Transverse beam profile measurement using the Heterodyne Near Field Speckles method at ALBA

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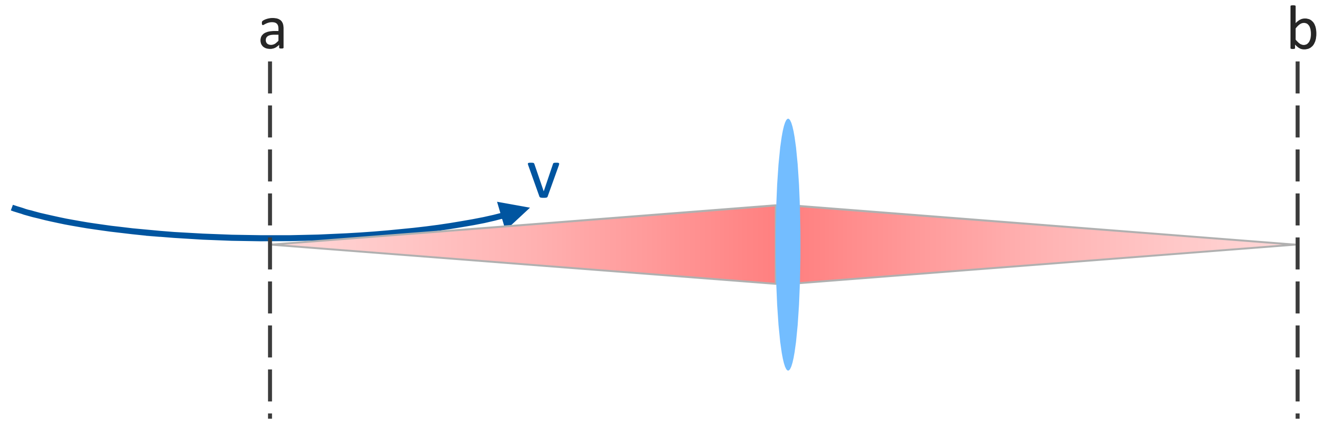
Outline

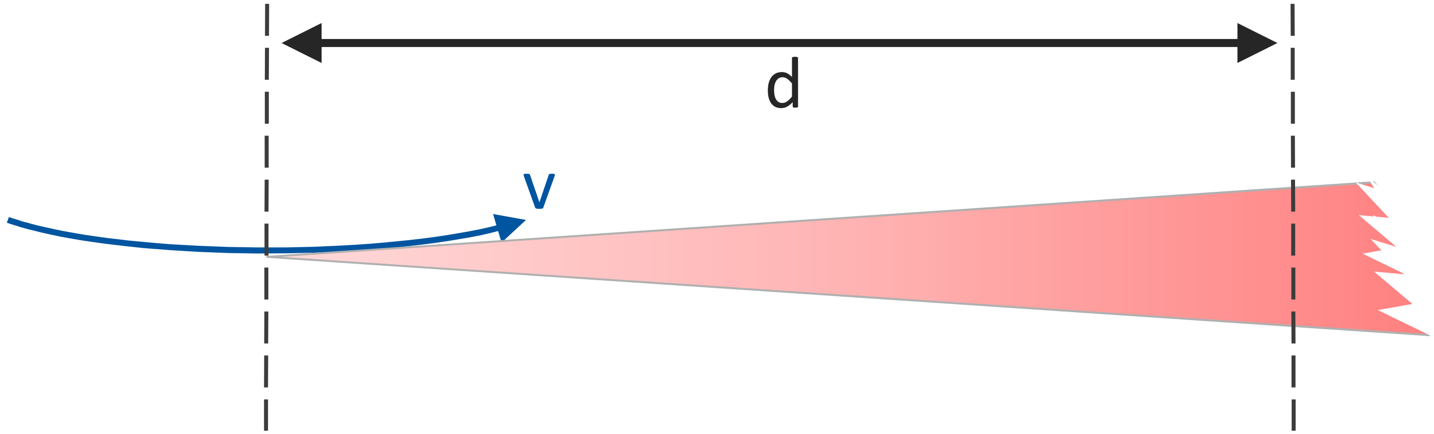
- Spatial coherence, beam size and their relation
- The HNFS technique
- Recent results obtained at ALBA
- Conclusions

