

TRANSVERSE BEAM SIZE DIAGNOSTICS USING BROWNIAN NANOPARTICLES AT ALBA

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Abstract

In this work we describe a novel beam diagnostic method based on coherence characterization of broad-spectrum bending magnet radiation through the Heterodyne Near Field Scattering (HNFS) technique. HNFS is a self-referencing technique based on the interference between the transmitted beam and the spherical waves scattered by each particle of a colloidal suspension. The resulting single-particle interferogram shows circular interference fringes modulated by the spatio-temporal Complex Coherence Factor (CCF) of the radiation. Superposition of a number of these patterns results in a stochastic speckle field, from which spatial and temporal coherence information can be retrieved in near field conditions. Here we describe the basics of this technique, the experimental setup mounted along the hard X-ray pinhole at the ALBA synchrotron light source, and the possibility of transverse electron beam size retrieval from the spatial coherence function of the emitted dipole radiation. We also show preliminary results concerning power spectral density of visible synchrotron radiation as obtained from temporal coherence.

INTRODUCTION

In the ALBA storage ring, electrons are kept circulating to produce hard X-ray synchrotron radiation through bending dipoles and other insertion devices. Transverse beam size measurements are routinely performed with an X-ray pinhole camera [1], while parallel reliable measurements are provided by classical Young interferometry for visible synchrotron radiation in the Xanadu beamline [2]. A novel approach to access the full 2D coherence map and hence the 2-dimensional beam profile, also suitable for X-ray wavelengths, is given by the Heterodyne Near Field Speckle technique (HNFS) [3–5]. It has already been successfully applied to visible ($\lambda = 402$ nm) SASE FEL radiation at SPARC_LAB, Laboratori Nazionali di Frascati [4] and to soft X-ray ($\lambda = 0.1$ nm) undulator radiation at ESRF, Grenoble [5]. Recently [6], we have overcome monochromatic requirements and extended the technique to broadband visible radiation. The aim of this work is to describe applicability of HNFS to hard X-ray spatial and temporal coherence measurements at ALBA and to discuss the related transverse beam size diagnostics.

The paper is organized as follows: we first provide the reader with an overview of the HNFS technique and its ex-

tension to broadband radiation; then we describe the ALBA facility and the related HNFS diagnostics; we show experimental results regarding temporal coherence measurements of visible synchrotron radiation along the Xanadu beamline; finally, we collect our conclusion.

HETERODYNE NEAR FIELD SPECKLE TECHNIQUE

Fundamentals of the Technique

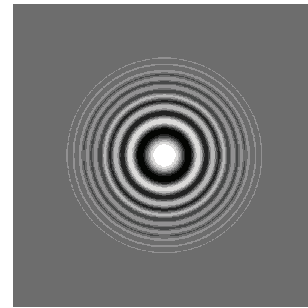


Figure 1: Single particle interferogram described by Eq. 2. Interference fringes have been modulated with a Gaussian coherence factor $e^{-2[(x-x_i)^2+(y-y_i)^2]/\sigma^2}$ with a coherence area of linear dimension $\sigma = 200$ μm . Mesh size 500×500 , parameters used for the computation are $\lambda = 632.8$ nm, $z = 5$ mm, frame dimension 0.7 mm.

Heterodyne Near Field Scattering (HNFS) is a self-referencing interferometric technique based on the superposition of the strong transmitted incident beam (E_0) and the weak spherical waves scattered by each particle of a colloidal suspension (E_s). The resulting intensity distribution is given by [7]

$$I = |E_0 + E_s|^2 = |E_0|^2 + 2\text{Re}\{E_0^* E_s\} \quad (1)$$

where in the last equality we have neglected the term $|E_s|^2$ accounting for multiple scattering and the interference between different scattered spherical waves (heterodyne conditions). The term $2\text{Re}\{E_0^* E_s\}$ describes the superposition of many single-particle interferograms, each showing circular interference fringes of the form

$$I_i(x, y) \propto \cos \left[\frac{k}{2z} \left[(x - x_i)^2 + (y - y_i)^2 \right] \right] \quad (2)$$

being $k = 2\pi/\lambda$, λ the radiation wavelength, (x, y) the transverse coordinates on the detection plane at a distance z from

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the sample and (x_i, y_i) the transverse coordinates of the i -th particle inside the colloidal sample. Partial coherence of the incident beam (either spatial or temporal or both) prevents the formation of higher order fringes, as shown in Fig. 1. The Complex Coherence Factor (CCF) of the incoming radiation could in principle be obtained from fringe visibility, as in standard interferometric devices. However, due to the random positions of the particles within the suspension, the superposition of many of these patterns generates a stochastic speckle field in which information about fringe position is lost (Fig. 2).

