X-RAY BEAM PROFILE MONITOR

gratefully acknowledging:
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FCC-ee from a BI perspective

(M. Wendt, eeFACT22)

Parameter [4 IPs, 91.2 km]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69

In the arcs (Zh): $\sigma_x \sim 100$ μm, $\sigma_y \sim 7$ μm

Vertical FCC-ee beam size in the IPs	$\ll$	current beam sizes in LS
Vertical FCC-ee beam size in the arcs	~	current beam sizes in LS
Horizontal FCC-ee beam size in the IPs	~	current beam sizes in LS
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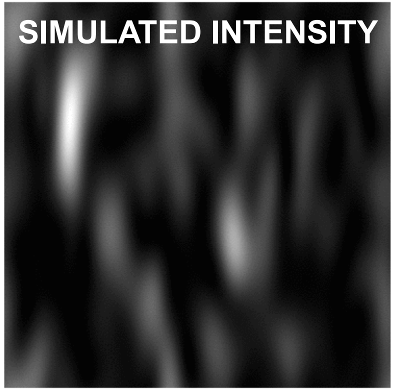
One of the most convenient ways to measure the beam size in LS is to analyze the emitted Synchrotron Radiation (SR). The high energy of the FCC-ee beams calls for the utilization of **X-ray interferometry**.

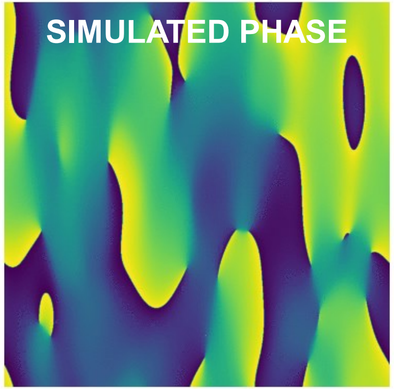
Contents

1. Interferometric beam size measurements
2. The X-ray Heterodyne Near Field Speckles (X-HNFS) technique
3. Results at ALBA
4. Ongoing R&D activities
5. Conclusions

J. W. Goodman, *Statistical Optics*

SR transverse coherence

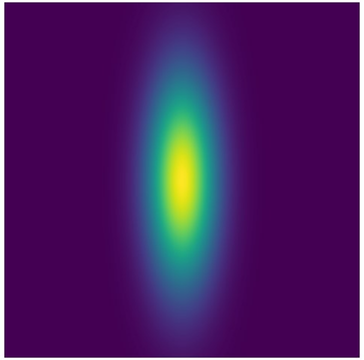




The average size and shape of the coherence areas are described by the Complex Coherence Factor (CCF):

$$\mu(\Delta\vec{x}) = \frac{\langle e(\vec{x})e^*(\vec{x}+\Delta\vec{x})\rangle}{\sqrt{\langle|e(\vec{x})|^2\rangle\langle|e(\vec{x}+\Delta\vec{x})|^2\rangle}}$$

