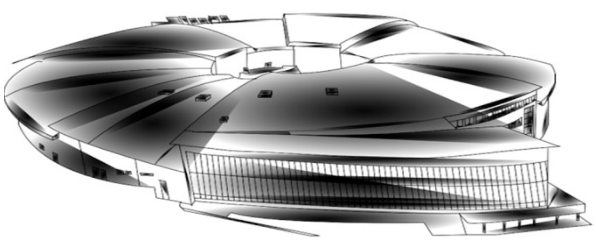
Summary of Topical Workshop: Emittance Measurements for Synchrotron Light Sources and FELs

Ubaldo Iriso (ALBA-CELLS),

F. Ewald (ESRF), G. Kube (DESY), T. Mitsuhashi (KEK),
V. Schlott (PSI) and K. Wittenburg (DESY)



ALBA – CELLS (Barcelona)
Jannuary 2018
https://indico.cells.es/indico/event/128/

Topical Workshop: ε-Measurements for Light Sources & FELs

Funding Network: **ARIES**

Accelerator Research and Innovation for European Science

https://aries.web.cern.ch/

See Poster

MOPB02 (P. Forck)

Topical Workshop: ε-Measurements for Light Sources & FELs

Some Numbers:

38 registrants
24 Talks:
- 12 Talks about SLS
- 9 Talks about FELs
- 2 Talks for Hadron Machines
- 1 Talk for Plasma Accel.

Workshop Programme

	Monday Jan. 29th	Tuesday Jan 30th
	Monday Morning I - Chair: U. Iriso (ALBA)	Tuesday Morning I - G. Kube (DESY)
9:00	Workshop Welcome and Introduction, U. Iriso (ALBA-CELLS)	Requirements from the FEL B.Dynamics community , E. Prat (PSI)
9:10 – 9:20	Requirements from the electron rings B Dynamics community, M. Boege (PSI)	

Day 1: Focused on **Synchrotron Light Sources**

- Requirements from B. Dynamics
- Direct Imaging Techniques
- Inverse Space Imaging Techniques
- “Uncommon” techniques: HNFS, x-ray diffraction/interferometry...

Day 2: Focused on **FELs**

- Requirements from B. Dynamics
- OTR/ODR techniques
- Wire scanner techniques
- Inheritance from other accelerators: from Hadron Colliders to Plasma Acceleration

16:50 – 17:10	Beam size diagnostics using x-rays imaging and interferometry, A. Snigirev (ESRF)	Emittance measurements for plasma accelerators, A.Cianchi (INFN)
17:20	Cherenkov Diffr. Rad. as a Beam Size Measurement Technique, M .Bergamaschi (CERN)	Proposals for future linear accelerators (Open Discussion)
17:30 – 17:50	Proposals for diffraction limited light sources (Open Discussion)	

Summary of ε- meas for SLS

Presentations are available at: https://indico.cells.es/indico/event/128

Technique	Smallest σ, μm (measured)	Workshop Talk
X-ray Pinhole	7	L. Bobb / F. Ewald
Compound Refractive Lenses	10	F. Ewald / A. Snigirev
In-air X-ray Detectors	9	F. Ewald
Vis. Light Interf.	3.9	T. Mitsuhashi
Vis. Light Inter. (Rotating Mask)	2 (sim)	L. Torino
π-polarization (vis)	3.7	A. Andersson
Coded Aperture	5	J. Flanagan
X-ray Diffraction	4.8	A. Snigirev
X-ray (multi/lens) Interferometry	4.8	A. Snigirev
HNFS	110	M. Siano

Summary of ε- meas for FELs

Presentations are available at: https://indico.cells.es/indico/event/128

Technique	Smallest σ, μm (measured)	Workshop Talk
Scintillating Screens	1.5	G. Kube (DESY)
OTR Screens	0.75	L. Sukhikh (Tomsk)
ODR/ODRi Techniques	10	E. Chiadroni (INFN)
COTR	~1	A. Potilytsin (Tomsk)
Wire Scanners	30	K. Wittenburg (DESY)
Wire Scanners (lithography)	0.490	S. Borrelli (PSI)
Laser Wire	3	P. Karataev (RHUL)
IPMs for e-machines	~25 (theo)	M. Sapinski (GSI)
Pepper pot (high energy e-)	~200	N. DeleRue (LAL)

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- **Introduction**
- **Emittance Measurements for SLS:**
  - Direct Imaging Techniques
  - Inverse Space Imaging Techniques
  - Future trends
- **Emittance Measurements for FELs:**
  - Screen Monitors
  - Wire Scanners
- **Summary**

Common for SLS and FELs: PSF characterization is crucial

Point Spread Function Dominated Imaging with SR A. Anderssen (Max-IV)

- With tiny small beams (few microns), imaging might be limited by several factors.
- Use of simulation tools (SRW and/or Zemax for SLS)

Example

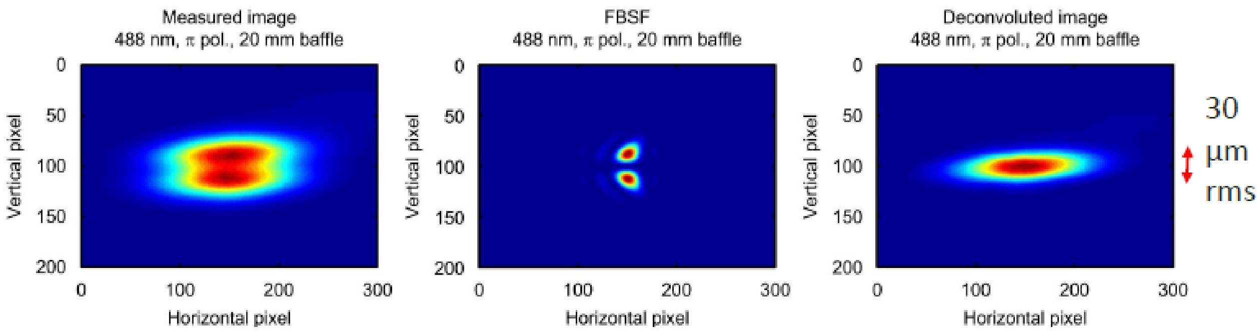


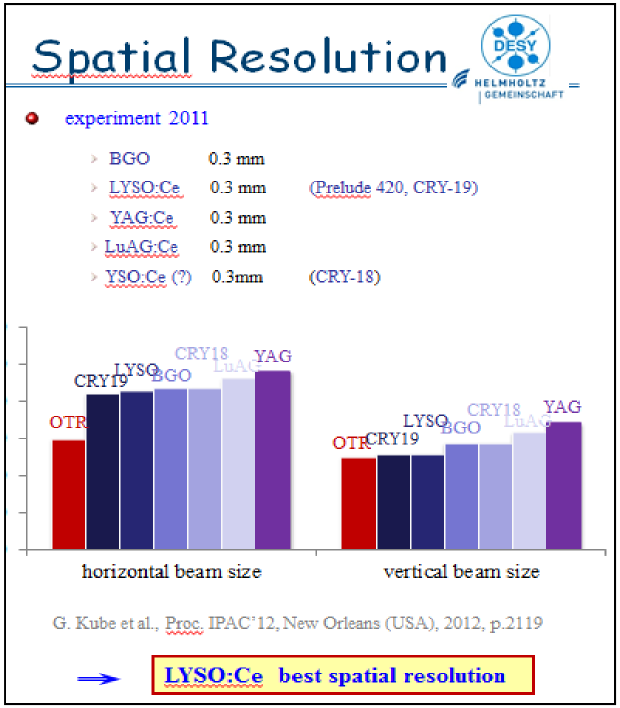
Fig. 7. Example of beam profile measurement with π-polarized light at 488 nm. Measured image, filament-beam-spread function and deconvoluted image for baffle aperture 20 mm (±5.4 mrad horizontal opening angle). Pixel size 3.75μm.

