieved for |ɣ|, affected by CCD noise, beam jitter and so on
  - For a 10 um beam, with we 4 mrad slit acceptance, we can achieve less than 0.4 um resolution, i.e., <4% beam size

- Beamline design requirements:
  - A good measurement region for |ɣ| is between 0.3-0.9
  - A large slit acceptance (D/L) (i.e., beamline acceptance) is required for a small beam size measurement
  - A shorter working wavelength λ is preferred
  - A high quality of optics with flatness < λ/16 is required to preserve wave-front when transported through optics



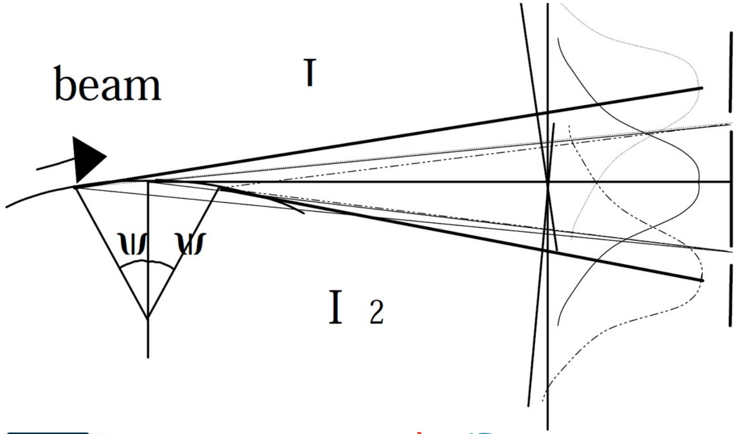



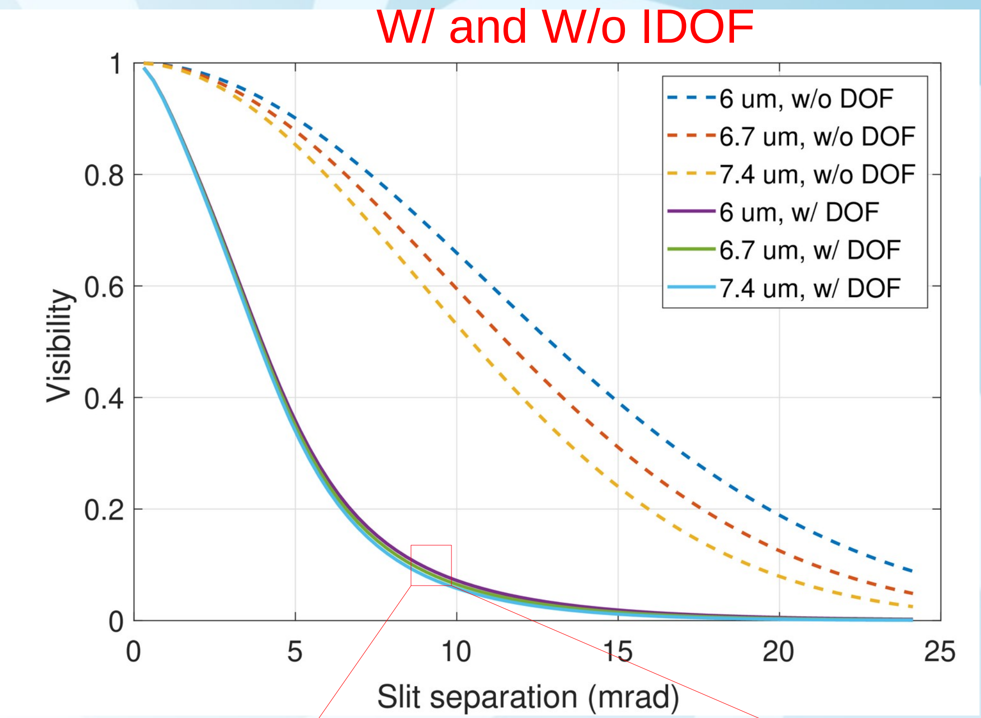
# Incoherent Depth of Field effect (IDOF)

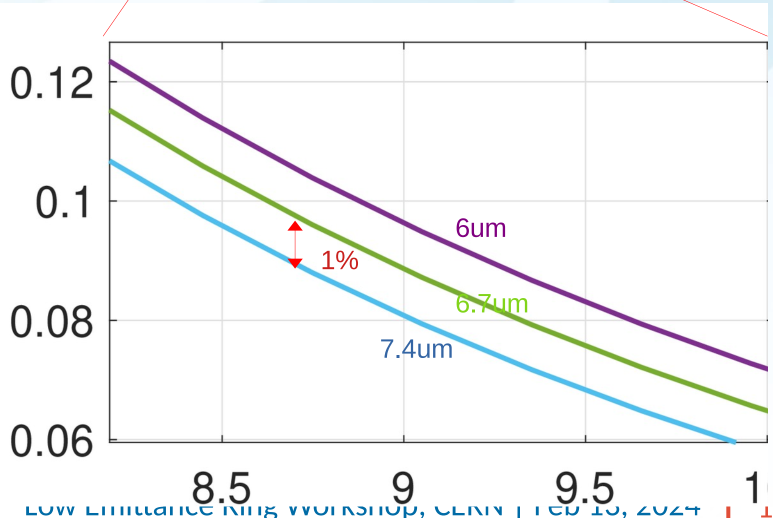
- Two effects are introduced by IDOF according to the theory
  - An effect of curvature of the trajectory in the bending magnet
  - An imbalance between the intensities of the two modes of light that illuminate the double slit of the interferometer
- The apparent beam size is larger than the real beam size and the visibility is smaller
  - This will reduce the beam size measurement resolution
  - Assuming the visibility measurement error is about 1%, for 7 um beam we can only achieve about ~10% (~0.7 um) measurement resolution

$$\gamma_h(D) = \iint \frac{2\sqrt{I_1\left(\theta + \frac{D}{2R}\right) I_2\left(\theta - \frac{D}{2R}\right)}}{I_1\left(\theta + \frac{D}{2R}\right) + I_2\left(\theta - \frac{D}{2R}\right)} \cdot I(\theta) \cdot \frac{\exp\left[\frac{-[x-\rho\{1-\cos(\theta)\}]^2}{2\sigma^2}\right]}{\sigma\sqrt{2\pi}} \cdot \cos\left(\frac{2\pi D x}{R\lambda}\right) d\theta dx$$

Intensity imbalance — Trajectory curvature



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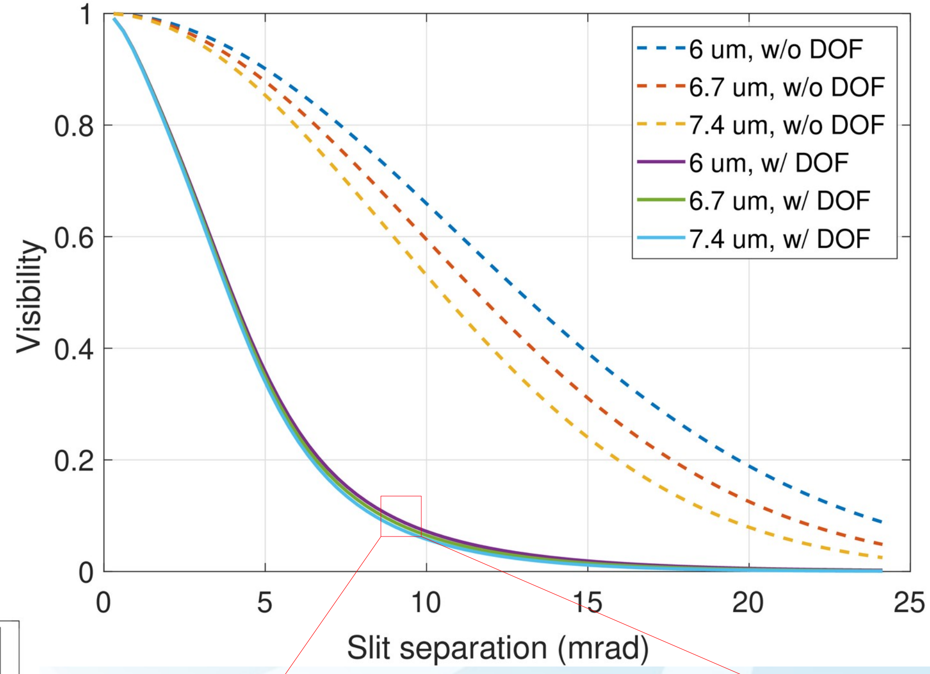
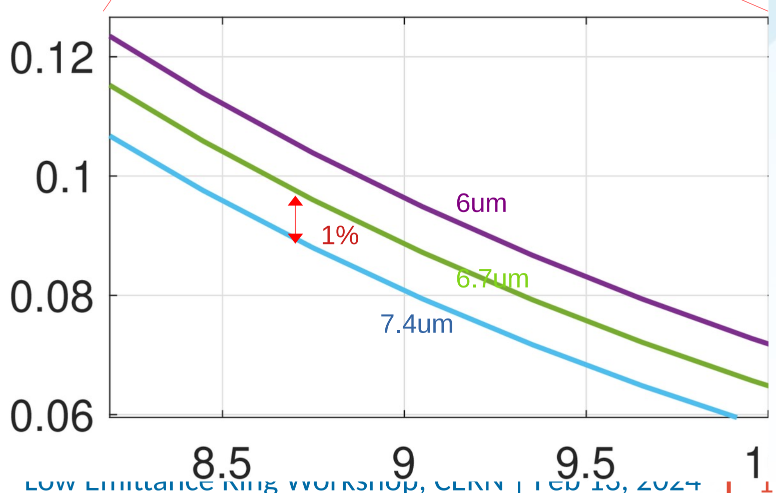
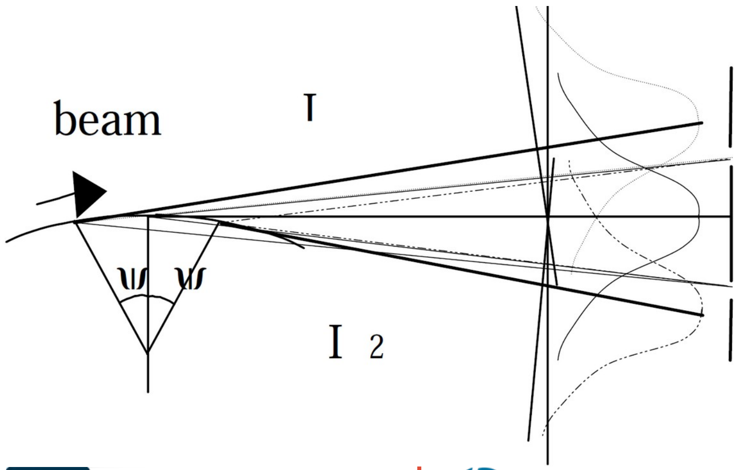
- SRW simulation results are inconsistent with theory, indicating that the IDOF effect could be overestimated by the theory

