TWO-DIMENSIONAL BEAM SIZE MEASUREMENTS WITH X-RAY HETERODYNE NEAR FIELD SPECKLES

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IBIC 2021
International Beam Instrumentation Conference

Outline

- Introduction
- The Heterodyne Near Field Speckles technique
- Results at ALBA
- Conclusions

Beam size measurements

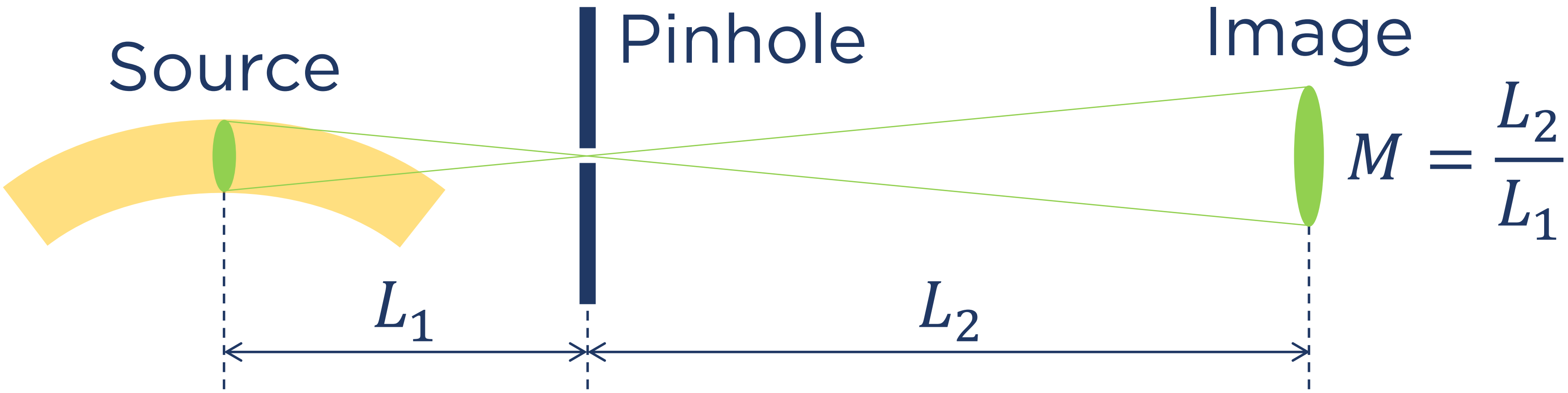
Why do we measure beam sizes?

- Emittance in storage rings
- Luminosity in colliders
- Coherence of emitted SR (X-rays)

How do we measure beam sizes?

- Imaging (X-ray pinhole camera)
- Interferometry (Young)
- Heterodyne Near Field Speckles (?)

