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PROGRESS ON TRANSVERSE BEAM PROFILE MEASUREMENT USING THE HETERODYNE NEAR FIELD SPECKLES METHOD AT ALBA

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Abstract

We present the recent developments of a study aimed at measuring the transverse beam profile using the Heterodyne Near Field Speckles (HNFS) method. The HNFS technique works by illuminating a suspension of Brownian nanoparticles with synchrotron radiation and studying the resulting interference pattern. The transverse coherence of the source, and therefore, under the conditions of validity of the Van Cittert and Zernike theorem, the transverse electron beam size is retrieved from the interference between the transmitted beam and the spherical waves scattered by each nanoparticle. We here describe the fundamentals of this technique, as well as the recent experimental results obtained with 12 keV undulator radiation at the NCD beamline at the ALBA synchrotron. The applicability of such a technique for future accelerators (e.g. CLIC or FCC) is also discussed.

INTRODUCTION

The HNFS method is a powerful, yet conceptually simple and inexpensive method to measure the transverse coherence properties of a light source. It is described mathematically by the Complex Coherence Factor (CCF):

$$\boldsymbol{\mu}(\boldsymbol{x_1}, \boldsymbol{x_2}) = \frac{\langle \boldsymbol{E}(\boldsymbol{x_1},t)\boldsymbol{E}^*(\boldsymbol{x_2},t)\rangle}{[I_1 I_2]^{1/2}} \qquad (1)$$

where $\boldsymbol{E}(\boldsymbol{x_i}, t)$ is the electric field at a given point in space and time, $I_i = \langle \boldsymbol{E}(\boldsymbol{x_i}, t)\boldsymbol{E}^*(\boldsymbol{x_i}, t)\rangle$ is the intensity of the electric field and $\langle \dots \rangle$ denotes time averaging. The ability to measure the CCF of a light source is of interest for beam diagnostics as, under the conditions of validity of the Van Cittert and Zernike (VCZ) theorem [1], the CCF is the Fourier transform of the source intensity distribution. As a consequence, when Synchrotron Radiation (SR) is used as the light source, a measurement of its transverse coherence allows the transverse profile of the beam at the emission plane to be retrieved.

The traditional method for measuring the beam size through the CCF is Young's two slit interferometer [2], where SR impinges on a pair of narrow slits forming an interference pattern. In this case, the CCF is retrieved from the *visibility* V of the fringes:

$$V \stackrel{\text{def}}{=} \frac{I_{max}-I_{min}}{I_{max}+I_{min}} = \frac{2\sqrt{I_1 I_2}}{I_1+I_2}|\boldsymbol{\mu_{12}}| \qquad (2)$$

where I_i is the time averaged intensity at slit i and $\boldsymbol{\mu_{12}}$ is a short form for the CCF as defined in Eq. 1. The HNFS method is an alternative to Young's double slit method that offers some potential advantages. HNFS does not require the almost completely blocking of SR radiation as in the Young's slits configuration, and it does not require the challenging fabrication of narrow slits in a medium that must be opaque to X-rays. While HNFS is known a well-known particle sizing technique, it has never, to our knowledge, been used for beam size monitoring in particle accelerators. We will report of the status of a proof of concept experiment at ALBA to measure beam size using X-ray radiation.

THE HNFS TECHNIQUE

A typical HNFS setup using X-ray radiation (see Fig. 1) is composed of a suspension of nanoparticles in water positioned at a distance z_1 from the source, which can be a dipole or insertion device. The transmitted and scattered fields propagate for a distance z_2 where they impinge on a YAG scintillator that produces visible light at 550 nm with the same intensity modulations as the incident X-ray radiation. The visible signal is extracted from the X-ray beam path by means of a mirror at 45º. A highly magnified image of the YAG screen is then produced on a sensor by means of a microscope objective.