Measuring the beam profile



- Beam size measurement via imaging: conjugation of object (a) and image (b) plane
- Optical instrument (visible/ IR), pinhole (X - rays)
- **+ +** Simple (visible / IR), direct measurement of profile, simple data analysis
- **- -** Aberrations, low flux (X), resolution (diffraction)

Measuring the beam profile

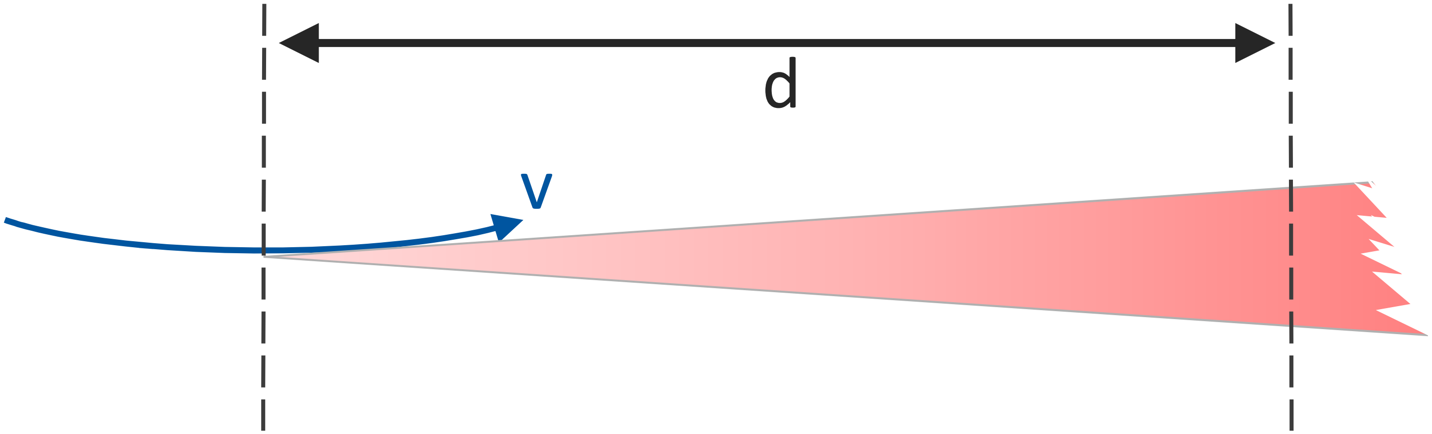


- Free propagation of radiation to the far field ($d \gg \lambda\gamma^2$)
- Measure the Transverse Spatial Coherence of the EM field
- Van Cittert & Zernike theorem (see W. Goodman, Statistical Optics):

Under certain* conditions, the far-field Spatial Coherence is the Fourier transform of the source intensity distribution

* *Quasi monochromatic,* incoherent *source*

Measuring the beam profile



- + + No optics (except monochromator), less aberrations,
- - - Indirect method,

...measuring the spatial coherence is a **+** or a **-**?