X-ray pinhole camera

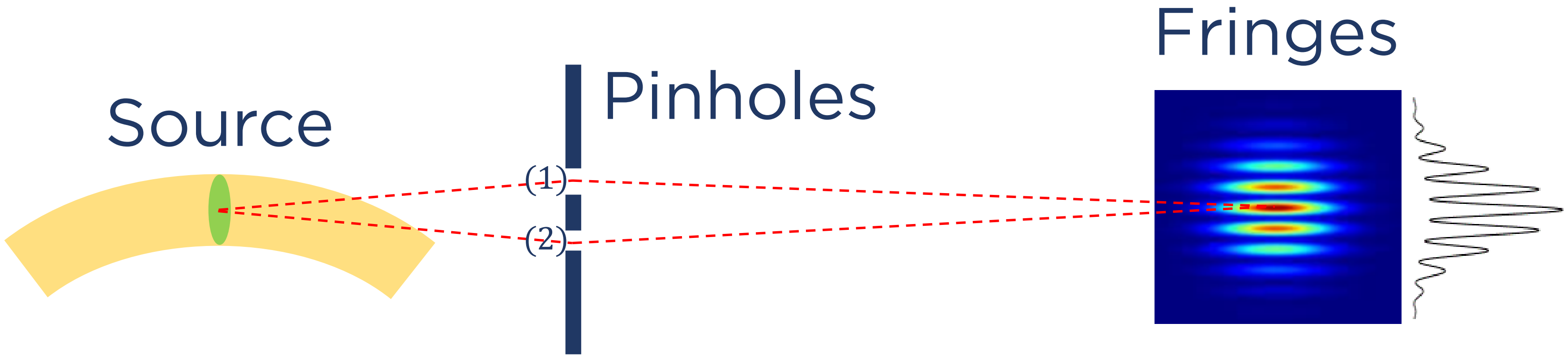


$$M = \frac{L_2}{L_1}$$

Light through the aperture forms an inverted, magnified image of the source

- Pros: 2D, simple
- Cons: limited resolution

Double-slit interferometry



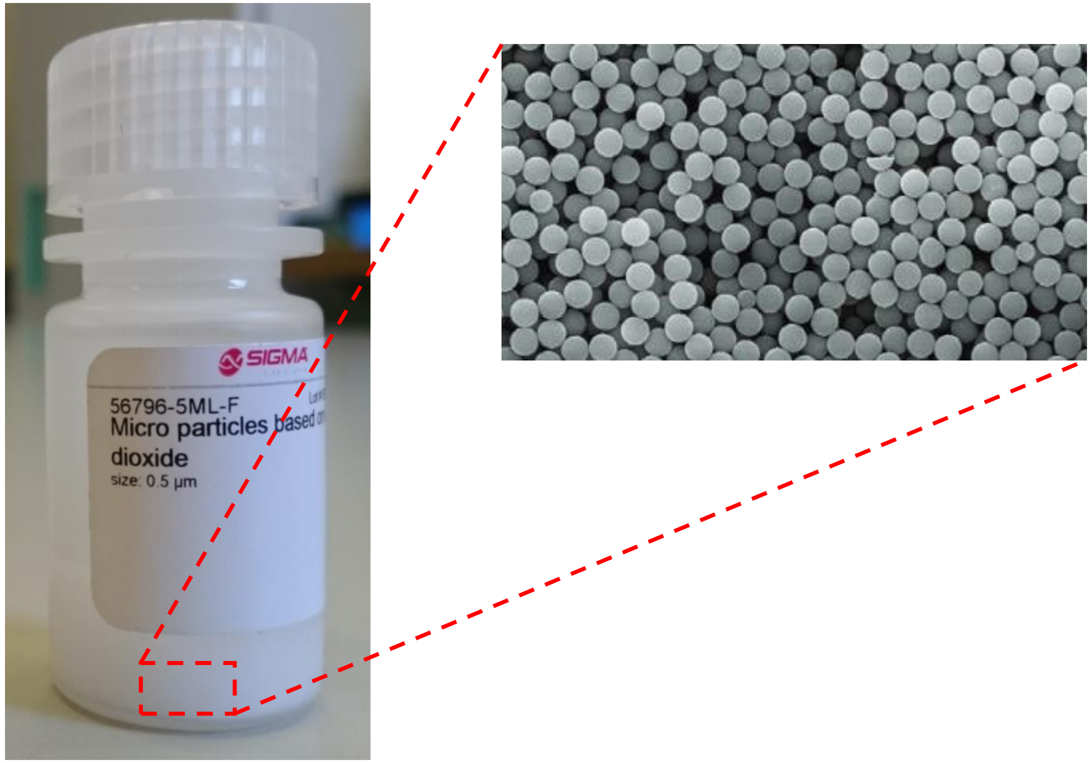
$$\mathcal{V} = |\mu_{12}|$$

$$\mu_{12} = \frac{\langle e_1 e_2^* \rangle}{\sqrt{\langle i_1 \rangle \langle i_2 \rangle}}$$

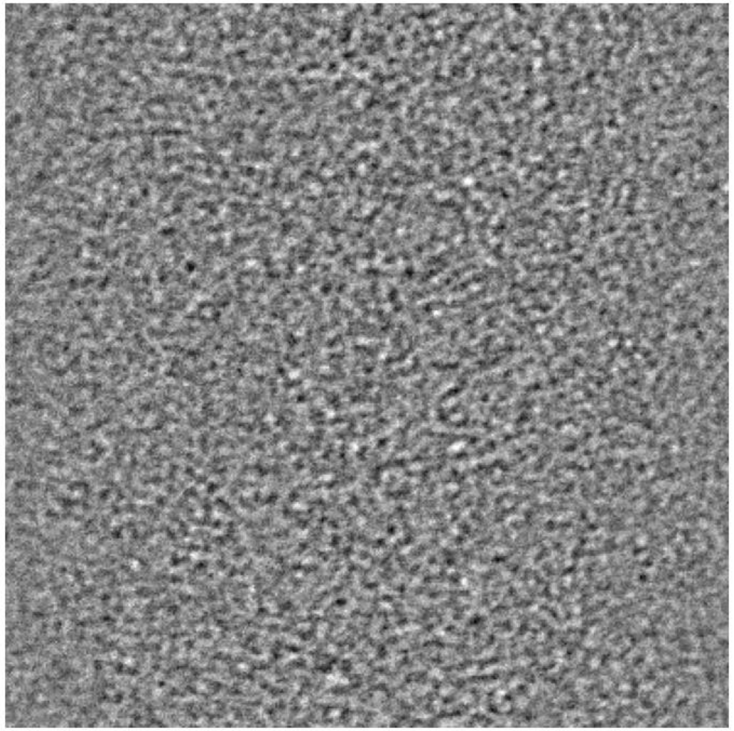
Beam size is inferred from the visibility of interference fringes (Complex Coherence Factor of the radiation, CCF)