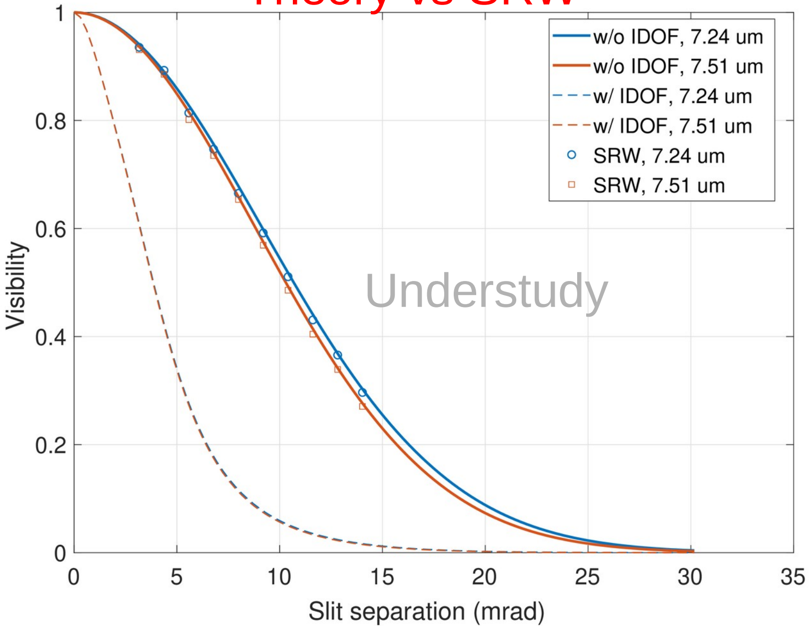
W/ and W/o IDOF



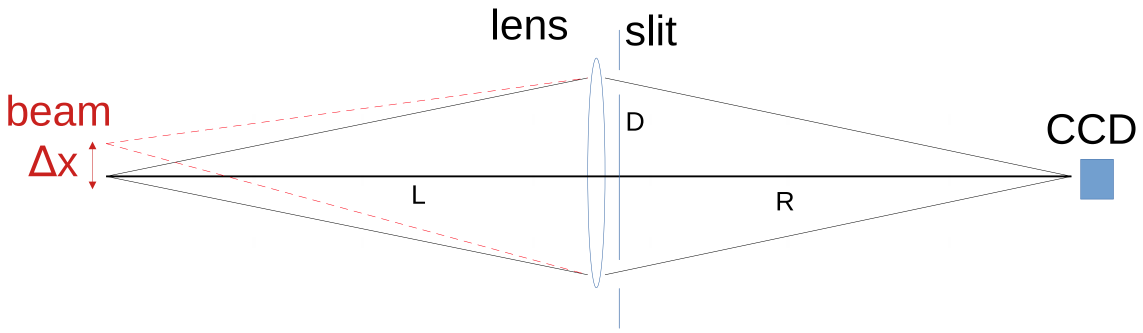




Theory vs SRW



# Effects of beam jitter and optics vibration



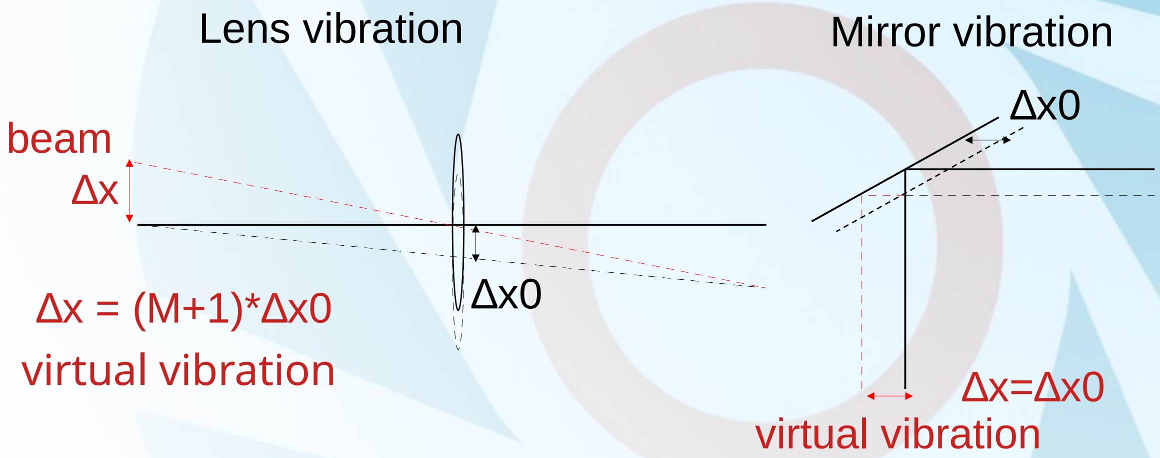

- Beam jitter results in a phase shift of the interference fringe, therefore reducing the visibility:

$$\Delta\psi = \frac{2\pi}{\lambda}\frac{D}{L}\Delta x$$

- Integrating the interference intensities over the phase shift, the averaged visibility is :

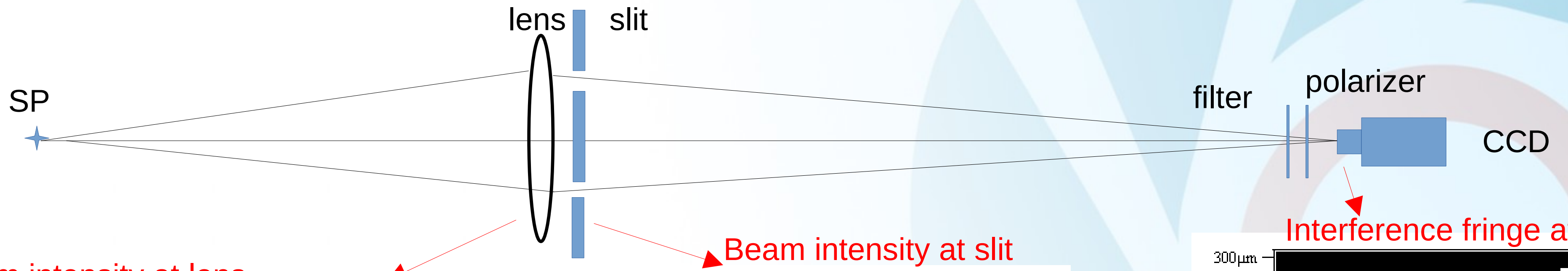
$$|\bar{\gamma}| = \mathrm{sinc}(\Delta\psi)|\gamma|$$

- For L = 3.3 m, D = 34 mm, λ = 430 nm, Δx = 1.5 um, the error due to beam jitter is Δ|γ| = 0.0085 which is within our assumption of 1%

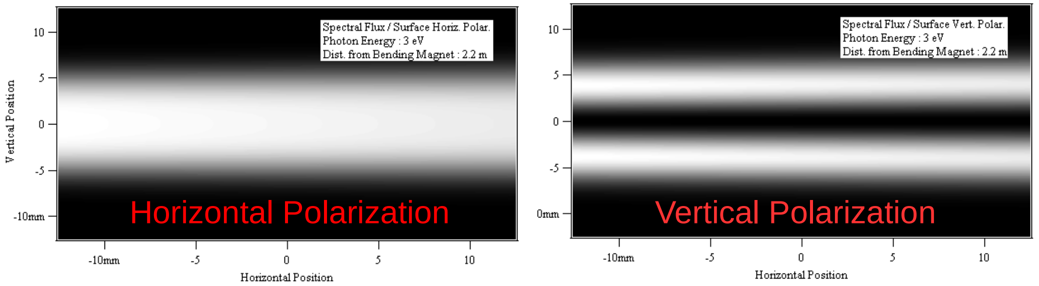



- The effect of a vibrating optics is equivalent to that of a virtually vibrating beam
- The equivalent vibration amplitude of the beam depends on whether the optics is lens or mirror
- The tolerable beam vibration (Δx0) is less than 10% of the 6 um beam size which requires:
  - The lens vibration (M=1) is less than 300 nm
  - The M2 mirror vibration is less than 600 nm
- The optics vibrations have been specified and studied during the mechanical design

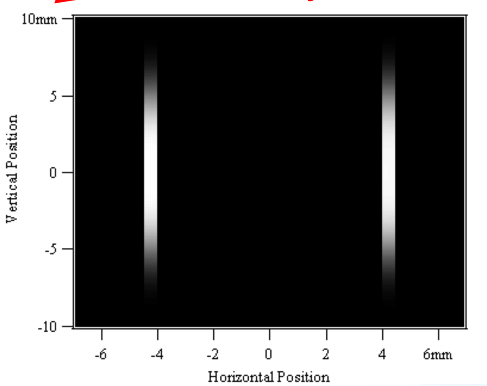
# Simulation with SRW code (Synchrotron Radiation Workshop)