Common for SLS and FELs: PSF characterization is crucial

High Resolution Scintillating Screens for Measurements of few Micrometer Beams

G. Kube (DESY)

See talk
WEOC03 (G. Kube)



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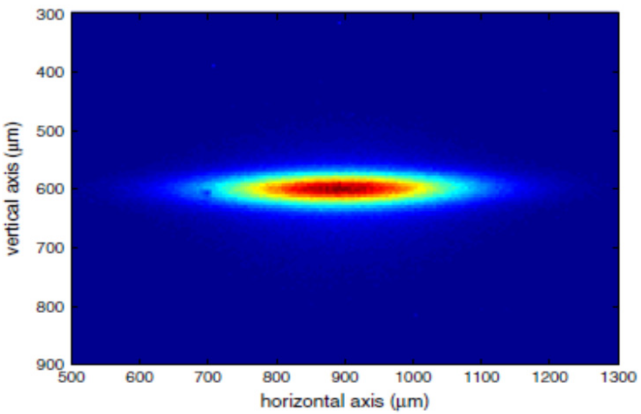
ε–meas for SLS: Direct Imaging Techniques

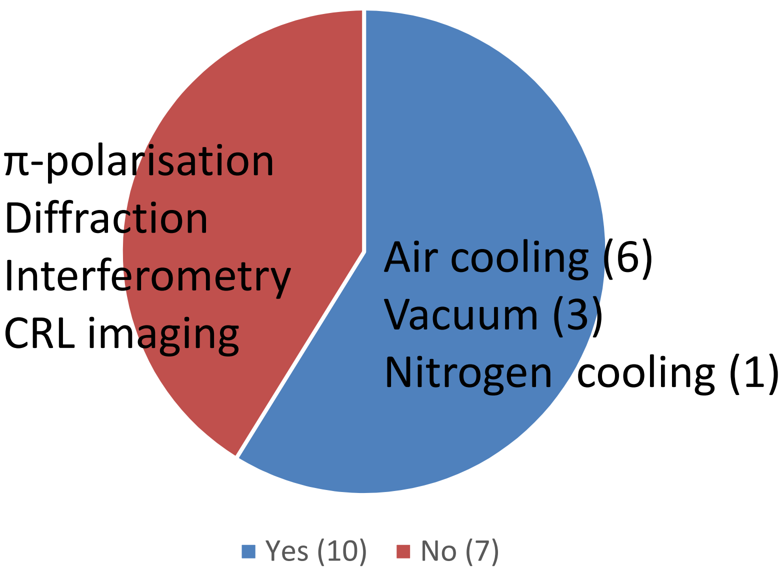
- Referred to those techniques in which the beam profile is directly imaged into a screen (and then to a camera) from the emitted SR

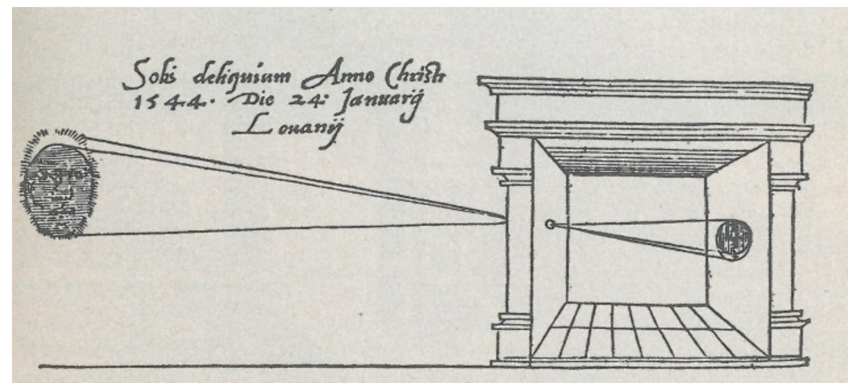
- Beam size inferred from fitting the image to (typically) a Gaussian fit (including convolution of PSF)

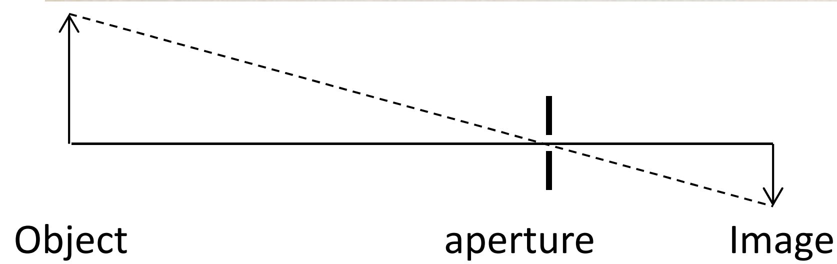


Status of X-Ray Pinhole Cameras for SLS, L. Bobb (Diamond)

- Well-known principle since 1545 (used to image solar eclipses)
- In accelerators, used since 1991 by P.Elleaume (ESRF)
- Currently, 10/17 SLS use x-ray pinholes for ε-meas







Status of X-Ray Pinhole Cameras for SLS, L. Bobb (Diamond)

Fundamental Limitations

$$\sigma^2_{PSF} = \sigma^2_{Pinhole} + \sigma^2_{Camera} > 0$$

Source resolution for optimised pinhole camera, given current spatial constraints at Diamond:

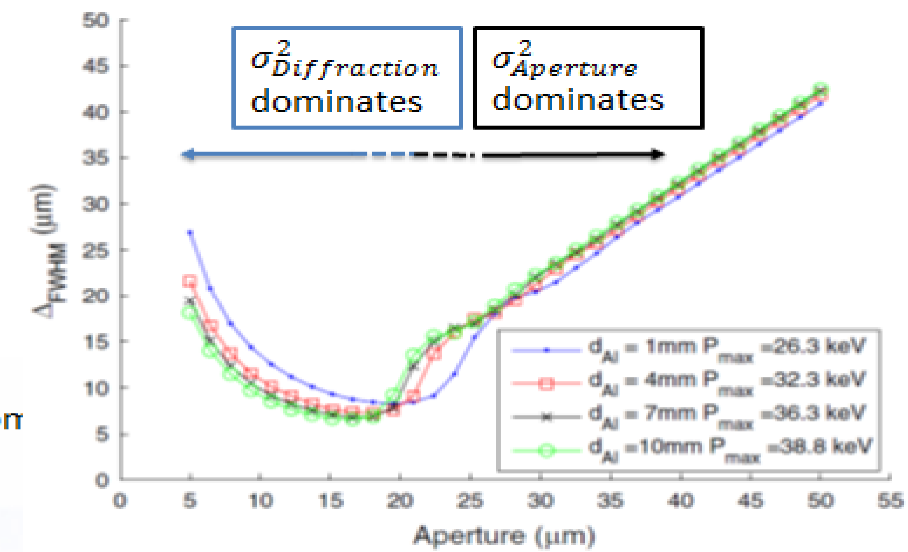
$$\frac{\left(\frac{\Delta_{FWHM}}{2.35}\right)}{|M_1|} \sim \frac{\left(\frac{6\ \mu\text{m}}{2.35}\right)}{2.65} \sim 1\ \mu\text{m}$$

with $\sigma^2_{Camera} = 0$.

Source resolution incl. contribution from camera using a 5µm P43 screen [4]:

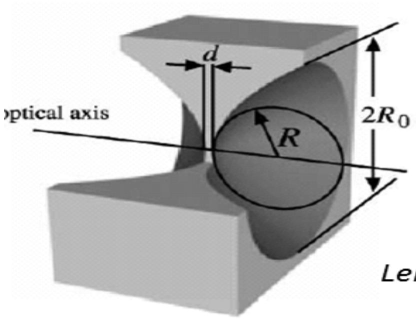
$\sim 3\ \mu\text{m}$

Phys. Rev. ST Accel. Beams **13**, 022805 (2010)

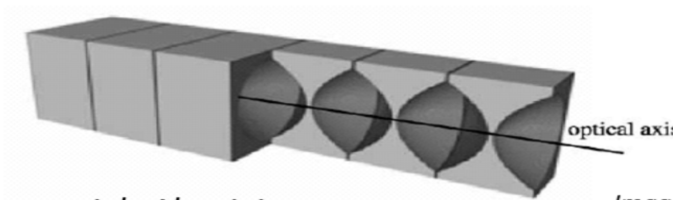


Beam Imaging Using X-ray Lenses, F. Ewald (ESRF)

Use of Compound Refractive Lenses (CRL):

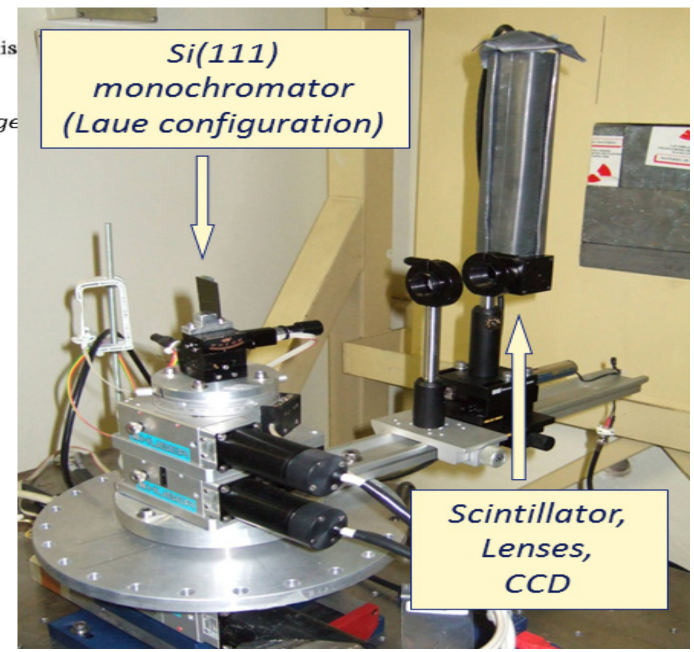


n_{Al} << n_{air} *for X-rays*



Lens material: Aluminium

Image



Focal length of CRLs (thin lens approximation):
R… Radius of curvature
N… Number of lenses
d… Index of refraction (real part)
E… Photon energy

$$f = R / 2N\delta(E)$$

Need monochromatic beams
→ Delicate and expensive (beamline-type) components

Beam Imaging Using X-ray Lenses, F. Ewald (ESRF)

Compound Refractive Lenses: precision?