- Pros: high resolution
- Cons: 1D, one length-scale, mainly with visible light

The probe: colloidal suspensions



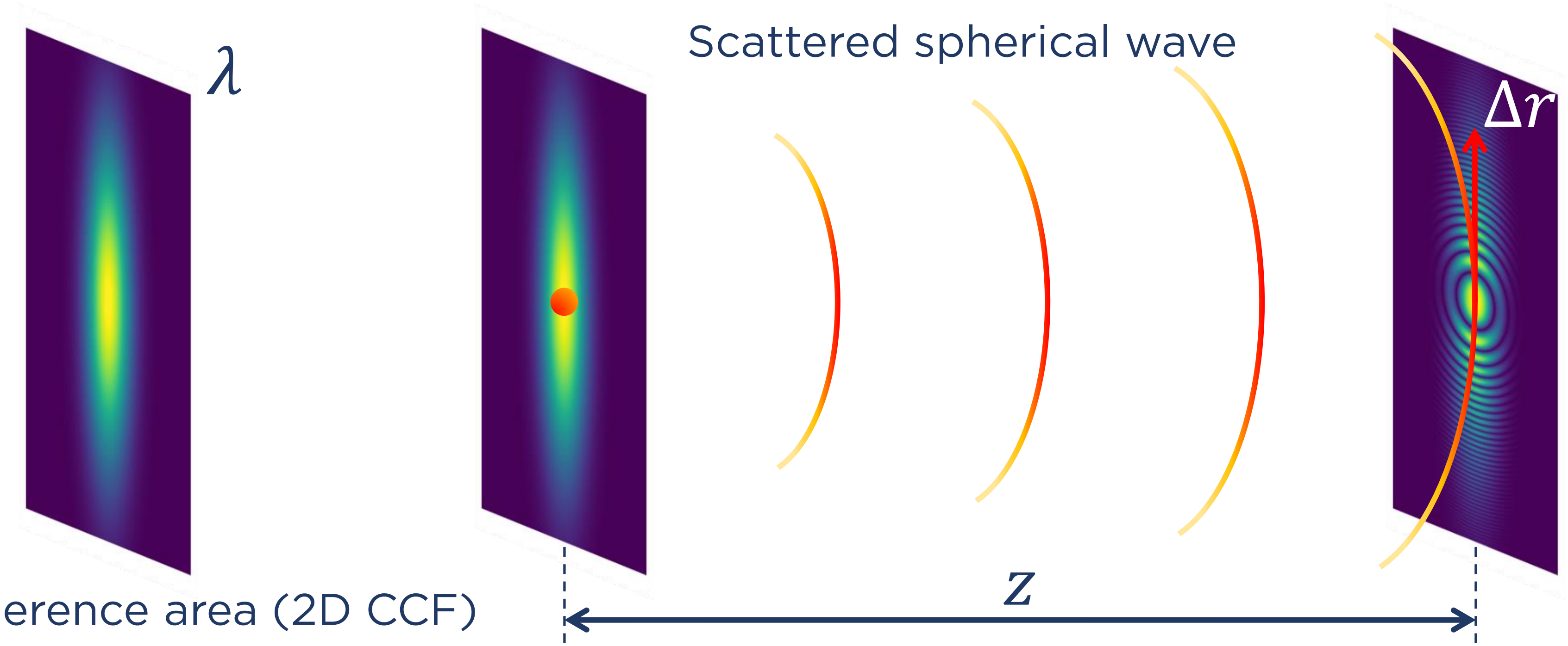
SiO_2 spheres,
500 nm diameter



X-ray speckles at NCD
undulator beamline (ALBA)

Cerbino R, *et al*, *Nat. Phys.* **4**, 238 (2008)
Alaimo MD, *et al*, *PRL* **103**, 194805 (2009)
Siano M, *et al*, *Adv. Phys. X* **6**, 1891001 (2021)

HNFS: the single particle case



$$i = |\mu(\Delta\vec{r})| \cos\left(\frac{k\Delta r^2}{2z}\right)$$

Complex Coherence Factor (CCF):

$$\mu(\Delta\vec{r}) = \frac{\langle e(0)e^*(\Delta\vec{r})\rangle}{\sqrt{\langle i(0)\rangle\langle i(\Delta\vec{r})\rangle}}$$

Circular interference fringes modulated by 2D CCF

Spatial frequency of fringes increases away from the center (chirped signal): spatial scaling

Spatial scaling

$$\boxed{\Delta r = z\frac{q}{k}}$$

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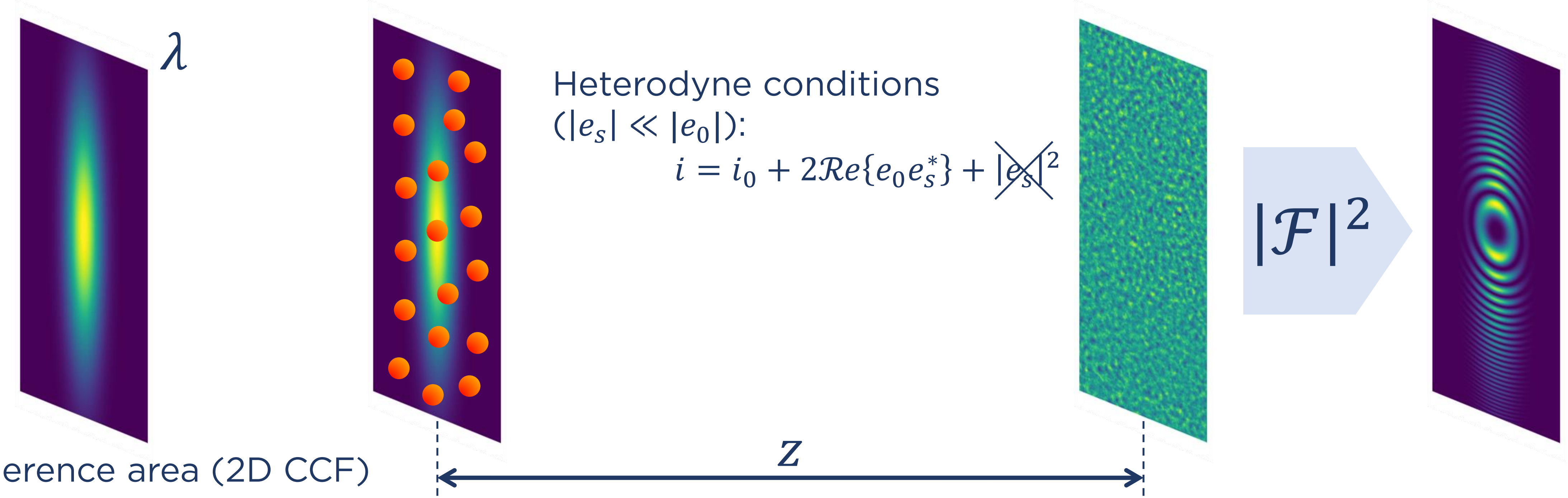
HNFS: many particles



Heterodyne conditions
($|e_s| \ll |e_0|$):

$$i = i_0 + 2\mathcal{R}e\{e_0 e_s^*\} + |\cancel{e_s}|^2$$

Coherence area (2D CCF)

2D coherence mapping via PS of heterodyne speckles

$$I(q,z) = T(q,z)C\left(z\frac{q}{k}\right)$$

$C = |\mu|^2$

$$T(q,z) = 2\left[\sin\left(\frac{zq^2}{2k}\right)\right]^2$$

Talbot oscillations

Cerbino R, *et al*, *Nat. Phys.* **4**, 238 (2008)
Alaimo MD, *et al*, *PRL* **103**, 194805 (2009)
Siano M, *et al*, *Adv. Phys. X* **6**, 1891001 (2021)