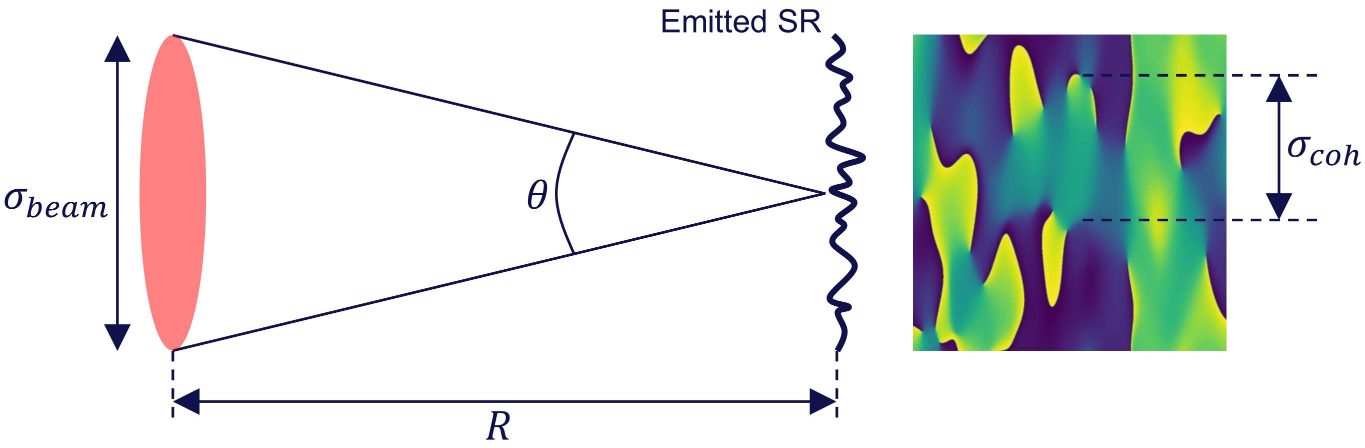
Example: Gaussian CCF



J. W. Goodman, *Statistical Optics*

The Van Cittert and Zernike theorem

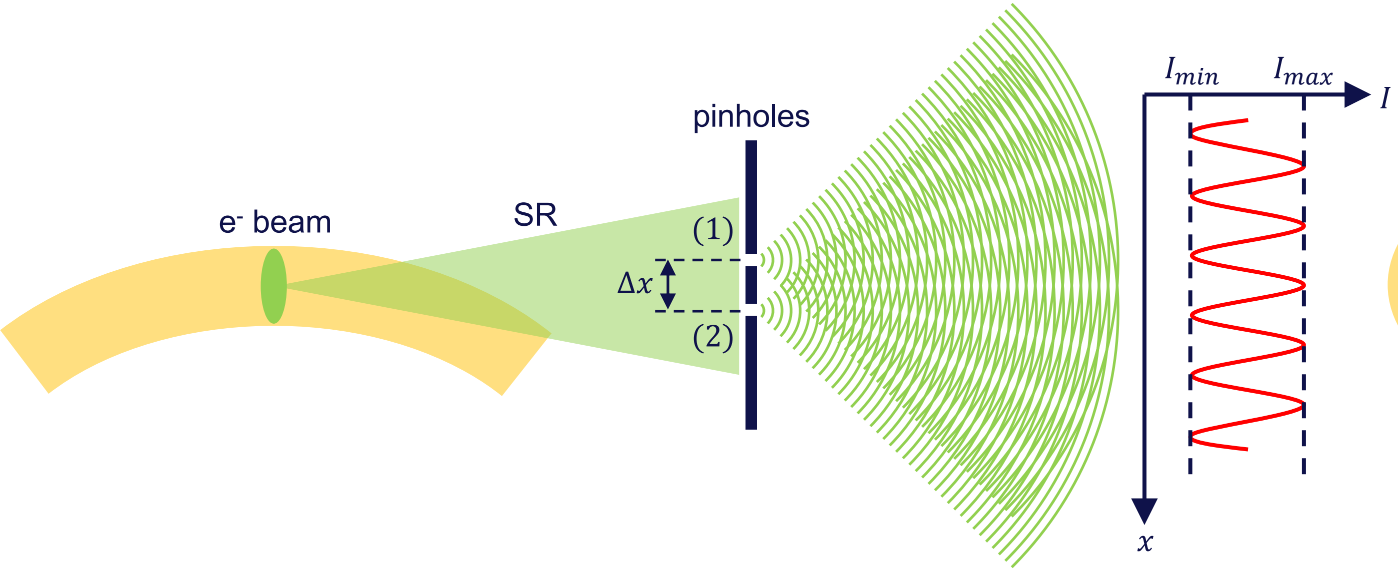
The CCF of SR is the Fourier transform of the transverse profile of the source (e⁻ beam)



Average size of SR coherence areas from e⁻ beams: $\sigma_{coh} \sim \frac{\lambda}{\theta} \sim \frac{\lambda R}{\sigma_{beam}}$