XRL for emittance measurement at ESRF (now removed)

Transverse 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 beam port D11 (calculated using [2] or [3]):

→ $\sigma_{min} = 3.3\ \mu m$

→ $\varepsilon_{z,min} = 0.3\ pm$

To be compared with a resolution of **~5um** obtained with their pinhole

[1] B. Lengeler et al. / Nuclear Instr. Meth. in Phys Res. A 4

[2] B. Lengeler et al. /J. of Appl. Phys. 84 (1998) 5855

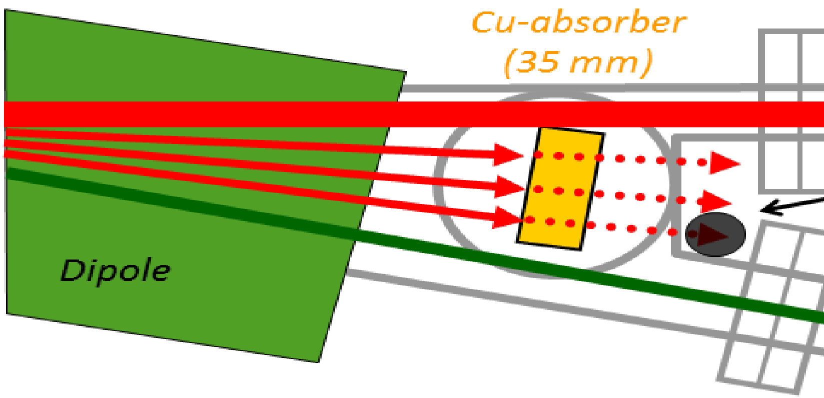
[3] http://purple.ipmt-hpm.ac.ru/xcalc/xcalc_mysql/crl_par.php

Beam Imaging Using In-Air X-ray Detectors, F. Ewald (ESRF)

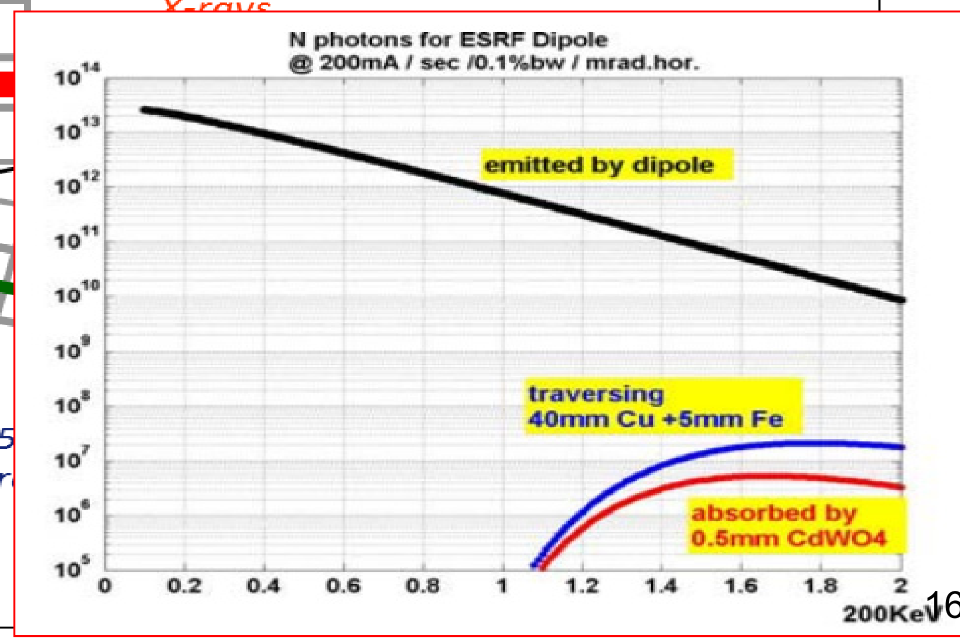
Dipole radiation X-ray Projection Monitors

Simple measurement of the X-ray beam projected from the source point in a bending magnet onto a scintillator screen

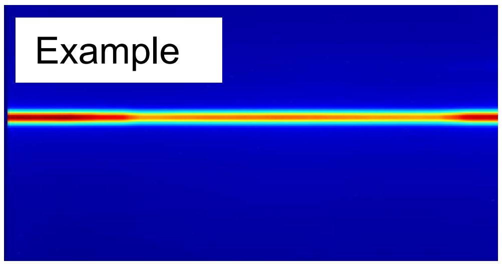
E_{PEAK} ~ 160 keV
$\sigma'_{SYNC\ RAD}$ = 17.5 μrad



- *Scintillator: $Lu_{1.8}Y_{.2}SiO_5:Ce$ ("PreLude") 5*
- *Focusing via motorised scintillator scr*
- *Double Achromat*
- *CCD: Flea (Point Grey Research)*
- *Pb - shielding*



Beam Imaging Using In-Air X-ray Detectors, F. Ewald (ESRF)



Total beam size on screen: $\Sigma^2_{tot} = \varepsilon\beta - 2\varepsilon\alpha D + \varepsilon\gamma D^2 + \sigma'^2_{ph} D^2)$

electron beam size and divergence — *divergence of synchrotron radiation*

- Simple, cheap, easy to use
- In operation at ALBA, ANKA, ESRF and Soleil
- Only vertical plane
- Precision: x-ray divergence limitation - @ ALBA: 50um!

At ESRF, use them for a number of machine parameters measurements (from global coupling correction to momentum compaction factor)

A. Franchi, TUODA01, IPAC11

MOPA17 (L. Torino)

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- **Introduction**
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  - ➢ Direct Imaging Techniques
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  - ➢ Screen Monitors
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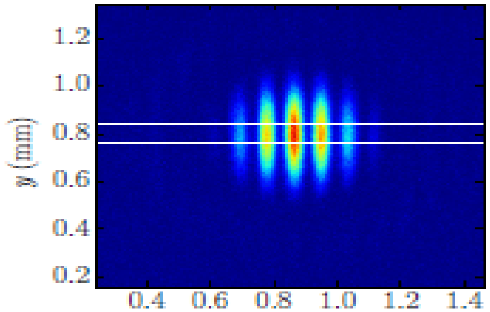
ε–meas for SLS: Inverse Space Imaging Techniques

- Based on the analysis of the Coherence of the Synchrotron Radiation (SR) after interfering with an obstacle (typical example, a double-aperture system)

- From the coherence size and using the Van Citter-Zernike theorem, calculate the electron beam size



1. **Visible Synchrotron Radiation Interferometry (SRI)** - T. Mitsuhashi, L. Torino (ESRF)
2. **X-ray Interferometry** - A. Snigirev (IKBF)
3. **Diffraction Pattern Analysis** - A. Snigirev (IKBF)
4. **Heterodyne Near Speckle Fiels (HNSF)**
5. **Coded-Aperture**

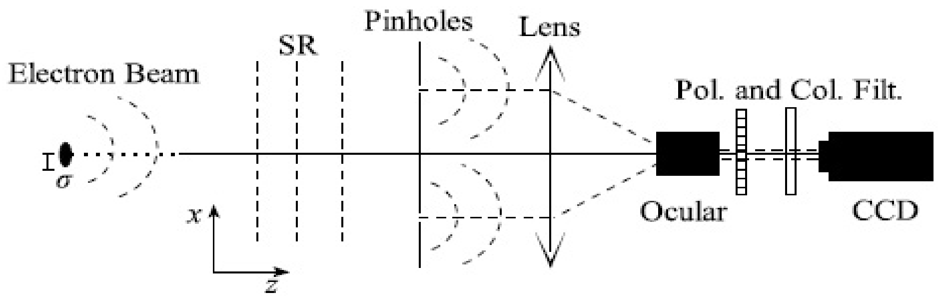
Details tomorrow: THOA03 (S. Mazzoni)

