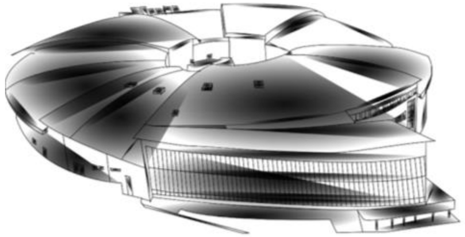
ALBA

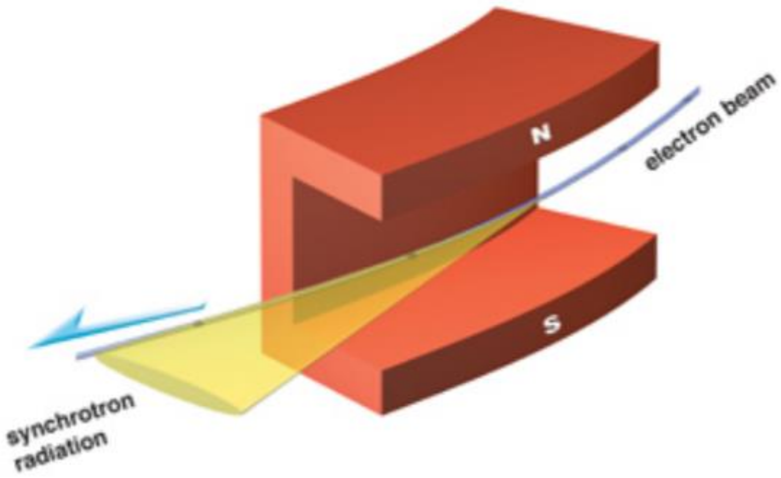
10 YEARS | ILLUMINATING THE UNKNOWN



Emittance Monitors for Low Emittance Rings

Ubaldo Iriso
ALBA-CELLS

Introduction: Emittance Measurement



Emittance (ε): area in transverse phase space

Inferred from the measurement of the beam size (σ), and knowledge of optics functions

$$\sigma^2 = \varepsilon * \beta$$

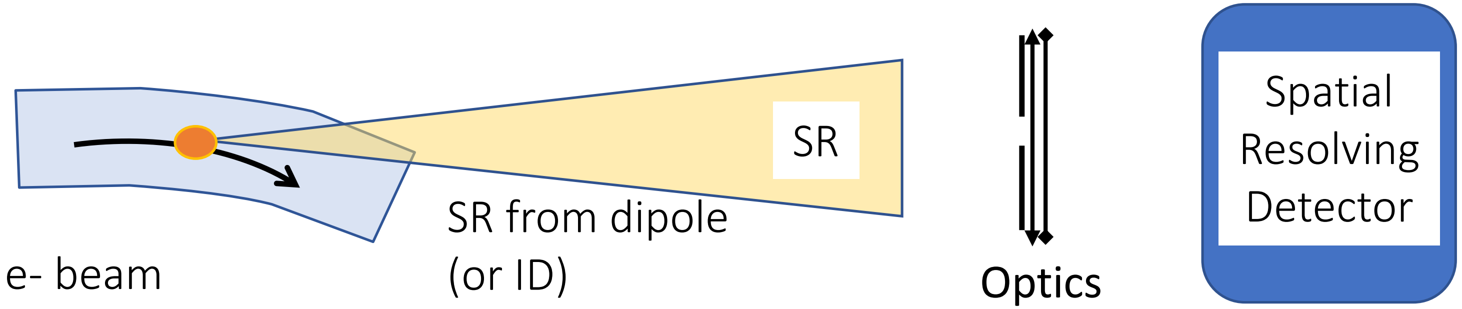
$$\sigma^2 = \varepsilon * \beta + D \cdot (\Delta E/E)$$ (if dispersion)

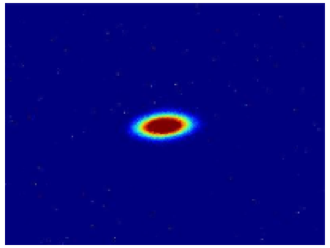
In Light Sources (LS), the most convenient method to measure the e-beam size is to analyze the Synchrotron Radiation (SR)

- Non-destructive method
- Continous and on-line measurement
- Use either dipoles or Insertion Devices (ID)

Introduction: Emittance Measurements using SR

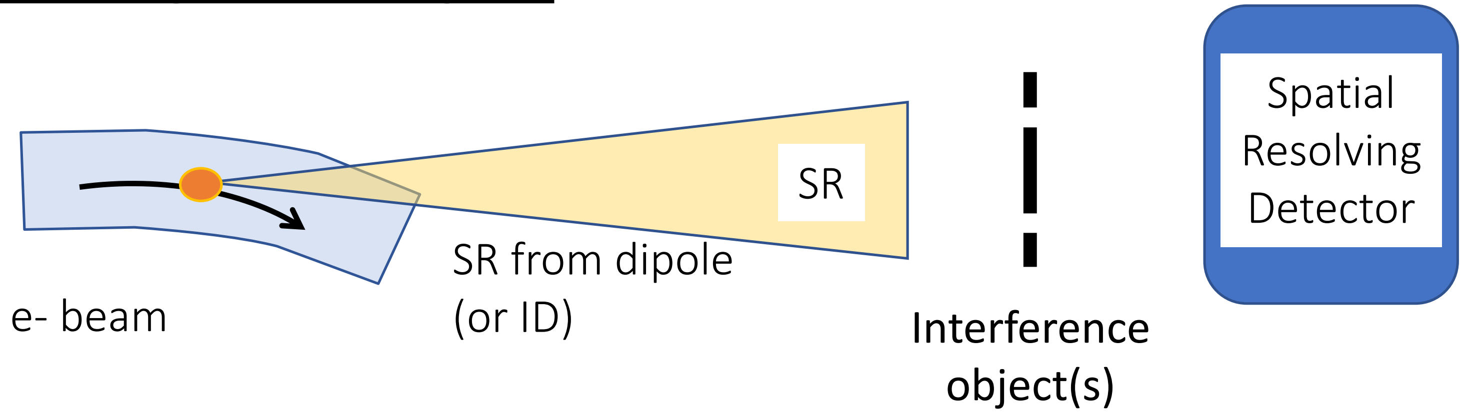
Direct Imaging Techniques:

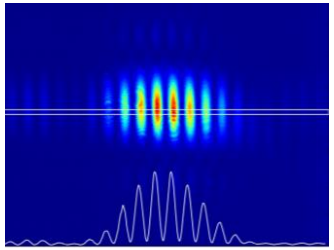




Example:
ALBA Pinhole Image

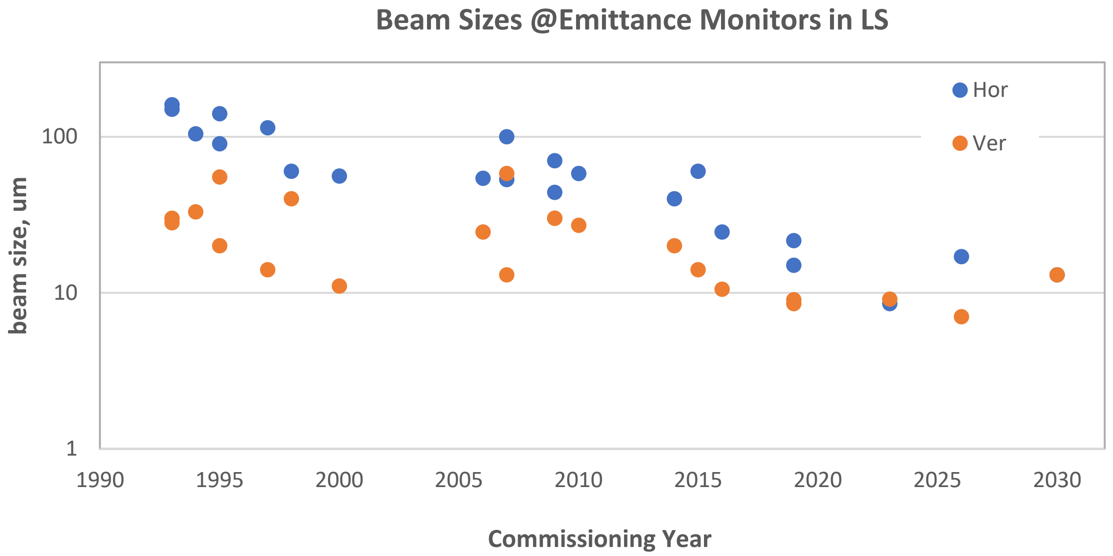
Coherence Analysis Techniques:

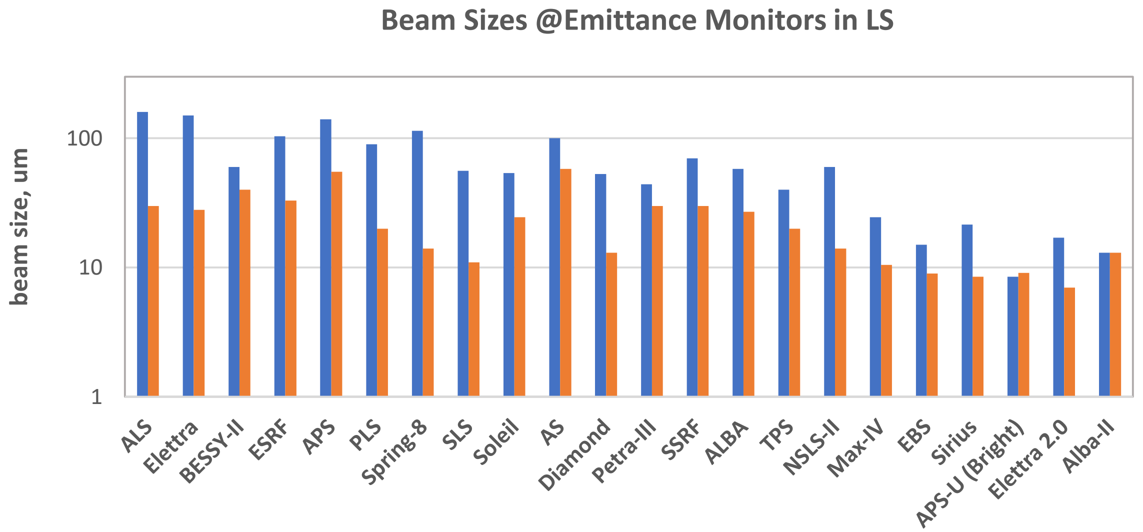




Example:
ALBA SRI Image

Introduction: Emittance (BeamSize) Measurements





- For future LER, the most significant change is the horizontal beam size decrease
- The existing techniques based on SR provide enough resolution in the ~1um range, so just enough for future MBA LER
- But careful design should be taken for reliable measurements, because mechanical (or instrumentation) limitations can arise
- What are these techniques?

Introduction: Emittance Measurements Techniques

Direct Imaging Techniques

X-Ray Pinhole	- XP
Compound Refractive Lenses	- CRL
In-Air X-ray Detectors	- IAX
ps-BPM	- pBPM

Coherence Analysis Techniques

SR Interferometry	- SRI
Pi-Polarization Diffraction	- πPol
Coded Aperture	- CA
Fresnel Diffraction	- FD
Htrdyne Near Field Speckles	- HNFS

ARIES Emittance Workshop @ALBA (2018): https://indico.cells.es/event/128

DISCLAIMER: This talk will be based on the review presented in this Workshop

Introduction: Techniques at Different LS

	Pinhole	IAX	CRL	SRI	pi-Pol	C.A.	DFR
KEK	x			x		x	
ALS	x						
Elettra	x						
BESSY-II	x		x	x			
ESRF	x	x	x				x
APS	x						
PLS	x		x				
Spring-8	x			x			
SLS	x				x		
Soleil	x	x					
AS	x			x			
Diamond	x					x	
Petra-III	x		x	x			
SSRF	x						
ALBA	x	x		x			
TPS	x			x			
NSLS-II	x		x				
Max-IV					x		
EBS	x						
Sirius	x						

Working Horse

Available at BLs

“easy-to-do”
in vis. range

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  - Multi-technique beamline @APSU
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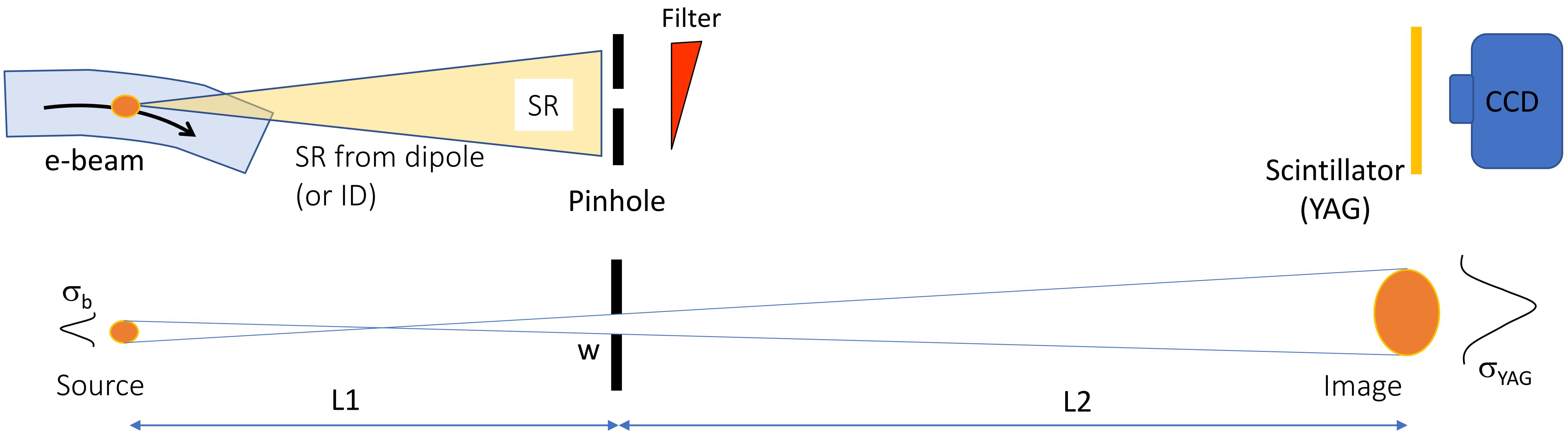
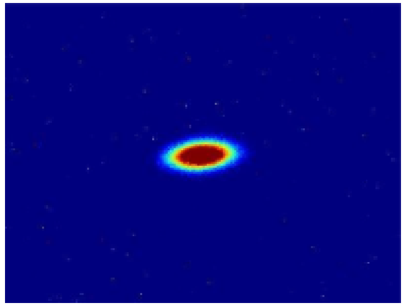
Direct Imaging: X-ray Pinhole Imaging

Pinhole Camera: provide a magnified image of the e-beam by factor X=L2/L1





At the scintillator (YAG) screen, the (ideal) image size is: $\sigma_{\mathrm{YAG}} = (X\sigma_{\mathrm{b}})$

But need to consider the Point Spread Function (PSF): $\sigma^2_{\mathrm{YAG}} = (X\sigma_{\mathrm{b}})^2 + (\sigma_{\mathrm{PSF}})^2$

Direct Imaging: X-ray Pinhole

PSF is due to diffraction, blurrring and screen contributions:

$$\sigma_{\mathrm{PSF}} = \sqrt{\sigma_{\mathrm{blur}}^2 + \sigma_{\mathrm{DIFF}}^2 + \sigma_{\mathrm{screen}}^2}$$

$$\sigma_{\mathrm{diff}} = \frac{\sqrt{12}}{4\pi}\frac{\lambda L_2}{w} \qquad \sigma_{\mathrm{blur}} = \frac{w(L_1 + L_2)}{\sqrt{12}L_1}$$

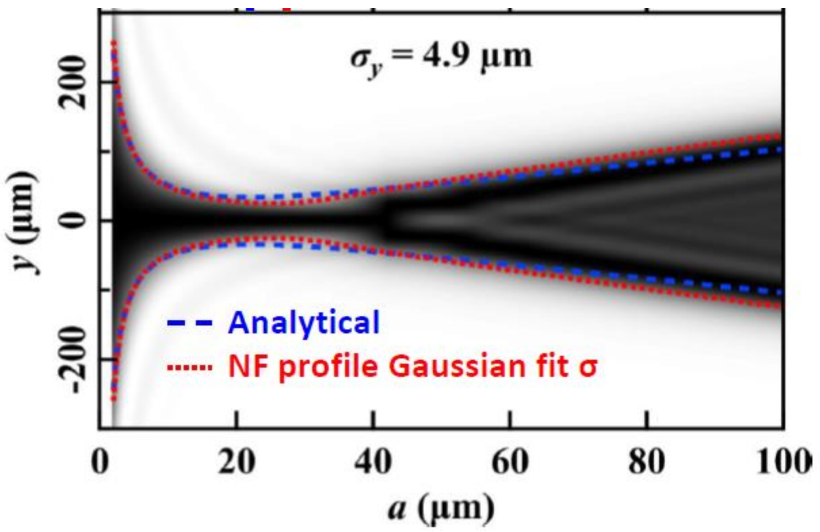
PSF needs to be minimized to optimize the system resolution

Key parameters are the observation wavelength λ and pinhole width (w)