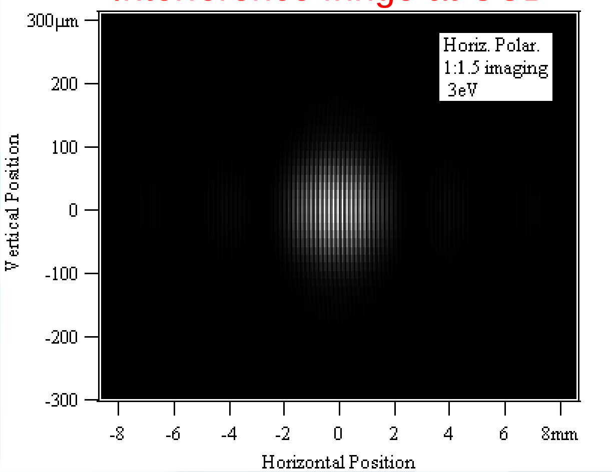

Beam intensity at lens

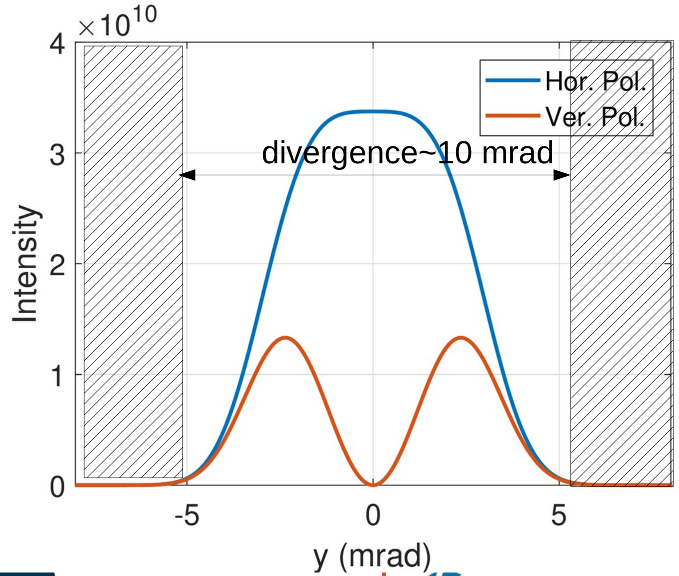



Beam intensity at slit

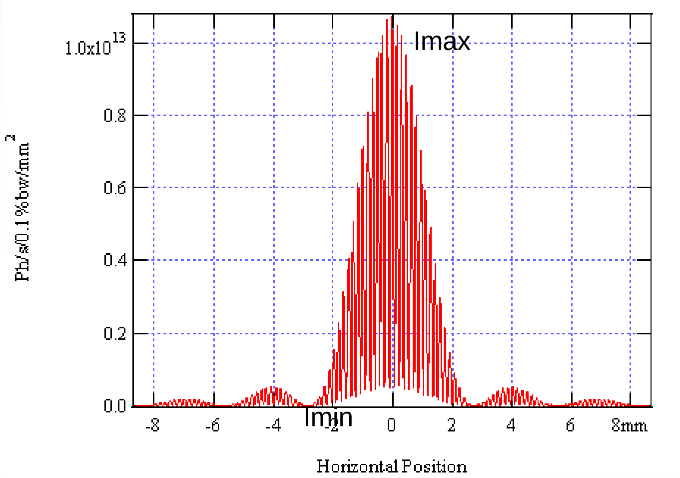



Interference fringe at CCD



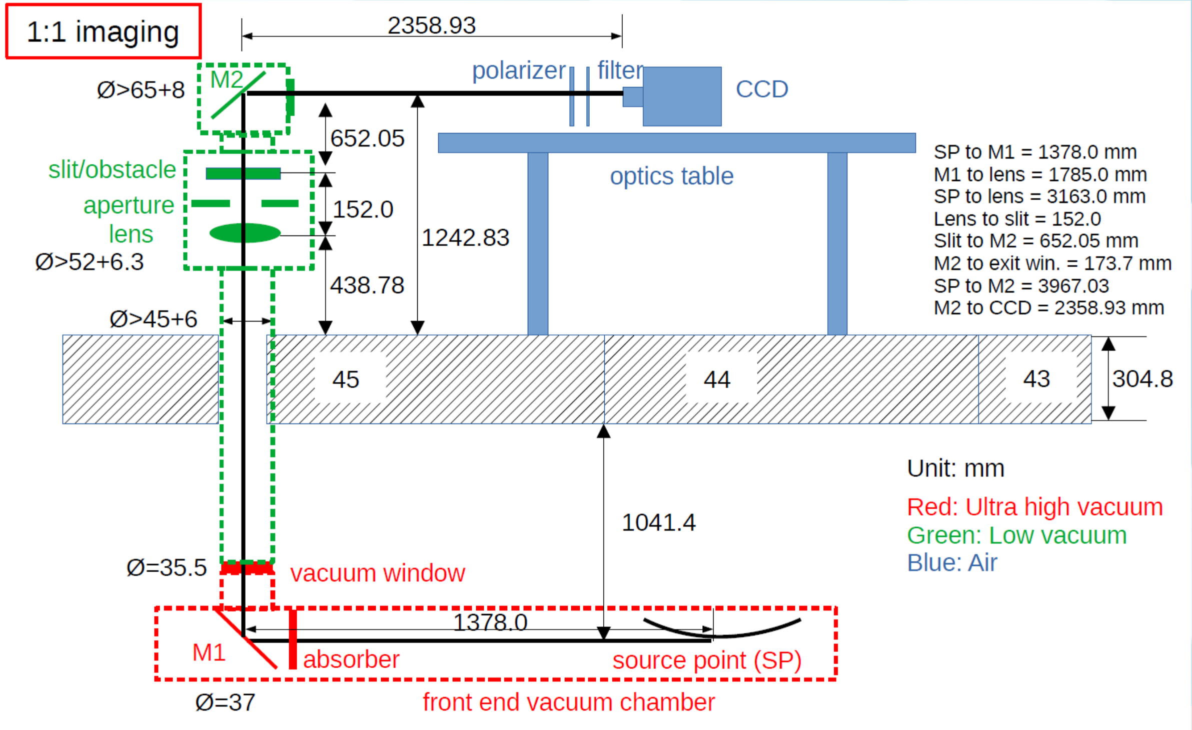

- Horizontal and vertical polarization components have different vertical distributions with a small divergence less than about 10 mrad
- To accept the beam fan, the beamline acceptance is larger than 10 umrad