Details Next Talk at WEOC02 (J. Flanagan)

Visible Synchrotron Radiation Interferometry (SRI)

T. Mitsuhashi (KEK) & L. Torino (ESRF)

Typical Setup:



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

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

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

Visible SRI - T. Mitsuhashi (KEK)

Precision using SRI -- Error Analysis

In actual optical component, for optical components of surface ~$\lambda/10$, this error corresponds to **0.26µm**

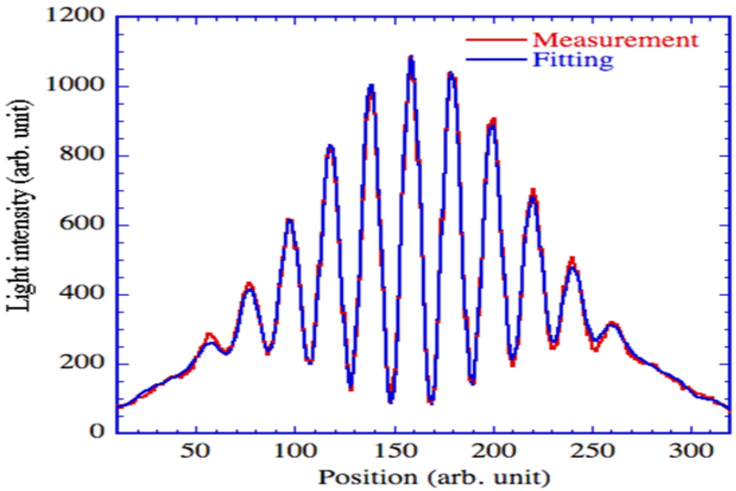
Real life: other limits show up

- Turbulence of air in the optical path
- Floor vibration
- Noise in CCD

Example:

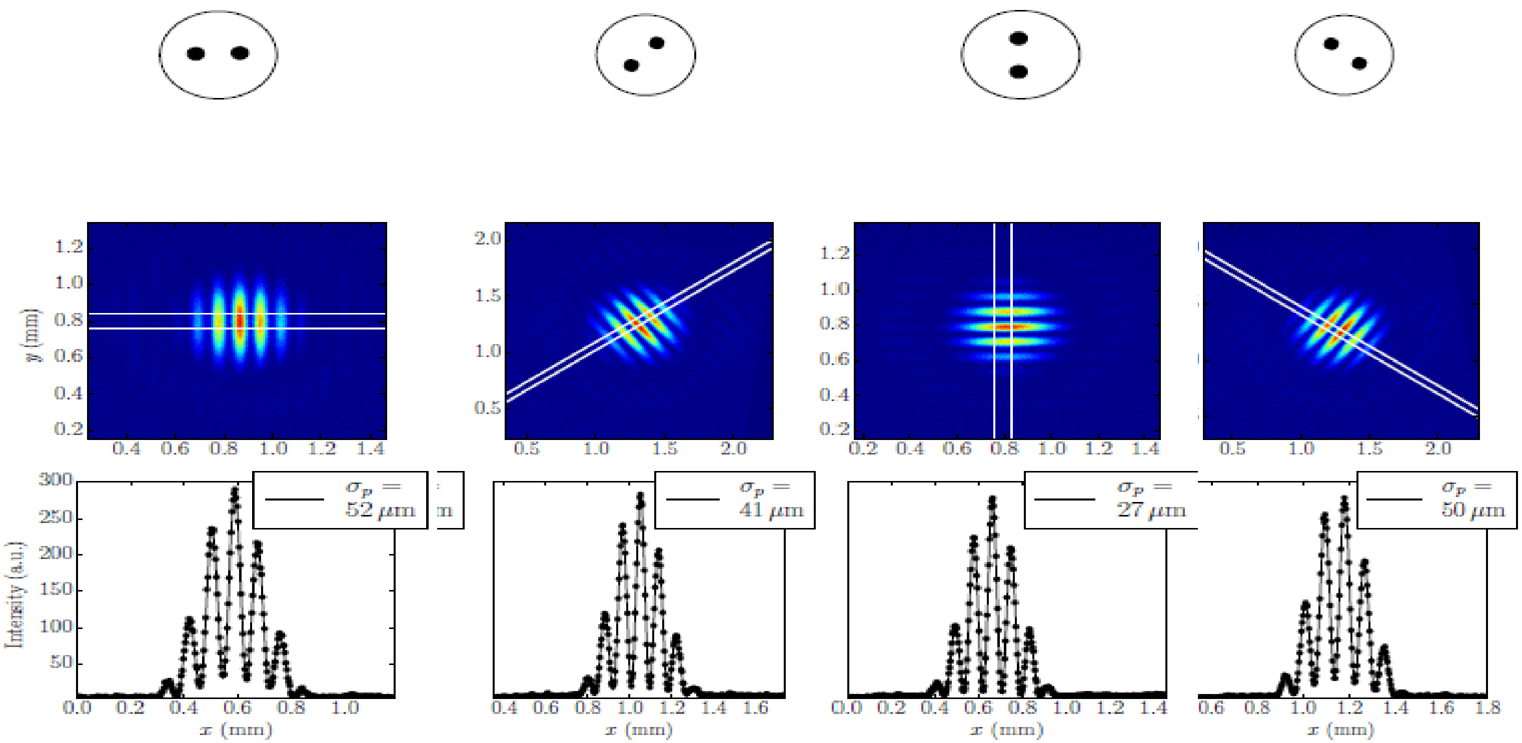
ATF at KEK

beam size is 4.73µm±0.55µm



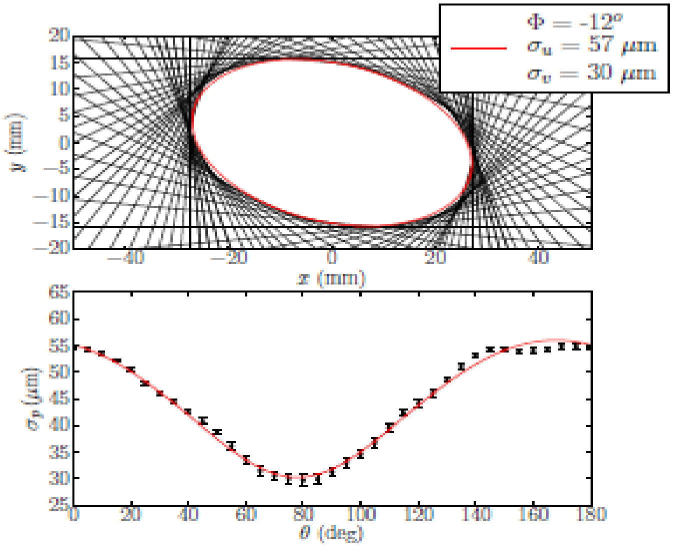
Visible SRI - L. Torino (ESRF)

- Analysis of Light Coherence provides projections in the hor or ver projection:
  - What if the beam is tilted??? → Use of Rotating Mask



Visible SRI – L. Torino (ESRF)

- Using a rotating mask, we can reconstruct beam profile and decrease minimum measurable beam size



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

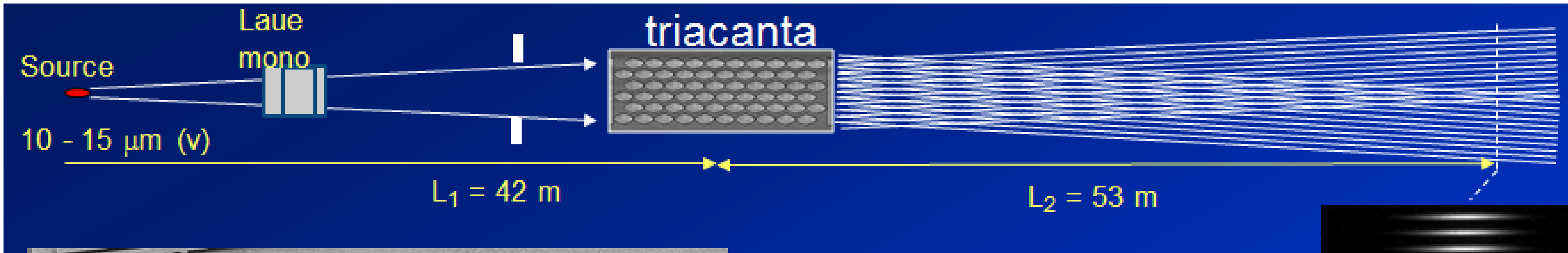
$$x(\theta) = \sigma_u \cos(\theta + \Phi)$$