→ Harder x-rays improve resolution

→ w optimization studies should be done at design stage

Pinhole Width Optimization:
Comparison of Analytic vs NF Propagation*



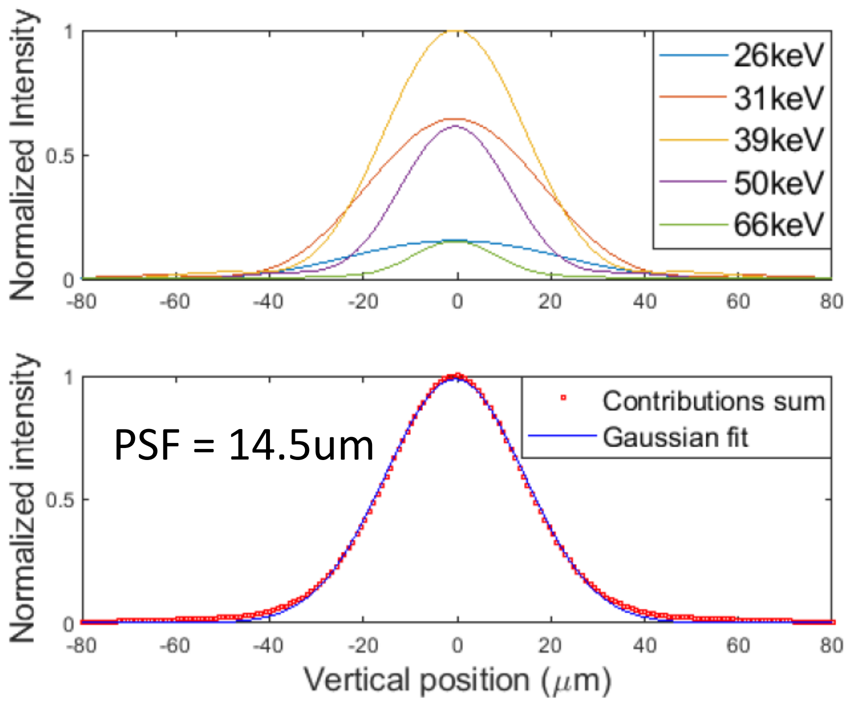
Diffraction dominated

Blurring dominated

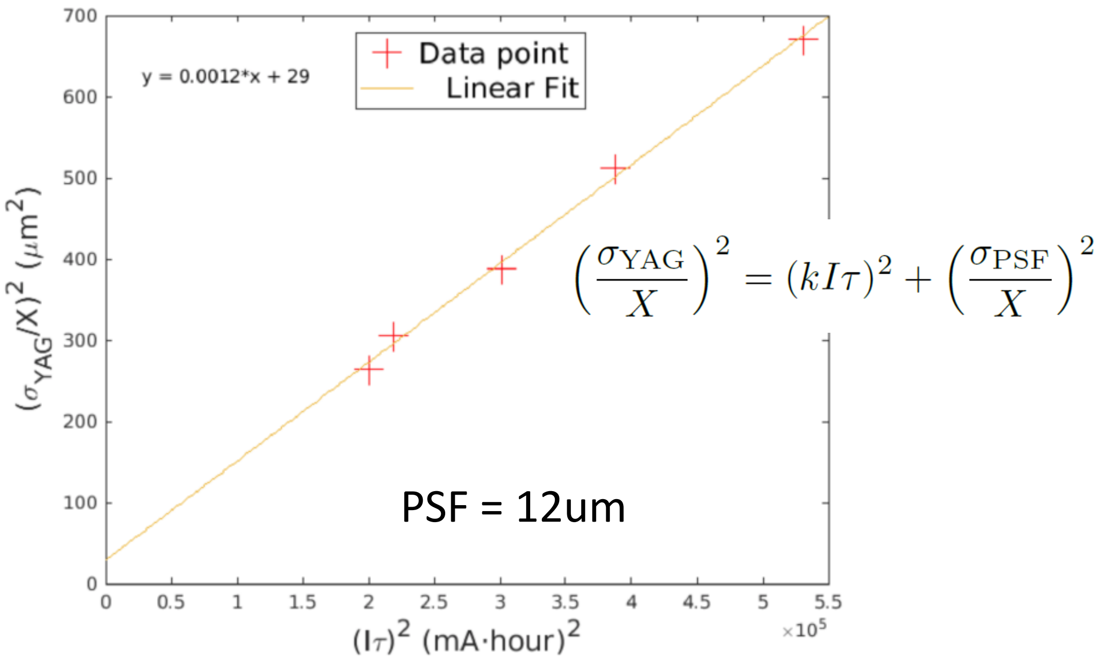
*APSU exemple, N.Samadi et al, IBIC20

Direct Imaging: X-ray Pinhole

PSF using SRW simulations



PSF crosscheck with beam: Touscheck Lifetime

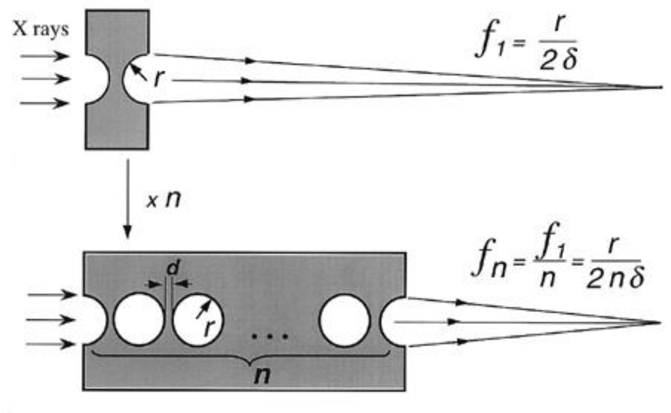


→ Minimum measurable beam size at ALBA: 5.1um
→ Minimum achievable beam size at ALBA: 14um

Diamond σ_{min}:	3um	-- L.Bobb, Emittance Workshop 2018
Soleil σ_{min}:	3.5um	-- M.A.Tordeaux, DIPAC07
ESRF σ_{min}:	5um	-- F.Ewald, Emittance Workshop 2018

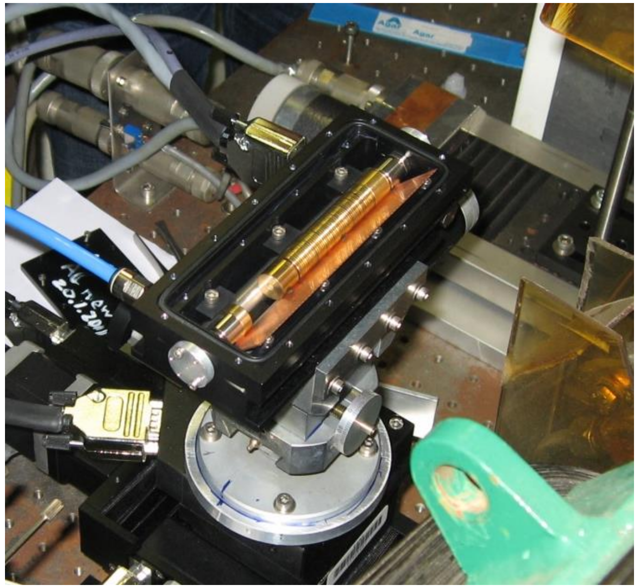
Direct Imaging: Compound Refractive Lenses (CRL)

Use of **x-ray** lenses to focalize the beam at image plane



- Small radius of curvature r (~100um)
- δ = Real part of refraction index (~1e-6) for a given photon energy
- Need monochromatic photon beams to avoid
- Materials with low Z to optimize x-ray transmission (Al, Be...)
- An array of n lenses (compound) to decrease focal length (n~20)

- CRL are usually expensive (and delicate) items, but are readily available at user BLs
- Tested at many labs (ESRF, Petra-III, NSLS-II...)
- Image magnification depends on the relative location between source point, lenses and image plane