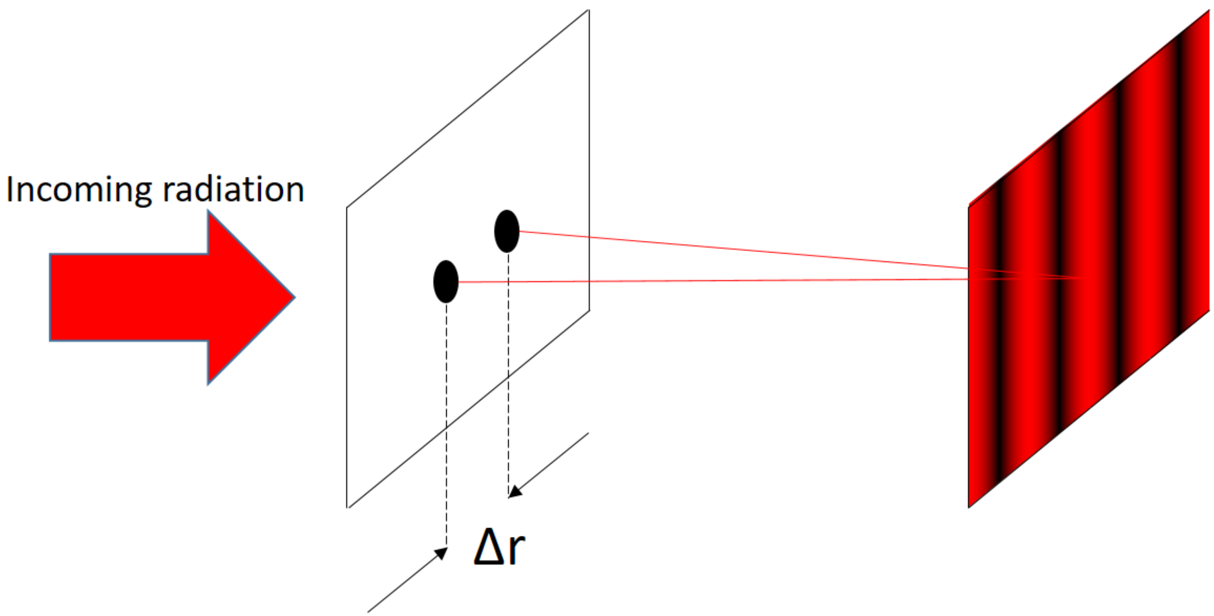
Complex Coherence Factor

- If we consider $\boldsymbol{E}(\mathbf{x}, t)$, we define the first order complex coherence factor

$$\gamma(x_1, x_2) \coloneqq \frac{\langle E(x_1)E^*(x_2)\rangle}{[\langle E(x_1)E^*(x_1)\rangle\langle E(x_2)E^*(x_2)\rangle]^{1/2}}$$

- $\gamma(x_1, x_2)$ is the normalized spatial correlation function of a field. Quantifies the 'degree of coherence' of a field.

Measuring the CCF



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

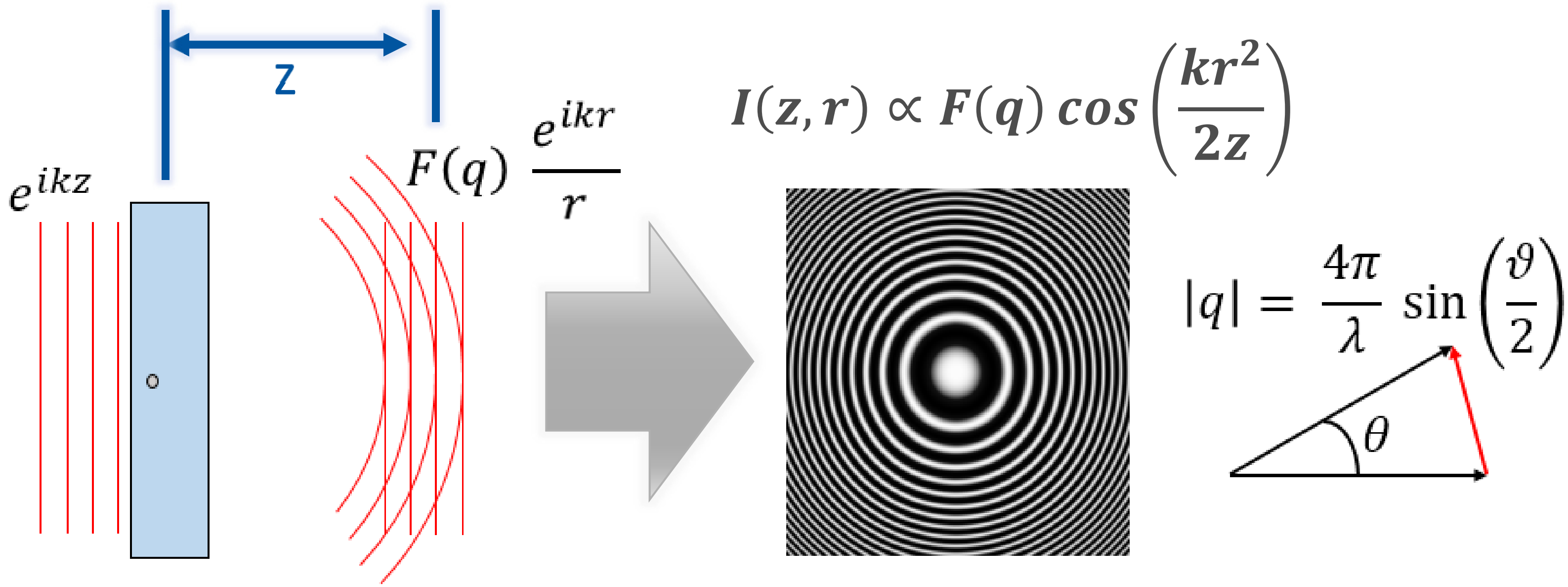
The CCF is proportional to the *visibility:*