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

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

Rotating Mask method used at:
ALBA: L. Torino and U. Iriso, Phys. Rev. Accel. Beams 19, 122801
Spear-3: C. L. Li, J. Corbett, MOPMR054, IPAC16

X-ray Interferometry lens arrays – A. Snigirev (IKBP)



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research papers

JOURNAL OF SYNCHROTRON RADIATION

ISSN 1600-5775

30-Lens interferometer for high-energy X-rays

Mikhail Lyubomirskiy,[a] Irina Snigireva,[a]* Victor Kohn,[b] Sergey Kuznetsov,[c] Vyacheslav Yunkin,[c] Gavin Vaughan[a] and Anatoly Snigirev[d]

[a]ESRF, Grenoble 38043, France, [b]National Research Centre 'Kurchatov Institute', Moscow 123182, Russian Federation, [c]Institute of Microelectronics Technology RAS, Chernogolovka 142432, Russian Federation, and [d]Baltic Federal University, Kaliningrad 236041, Russian Federation. *Correspondence e-mail: irina@esrf.fr

Received 26 April 2016
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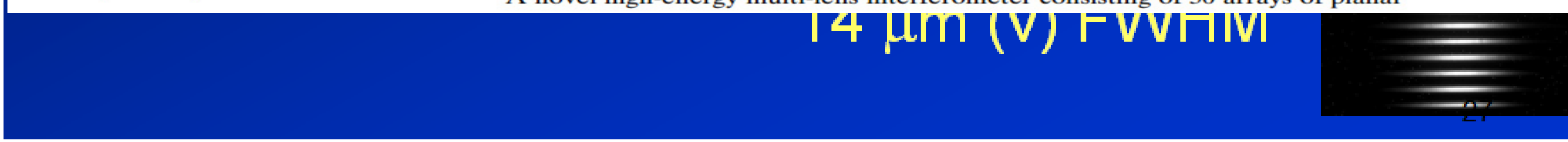
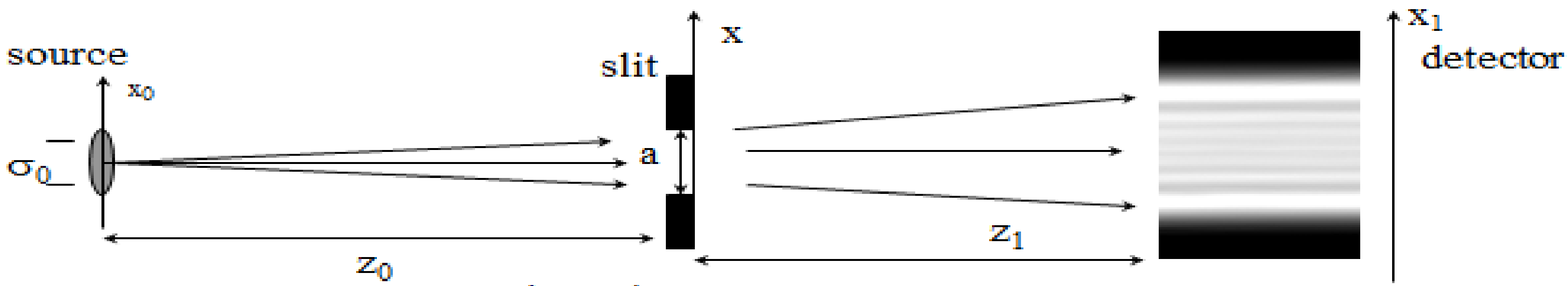
A novel high-energy multi-lens interferometer consisting of 30 arrays of planar



X-ray Diffraction – A. Snigirev (IKBP)

Coherence Characterisation by Fresnel Diffraction / Slits



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

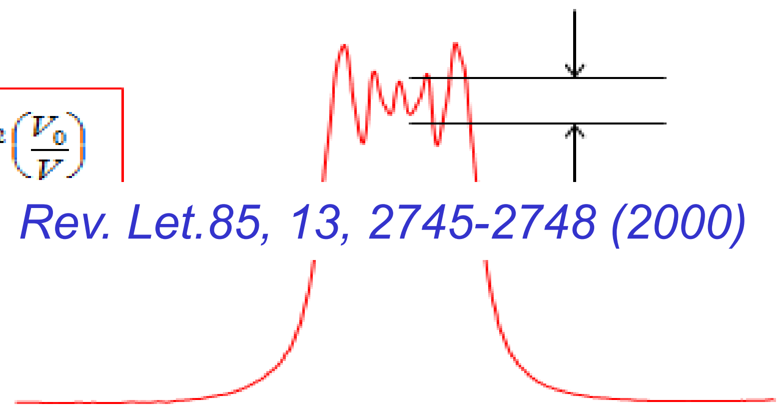
$$V(x_1) = \frac{I(x_1)_{max} - I(x_1)_{min}}{I(x_1)_{max} + I(x_1)_{min}}$$

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

V. Kohn, I. Snigireva, A. Snigirev. Phys. Rev. Let.85, 13, 2745-2748 (2000)

$$V_0 = \frac{\ldots}{\pi}\left(\frac{\ldots}{z a^2}\right) \quad \left|\cos\left(\frac{\ldots}{4\pi z_0 z_1} - \frac{\ldots}{4}\right)\right|$$

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



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Planned X-ray Diagnostics for APSU ε-Meas – B. Yang (APS)

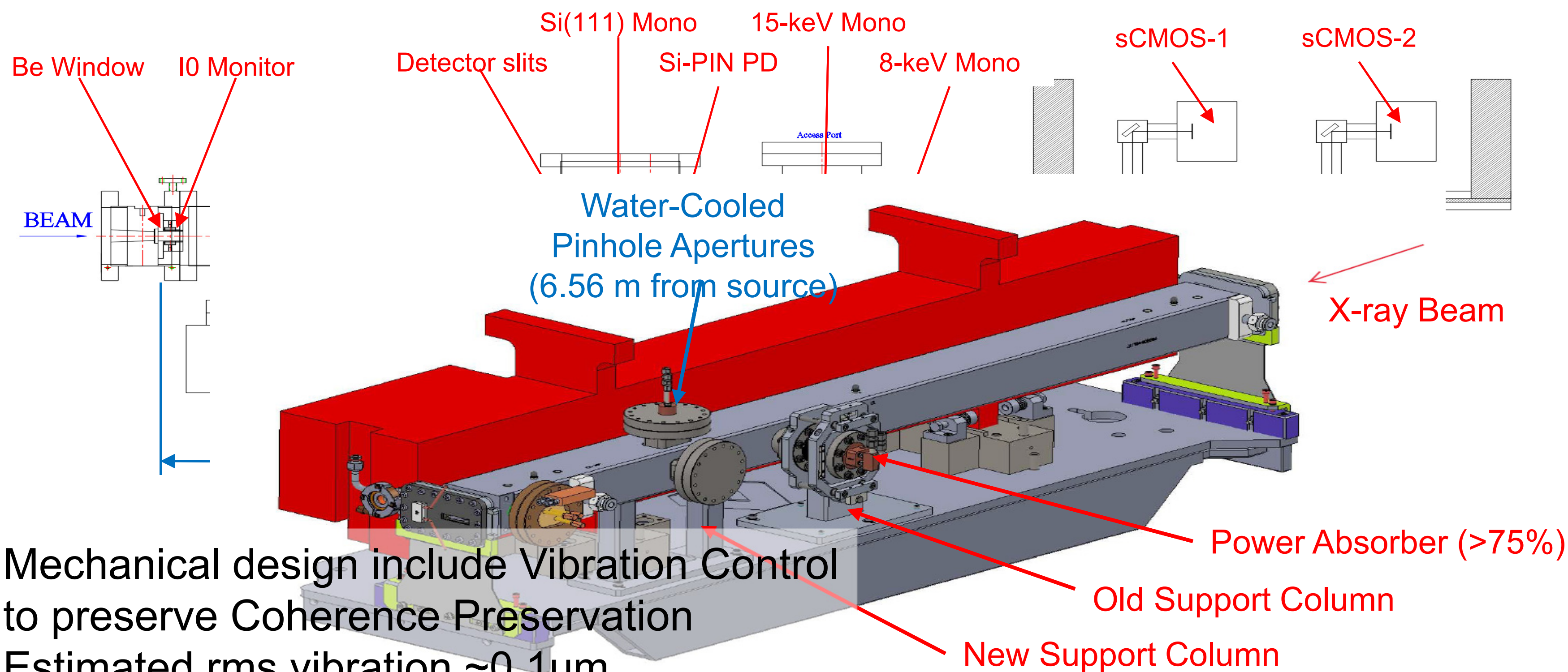
- The x-ray optics is a 0.1-mm tungsten foil with **six apertures** of different sizes to cover all the machine requirements:
  - Apertures may be put into **two function groups.**