HNFS: general formulation

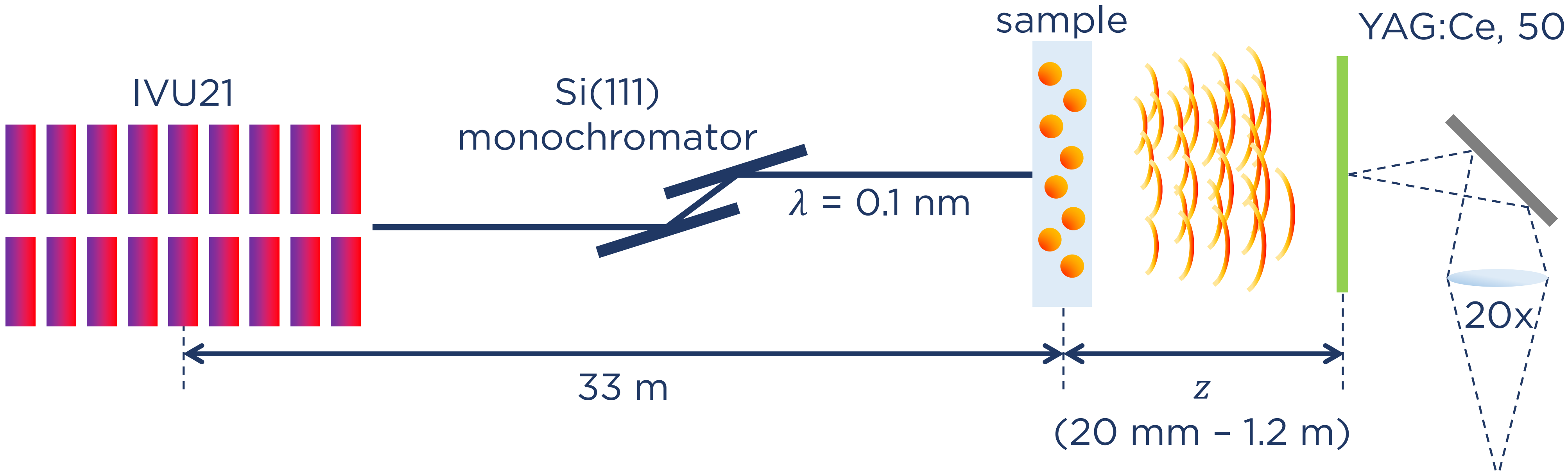
$$I(q,z) = T(q,z)C\left(z\frac{q}{k}\right)H(q)S(q) + P(q)$$

$H(q)$ = MTF (resolution)
$S(q)$ = particle form factor
$P(q)$ = noise

We can measure the MTF under actual operating conditions (in-line, at-wavelength) from speckles at short z:

$$C\left(z\frac{q}{k}\right) \to 1 \qquad \text{for} \qquad z \to 0$$

The HNFS setup at NCD (ALBA)



IVU21

Si(111) monochromator

$\lambda = 0.1$ nm

sample

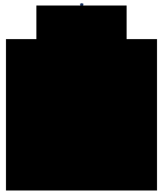
YAG:Ce, 50 µm

20x

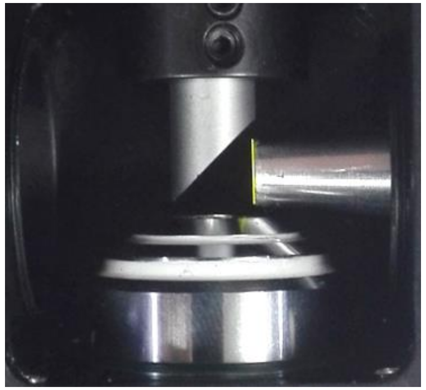
33 m

z

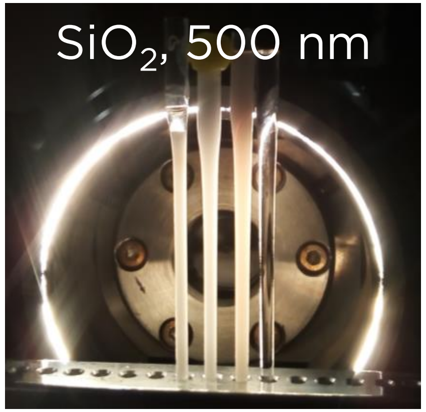
(20 mm – 1.2 m)



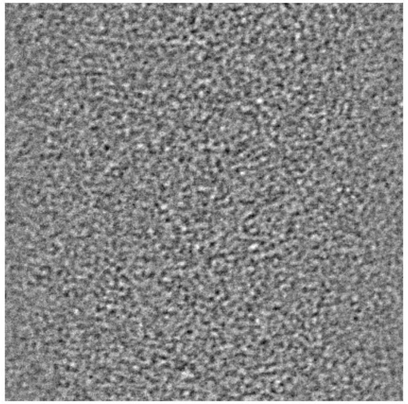
acA4112-8gm
4096 x 3000 px
3.45 x 3.45 µm^2



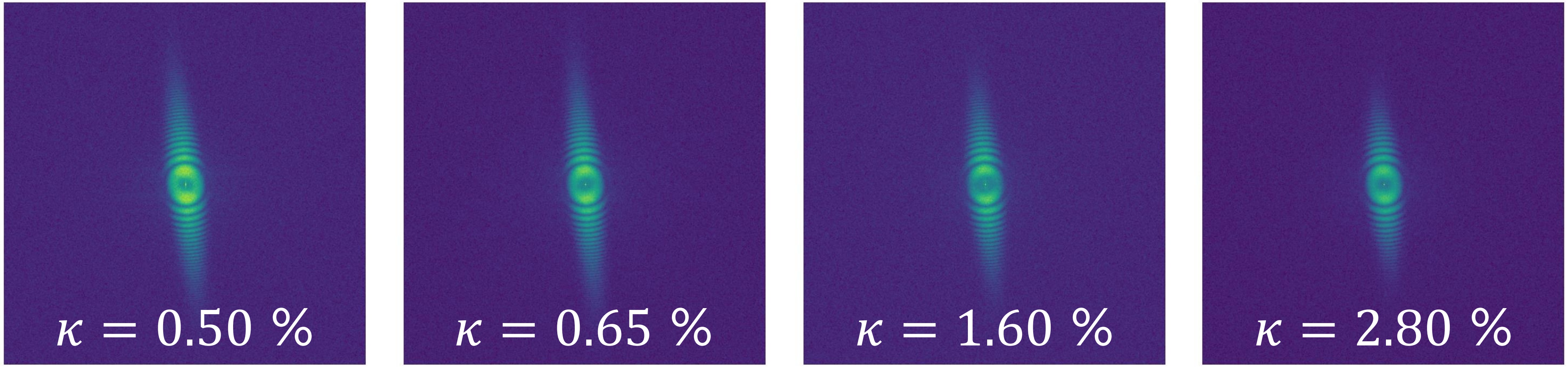
Period	21.6 mm
Number of periods	92
Photon energy	12.4 keV
Harmonic number	7
Bandwidth	10^{-4}