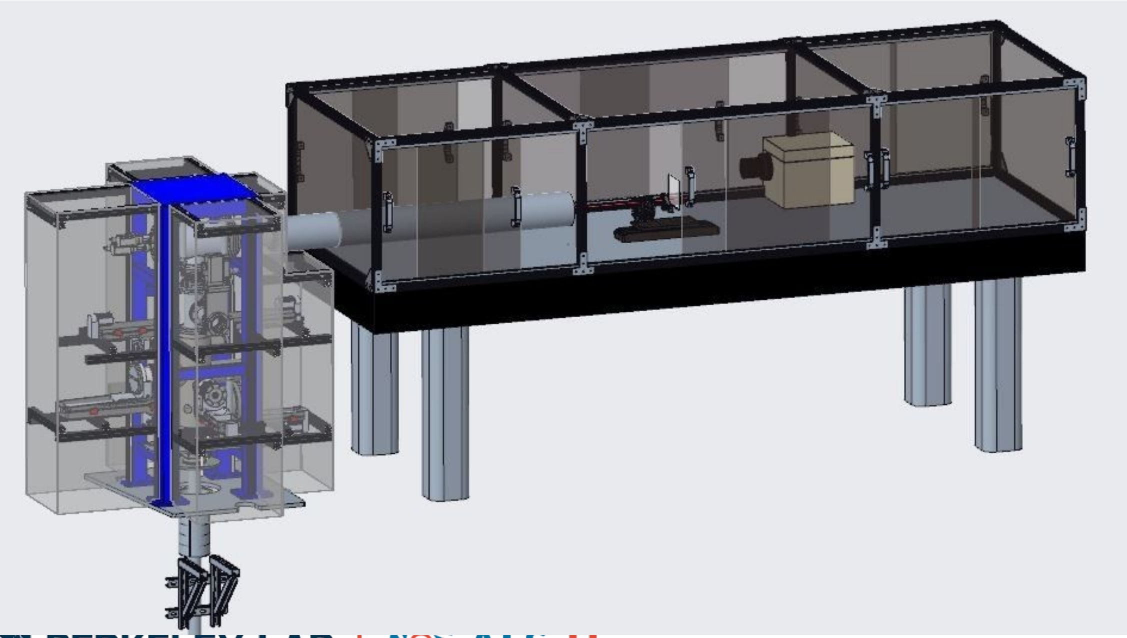


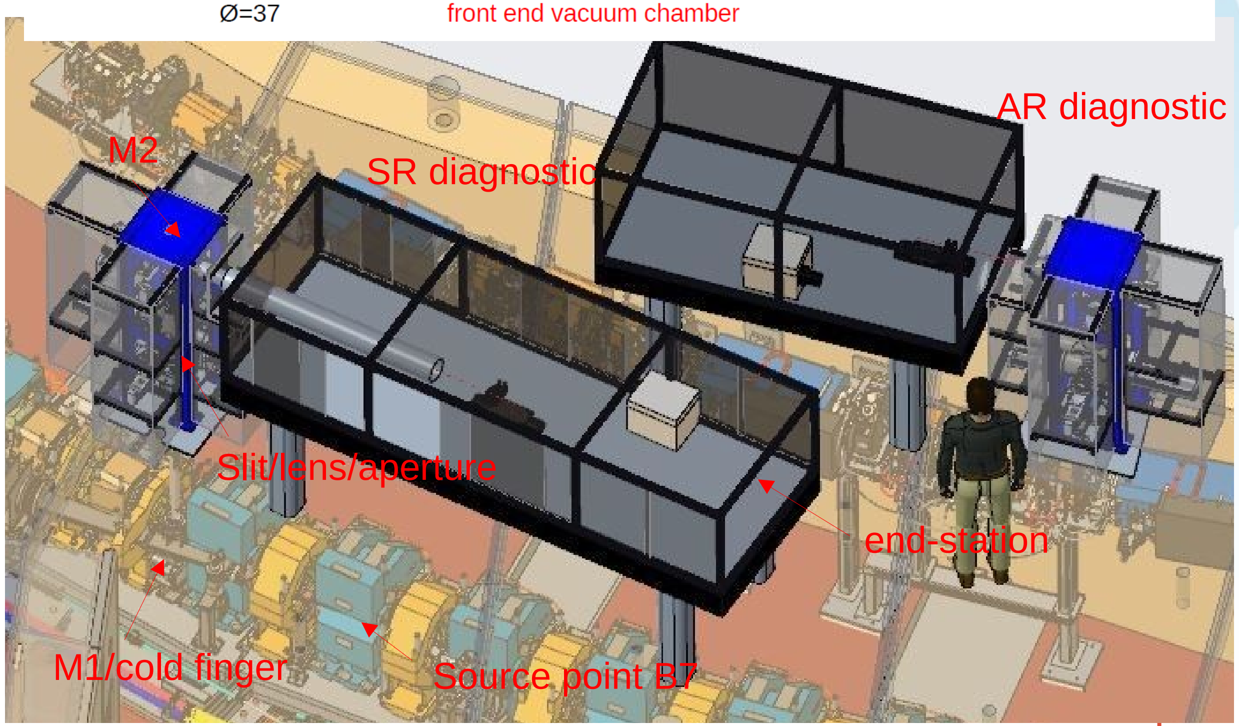
# Mechanical design

# Design layout

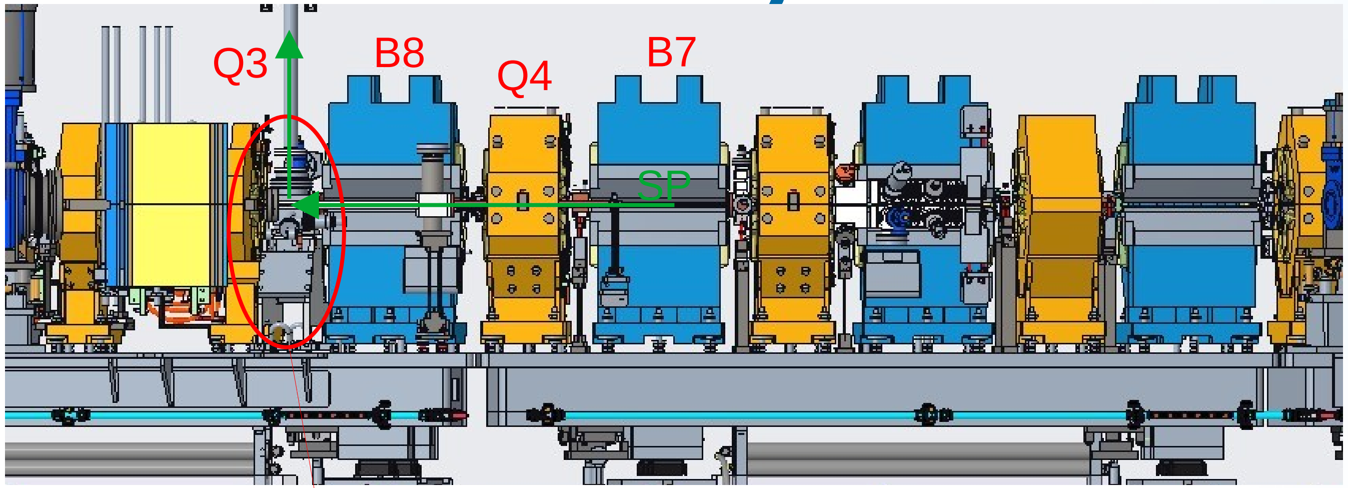
- Due to lateral space constraints, the beam is vertically extracted by M1 to the rooftop
- The diagnostic chamber housing the slit/lens/aperture on the roof top for easy access and support
- Design specification
  - Acceptance:  16.5 mrad (H) x 11 mrad (V)
  - Slit separation: 10 mrad (H) x 4 mrad  (V)
  - Work wavelength: 430 – 580 nm
  - Optics quality < λ/16