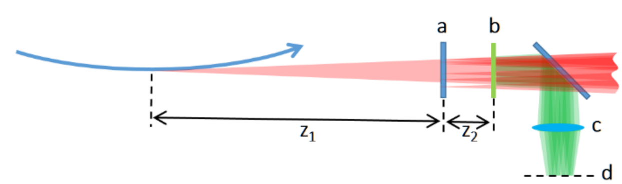

Figure 1: A typical HNFS setup for X-rays (shown in red). a) target composed of a suspension of nanoparticles in water. b) YAG screen with visible light shown in green. c) microscope objective. d) sensor

Heterodyne Near Field Scattering (HNFS) is an interferometric technique where the incident light beam $\boldsymbol{E_0}$ impinging on the target generates a large number of weak spherical waves ($\boldsymbol{E_s}, |\boldsymbol{E_s}| \ll |\boldsymbol{E_0}|$) that interfere with the transmitted field. The resulting intensity distribution is known as a speckle field and it is recorded onto the scintillator plane at a distance z_2 downstream the scattering sample. The coherence properties of the source are determined from analysis of the stochastic interferogram formed at the scintillator plane with the resulting light intensity distribution given by:

$$I = |\boldsymbol{E_0} + \boldsymbol{E_s}|^2 = |\boldsymbol{E_0}|^2 + 2Re|\boldsymbol{E_0}^* E_s| \qquad (3)$$

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where the multiple scattering term $|\boldsymbol{E}_s|^2$ is neglected because of the weak scattering. The second term of Eq. 3 is reminiscent of the CCF (Eq. 1), and represents the sum of the many interference patterns generated by the overlap of the transmitted wave and the weak spherical waves generated by single nanoparticles. However, due to the random position of the nanoparticles, the intensity I results in a stochastic speckle field where the information about the single interferogram is lost.

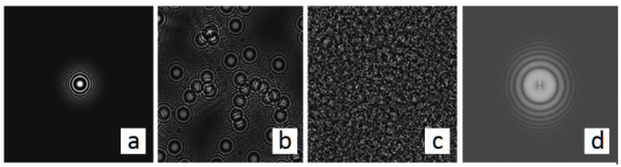

Figure 2. Principle of the HNFS method. The single particle simulated interference pattern (a) is stochastically overlapped for a large (b) and very large (c) number of nanoparticles, resulting in a speckle field. The single particle interferogram is retrieved from the square modulus of the 2D Fourier transform

This can be seen in Fig. 2, where the simulated interference pattern resulting from the interference of a single particle (spherical wave) and a plane wave is shown in (a). When the pattern is overlapped according to the random distribution of a very large number of particles, information about the single interferogram is lost. However, by computing the square modulus of the two-dimensional Fourier transform of the image $I(q)$, the square modulus of the CCF can be retrieved in the reciprocal space. It can be shown [3] that in the reciprocal space with coordinates $q = |\boldsymbol{q}| = 2k\sin\frac{\vartheta}{2} \approx k\vartheta$ (k being the radiation wavenumber, ϑ the scattering angle):

$$I(q) = |\boldsymbol{\mu}(q)|^2 T(q) H(q) + P(q) \tag{4}$$

where $T(q)$ is a single particle interferogram, $H(q)$ combines the Instrument Transfer Function (ITF) – mainly the phosphor and particle form factor (the latter being essentially a constant in our case), and $P(q)$ the shotnoise and other spurious contributions. Since $T(q)$ is known theoretically quite precisely and the other terms can be measured, the 2D power spectrum of the image yields the square modulus of the CCF expressed in reciprocal space. The relation between Eq. 4 and Eq. 1 is given by the spatial scaling $\Delta x(q) = qz_2/k$ [3, 4] (in Eq. 1, we assume that the radiation CCF depends only on $\Delta x = x_1 - x_2$). Then, a simple two dimensional Fourier transform of the square root of $I(\Delta(x(q))$ allows the two dimensional intensity distribution of the source to be recovered.

THE EXPERIMENTAL SETUP

An HNFS setup has been installed in the NCD-SWEET beamline at ALBA (see Table 1).