- **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

Planned X-ray Diagnostics for APSU ε-Meas – B. Yang (APS)

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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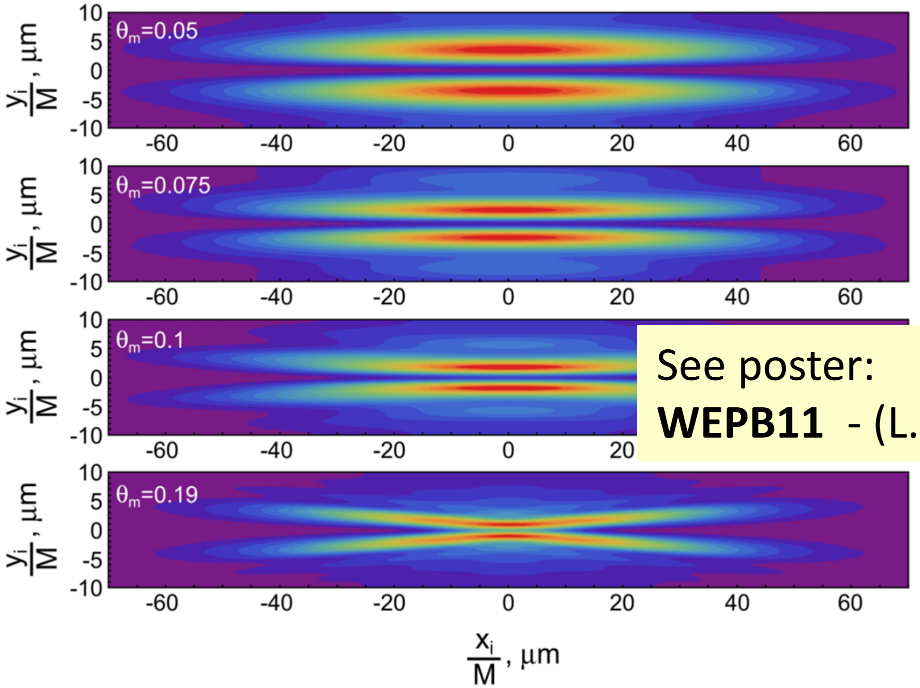
OTR PSF dominated beam imaging of micron beams with submicron resolution, L.G. Sukhikh

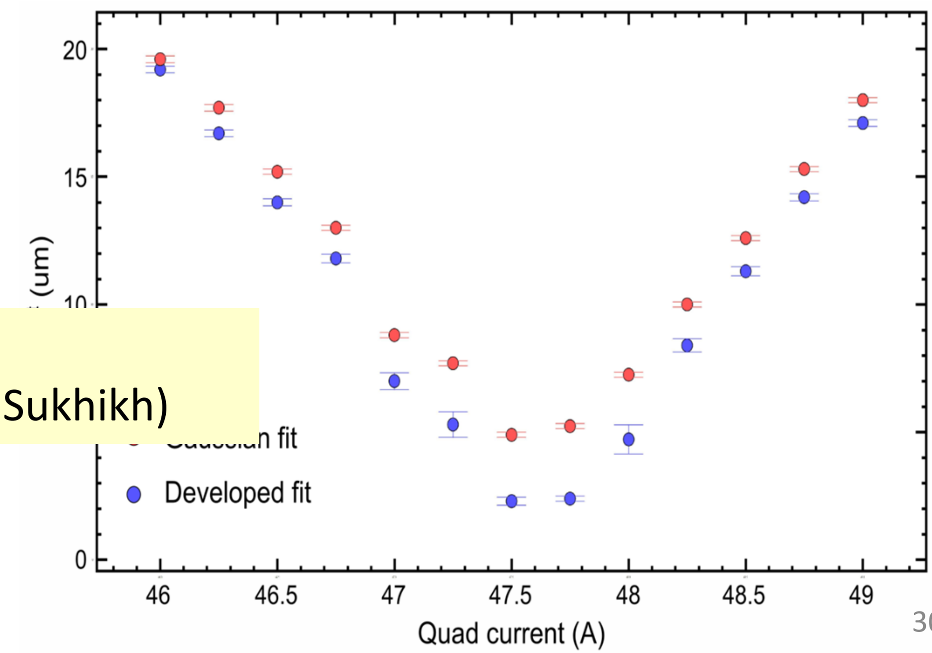
- Simulation of PSF dominating images
  see PRST-AB, 20, 032802 (2017)

Sim for different NA



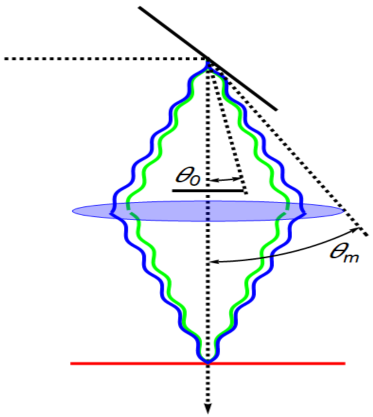
- Developed own fit for PSF using simulations and numerical analysis

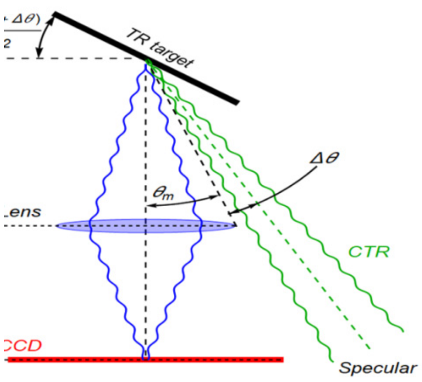
Results for a complete Quad Scan



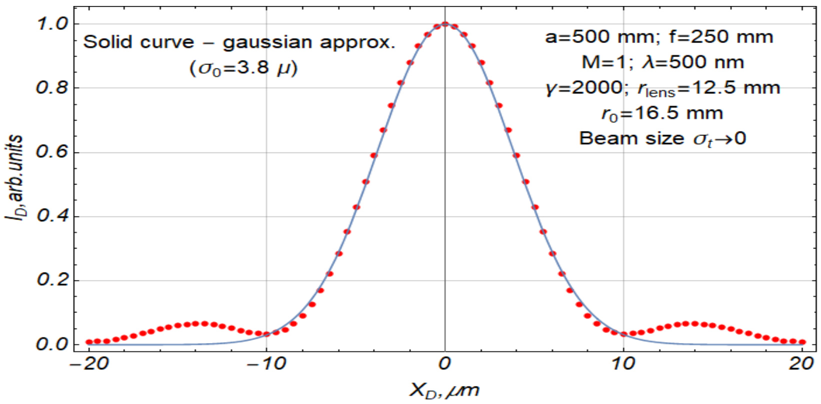
See poster:
WEPB11 - (L. Sukhikh)

Coherent Optical Transition Radiation for measurements of the transverse beam size, A. Potylitsyn