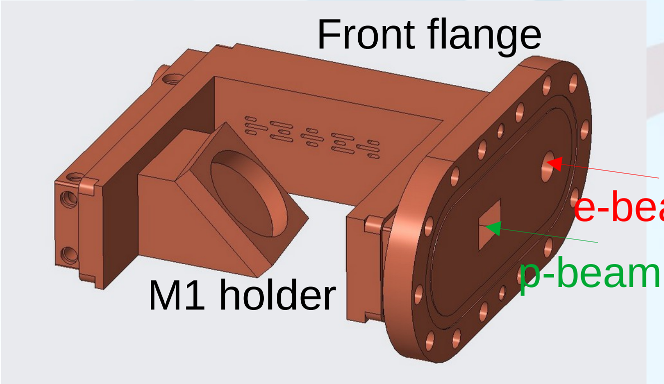


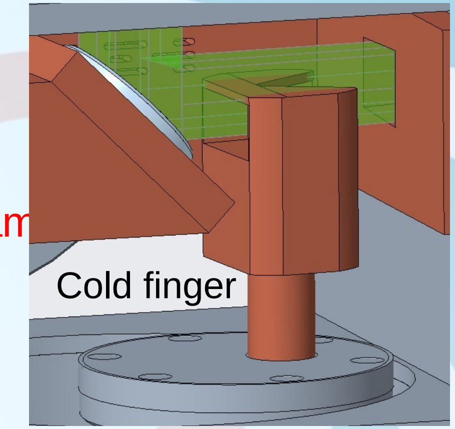



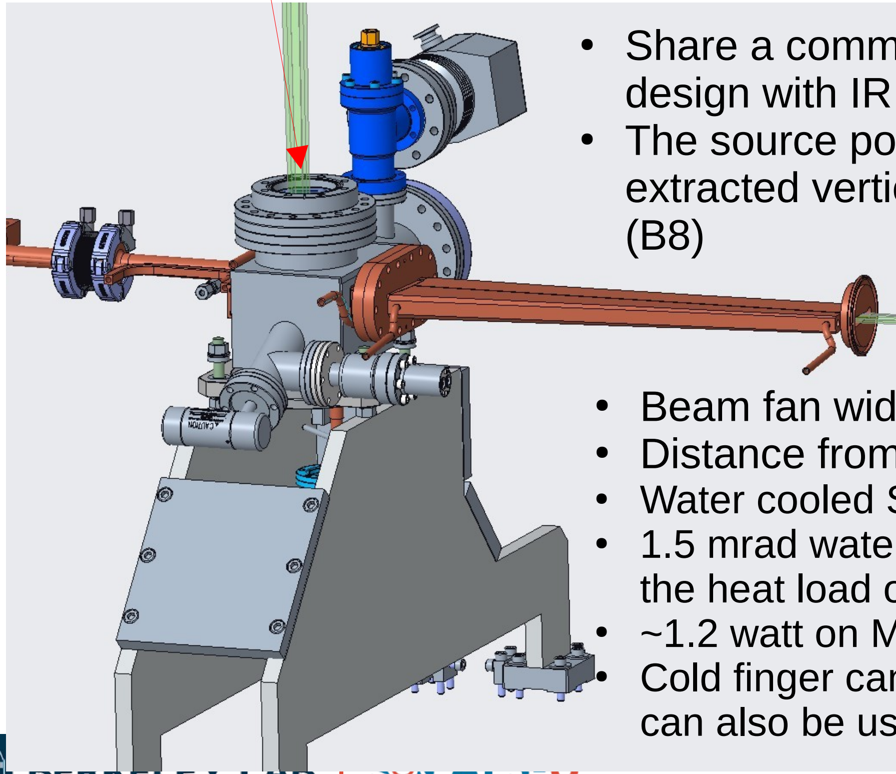


# Front-end UHV system



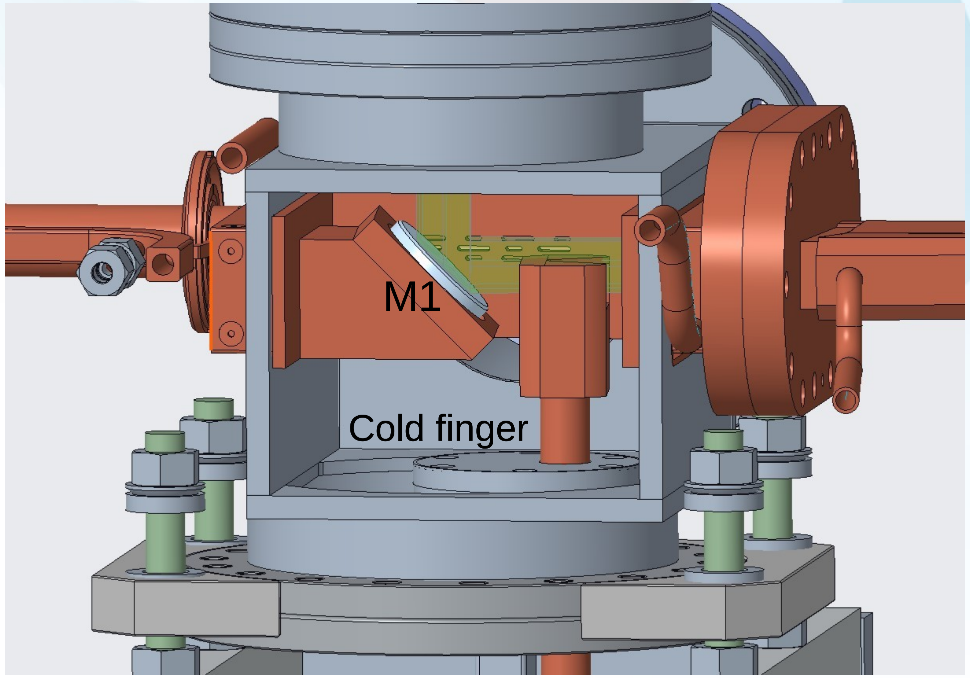



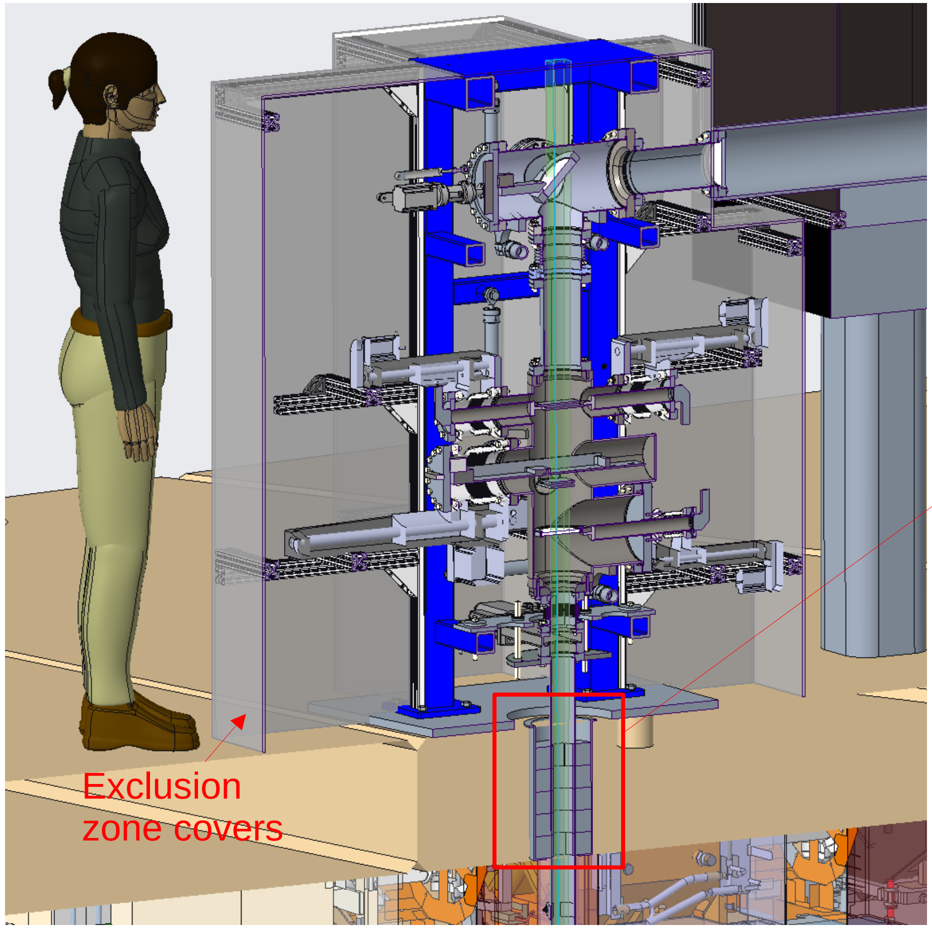



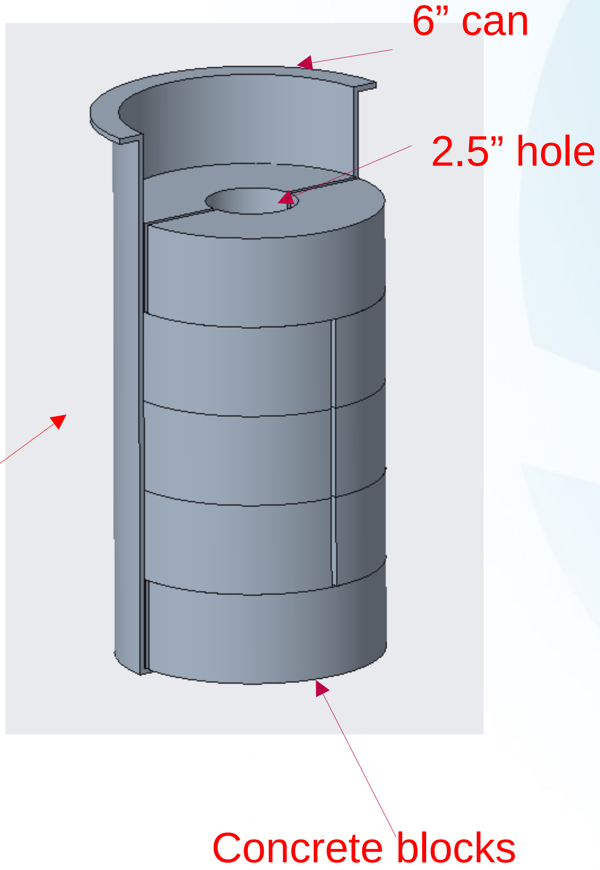

- Share a common vacuum chamber design with IR beamlines
- The source point is at dipole #7 (B7) and extracted vertically right after dipole #8 (B8)

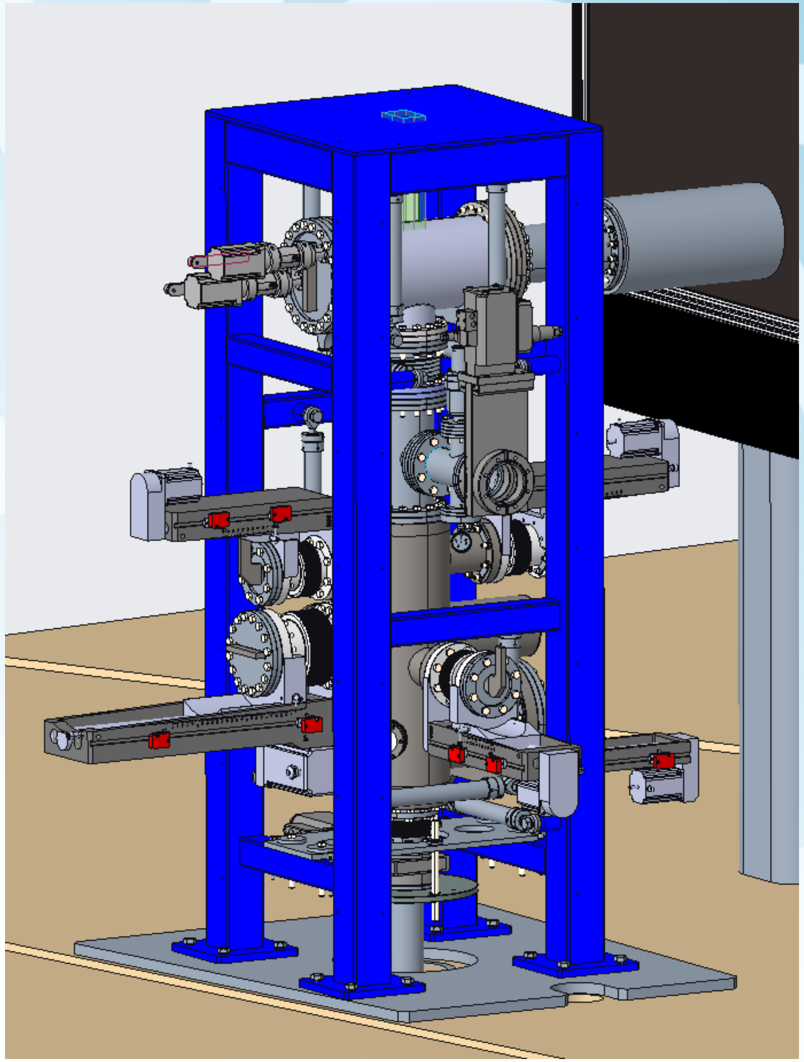
- Beam fan width is 16.5x11 mrad
- Distance from SP to M1 is 1.378m
- Water cooled SiC M1 with quality <λ/16
- 1.5 mrad water cooled cold finger reduces the heat load on M1 by 99.5 %
- ~1.2 watt on M1 after the cold finger
- Cold finger can track e-beam vertically and can also be used as a photon stopper