$$\mathrm{V}(\Delta \mathrm{r}) = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} |\gamma(\Delta r)|$$

experimentally "easy" to measure

The HNFS technique

- NFS: intensity distribution of interference between (strong) transmitted and (weak) scattered EM field at a distance z from the sample. In case of a single particle:



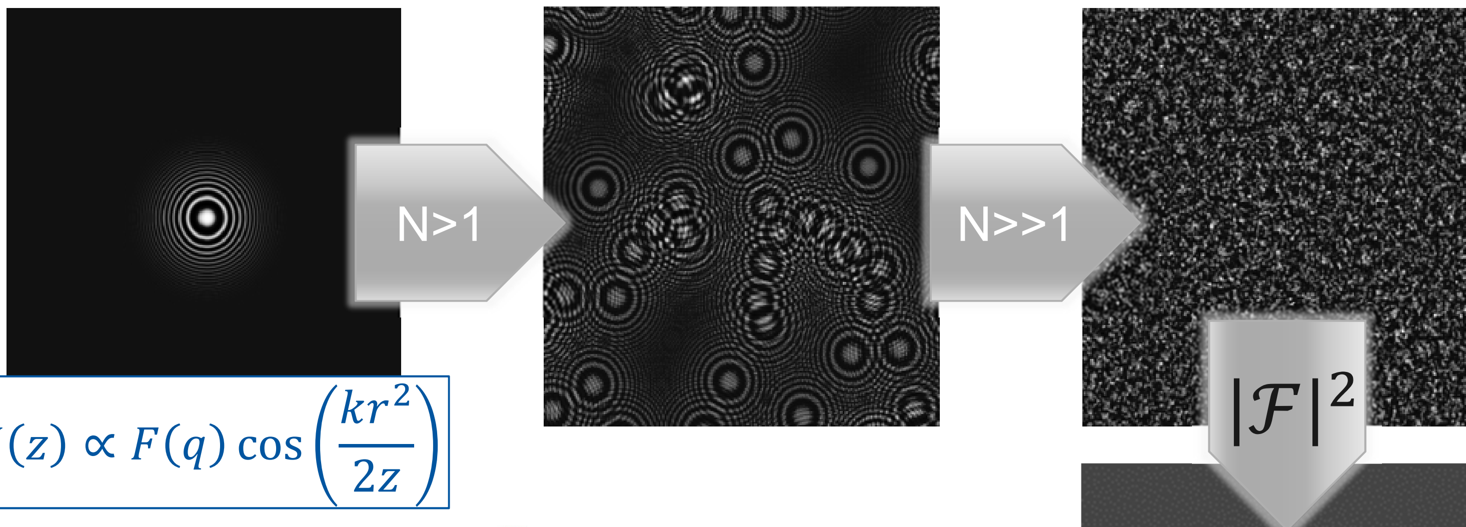
$$I(z,r) \propto F(q)\cos\left(\frac{kr^2}{2z}\right)$$

$$|q| = \frac{4\pi}{\lambda}\sin\left(\frac{\vartheta}{2}\right)$$

Where F(q) is the form factor, **q** the scattering wave vector

The HNFS technique

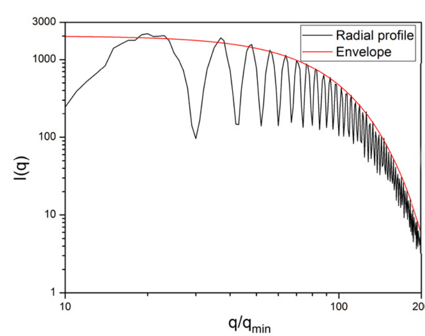
- When number N of scatterers is LARGE, scattered intensity can be retrieved through the square modulus of Fourier Transform:

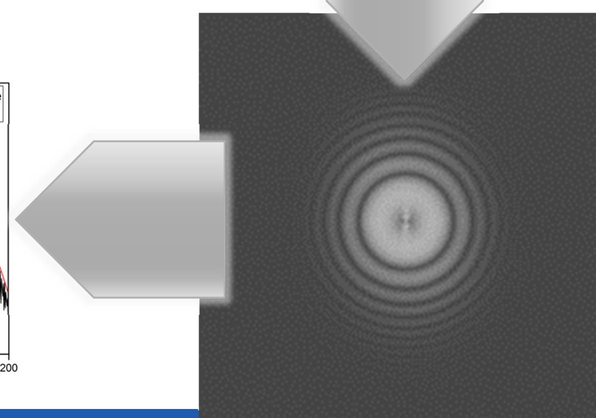


$$I(z) \propto F(q) \cos\left(\frac{kr^2}{2z}\right)$$

$$I(q) \propto S(q) \sin^2\left(\frac{zq^2}{2k}\right)$$

Single particle interferogram modulated by particle form factor





General formulation of HNFS

- HNFS: intensity distribution of interference between (strong) transmitted and (weak) scattered quasi monochromatic EM field.
- Distribution sampled at distance z from the sample
- Provided that $z < \frac{{\sigma_{coh}}^2}{\lambda}$ (NFS condition) where σ_{coh} = tranverse coherence length of radiation, θ_{max} the maximum angle of scattered radiation, it can be shown that:

$$I(q) = S(q)T(q)C(q)H(q) + P(q)$$

$S(q)$: Intensity scattered by single particle

$T(q)$: Single particle interferogram

$C(q) \equiv |\gamma(q)|^2$
Square modulus of CCF

$H(q)$: Instrument transfer function

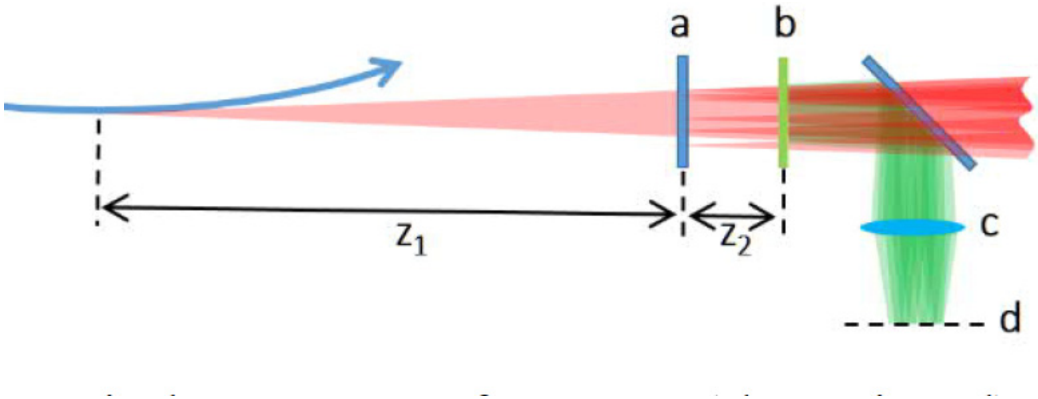
$P(q)$: Sensor noise

Why HNFS? Why nanoparticles?