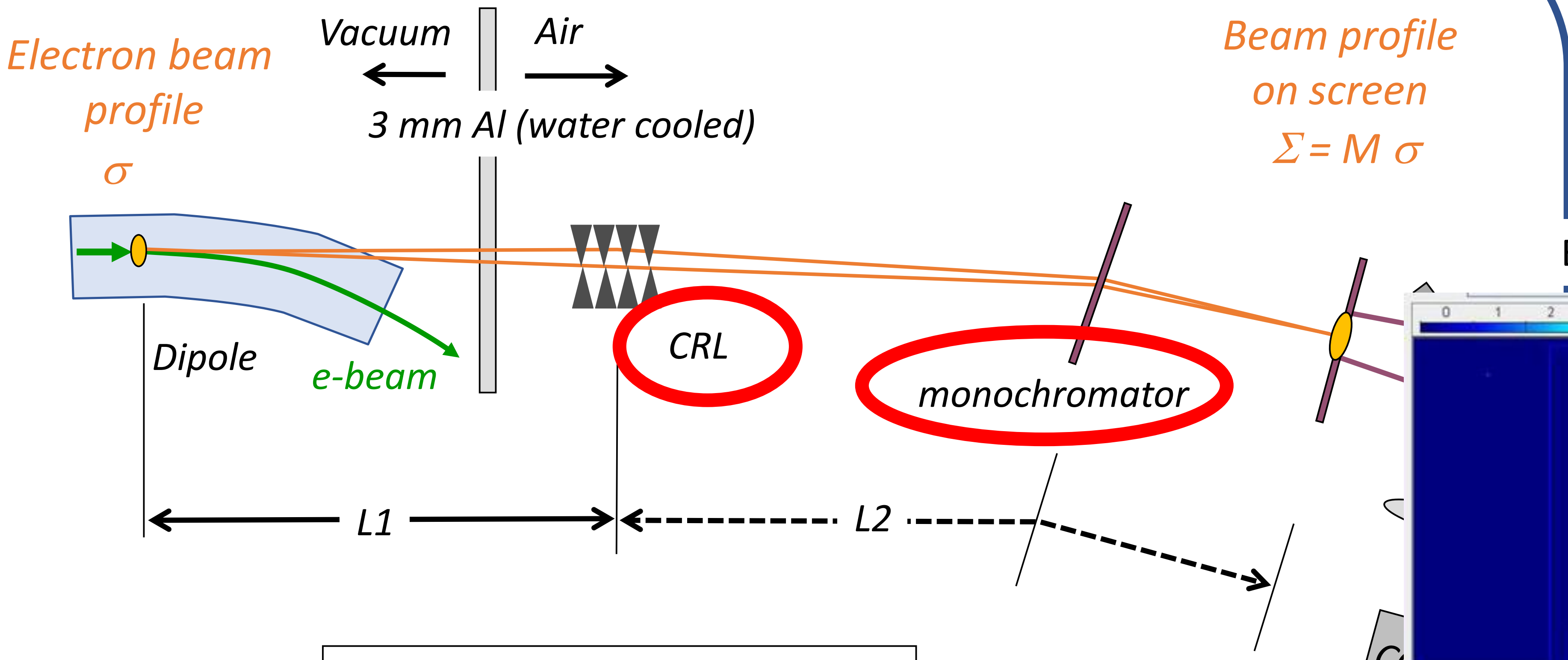


CRL @ESRF

Image from F. Ewald (ESRF)

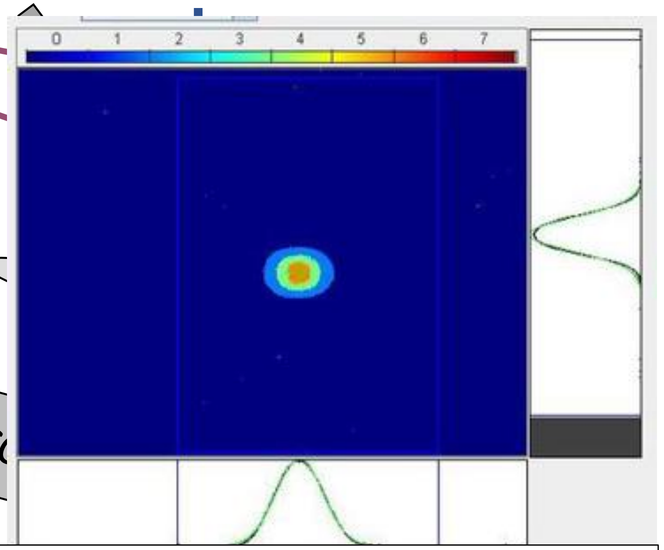
Direct Imaging: Compound Refractive Lenses (CRL)

Example of beam imaging using CRL @ESRF



CRL magnification $M = L2 / L1$

Example at Petra-III**:



F. Ewald, Beam Size Monitoring at the ESRF: Comparison of different X-ray based techniques ARIES Emittance Workshop (2018)

**G. Kube, Synchrotron Radiation based transverse Emittance Diagnostics at LS, FLS2006

Direct Imaging: CRL Precision

Ultimate resolution determined by diffraction on lens aperture*:

$$\sigma_{min} = 0.75 \cdot L_1 / D_{eff} \quad [1]$$

D_{eff} ...... effective aperture of the lens
determined by geometric aperture, absorption and surface/shape imperfections.

Diffraction limited resolution of lens at ESRF beam port D11 (calculated using [2] or [3]):

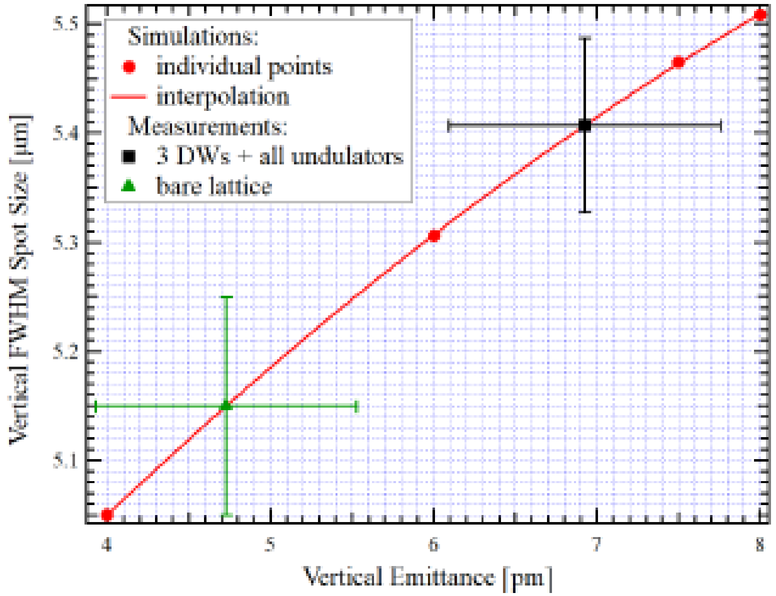
$\rightarrow \quad \sigma_{min} = 3.3\ \mu m$

$\rightarrow \quad \varepsilon_{z,min} = 0.3\ pm$

[1] B. Lengeler et al. , NIM-A 467-468 (2001) 944-950
[2] B. Lengeler et al. /J. of Appl. Phys. 84 (1998) 5855
[3] http://purple.ipmt-hpm.ac.ru/xcalc/xcalc_mysql/crl_par.php

*F. Ewald, Beam Size Monitoring at the ESRF: Comparison of different X-ray based techniques ARIES Emittance Workshop (2018)

See Monday Talk – V. Smaluk, Effect of undulators on the lattice, emittance, and energy spread of NSLS-II



$\sigma_{min} = FWHM/2.35 = 2.3\ \mu m$

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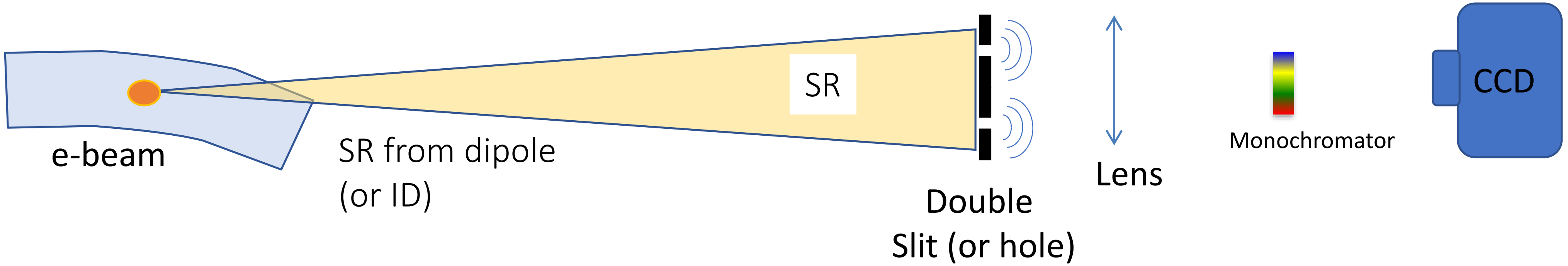
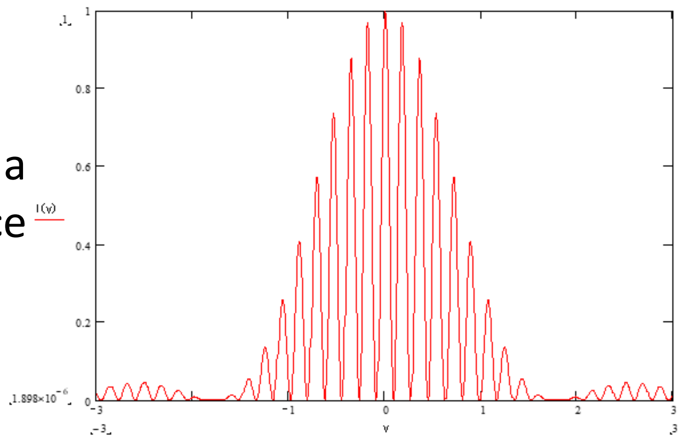
Coherence Measurements: SR Interferometry