# Roof penetration, exclusion zone and chamber support



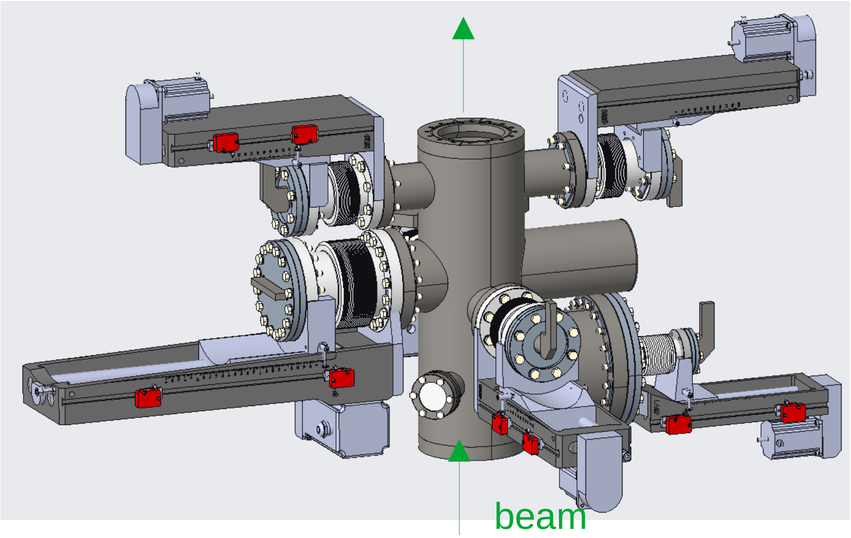



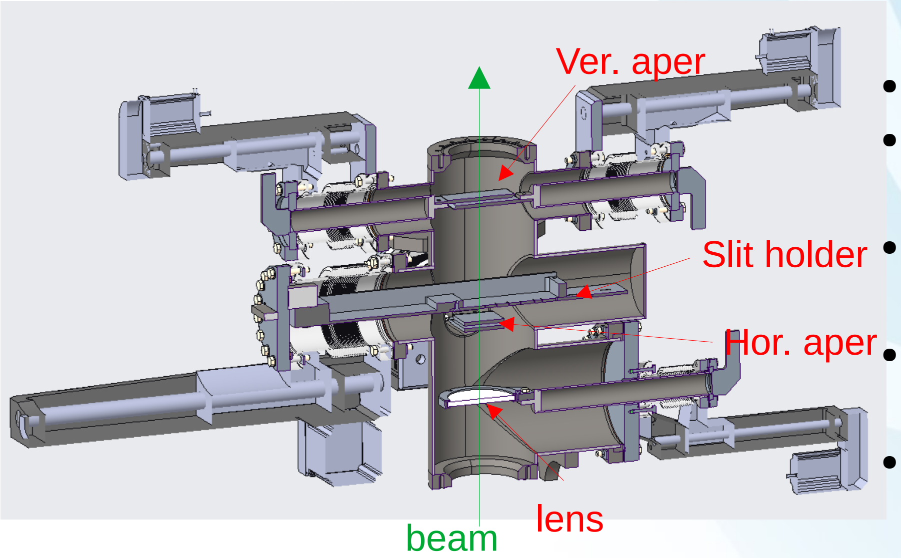
- The penetration hole (6”) is larger than the tube (2.5”) for installation and alignments
- After installation and alignment, the hole will be scanned and filled with concrete blocks
- Exclusion zone to confine the radiation

- 6-strut support system allows easy and precise alignments of chambers

# Diagnostic and M2 chamber designs

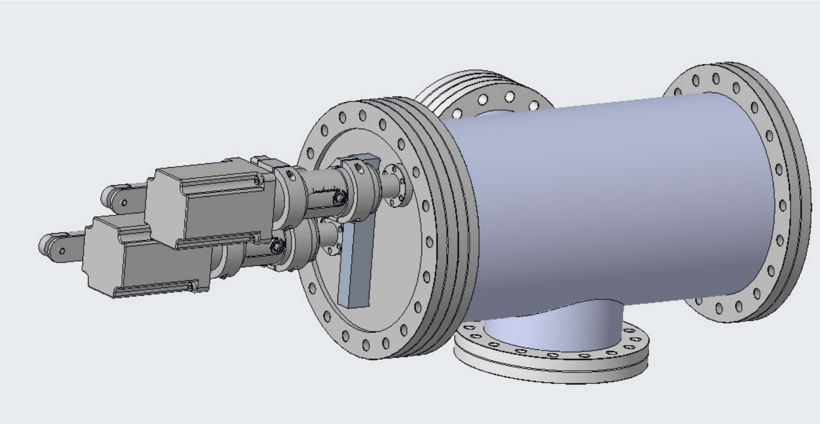
## Diagnostic chamber

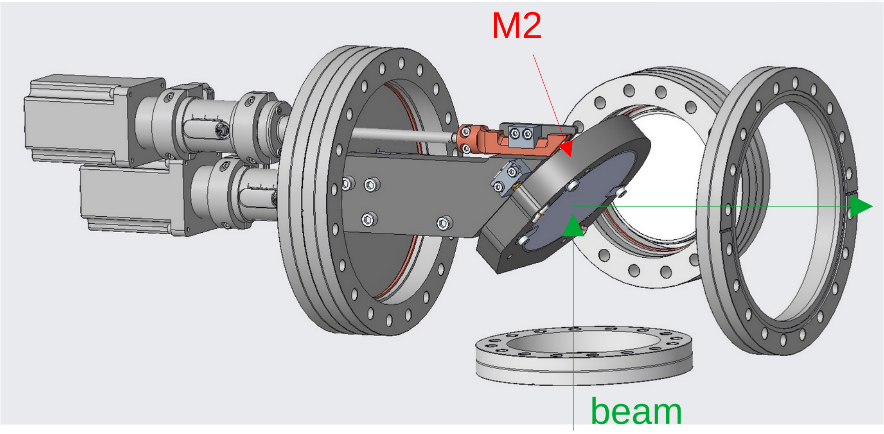



- A copy of MAX-IV chamber design
- A compact chamber housing lens, apertures and slits
- Both horizontal and vertical aperture size are adjustable
- Slit holder can hold several slit patterns
- All these components are retractable controlled by actuators

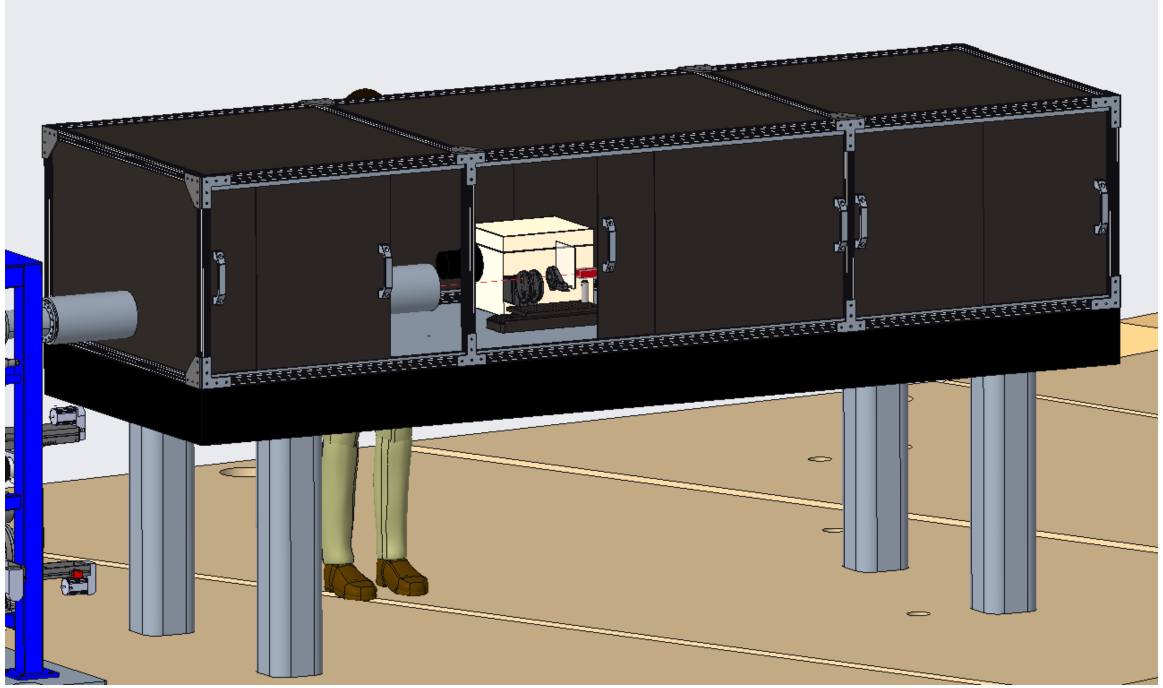
## M2 chamber





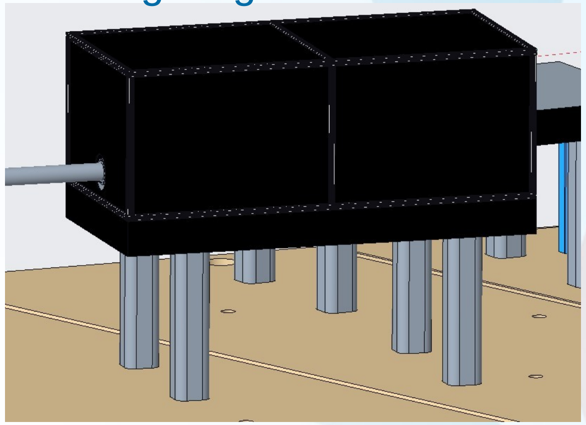

- M2 mirror with error <λ/16
- Has both yaw and pitch angle controls

# End-station

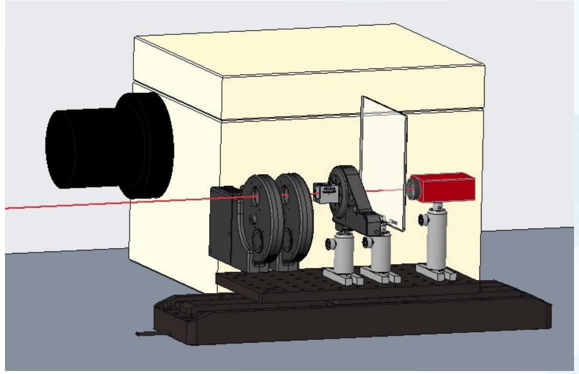


- 12x4 feet optical table with vibration isolation
- Light tight enclosure reduce the background light
- Commercial available linear stage, filter and polarizer
- Equipped with multiple cameras for different purposes
  - Low cost CCD – High current routine operation
  - High cost cooled emCCD (purchased the same one for AR) – Low current operation
  - High cost gated iCCD (existing)  –  Physics study
  - Streak camera (existing) – Longitudinal measurement