- Advantages:
  - Gives **2d** coherence map with single measurement
  - Simple, cheap, robust
  - Nanoparticles > **high statistics**: 10^6 interference patterns
  - **Wavelength-independent** (optics, X-rays), but need mismatch of refractive index.
  - Rigorous subtraction of optical background

- Disadvantages/unknowns:
  - Long term exposure of particles to radiation to be studied
  - Sedimentation > a mechanical stirrer / clinostat is needed
  - Low n mismatch for hard X-rays
  - Resolution / accuracy to be studied

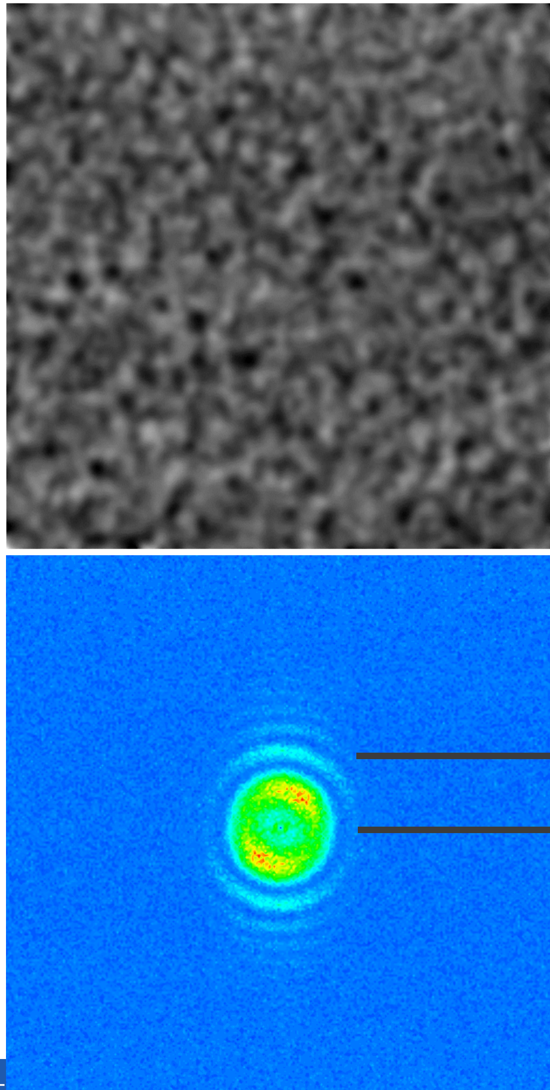
HNFS tests at ALBA



Source type	In vacuum undulator
Period	21.3 mm
Number of periods	92
Gap	5.86 mm
Resonant energy	12.4 KeV
Beam current	150 mA
Bandpass	3.1×10^{-4} (@ 10 keV)
SR source size (RMS)	$131\times8\ \mu m^2$ (HxV)

- HNFS beam size tests at NCD-SWEET beamline at ALBA started in 2017
- Target (a): 500 nm SiO_2 spheres suspended in water at z_1 = 32.5 m from the source. (b) 0.1 mm thick YAG:Ce crystal at z_2 = 252 mm, imaged with a 20X microscope objective (c) onto a CCD camera (d)
- Results from 4th shift (July 2018)