Table 1: NCD-SWEET Beamline Parameters

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	$3.1\text{x}10^{-4}$ (@ 10 keV)
SR source size (RMS)	131x8 μm^2 (HxV)

A channel cut silicon monochromator is positioned 22 m away from the centre of the in-vacuum undulator. The sample position can be adjusted to be between 30 and 33 metres from the source, and was fixed at 32.5 m for the measurement here presented. The target is composed of a series of capillaries of 1.5 mm diameter positioned on a motorised stage. The capillaries are filled with a suspension of silica nanoparticles of 500 nm of diameter, with a 10% volume fraction concentration. A reference capillary filled with distilled water without nanoparticles is also present. The scintillator is a YAG:Ce crystal of 0.1 mm thickness, mounted on a long translation stage that allows the distance z_2(see Fig.1). The measurements here presented were performed at a distance $z_2 = 252$ mm The optical system is mounted on the same YAG support and is composed of a 45º mirror, and a 20X microscope objective that forms the image on a Basler scA1300-32gc CCD camera.

RESULTS AND DISCUSSION

The typical result of a 2D power spectrum obtained through HNFS for a 12.4 keV X-ray beam at NCD-SWEET is shown in Fig. 3. The interference is more prominent along the direction with the larger transverse coherence length (vertical), as expected from theory [4, 5]. This can be understood from the beam shape (smaller size in the vertical direction) and the fact that there exist a Fourier transform relation between the transverse intensity of the source and the far-field transverse coherence. The poor horizontal coherence induces an almost complete lack of single particle interferogram fringes along the corresponding direction, as can be seen in Fig. 3b and 3c. For completeness the horizontal and vertical profile of the shot-noise contribution, can be inferred from the power spectrum of the capillary filled with only distilled water.

Due to limitations in the set-up, it is not possible to access sample-YAG distances smaller than a few cm where we would be sensitive to the phosphor Transfer Function (TF), and where the power spectrum would be perfectly symmetric [5], before coherence effects start to be dominant.

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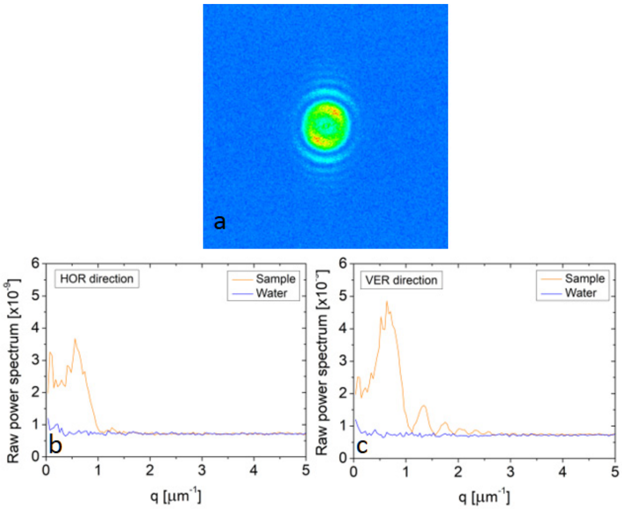

Figure 3: Two dimensional power spectrum of the speckles field (a) with its horizontal (b) and vertical (c) profiles (orange curves).

Surveying the literature [6,7], the transfer function of crystal scintillators is measured to be a negative exponential $H(q) = H_0 \exp(-q/q_{scint})$, with q_{scint} ranging from 0.6 um^{-1} [6] to 0.8 um^{-1} [7]. If we assume a similar TF for our YAG phosphor then we can produce corrected plots for different values of q_{scint} (0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0). Results for values 0.7-1 are reported in Fig. 4 for the vertical direction.