Light tight enclosure



Filters and camera



Manta G145


ProEM HS: 1KBX3

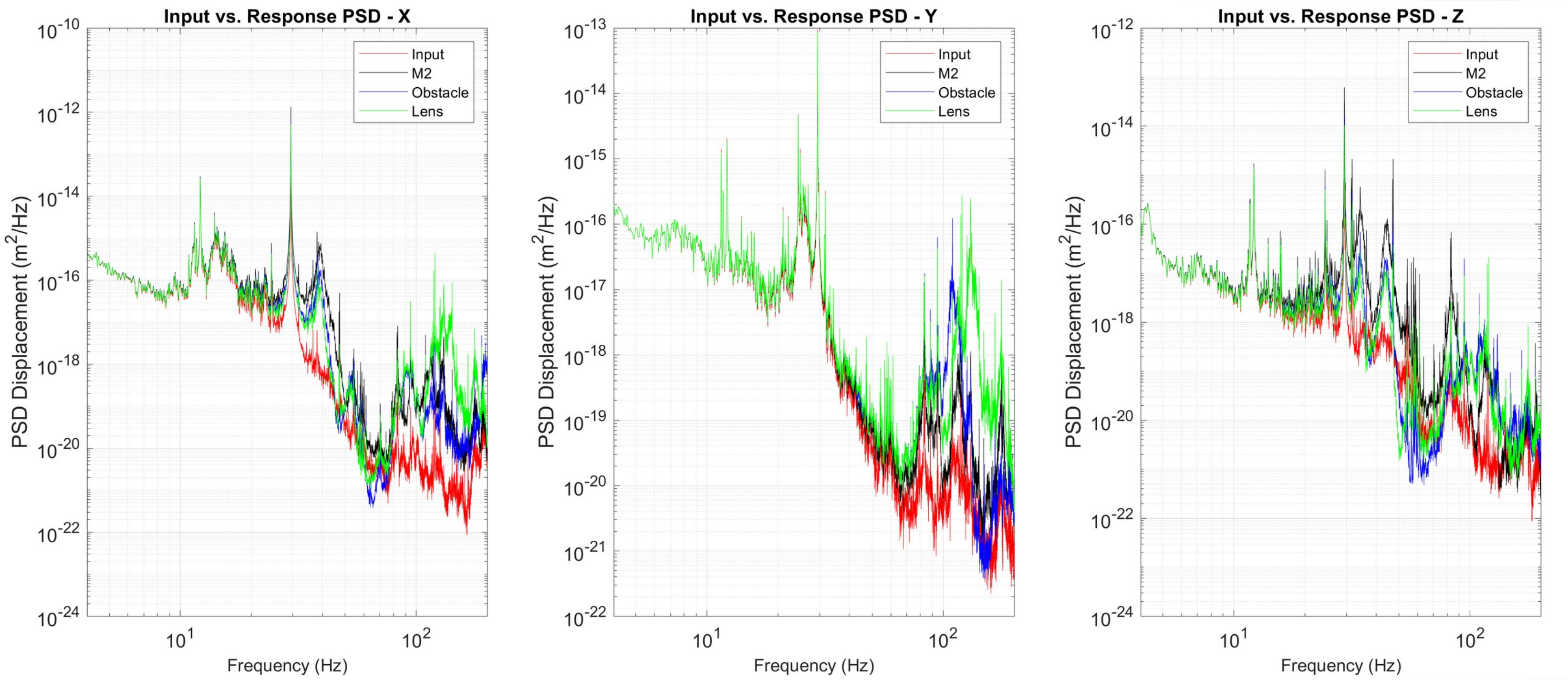

Hamamatsu C5860

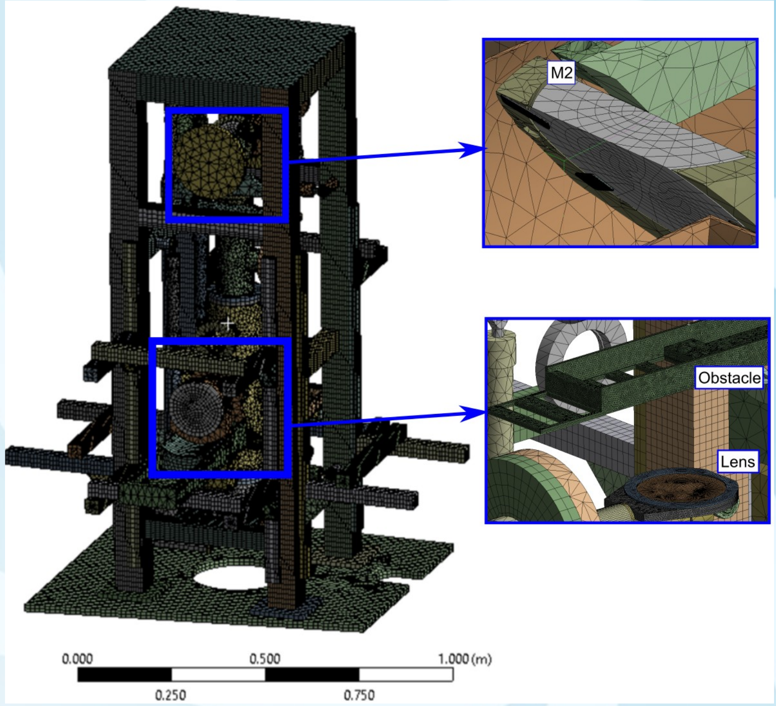
# Summary

- Construction of ALS-U is in progress to deliver world-class soft x-ray beams
- Development of ALS-U diagnostic beamlines is based on the 2-slit interferometer technique
  - SRW simulations were conducted to study the design
  - The impact of beam jitter and optics vibration were analyzed
  - The impact of depth of field effect on measurement resolution is studied
- Mechanical design is completed and currently in the procurement/fabrication process
- The beamline is expected to provide sub-micron resolution upon completion

# Backup slides

# Vibrations are within in acceptable levels



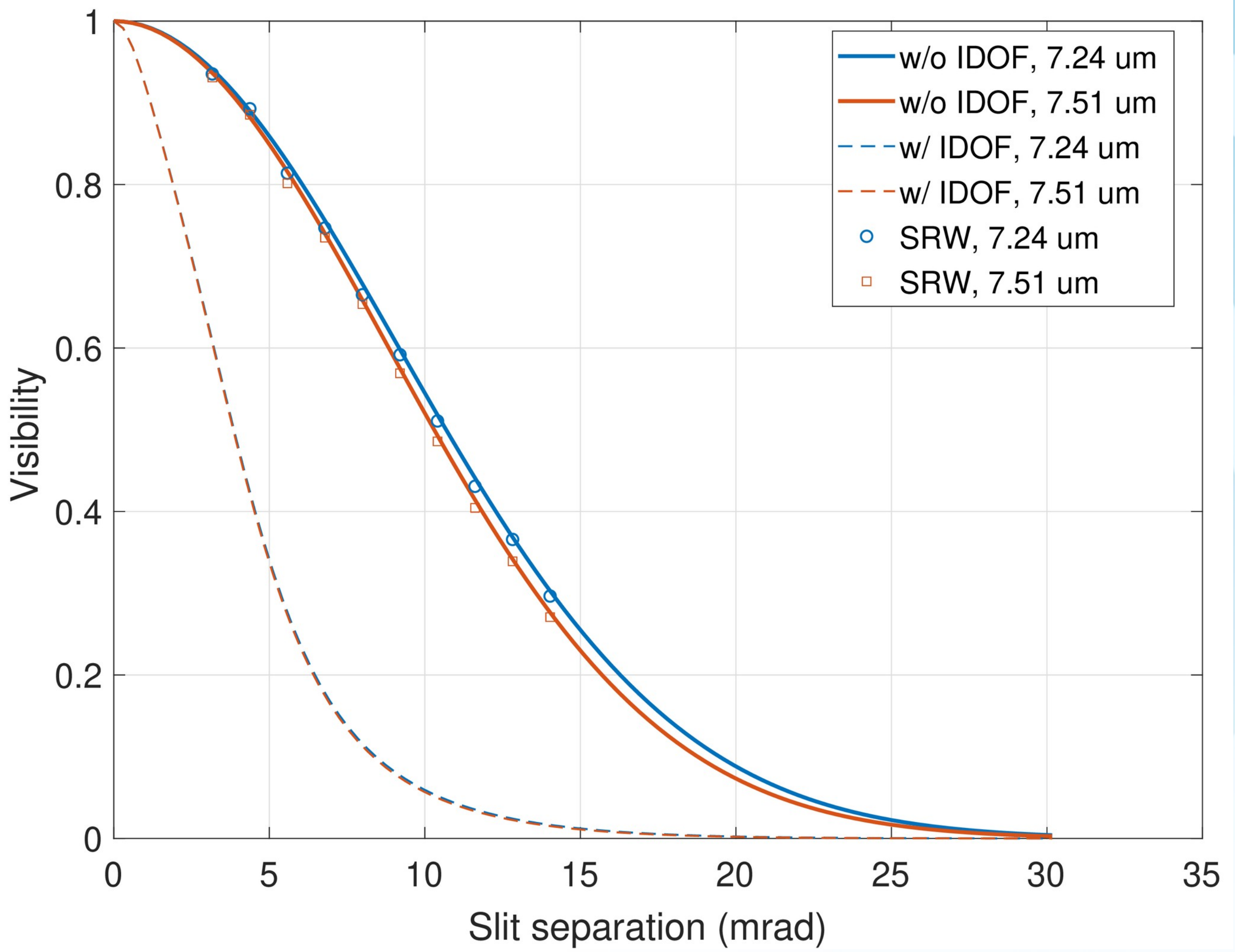




| Risk No. | Result | Value | Acceptable? |
|---|---|---|---|
| 01 | Predicted displacement at the center of **M2** meets requirement | Integrated RMS displacement (>4 Hz)<br>X: 304.9 nm<br>Y: 83.5 nm<br>Z: 77 nm | YES |
| 02 | Predicted displacement at the center of the **Obstacle** meets requirement | Integrated RMS displacement (>4 Hz)<br>X: 223.6 nm<br>Y: 87.9 nm<br>Z: 41.1 nm | YES |
| 03 | Predicted displacement at the center of the **Lens** meets requirement | Integrated RMS displacement (>4 Hz)<br>X: 198.2 nm<br>Y: 90.1 nm<br>Z: 34.6 nm | YES |
| 01 | Predicted rotation at the center of **M2** meets requirement | Integrated RMS rotation (>4 Hz)<br>X: 1.1 nrad<br>Y: 1.2 nrad<br>Z: 1.9 nrad | YES |
| 02 | Predicted rotation at the center of the **Obstacle** meets requirement | Integrated RMS rotation (>4 Hz)<br>X: 1.7 nrad<br>Y: 0.8 nrad<br>Z: 3.0 nrad | YES |
| 03 | Predicted rotation at the center of the **Lens** meets requirement | Integrated RMS rotation (>4 Hz)<br>X: 2.1 nrad<br>Y: 2.0 nrad<br>Z: 2.8 nrad | YES |