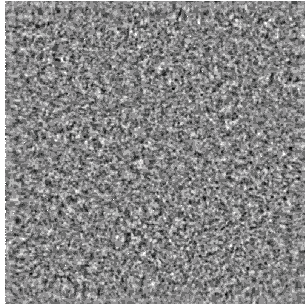


Figure 2: Heterodyne speckle field simulated as a sum over 10000 single-particle interferograms. Mesh size 500×500 , parameters used in the simulation are $\lambda = 632.8$ nm, $z = 5$ mm, frame dimension 1.75 mm.

Despite coherence properties cannot be accessed in direct space, the squared modulus of the radiation CCF can be measured via spatial frequency analysis of near field speckle fields. By calling the reciprocal space coordinates as $\vec{q} = (q_x, q_y)$, it can be shown [3, 5] that power spectra of near field speckle fields can be written as

$$I(q) = S(q)T(q)C(q)H(q) + P(q) \quad (3)$$

where $q = |\vec{q}|$. The function

$$T(q) = \sin^2 \left[\frac{zq^2}{2k} \right] \quad (4)$$

describes power spectra fluctuations known as Talbot oscillations [3, 8, 9] whose amplitude is modulated by the squared modulus of the radiation CCF ($C(q)$), as shown in Fig. 3.

It is worth noting here that the Talbot transfer function and the single-particle interferogram form a Fourier transform pair. For completeness, the other terms describe power spectra contributions arising from the particle form factor ($S(q)$), the response function of the detection system ($H(q)$) and spurious and shotnoise signals ($P(q)$). Finally, in order to express the radiation CCF as a function of transverse coordinates, we apply the near field scaling law [5]

$$\Delta r = \frac{zq}{k} \quad (5)$$

that allows to directly convert Fourier wavevectors into transverse displacements. As a further consequence, performing measurements at different distances will cause all

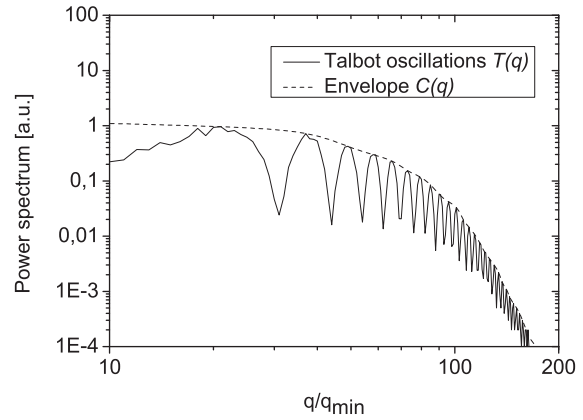


Figure 3: Typical radial profile of speckle power spectra showing Talbot oscillations (solid line) enveloped by the squared modulus of the radiation CCF (dashed line). Reduced wavevectors have been reported on the X-axis, being $q_{min} = \frac{2\pi}{D}$ where D is the effective frame dimension.

power spectra to collapse under the same enveloping curve (the squared modulus of the radiation CCF) upon the described scaling.

Advantages of the Technique

Since Talbot oscillations are reminiscent of the 2-dimensional single particle interferogram, Fourier analysis of single speckle images provides the full 2-D coherence map of the impinging radiation. This result also relies on the self-referencing scheme of the technique, which allows to directly measure field correlation functions. Exploiting the dynamical nature of colloidal suspensions, averages over many different speckle fields can be performed to greatly improve the finesse of the technique. The full bi-dimensional source profile can then be retrieved by applying the Van Cittert-Zernike's theorem [10, 11], thus making the technique a promising and powerful 2D diagnostics tool. Further advantages arise at X-ray wavelengths, since the technique does not require any dedicated X-ray optics nor alignment constraints, contrarily to other interferometric methods.