SiO_2, 500 nm



Experimental data: coupling scan

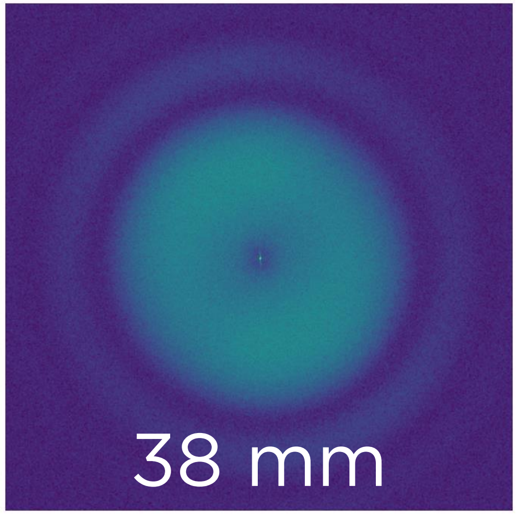


Power spectra are tilted by 5 deg (beam? optics?)

As the beam coupling increases:

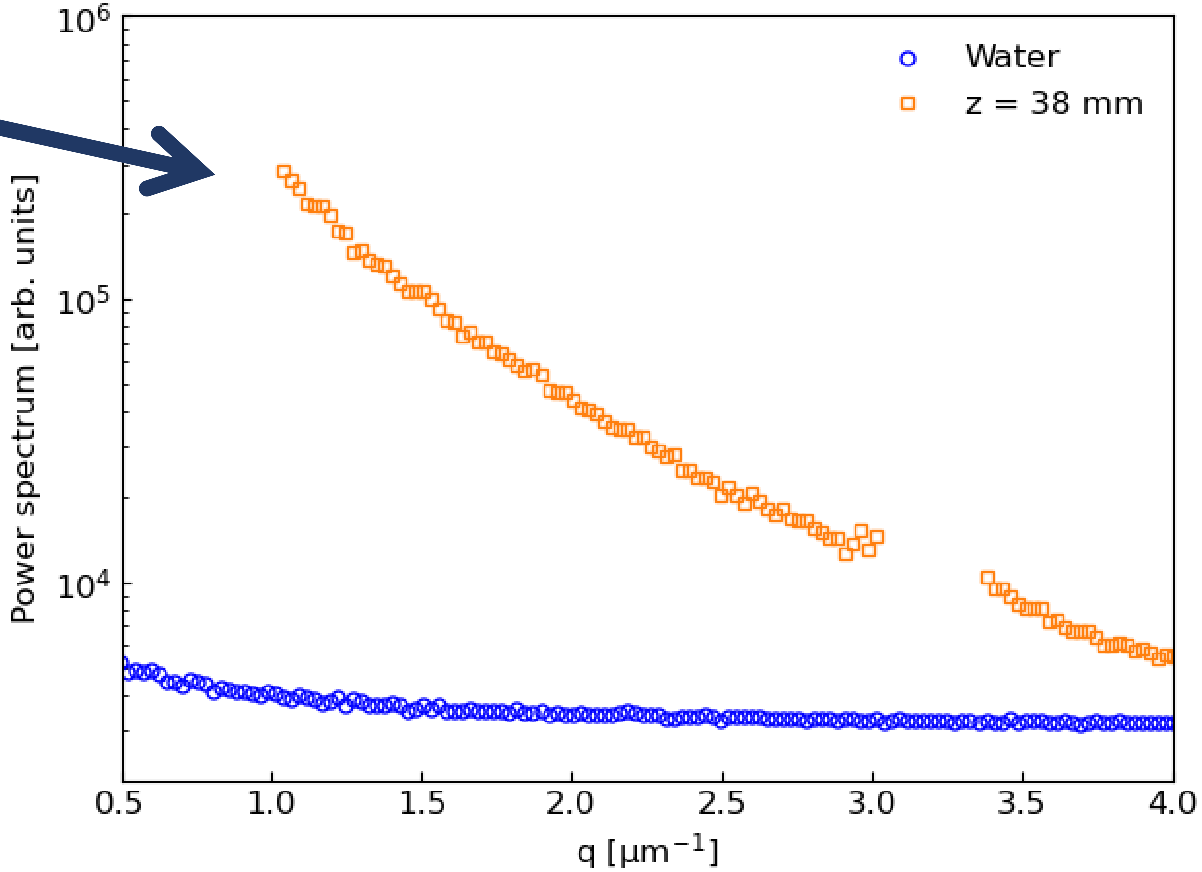
- same hor coherence (beam size unchanged)
- ver coherence decreases (beam size increases)