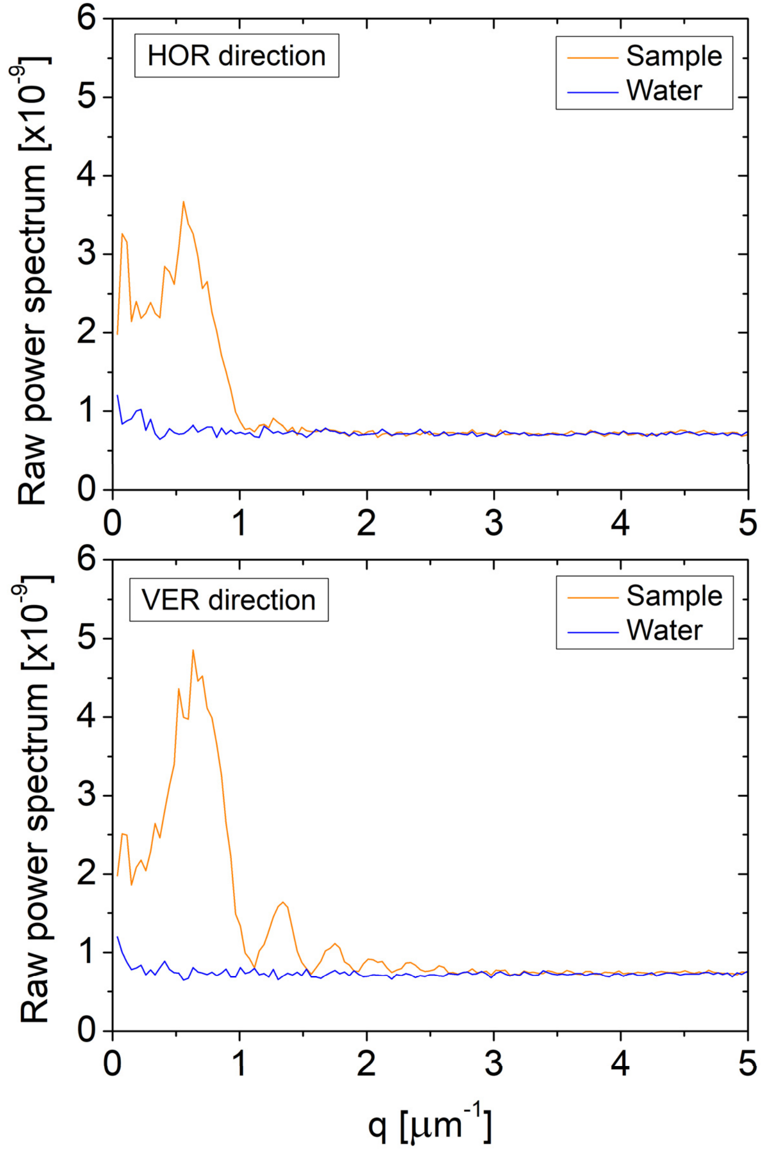
Results and analysis



150 um

$\theta \cong$ 20 urad

$\Delta r \cong$ 5 um

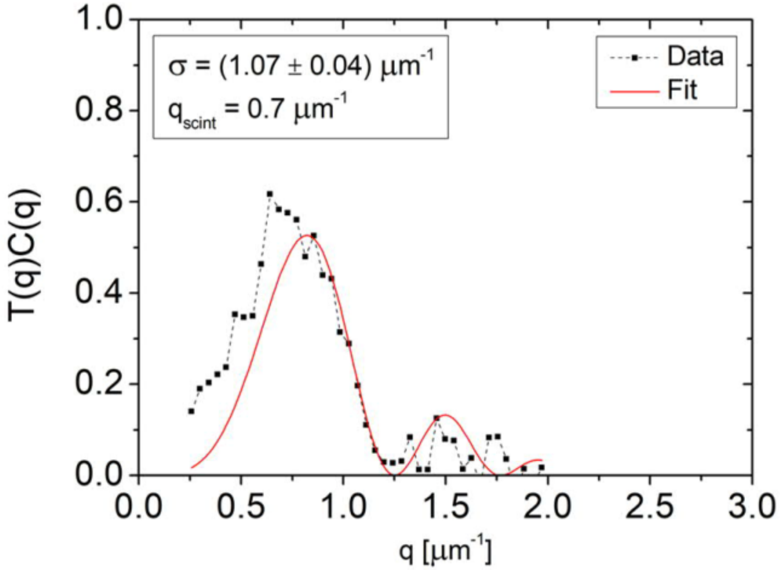


Results and analysis

- We assume a Gaussian CCF: $\mu(q) = \exp(-q^2/2\sigma^2)$

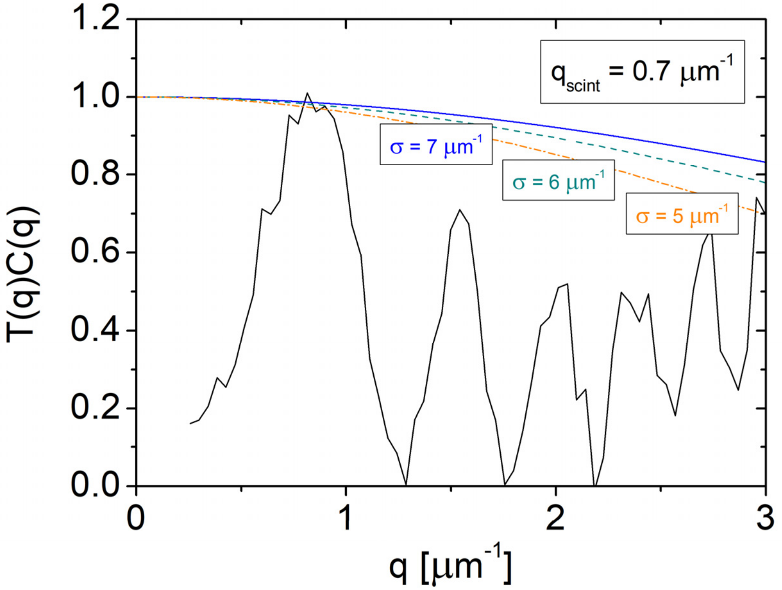
Coherence length (at distance z_1): $\sigma_{coh} = \frac{\sqrt{\pi}}{k} z_2 \sigma$

Beam size (source): $\sigma_{size} = \frac{\sqrt{\pi}}{k} \frac{z_1}{\sigma_{coh}}$



- Hor. I(q) insensitive to choice of transfer function $H(q)$
- Noisy 2nd peak (should increase z_2)
- $\sigma_{size} = 111 \pm 10$ μm (fair agreement with 130 μm)

Results and analysis



- V profile: presence of a revival at 3 μm^{-1} . Incompatible with free space propagation (monochromator?). Not understood yet.
- "Fit" of envelope gives 17 μm < σ_{size} < 38 μm. Expected is 8 μm