HNFS with Broadband Radiation

In case of radiation endowed with a broad spectrum, Talbot oscillations are generally modulated by the spatio-temporal coherence function of the impinging radiation, since a given scattering angle corresponds to a certain time delay between the transmitted beam and the wavefront of the scattered spherical wave. Close to the sample, the optical path difference associated to the angle subtended by coherence areas is much larger than the longitudinal coherence length. As a consequence, the envelope of Talbot oscillations together with the scaling law [6]

$$\Delta t = \frac{zq^2}{2k^2c} \quad (6)$$

allows to reconstruct the temporal coherence function of the radiation. Similarly to source profile retrieval, the emitted power spectral density can then be recovered by applying the Wiener-Khintchine's theorem [10, 11]. A peculiar behavior is observed under the near field scaling: power spectra measured at different distances, besides collapsing under the same enveloping curve, exactly superimpose one on the other. Spatial coherence can still be measured either by inserting a monochromator or by detecting speckle fields at larger distances (as long as near field conditions are fulfilled), since the angle subtended by coherence patches would be small enough to neglect temporal effects. The main limitations of the latter approach may be the minimum distance at which optical path differences become negligible (it must satisfy near field requirements) and the decay of the scattered signal due to the term $1/z$ of spherical waves.

ALBA FACILITY AND THE HNFS DIAGNOSTICS

The ALBA facility is a high flux, high brilliance synchrotron light source consisting of a 100 MeV Linac followed by a Booster that accelerates electrons to their final energy of 3 GeV before they are transferred into the Storage Ring. The main electron beam parameters are summarized in Table 1.

Table 1: Main Beam Parameters at ALBA

Hor beam size	$\sigma_{el,x}$	60 μm
Ver beam size	$\sigma_{el,y}$	30 μm
-	β_x (at pinhole)	0.3 m
-	β_y (at pinhole)	25.08 m
Dispersion (at pinhole)	D	0.0387 m
Emittance	ϵ	4.6 nm rad
Coupling	-	0.53 %
Beam current	I_{beam}	130 mA

The HNFS diagnostic will be installed alongside the already existing hard X-ray pinhole camera beamline. An Aluminum vacuum window and a Molybdenum filter select the hard X-ray part of the synchrotron radiation emitted by a bending dipole. A Copper filter with variable thickness (triangular profile) can be inserted to narrow the broad spectrum down to a Full Width at Half Maximum (FWHM) of 20 keV at a mean energy of 40 keV (Fig. 4), corresponding to a mean wavelength $\lambda = 0.3 \text{ \AA}$.

The optical bench will be installed at 15 m from the source, where coherence areas are expected to have dimensions of $\sigma_{coh,x} \approx \lambda z / \sigma_{el,x} = 6.9 \mu\text{m}$ and $\sigma_{coh,y} \approx \lambda z / \sigma_{el,y} = 13.7 \mu\text{m}$. It hosts two step-motor for transverse and longitudinal movements of the sample. The longitudinal screw motor is a 1m-long stage that allows to perform measurements at different distances and monitor Talbot collapse. Transverse motor is used to select the sample since three different scattering cells can be supported. Speckle fields are acquired through a 0.1 mm thick

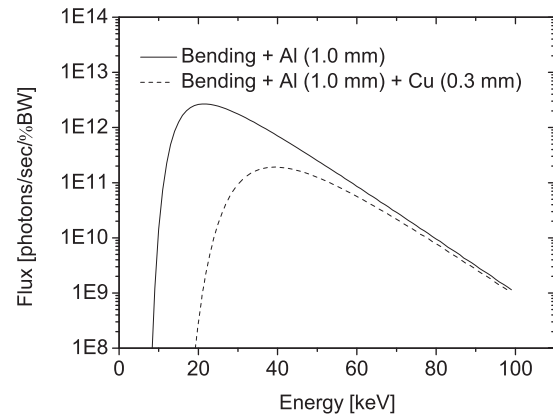


Figure 4: Power spectral density of the synchrotron radiation emitted by the bending dipole without (solid line) and with (dashed line) the Copper filter.

YAG:Ce phosphor screen with diameter of 6 mm coupled to a Basler scA1300-32cm/gc CCD camera through a 10x infinite-conjugated microscope objective. The minimum distance between the sample and the scintillator is set to 4 cm due to mechanical issues. A 45 degrees mirror deflects visible light arising from the scintillator in order to avoid sensor damage from the transmitted X-ray photons. An additional transverse motor allows to switch from the speckle diagnostics to the pinhole camera by simply moving out the sample and inserting the pinhole, thus allowing direct comparison of the experiments. Images are then acquired and processed remotely.

The chosen samples are monodispersed water suspensions of calibrated silica nanospheres with diameters of 100 nm and 500 nm at a nominal concentration of 0.1 w/w contained in a 1mm thick quartz cell. When compared with polystyrene nanoparticles usually employed in similar experiments with visible light, the X-ray scattered signal is enhanced due to the higher refractive index mismatch [12]. Calculation of the scattering cross section and forward scattering amplitude were performed with the Rayleigh-Gans approximation of the Mie theory, always valid at X-ray wavelengths [13].