PSF for OTR off-axis lens

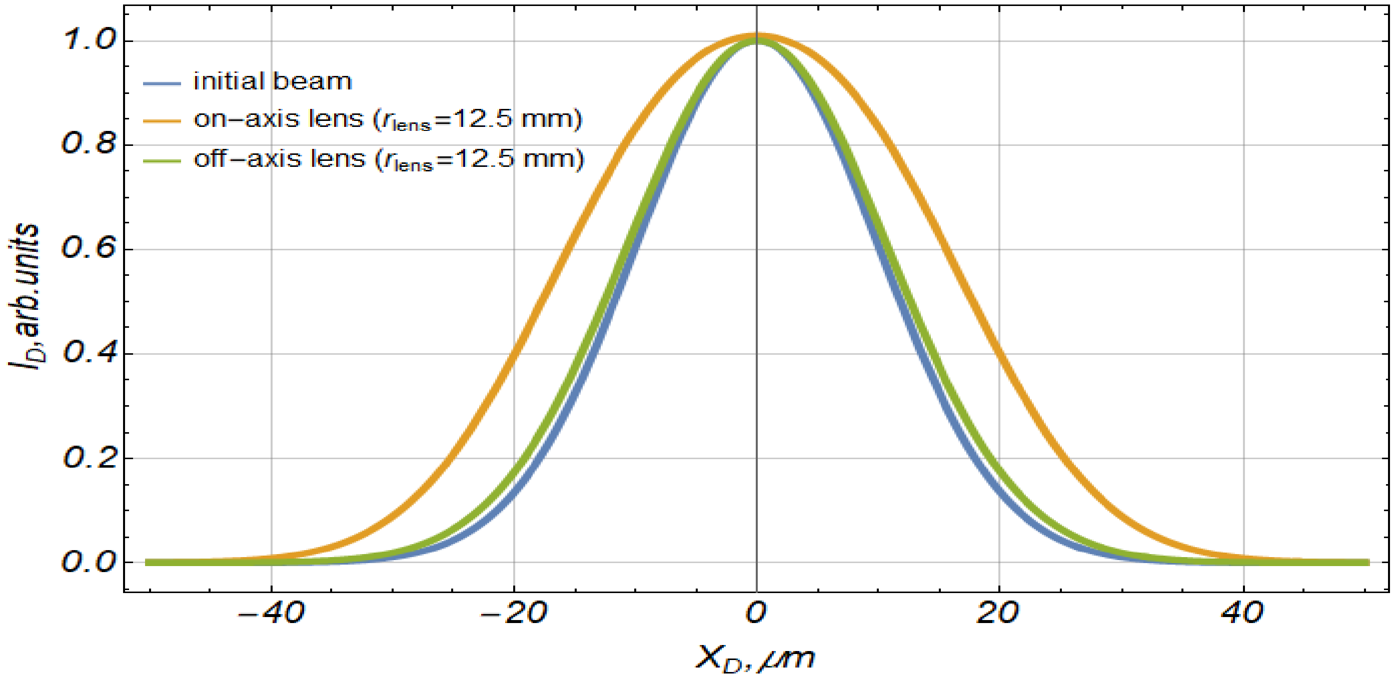


- For large emission angles $\theta_t^e > (\lambda / 2\pi\sigma_t)(\log N_e)^{1/2}$ COTR is suppressed strongly and the photon yield is caused by OTR process only;
- off-axis light collection geometry can be used for spatial separation of COTR photons in order to measure a transverse beam size if $\theta_t^e < 50 / \gamma$ and $N_e \geq 10^7$
- geometry with off-axis light collection can provide more precise beam profile measurements

TOMSK POLYTECHNIC UNIVERSITY

DESY

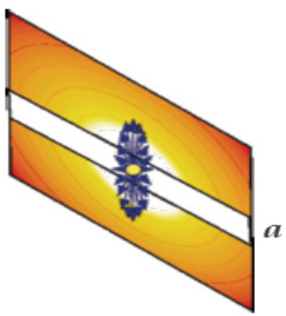
Beam images (σ^t = 10μ)



Beam Size Using ODR Techniques - E. Chiadroni (INFN)

Optical Diffraction Radiation:
only screen monitor technique can be non-destructive

$$I \propto e^{-\frac{2\pi a}{\gamma\lambda}}$$



The beam goes through the hole without touching the screen (**non-intercepting**)

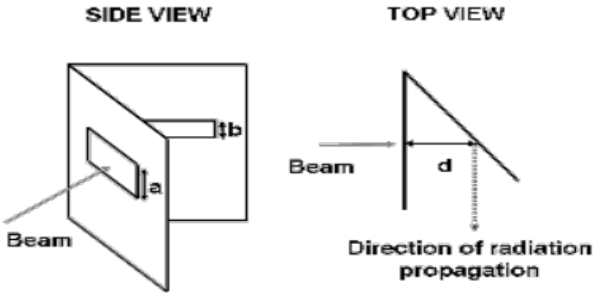
The visibility of the interference fringes provides the transverse beam size

But **very** sensitive technique: the angular distribution of the radiation depends on the beam transverse size, angular spread and position inside the slit

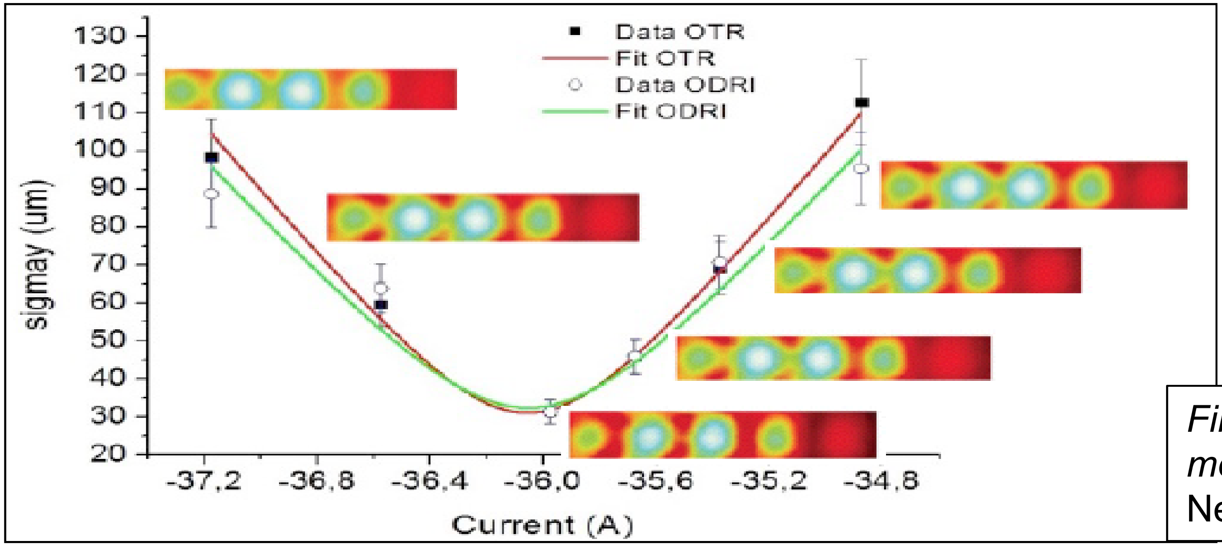
Beam Size Using ODR Techniques - E. Chiadroni (INFN)

Optical **D**iffraction **R**adiation **I**nterference (ODRI):

- Suppression of possible SR background
- Avoids mixing the contributions from beam size and angular divergence



Non-intercepting QP Scan:



Comparison OTR vs ODRI:

- ε=2.3 (0.4) mm*mrad – ODRI
- ε=2.4 (0.4) mm*mrad – OTR

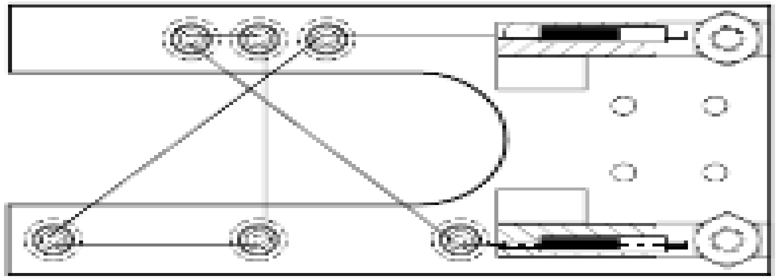
First non-intercepting emittance measurement by means of ODRI
New Journal of Physics **16** (2014) 113029

Summary of Topical Workshop:
Emittance Measurements for Synchrotron Light Sources & FELs

- **Introduction**
- **Emittance Measurements for SLS:**
  - ➢ Direct Imaging Techniques
  - ➢ Inverse Space Imaging Techniques
  - ➢ Future trends
- **Emittance Measurements for FELs:**
  - ➢ Screen Monitors
  - ➢ Wire Scanners
- **Summary**

Beam size measurements using Wire Scanners, K. Wittenburg

- About 30 different designs of wire supports depending on beam parameters
- An X-design (hor + ver in 45deg) reduces the number of scanners, but it is sensitive to vibrations



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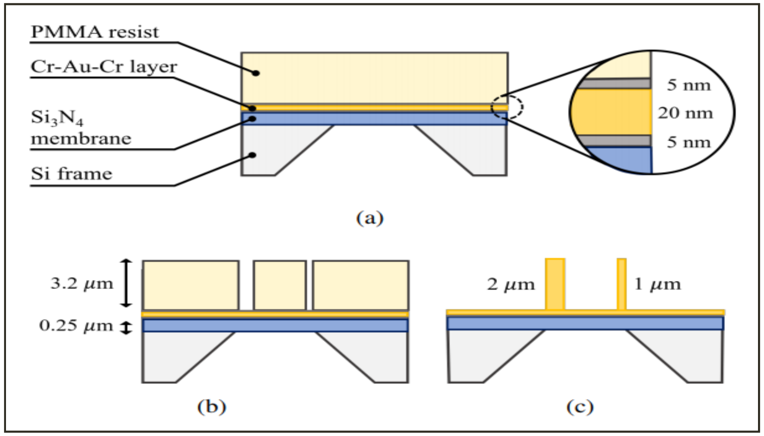
- Used in Hadron and e-Linacs, but no wire scanners in ring based SR sources
- Typical resolution of better 10 μm is achieved, but for very small beam sizes there is a limit on the wire size: diameter + precision.
- Outlook: new approach based on nanofabricated wires