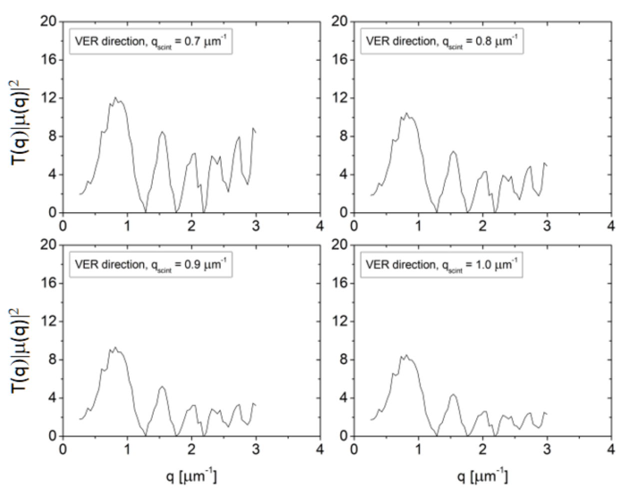

Figure 4: Vertical profiles corrected with an exponential phosphor transfer function $H(q)$ for four different values of the characteristic exponential decay, q_{scint} . Horizontal profiles are not shown for brevity

If we had truly measured the H(q) of the optics, the reduced curves T(q) $|\boldsymbol{\mu}(q)|^2$ would be normalized to a maximum value of 1 at q=0. Here, the first Talbot maximum appears at roughly q=0.8? µm^{-1}, corresponding to a transverse displacement $\Delta r = qz_2/k$ = 4 µm. This value lies well within the extent of the coherence in the vertical direction, meaning that the corresponding curves T(q) $|\boldsymbol{\mu}(q)|^2$ along the vertical direction would have a value of 1 in normalized units. The same analysis applies to horizontal profiles. We thus normalize the corrected horizontal and vertical profiles according to the value of the first Talbot maximum along the vertical direction

$$I_{corr}(q) = \frac{1}{I_0}\frac{I(q)}{H(q)} \propto |\boldsymbol{\mu}(q)|^2 T(q) \qquad (5)$$

We do not consider the three power spectra (corresponding to q_{scint} = 0.4, 0.5, 0.6) since the normalised coherence function of the radiation exceeds 1, an unphysical result that points to an incorrect value of q_{scint}.

Let us discuss separately the horizontal and vertical profiles. Fig. 5 shows the normalized horizontal profile $I_{corr}(q)$, together with a fitting function which assumes a Gaussian CCF $\mu(q) = \exp -(q^2/2\sigma^2)$ where σ, expressing the width of $\mu(q)$ depends on the distance z_2 [5] (252 mm in our case – see Fig. 1). We define the transverse coherence length as

$$\sigma_{coh} = \int_{-\infty}^{+\infty} |\mu(\Delta r)|^2 d\Delta r$$

according to [1], where Δr is a radial transverse displacement from the optical axis defined in the previous paragraph. Under Gaussian approximation, σ can be related to the transverse coherence length of the source as measured at the target plane:

$$\sigma_{coh} = \frac{\sqrt{\pi}}{k} z_2 \sigma \qquad (6)$$

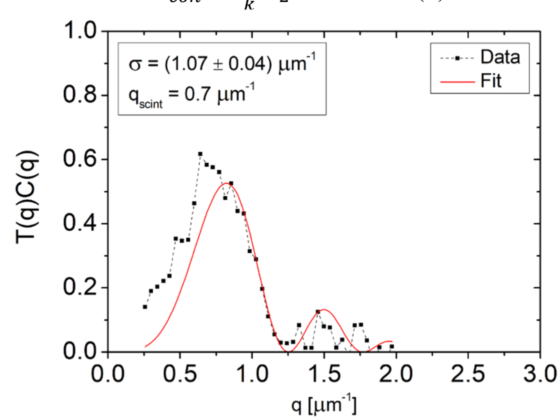

Figure 5: Horizontal profile of $I_{corr}(q)$ with a q_{scint} = 0.7 µm fitted with the single particle interferogram $T(q)$ modulated by a Gaussian CCF

In principle, our "manual" data reduction should lead to a value of σ_{coh} which is related to the choice of σ_{scint} used to calculate the corrected intensity. We find however that σ_{coh} shows a very weak dependence on the unknown q_{scint} , its value changing by only 2% for values of q_{scint} from 0.7 – 1.0. This means that the envelope of the single particle interferogram fringes along the horizontal direction is entirely dictated by the coherence properties of the source. We therefore consider q_{scint} = 0.7 µm^{-1}, for which we obtain