Data reduction

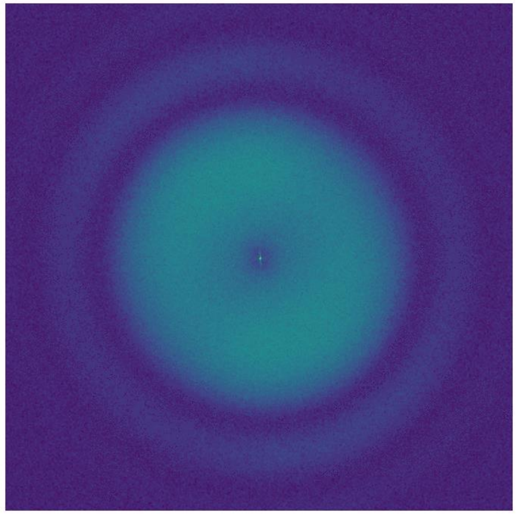


$$H(q)S(q) = \frac{I(q,z) - P(q)}{T(q,z)}$$

H(q)S(q)
from short z

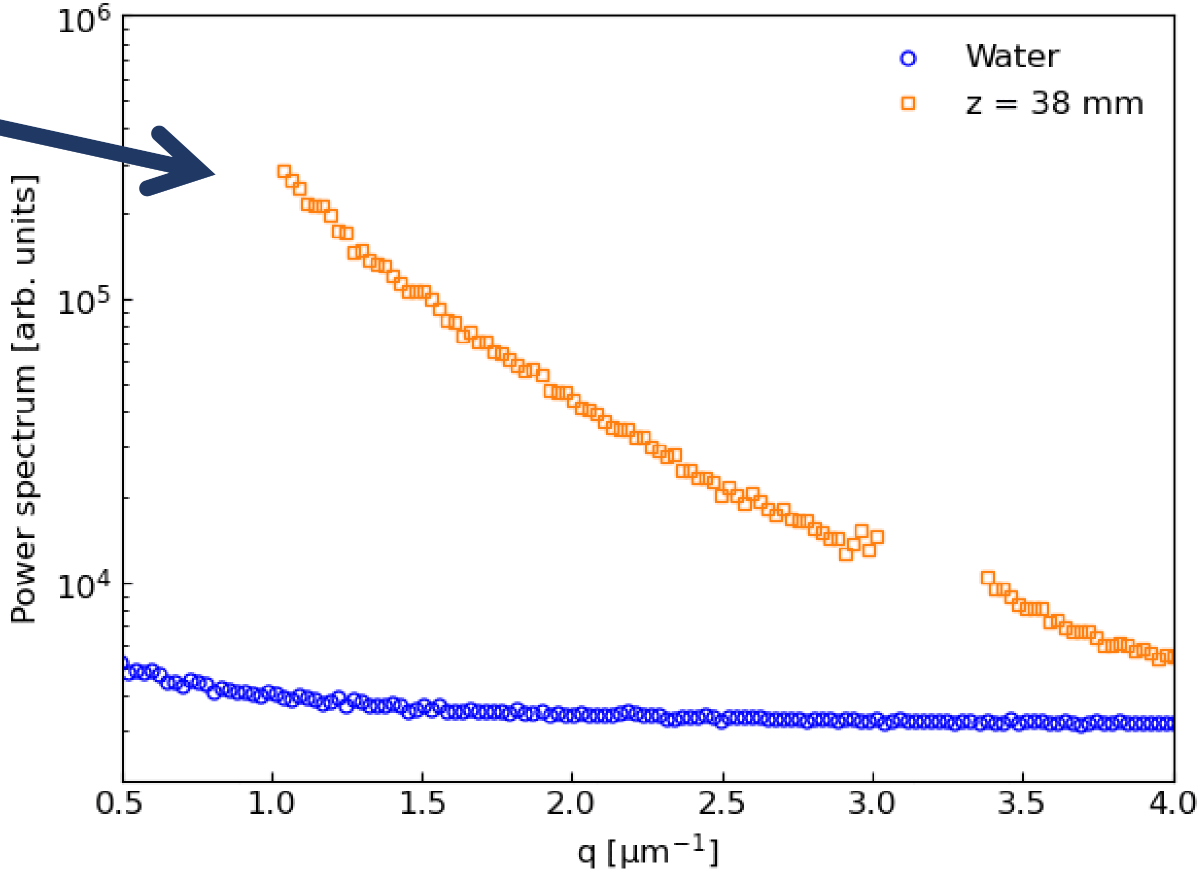


Data reduction



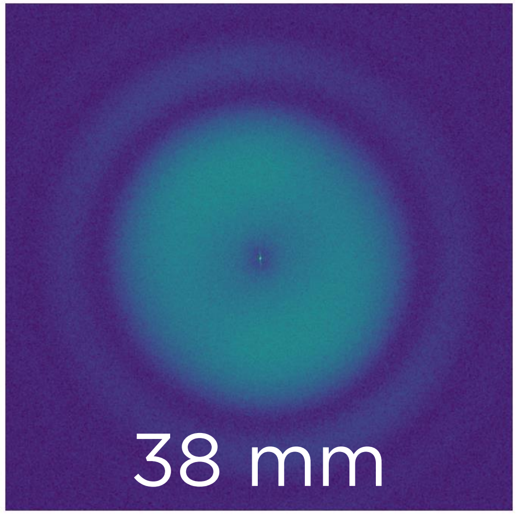
$$H(q)S(q) = \frac{I(q,z) - P(q)}{T(q,z)}$$