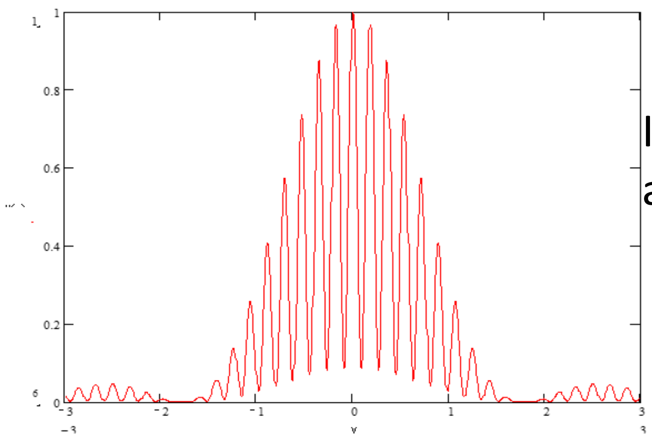
Set-up for a Double Slit (or double-pinhole) Interferometry



- The Interference image is used to calculate the spatial degree of coherence of the SR, from where the source size is inferred using the Van-Citter Zernike theorem.
- Pioneer implementation by T. Mitsuhashi in Spring-8 and KEK

Interference profile from a point-like source

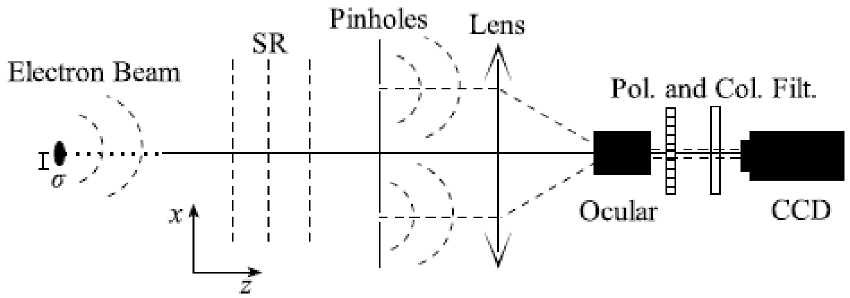




Interference profile from a finite source ($\sigma > 0$)

Coherence Measurements: SR Interferometry

SRI Set-up (Visible Range)



$$I = I_0 \left\{ \frac{J_1\left(\frac{2\pi a x}{\lambda f}\right)}{\left(\frac{2\pi a x}{\lambda f}\right)} \right\}^2 \times \left\{1 + V \cos\left(\frac{2\pi D x}{\lambda f}\right)\right\}$$

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

I_0: Intensity

a: Pinholes radius

λ: SR wavelength

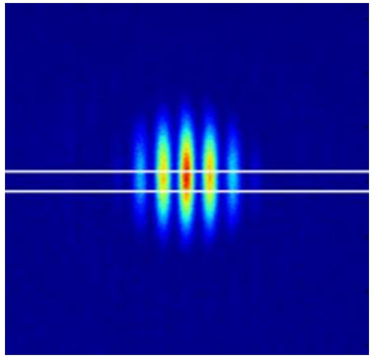
f: Focal distance of the optical system

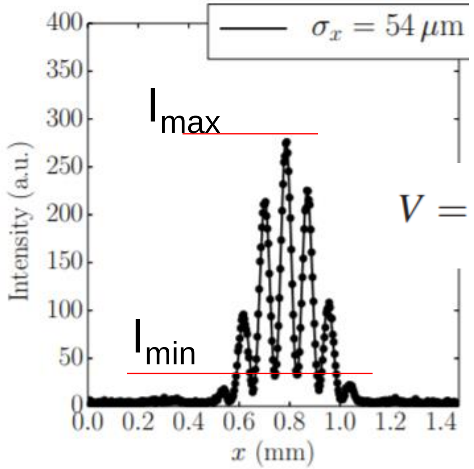
D: Pinholes distance

V: Visibility

L: Distance from the source

L. Torino, ARIES Emittance Workshop (2018)





$$V = \frac{I_{Max} - I_{Min}}{I_{Max} + I_{Min}}$$

- Used in Spring-8 and KEK for real-time measurement
- Also used in other LS as a redunant/alternative measurement to the pinhole camera using the visible diagnostic beamline

Coherence Measurements: SR Interferometry

SRI Limitations

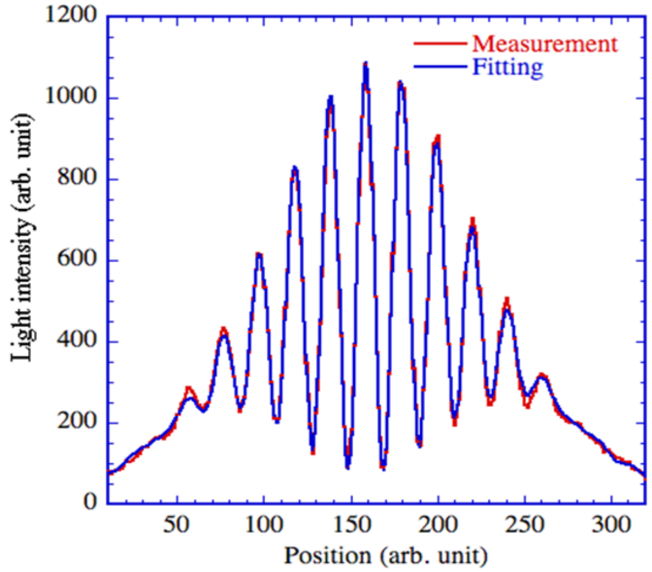
Measurement limitations are associated to phase fluctuations of the SR wavefront propagation along the optical components.

Since $\sigma = \frac{\lambda d_0}{\pi D}\sqrt{\frac{1}{2}\ln(\frac{1}{V})}$ → Better resolutions if λ is decreased t uv or x-rays regimes

In the visible range, the optical components (mirrors, windows…) can be manufactured with surface flatness better than $\lambda/10$, error measurement ~**0.5um**

Instead, significant errors are associated to experimental setup like:

- Air turbulences in the optical path
- Mechanical vibrations
- CCD noise and linearity



Example @ATF:

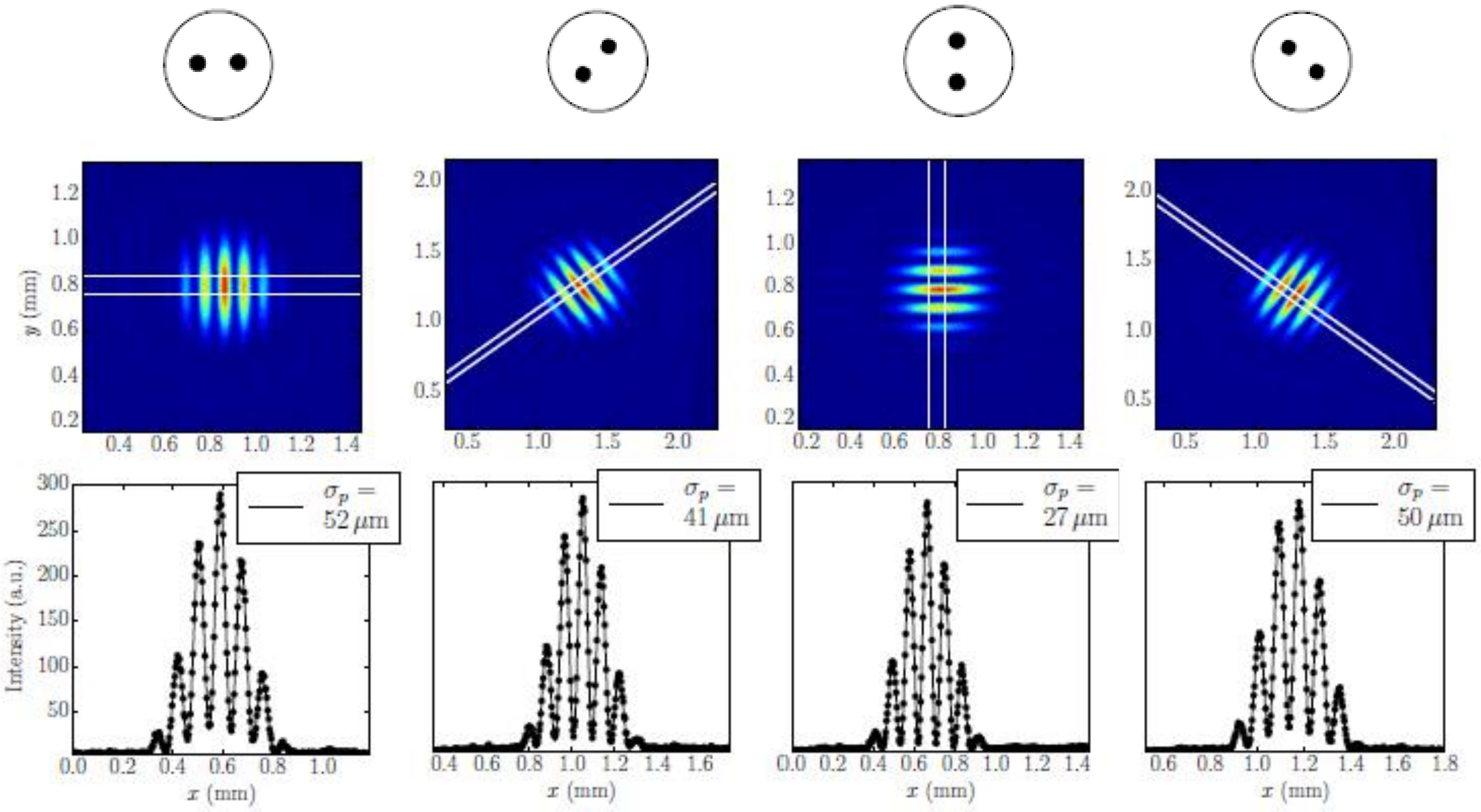
$\sigma = 4.73\mu m \pm 0.55\mu m$

(→ $\varepsilon = 9.7$pmrad)