J. W. Goodman, *Statistical Optics*

Interferometric beam size measurements



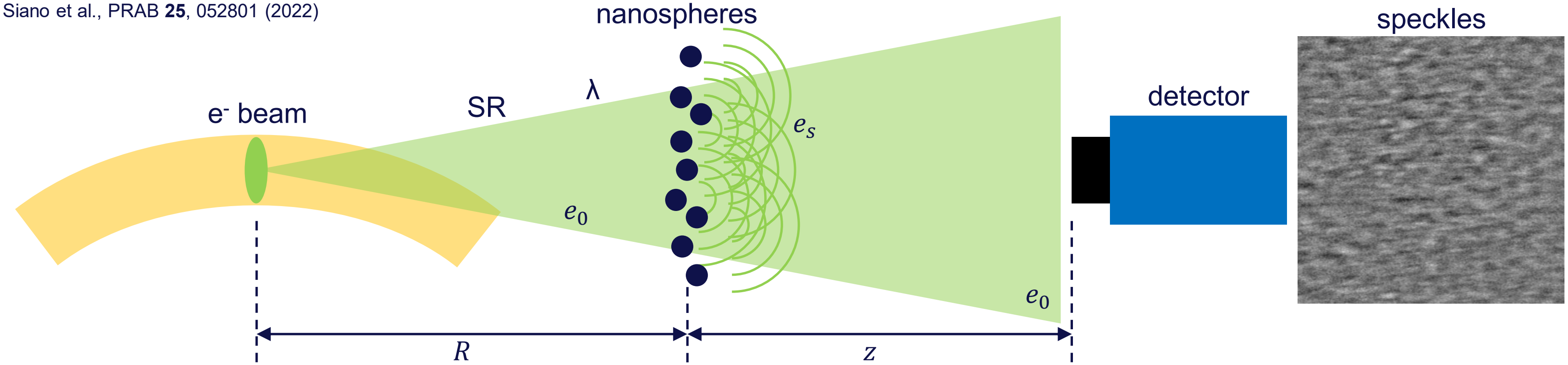
$$\mathcal{V} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

$$\mathcal{V} = |\mu(\Delta x)|$$

The visibility of interference fringes provides a direct measurement of the transverse coherence of the emitted SR, from which the beam size/profile is retrieved by means of the VCZ theorem

X-HNFS: overview

M. D. Alaimo *et al.*, *PRL* **103**, 194805 (2009)
M. Siano *et al.*, *APX* **6**, 1891001 (2021)
M. Siano et al., PRAB **25**, 052801 (2022)



Light through a disordered ensemble of nanospheres forms random speckles

- Fully 2D, high-resolution
- Suitable for X-rays

X-HNFS: single particle

heterodyne conditions
$|e_s| \ll |e_0|$

$$I = |e_0 + e_s|^2 = |e_0|^2 + 2\Re\{e_0 e_s^*\} + \cancel{|e_s|^2}$$

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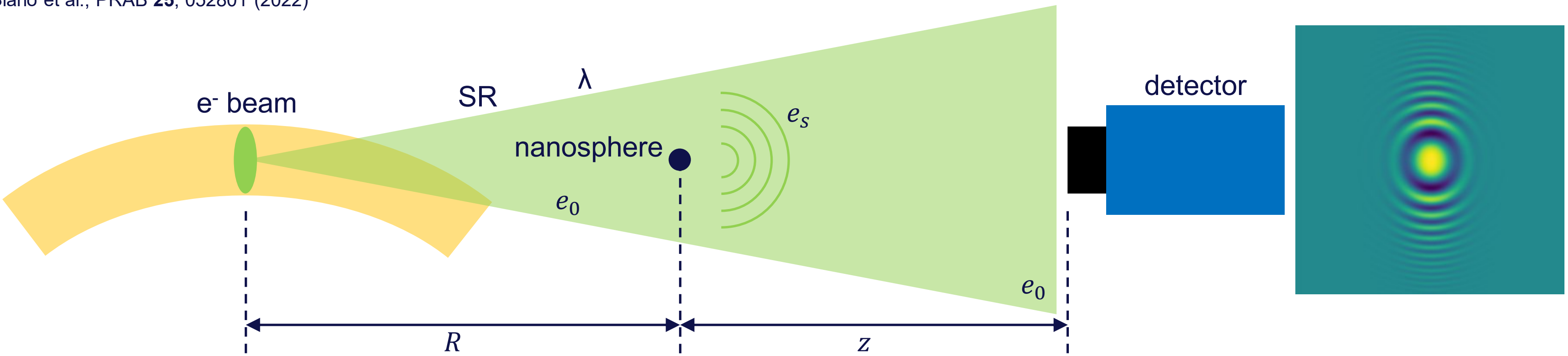