Preliminary tests aimed at detecting speckle fields generated by broadband hard X-ray synchrotron light are scheduled in September. Simulations are in progress to optimize distances and spectral bandwidth in order to maximize detected signal (enhance speckle contrast with respect to background and CCD noise). Furthermore, feasibility of spatial coherence measurements at large sample-detector distances, as explained earlier, will be checked both in terms of scattered radiation (the most demanding issue at such high photon energies) and near field conditions.

TEMPORAL COHERENCE RESULTS

ALBA is also equipped with a diagnostic beamline (Xanadu) where a classical double pinhole Young setup is

mounted to perform spatial coherence measurements at visible wavelengths through interferometry [2]. Eight extraction mirrors select the visible part of the spectrum and deflect and transfer light into the experimental hall. Due to the larger wavelength, coherence areas have transverse dimensions $\sigma_{coh} \approx \lambda z / \sigma_{el}$ of the order of a few centimeters. Regarding HNFS experiments, this means that fully coherent radiation impinges on the sample, thus making spatial coherence measurements not feasible. We took advantage of such large coherence areas to perform temporal coherence measurements aimed at retrieving the power spectral density of the emitted radiation. We used a colloidal suspension of polystyrene spheres with concentration $\approx 10^{-5}$ w/w and diameter of 1 μm .

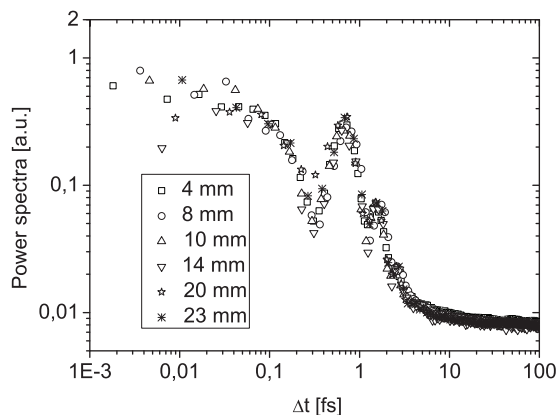


Figure 5: Collapse of speckle power spectra under the scaling $\Delta t = \frac{zq^2}{2k^2c}$, probing the limited temporal coherence of visible synchrotron radiation.

The peculiar Talbot collapse was probed for a longitudinal scan from 4 mm to 24 mm and is shown in Fig. 5. From the measured temporal coherence factors, the power spectral density of the visible synchrotron radiation has been calculated by virtue of the Wiener-Khintchine's theorem. Results are in fair agreement with independent measurements performed with a spectrometer and are summarized in Fig. 6.

CONCLUSION

We have described the fundamentals of the Heterodyne Near Field Speckle technique and shown how it can be applied to measure spatial and temporal coherence properties of synchrotron radiation emitted by a bending dipole. Attention has also been devoted to the advantages of the technique over other interferometric methods for coherence characterization of X-ray radiation. We have described the experimental setup that will be installed at ALBA synchrotron light source alongside the existing hard X-ray pinhole camera. We have also reported on results obtained on a visible line regarding measurements of temporal coherence and power spectral density with the HNFS technique.

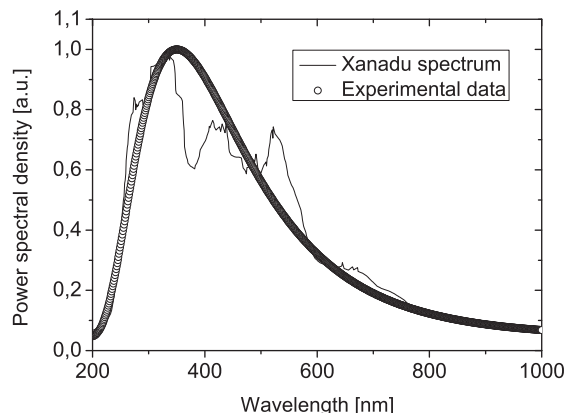


Figure 6: Comparison between the power spectral density of visible synchrotron radiation as retrieved with the HNFS technique via Wiener-Khintchine's theorem (open circles) and as independently measured along Xanadu beamline (solid curve).

The good accordance with independent measurements of the emitted spectrum shows the powerfulness of the technique as a beam diagnostics tool.

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