T. Mitsuhashi, ARIES Emittance Workshop (2018)

Coherence Measurements: SR Interferometry

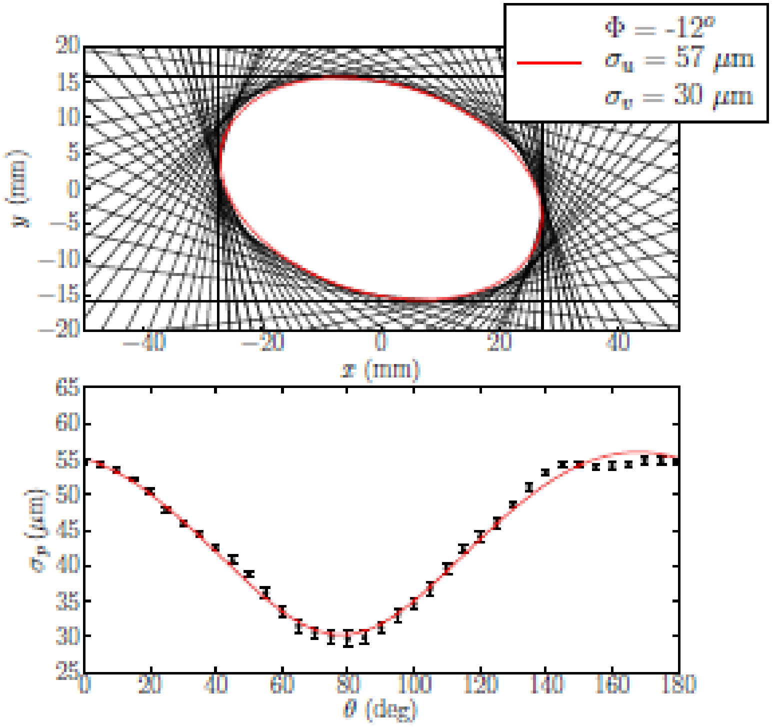
- SRI limitation: provide only 1d measurement → The orientation of the two apertures provides the direction analysis
- Using a rotating mask, we can reconstruct beam profile and decrease minimum measurable beam size*



*L.Torino and U.Iriso, PRST-AB 19, 122801 (2016)

Coherence Measurements: SR Interferometry

- Using the rotating mask, and sampling the slit orientation from 0 – 180deg, we can reproduce the 2-d ellipse



The beam reconstruction shows clearly that the beam can be approximated as an ellipse.

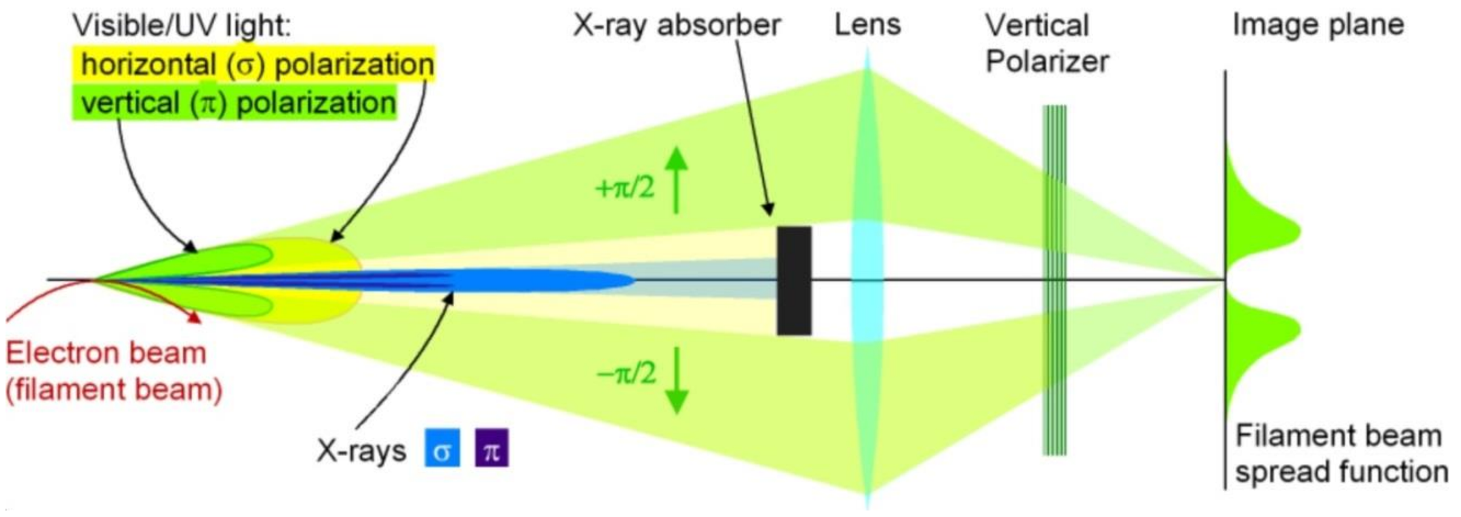
$$x(\theta) = \sigma_u \cos(\theta + \Phi)$$

$$y(\theta) = \sigma_v \sin(\theta + \Phi)$$

$$\sigma_p(\theta) = \sqrt{\sigma_u{}^2 \cos^2(\theta + \Phi) + \sigma_v{}^2 \sin^2(\theta + \Phi)}$$

*L.Torin, ARIES Emit workshop (2018)

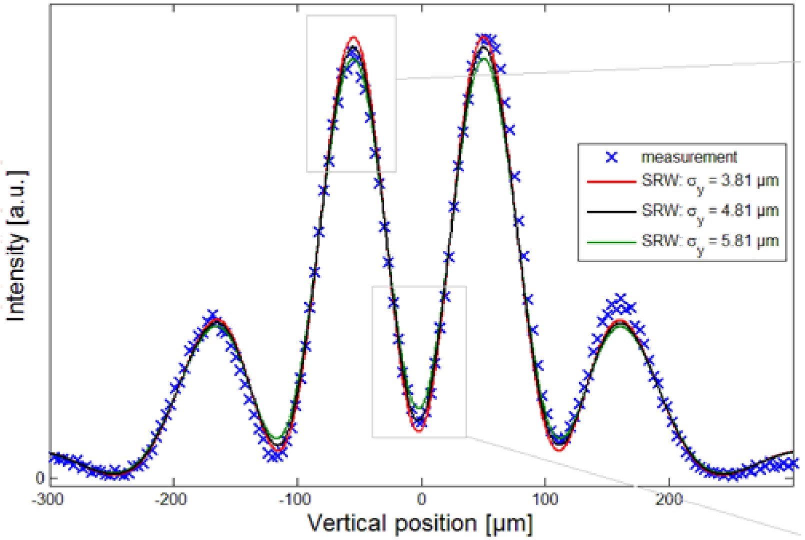
Coherence Measurements: π - Polarization



Use of vertically polarized SR in the visible/UV

In the center, phase shift of π between two radiation lobes produces destructive interference in the mid plane

As SRI, the interferences produces:
- zero intensity for a point-like beam ($\sigma = 0$)
- residual intensity for a beam with finite beam size ($\sigma > 0$)



Example at SLS (A. Saa and A. Anderssen*)