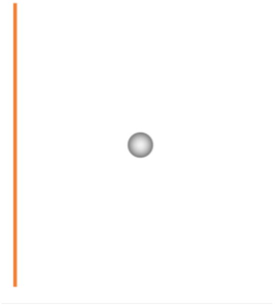

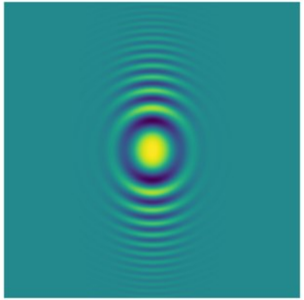

constant

$$I(\vec{x}) = I_0 \cdot \left\{1 + \cancel{S(\vec{\theta})} \cdot |\mu(\Delta\vec{x})| \cdot \cos\left(\frac{kr^2}{2z}\right)\right\}$$

$$\Delta\vec{x} = \frac{z\vec{q}}{k}$$

High-frequency fringes are localized away from the center: **spatial scaling**

X-HNFS: many particles

heterodyne conditions

$|\sum e_{s,i}| \ll |e_0|$

$$I = \left| e_0 + \sum_{i=1}^{N} e_{s,i} \right|^2 = |e_0|^2 + \sum_{i=1}^{N} 2\Re\{e_0 e_{s,i}^*\} + \cancel{\left| \sum_{i=1}^{N} e_{s,i} \right|^2}$$

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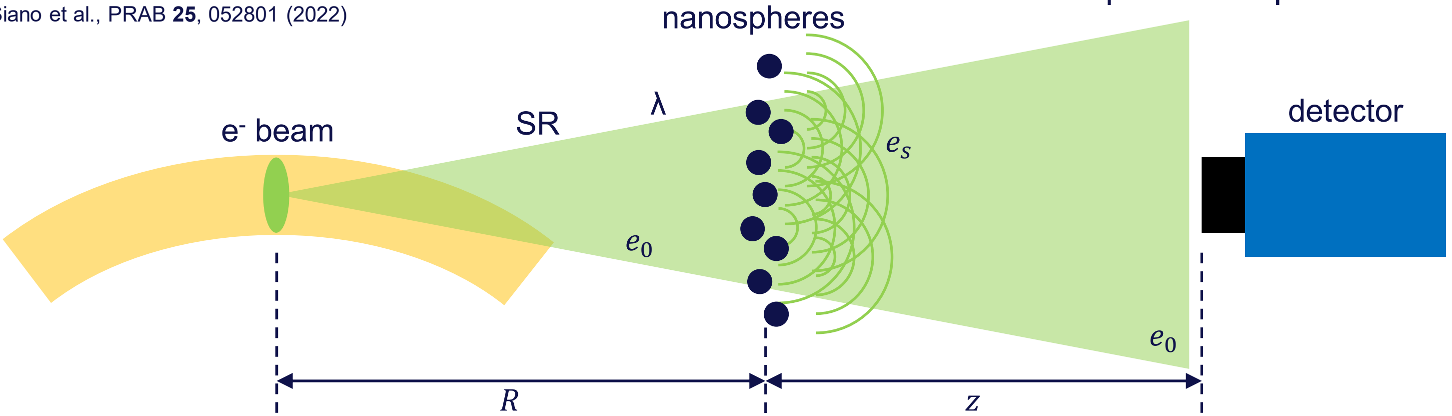
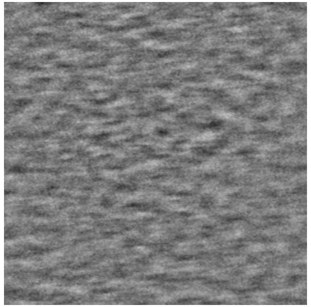
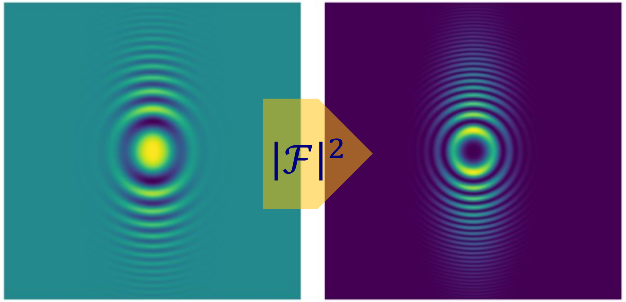