- Additional measurements needed at different z_2 to find out

Conclusions

- HNFS has potential for X – rays beam size measurement technique: simple, inexpensive, robust, 2D information
- Studies are in progress: S/N, optimization of sample, data analysis, resolution and other limiting factors
- Future studies: can HNFS be applied to SR from a dipole with "relaxed" BW? Possible application for CERN Future Circolar Collider ee

Thank you for your attention

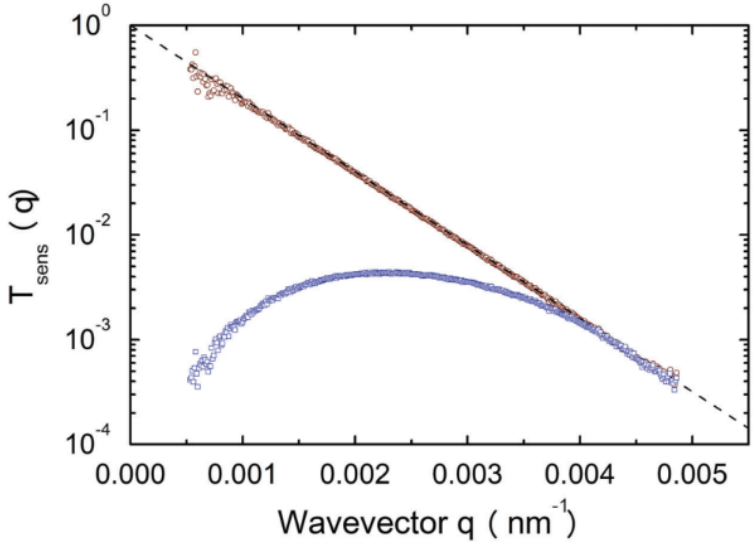
Extra slides

Results and analysis

- Instrument transfer function H(q) hasn't been measured so far. H(q) dominated by YAG:Ce angular emission. Can be obtained al low z_2 distances and has the form

$$H(q) = H_0 e^{q/q_{scint}}$$

- We use a 'typical' $q_{scint} = 0.7\ \mu m^{-1}$ value from literature*.



Cerbino et al, Nature Phys. 2008: 0.62 um^{-1}
Kashyap et al., Phys. Rev. A 2015: 0.8 um^{-1}