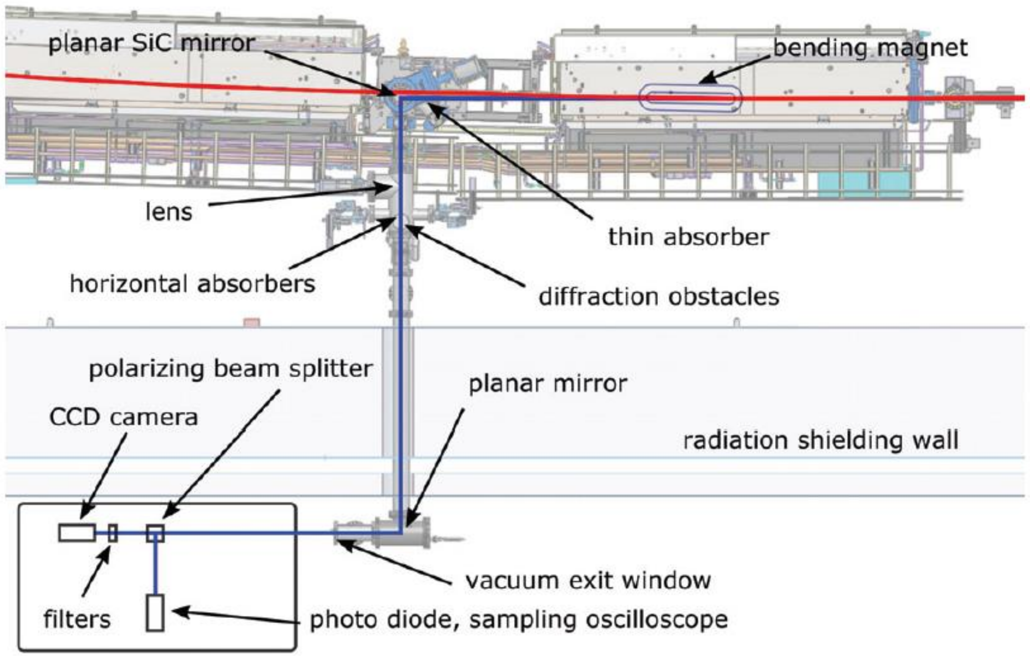
Measurements are compared with SRW simulations in a Look-Up-Table (LUT)

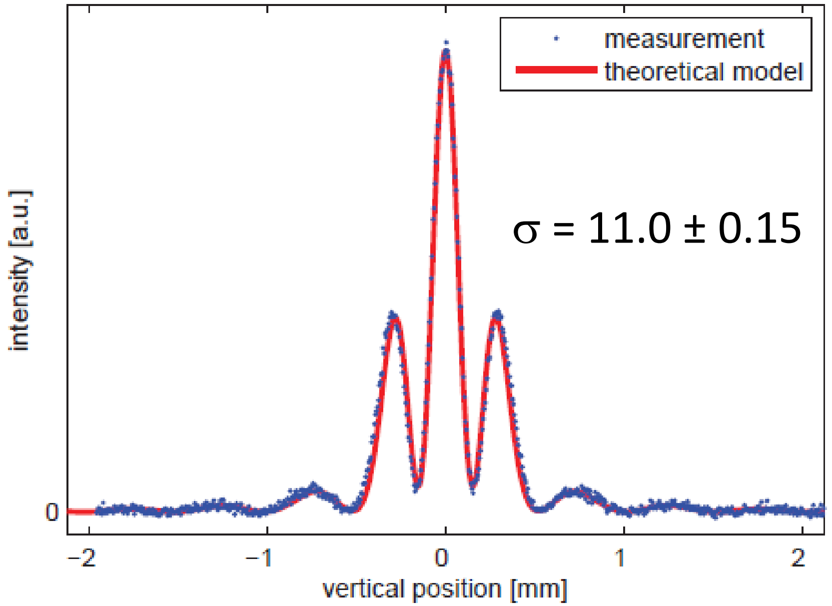
At SLS, reach the record of **σ = 3.5um → ε = 0.9 +/- 0.4 pm·rad****

*A. Saa, ALERT Workshop (2014)
**M. Aiba, Ultra-low emittance at SLS through systematic and random optimization, NIM-A (2012)

Coherence Measurements: π - Polarization

Implementation at Max-IV*



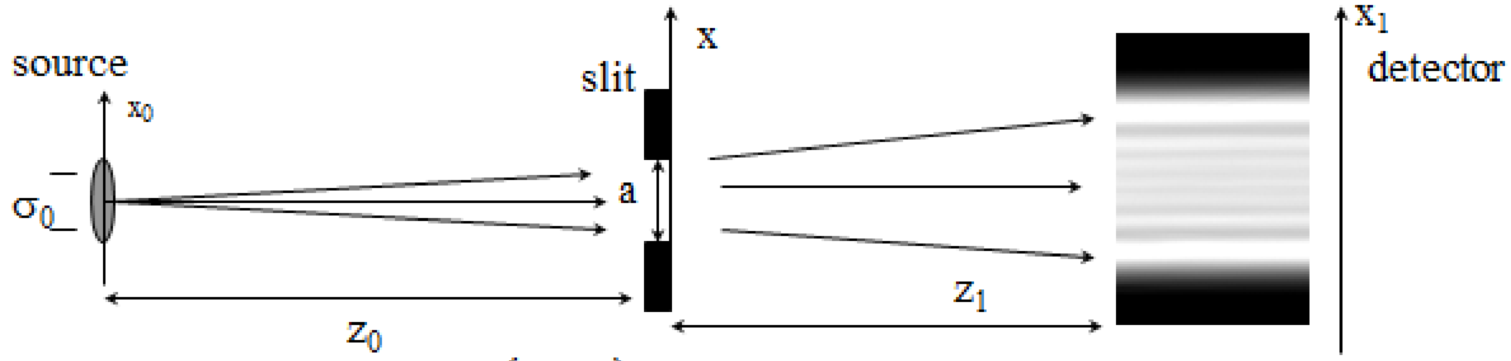


Beam sizes at Max-IV around 10um are measured, willing to reach **3um** soon
To further decrease the system resolution, the beamline is also optimized for uv range (**λ=250nm**)
Watch out: due to small σ_x, horitzontal aperture can be quite large (~15mrad)

*A. Anderssen, Emittance Diagnostics in Max-IV (IPAC – 2016)

Coherence Measurements: X-ray Diffraction

X-ray Fresnel Diffraction through Slit



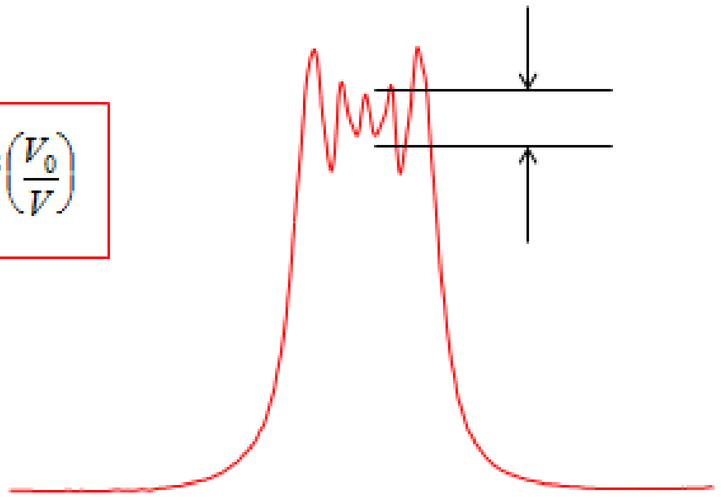
$$I(x_1) = 1 + \frac{4}{\pi}\left(\frac{4\lambda z_0 z_1}{z a^2}\right)^{1/2} \cos\left(\frac{\pi z a^2}{4\lambda z_0 z_1} - \frac{3\pi}{4}\right)\exp\left(-\frac{a^2}{4\sigma_{mc}^2}\right)\cos\left(\frac{\pi a}{\lambda z_1}x_1\right)$$

$$V(x_1) = \frac{I(x_1)_{\max} - I(x_1)_{\min}}{I(x_1)_{\max} + I(x_1)_{\min}}$$

$$V = V_0 \exp\left(-\frac{a^2}{4\sigma_{mc}^2}\right), \quad \sigma_{mc} = \frac{2\lambda z_0}{\pi\sigma_0} \quad \Rightarrow \quad \boxed{\sigma_0 = \frac{4\lambda z_0}{\pi a}\ln^{1/2}\left(\frac{V_0}{V}\right)}$$

$$V_0 = \frac{4}{\pi}\left(\frac{4\lambda z_0 z_1}{z a^2}\right)^{1/2}\left|\cos\left(\frac{\pi z a^2}{4\lambda z_0 z_1} - \frac{3\pi}{4}\right)\right|$$

$$a \geq 3\left(\frac{2\lambda z_0 z_1}{z}\right)^{1/2}, \quad x_1 = \frac{az}{10 z_0}$$



*A. Snigirev, Beam size diagnostics using x-rays, ARIES Emit Workshop (2018)