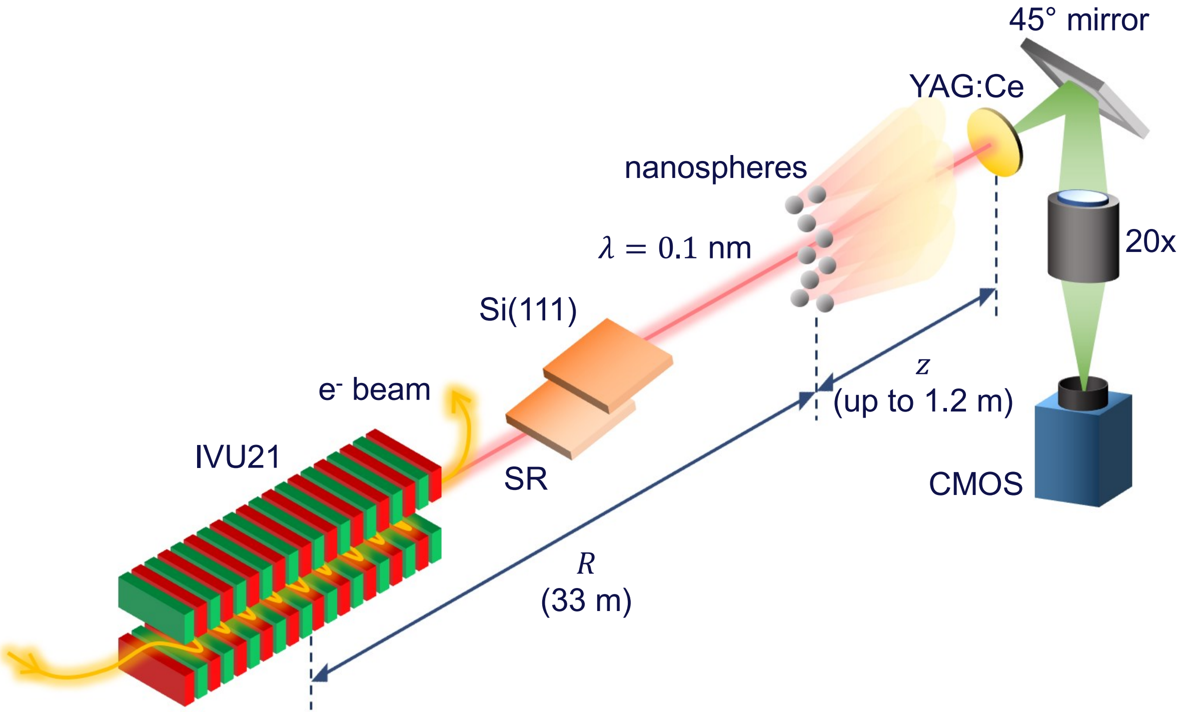
constant

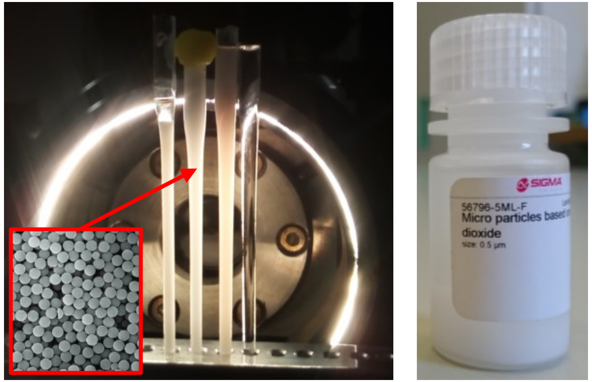
Talbot oscillations

$$I(\vec{q}) = N \cdot I_0 \cdot \cancel{S(\vec{q})} \cdot \left| \mu\left(\frac{z\vec{q}}{k}\right) \right|^2 \cdot 