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$$\sigma^h{}_{coh} = 7.6 \pm 0.3 \ \mu\text{m}. \quad (7)$$

This value is in fair agreement with the expected results from simulations assuming perfect resonance conditions and no energy spread effects [4], for which $\sigma^h{}_{coh}$= 7.1 µm. Under the conditions of validity of the VCZ theorem, we finally retrieve the transverse horizontal size of the source as

$$\sigma^h{}_{size} = \frac{\sqrt{\pi}}{k}\frac{z_1}{\sigma^h{}_{coh}} = 111 \pm 10 \ \mu\text{m} \quad (8)$$

which is in fair agreement with the expected value of 131 µm.

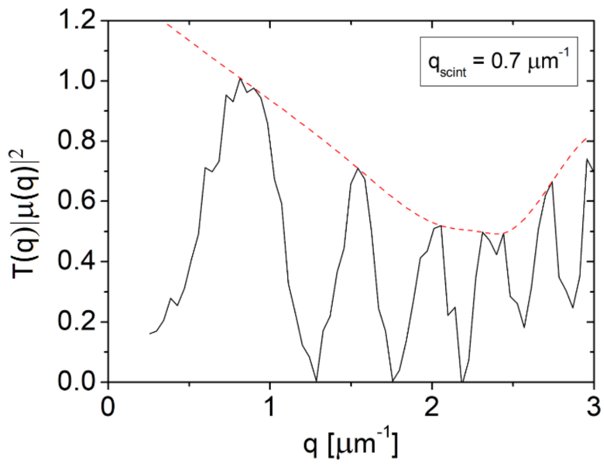

Figure 6: Vertical profile of $I_{corr}(q)$ for q_{scint} = 0.7 µm.

A similar procedure cannot be applied to the vertical profiles since the envelope of the single particle interferogram is not Gaussian but rather exhibits a sort of echo at q=3 µm^{-1}, as shown in Fig 6 for the case of q_{scint} = 0.7 µm . Here the dashed red line is drawn simply to guide the eye.

Such a peculiar behavior is not predicted by theory for free-space propagation [4] and might be ascribed to "defective" optics, as was similarly reported in previous observations [3]. In particular it can be caused by the monochromator, whose surface is known to be corrugated. Further measurements are however needed in order to understand this peculiar modulation in the vertical envelope of the Talbot oscillations. Following [3], the coherence function could be given by the overall envelope curve of such echoes. The σ of such curves ranges from 3 to 7 µm^{-1}, corresponding to a transverse beam size $\sigma^v{}_{size}$ between 17 and 38 µm in the vertical direction, a range of values that is quite far from the expected 8 µm. This could be due to a poor correction for the phosphor TF, which is expected to influence the vertical power spectrum much more than the horizontal one [5]. Beam energy spread might also affect the coherence properties of SR from an undulator in the vertical direction, as mentioned in [4].

CONCLUSIONS

We have reported recent measurements of transverse coherence length of a 12.4 keV X-rays beam at the NCD-SWEET beamline at ALBA. Under the conditions of validity of the VCZ theorem, the transverse beam size of the source was determined. The horizontal beam size is in good agreement with the expected value of 131 µm, while the vertical is affected by large experimental uncertainties that result in a value from 2 to 5 times larger than the expected 8 µm. The cause of such discrepancy is still under investigation, but is believed to be partly related to the approximate knowledge of the phosphor transfer function.

HNFS is still a relatively new technique in accelerator beam diagnostics using X-rays. Our ongoing studies aim at understand its experimental advantages and limitations when compared to the more established two-slit interferometer. In particular, we plan to optimise the HNFS target to produce a high contrast speckles field for an improved measurement of the coherence length and beam size. This could be achieved by using different nanoparticles, or alternatives to a suspension like masks or membranes. Future work also aims at testing HNFS on dipole SR with possible applications on future machines such as the Future Circular Collider.

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