Analyze the diffraction patern produced by x-rays and slit

Similar as the visible SRI, the beam size is obtained through the visibility

X-ray monochromator required

Used at ESRF is specific beamline*

Measured down to **σ = 5um**

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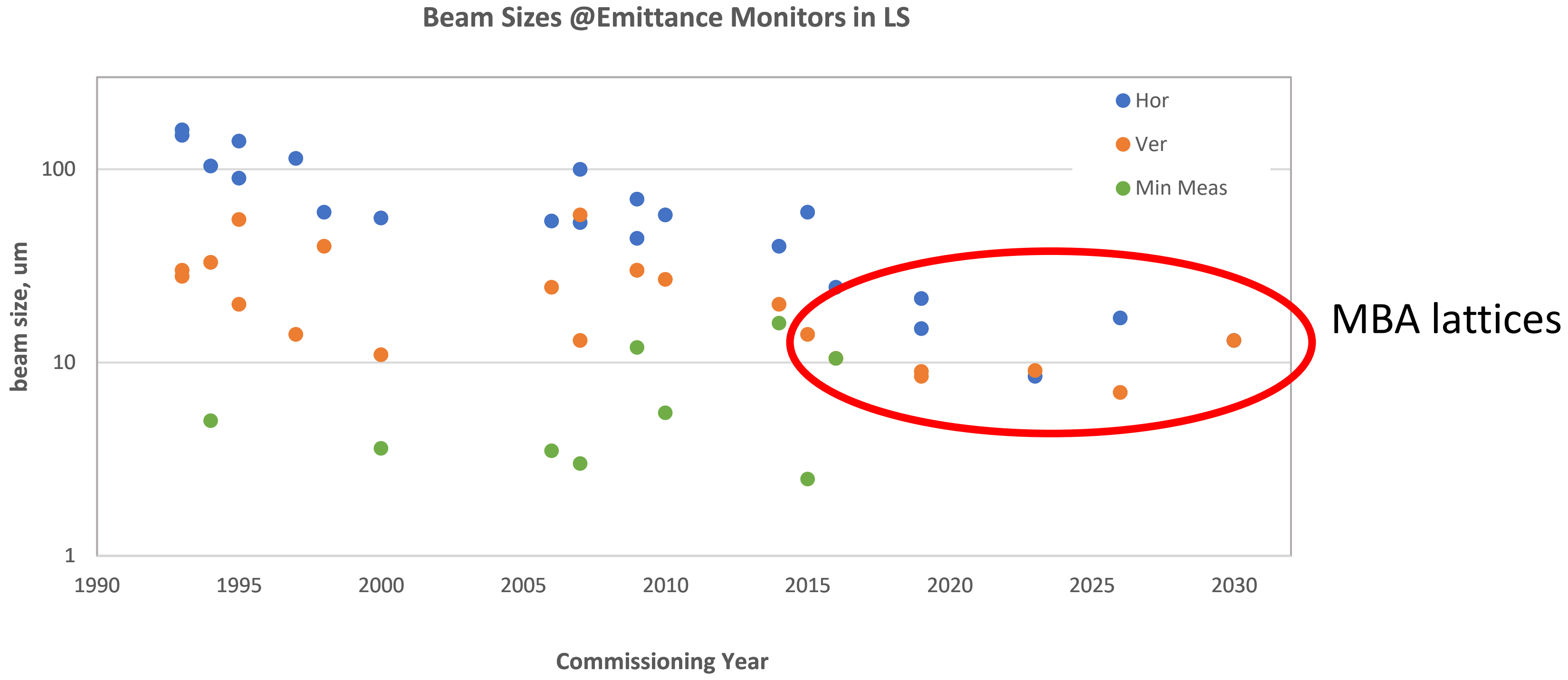
Requirements for LER:



- Existing techniques already provide the require resolution for future LER
- Nevertheless, these beamsize measurments need to be reliable for fast measurements, small beam sizes or larger dynamic ranges → mechanical constrains need to be addressed with due care

Requirements for LER: APSU Example (B. Yang)

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.

B. Yang (APS, Planned X-ray Diagnostics for APSU ε-Meas, ARIES Emit Workshop (2018)

Requirements for LER: APSU Example (B. Yang)

X-ray Diffraction Optics

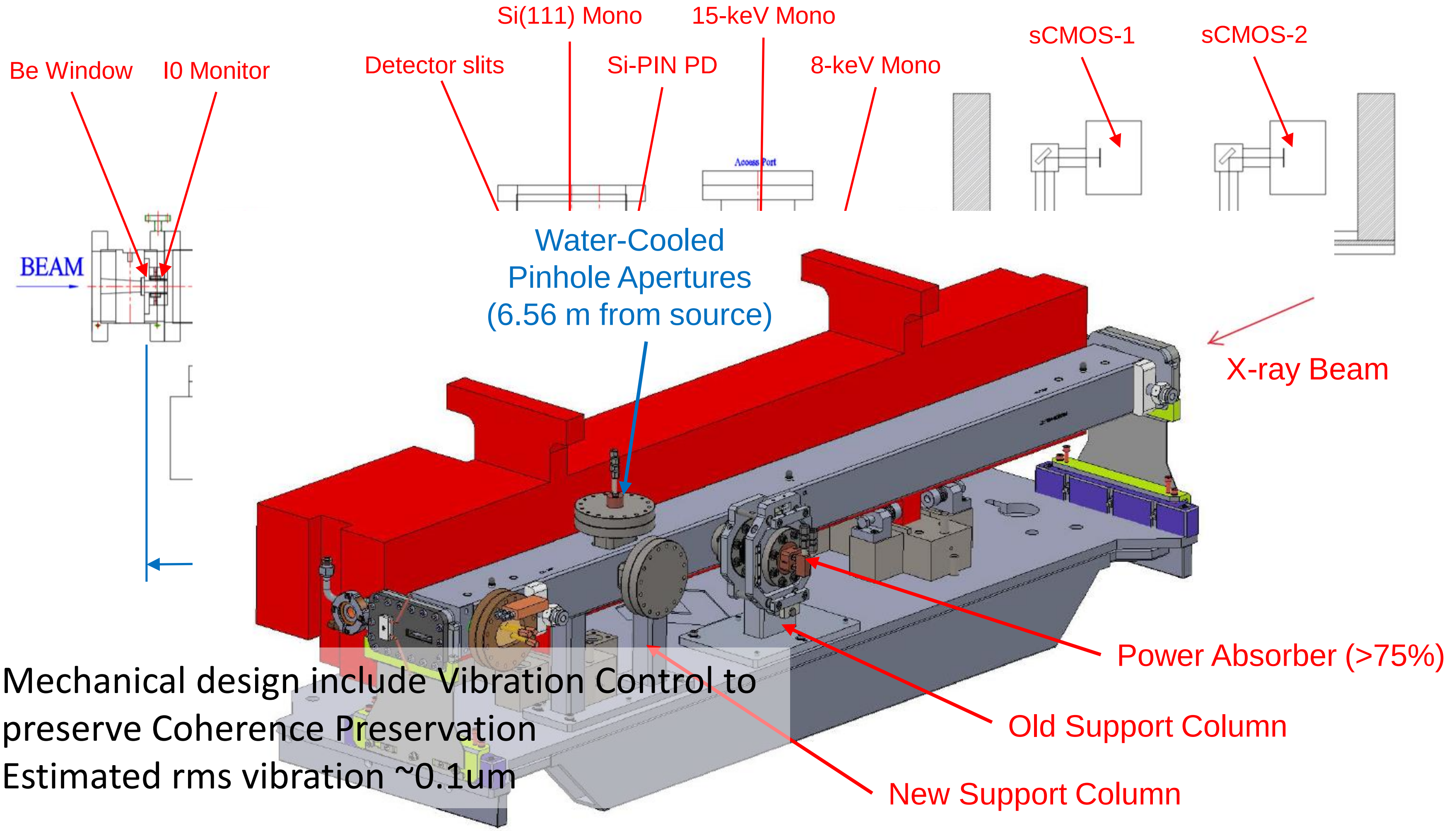
- The x-ray optics is a 0.1-mm tungsten foil with **six apertures** of different sizes to cover all the machine requirements:
  - Apertures may be put into **two function groups.**

- **Absolute beam size monitor (ABSM)**: operating in 0.1 – 1 Hz range, different techniques available according to beam size ranges:
  - Monochromatic **x-ray pinhole camera** (15 keV): for 8 – 100+ μm beam size
  - 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

Requirements for LER: APSU Example (B. Yang)

X-ray Optics Design – “user-type” instrumentation



- Mechanical design include Vibration Control to preserve Coherence Preservation
- Estimated rms vibration ~0.1um

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  - X-ray Diffraction
- LER Requirements & New trends:
  - Multi-technique beamline @APSU
- Summary

Summary:

- Existing techniques provide beamsize measurements for the LER, but the required instrumentation and its stability can become a real challenge to measure beamsizes ~1um.
- X-ray instrumentation like CRL and monochromators in stable girders can increase the budget for the diagnòstics beamlines significantly
- From “parasitic” diagnostics beamlines to “user-type” diagnostics beamlines, combining different techniques to cover different needs (APSU Example)

THANKS!

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