2\left[\sin\left(\frac{zq^2}{2k}\right)\right]^2$$

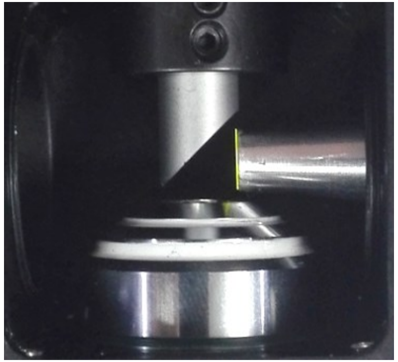
spatial scaling

X-HNFS setup at NCD-SWEET (ALBA)





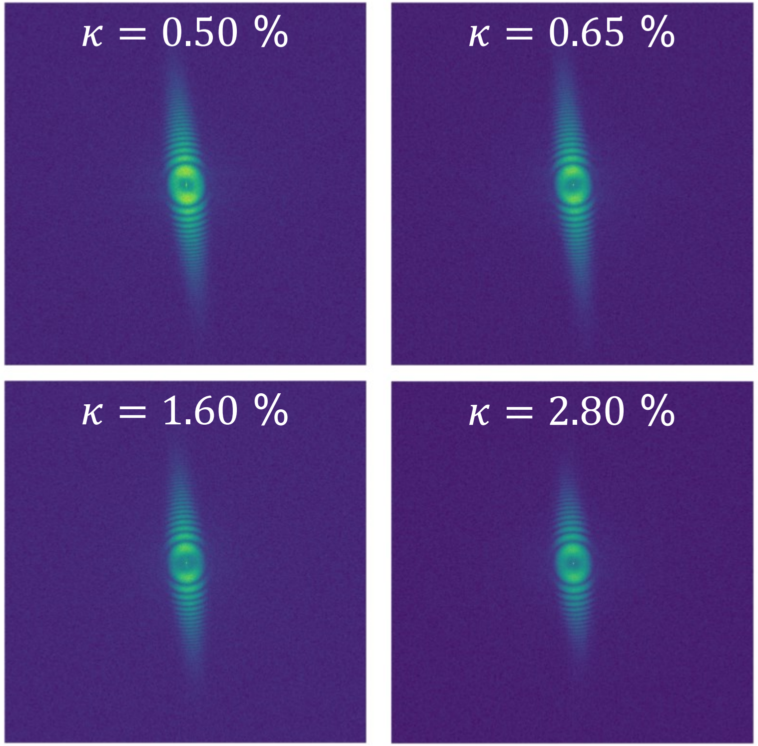
The probe: silica (SiO_2) spheres, 500 nm, in water