H(q)S(q)
from short z

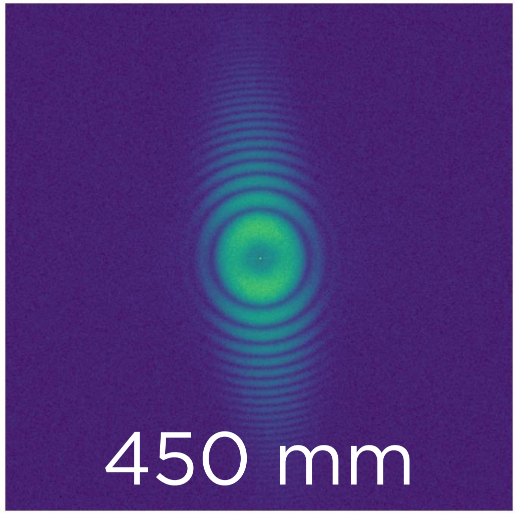


Data reduction

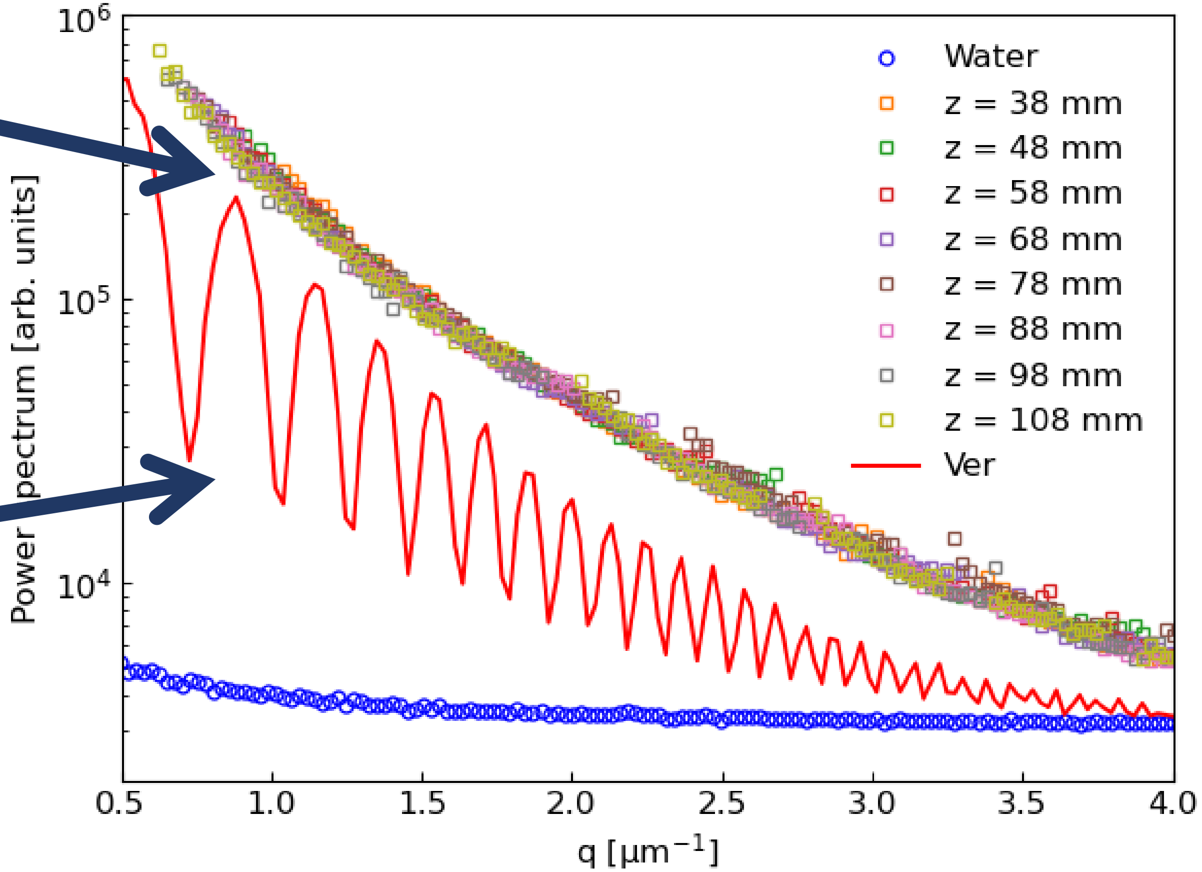
$$C\left(z\frac{q}{k}\right)T(q,z) = \frac{I(q,z)-P(q)}{H(q)S(q)}$$