- Floor vibration levels are amplified at each scoped point M2, obstacle and lens
- Improves have been made to to reduce the vibration amplitude at these scoped points
- The analysis shows that X, Y, and Z displacements and rotation are within acceptable levels (less than about 300 nm) after the improvements

# SRW simulation is inconsistent with the “theory”

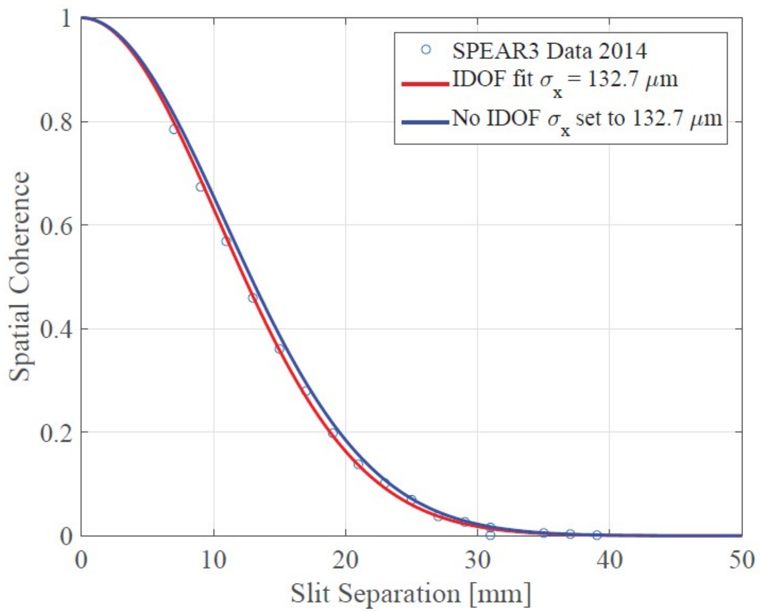
- To study the DOF effect, a new version (python) SRW needs to be used by integrating macro-particle tracking with parallel computing technique
- The IDOF effect could be overestimated by the “theory” and its impact on beam size measurement could be much smaller according to SRW simulations

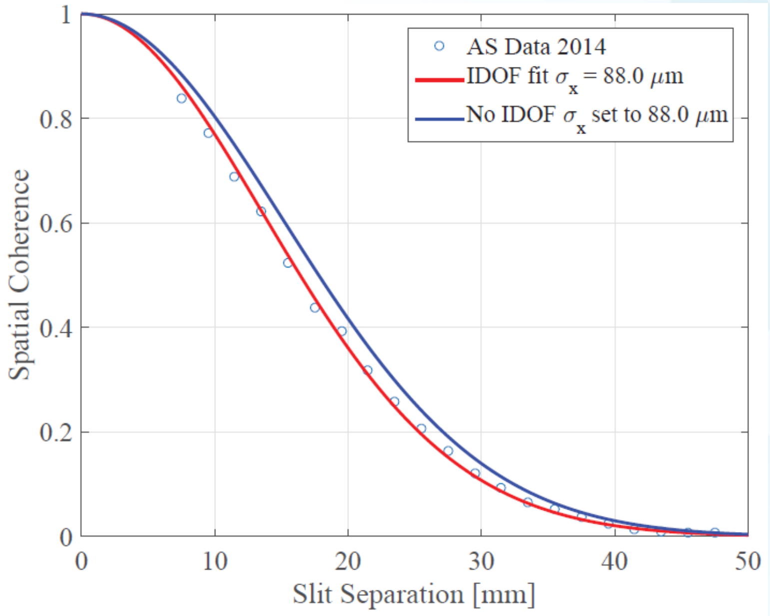


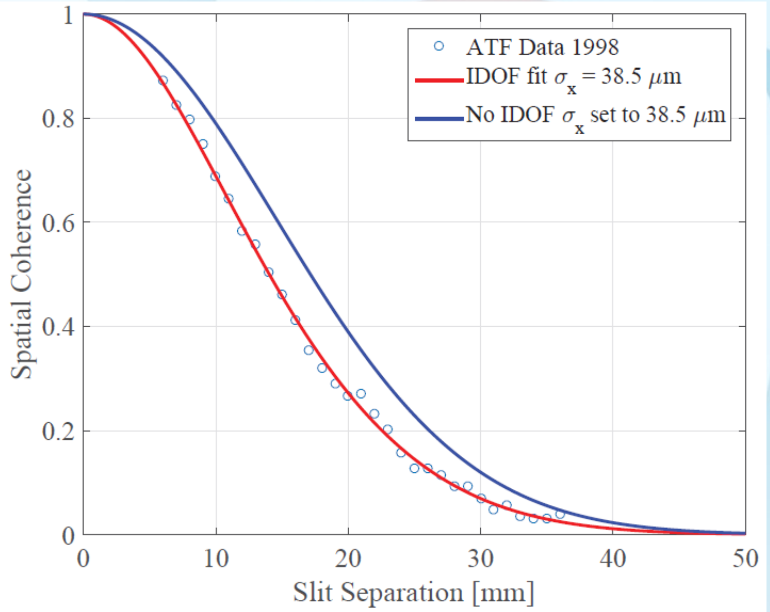

Message from O. Chubar:

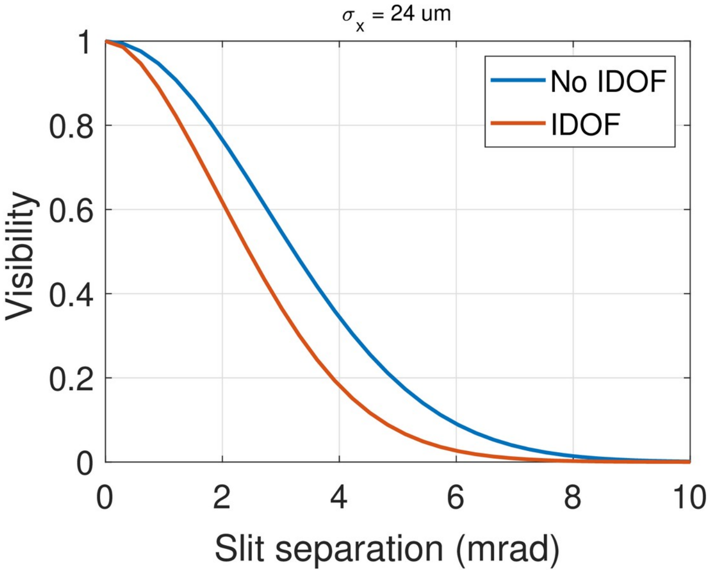
I don’t want to get into discussion at this point about comparing these results with others based on the paper you forwarded to me earlier. I can only repeat that we are doing fully consistent classical (not quantum😊) electrodynamics / physical optics simulations with SRW, using the well established fact that spontaneous emission in storage rings is temporary incoherent for the most part of the spectrum, so we can safely sum up propagated intensity distributions from different macro-electrons. This is the method that we are applying to ~all emission and propagation simulations for storage ring based light sources (sometimes using different realizations of this well proven general method).

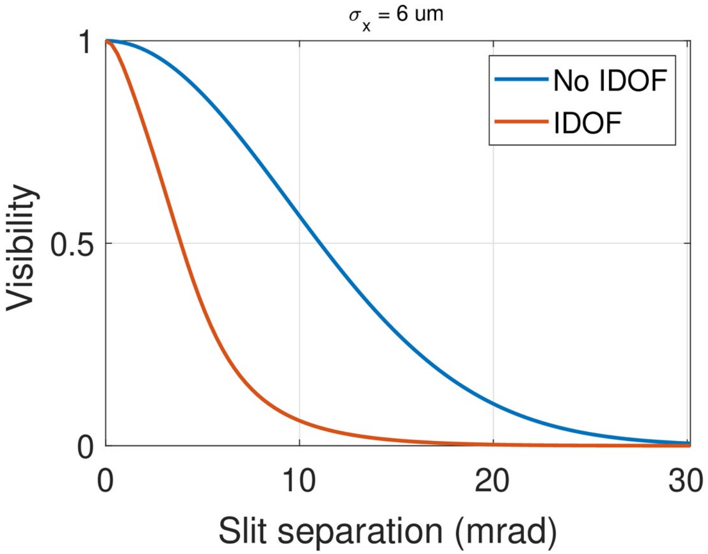
# Spatial coherence with/without IDOF for different beam sizes

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**MEASUREMENT OF THE INCOHERENT DEPTH OF FIELD EFFECT ON HORIZONTAL BEAM SIZE USING A SYNCHROTRON LIGHT INTERFEROMETER**

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