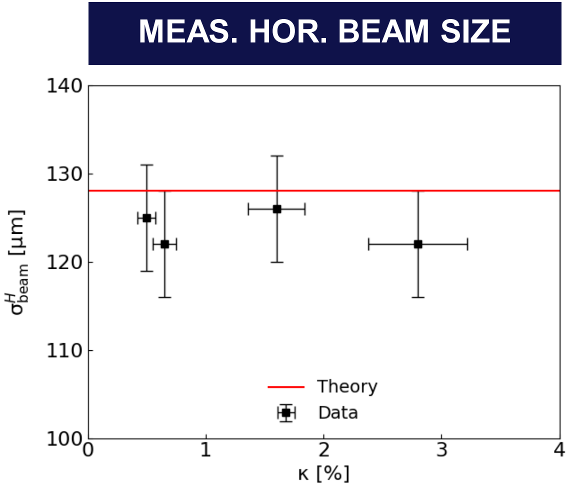


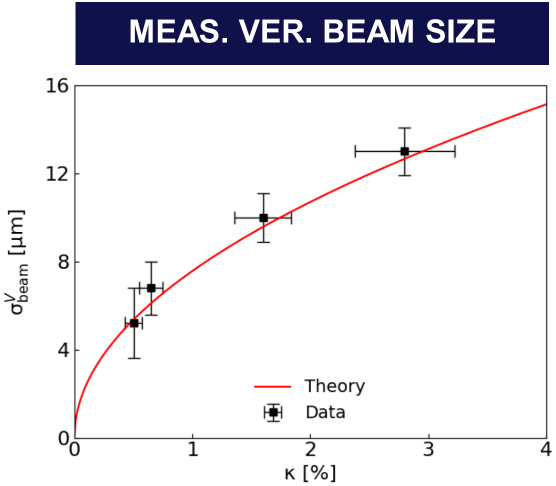
Optical setup: YAG + mirror + optics + CMOS

Results at NCD-SWEET (ALBA)

Coupling scan: by changing the machine coupling κ, we vary the vertical beam size at NCD



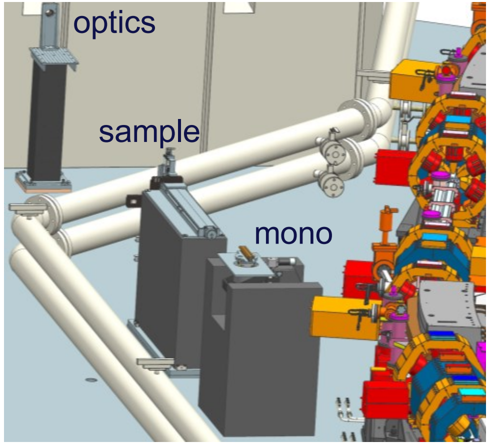




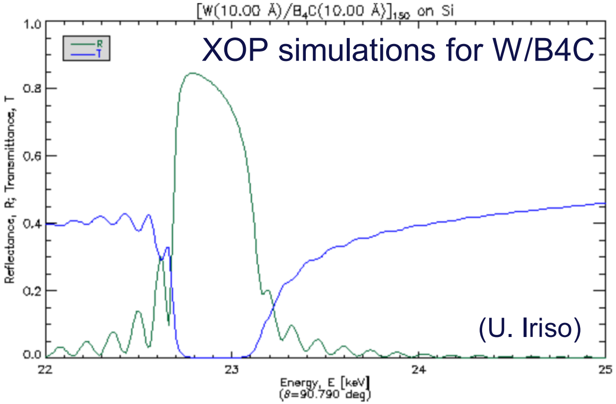
Minumum beam size measured with current setup: **4.5 µm**