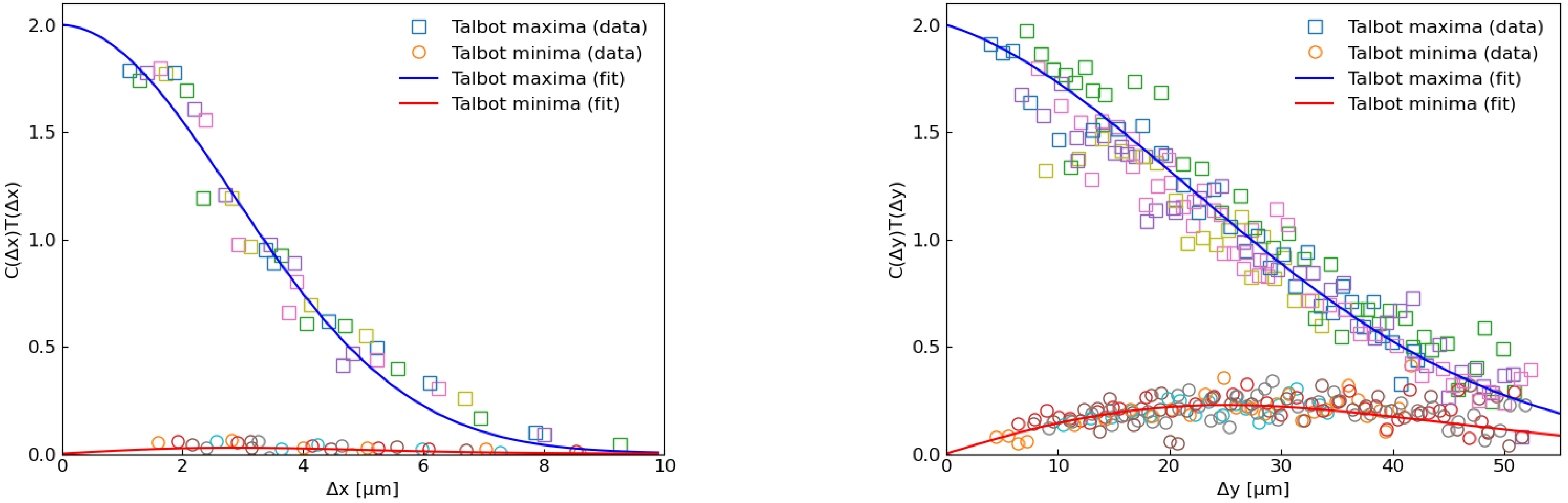
H(q)S(q)
from short z



CCF profiles
from larger z



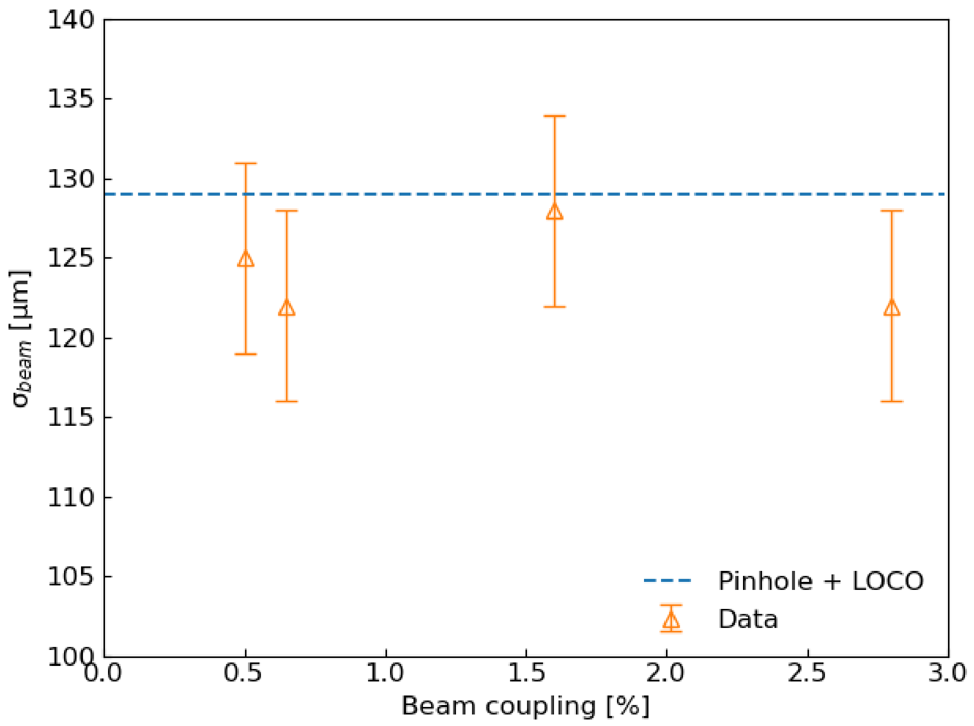
Results: coherence

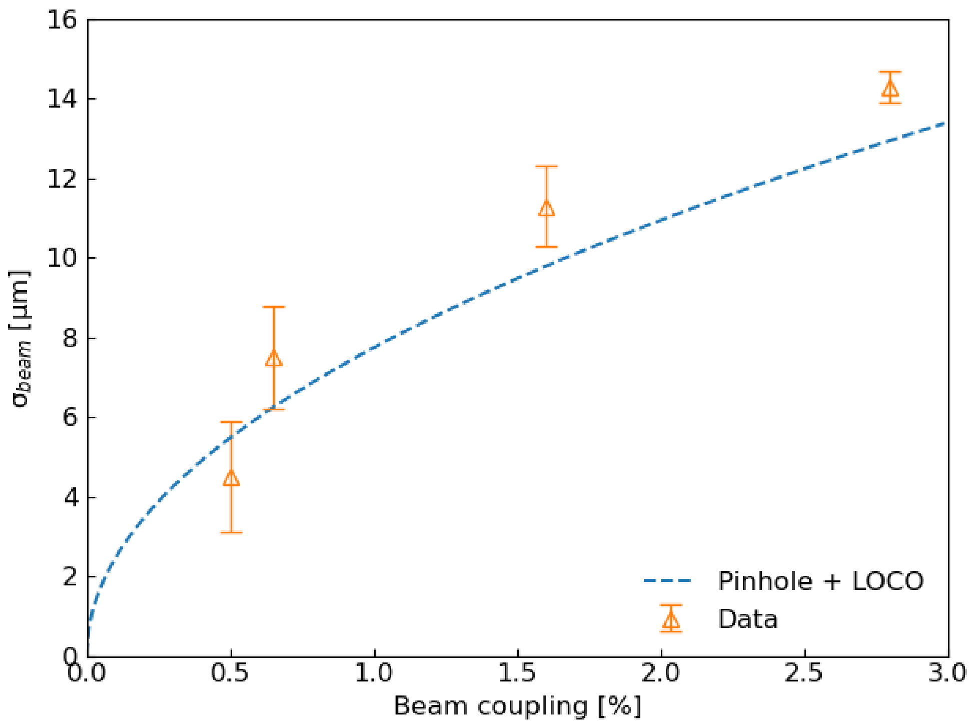


Horizontal coherence length (rms) [μm]			
κ = 0.50 %	**κ = 0.65 %**	**κ = 1.60 %**	**κ = 2.80 %**
4.2 ± 0.2	4.3 ± 0.2	4.1 ± 0.2	4.3 ± 0.2

Vertical coherence length (rms) [μm]			
κ = 0.50 %	**κ = 0.65 %**	**κ = 1.60 %**	**κ = 2.80 %**
105 ± 32	65 ± 11	44 ± 4	36 ± 1

Results: beam sizes





Horizontal beam size (rms) [µm]			
κ = 0.50 %	**κ = 0.65 %**	**κ = 1.60 %**	**κ = 2.80 %**
125 ± 6	122 ± 6	126 ± 6	122 ± 6

Vertical beam size (rms) [µm]			
κ = 0.50 %	**κ = 0.65 %**	**κ = 1.60 %**	**κ = 2.80 %**
4.5 ± 1.4	7.5 ± 1.3	11.3 ± 1.0	14.3 ± 0.4

Conclusions and perspectives

- HNFS as a 2D interferometric technique for measuring few-µm beam sizes
- Tested at NCD (ALBA) for 4 different values of the beam coupling
- Further outcome: in-line at-wavelength measurement of the system MTF
- In the future, test novel samples (gold) to increase SNR