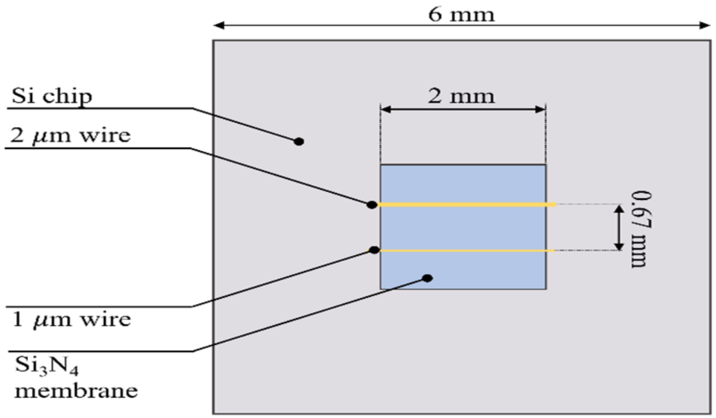
NANO-EMITTANCE MEASUREMENTS IN THE SWISS FEL

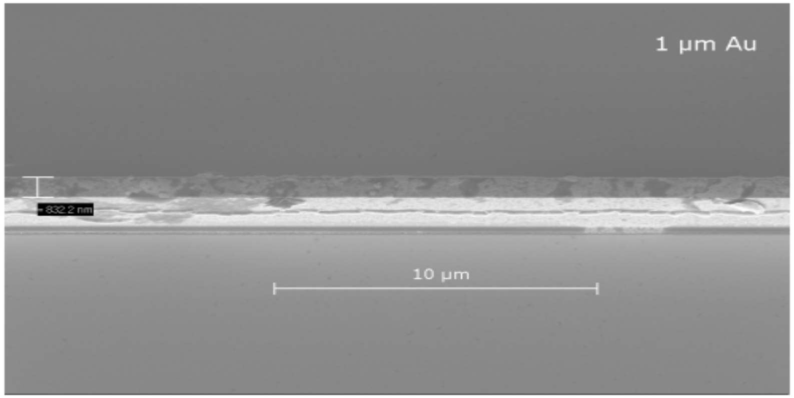
S. BORRELLI (PSI)

Wire Scanner on a Chip: Fabrication

- Electron beam lithography on a Cr-Au resist
- Removal of the Cr with plasma so the Au layer gets exposed
- Trenches (1um and 2um) are filled with electroplating







NANO-EMITTANCE MEASUREMENTS IN THE SWISS FEL

S. BORRELLI (PSI)

Convolution Fit

$$f(y;\Delta,\alpha,\sigma,\gamma) = \int t(u)\left[\Delta + \alpha e^{\frac{-(u-y-\gamma)^2}{2\sigma^2}}\right]du$$

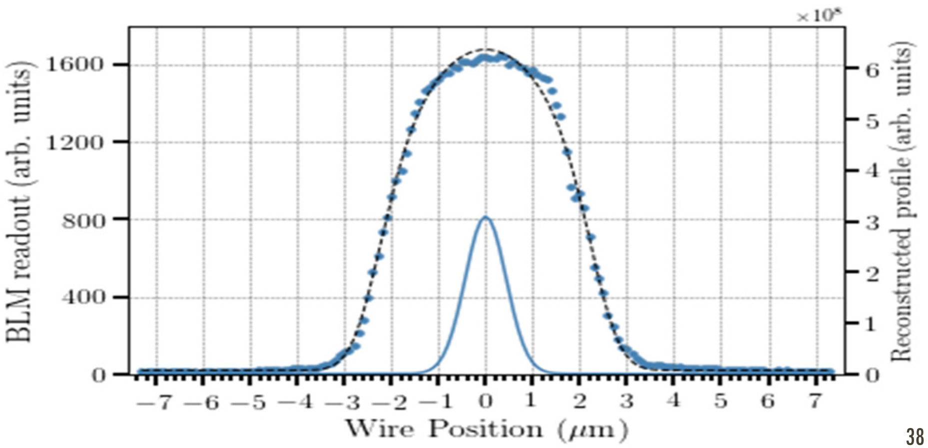
Wire shape

hyp: Gaussian Beam profile

Results

- • Measured profiles
- —— Gaussian profile
- ------- Fitting function

Wire	σ_y (nm)
5 µm W	*462 ± 11*
2 µm Au	*491 ± 4*
1 µm Au	*491 ± 5*



Laser Wire Techniques , P. Karataev (Univ. of London)

Non destructive

Micrometer resolution

Key turn device vs. Team to run and maintain the scanner

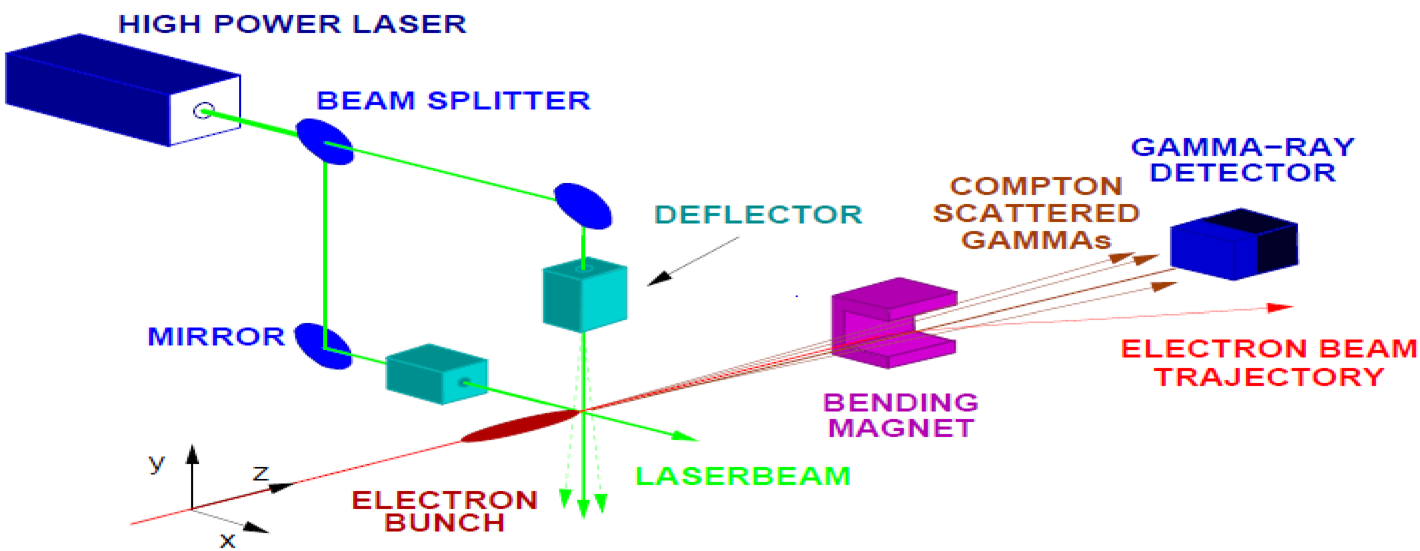


Figure 1: Operation principle of a laser wire profile monitor.

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  - ➢ Wire Scanners
- **Conclusions**

Conclusions for SLS Techniques

- Knowledge of PSF of the measuring system is crucial, and careful studies/simulations should be performed l
- **For 3GSLSs**, the most used technique is the x-ray pinhole. With a careful design, the smallest beam size measurable with this technique is **3um**.
- **For 3GSLSs,** light Coherence analysis such as SRI using visible light, the measuring error can be **<1um**, but the ultimate resolution is given by mechanical limitations
- **For future MBA lattices:** dedicated beamlines with specific beamline instrumentation will be needed to cope with the future machine requirements

Conclusions for FELs Techniques

- Knowledge of PSF of the measuring system is crucial, and careful studies/simulations should be performed to understand your system
- OTR and COTR can be combined to reach measuring beam sizes down to **1um**
- ODRI is a non-destructive technique which has been used to measure beam sizes down to **~10um**, but is sensible to many parameters such as beam size and position at the slit
- Future trends of wire scanners are nanometer width wires performed with lithography techniques. First measurements of **0.5um** beams performed

Thank you!

…and may be see you in the next ARIES-ADA Workshop…
"Next Generation of BPM Acquisition and Feedback Systems"

https://indico.cern.ch/event/743699/overview