Ongoing R&D activities

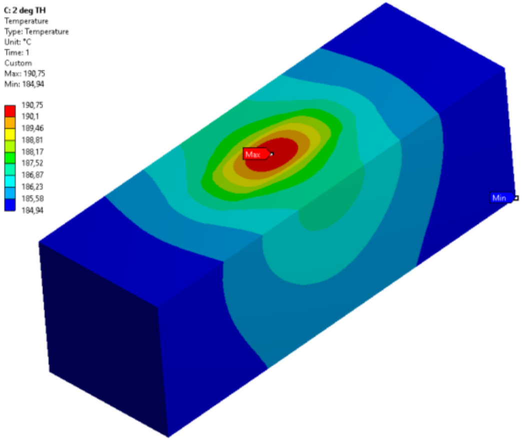
- Design of a dedicated X-HNFS dipole beamline for beam diagnostics @ ALBA
- First studies on monochromator material (W/B4C)



- Design of a dedicated X-HNFS beamline
- Dipole source
- First tests in 2024



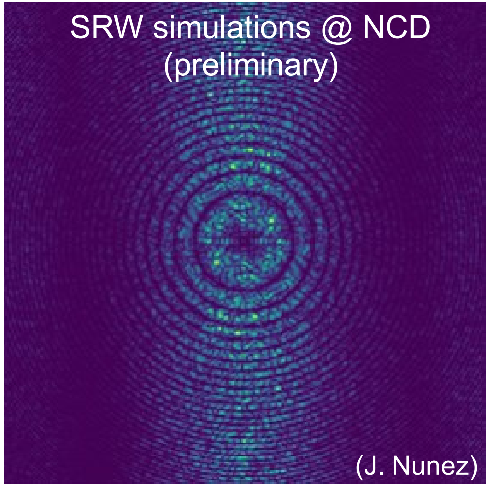
- Preliminary studies on monochromator
- Energy range: 20 - 30 keV
- Peak energy: 24 keV
- Bandwidth: 1% - 5%



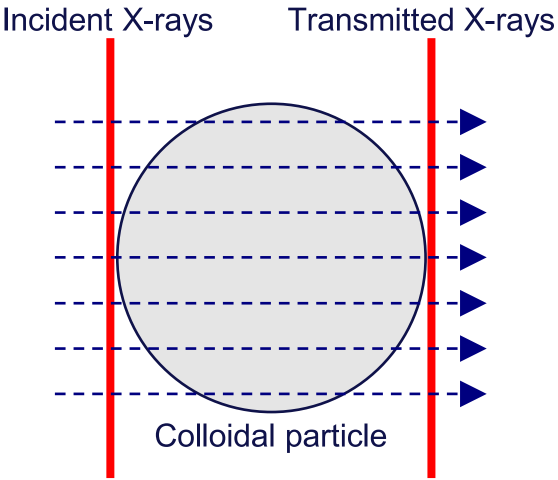
- Preliminary heat load evaluation on monochromator
- Air / water cooling

Ongoing R&D activities

- Numerical studies to optimize bandwidth, sample material and detected signal
- Development of a beam profile monitor based on X-HNFS and advanced solid targets



- Full SRW simulations
- Fourier-optics-based simulations
- Evaluate temporal coherence
- Optimize beamline parameters



- Numerical simulations of X-ray scattered signal
- Compare and validate different approaches (Mie theory, ADA, …)
- Identify best materials for targets

- Development of X-HNFS instrument
- Solid targets for continuous on-line operations at FCC-ee
- New screens to maximize light yield and detected signal

Summary and outlook

Current status:

- Development of a novel 2D beam profile monitor based on X-HNFS
- Validated at the NCD-SWEET undulator beamline at ALBA with hard X-rays
- X-HNFS can resolve few-μm beam sizes (down to 4.5 μm with current setup)

Many **ongoing R&D activities** for applications to FCC-ee, including (but not limited to):

- Design of a dedicated X-HNFS dipole beamline at ALBA for beam diagnostics
- First studies on monochromator bandwidth and materials
- Numerical studies on wavefront propagation to optimize beamline parameters
- Investigations on different materials and advanced solid targets to improve SNR
- Development and optimization of an X-HNFS instrument with higher resolution

Thank you
for your attention.