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Two-dimensional electron beam diagnostics with X-ray heterodyne near field speckles

M. SIANO(*)

Dipartimento di Fisica, Università degli Studi di Milano - Milan, Italy

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Summary. — In this work we report on recent two-dimensional (2D) electron beam diagnostics at the NCD-SWEET undulator beamline at the ALBA Synchrotron Light Source with a novel interferometric technique based on X-ray Heterodyne Near Field Speckles. We show that the method is intrinsically 2D and can resolve beam sizes as small as 5 μm. We also discuss relevance to future fourth-generation light sources near the diffraction limit.

1. – Introduction

The recent advances in accelerator technologies are pushing electron beams towards unprecedented ultra-low emittances and transverse dimensions of a few micrometers. In view of next-generation Synchrotron Light Sources (SLS), current electron beam diagnostics based on standard imaging techniques such as the X-ray pinhole camera are fully two-dimensional (2D), but cannot resolve beam sizes smaller than 10–15 μm [1]. Contrarily, interferometric methods provide higher resolutions, but are limited to one-dimensional (1D) measurements only [1]. Furthermore, implementations with X-rays typically require challenging fabrication of high-quality apertures and masks [2].

In this paper we report on full 2D electron beam size measurements with a non-conventional interferometric technique based on X-ray Heterodyne Near Field Speckles (HNFS) [3]. The method relies on Fourier analysis of the random speckle patterns generated by the self-referencing interference between the weak spherical waves scattered by a water suspension of nanospheres and the intense transilluminating X-ray radiation. The method is intrinsically 2D and remarkably free of any dedicated X-ray optics. We show recent results obtained at the NCD-SWEET undulator beamline at the ALBA SLS in Spain, where for the first time we have measured beam sizes as small as 5 μm.

(*) E-mail: mirko.siano@unimi.it

2. – Materials and methods

The experimental setup is depicted in fig. 1(a). X-ray radiation is generated by 3 GeV electrons moving through the undulator. A channel-cut Si(111) monochromator selects the radiation wavelength $\lambda = 0.1\,\text{nm}$. The X-rays impinge onto a water suspension of SiO_2 spheres 500 nm in diameter, located at $Z_0 = 33\,\text{m}$ from the undulator center. The volume concentration of the sample is roughly 10%. We observe speckles at distances z ranging from 2 cm up to 1.2 m downstream the sample. We use a standard detection system composed of a YAG:Ce scintillator, relay optics and a CMOS camera. To test the sensitivity of the technique, during the experiment we change the beam coupling κ in the storage ring, which results in different beam sizes at the undulator location.

An example of X-ray speckle pattern is shown in fig. 1(b), and the corresponding 2D power spectrum is reported in fig. 1(c). Upon proper processing, power spectrum $I(\vec{q}, z)$ at a distance z from the sample reduces to [4-6]:

$$I(\vec{q}, z) = T(q, z) C\left(\frac{z\vec{q}}{k}\right), \tag{1}$$

where $\vec{q}$ represents Fourier wavevectors, $q = |\vec{q}|$, $k = 2\pi/\lambda$, $T(q, z) = 2\sin^2[zq^2/(2k)]$ describes the so-called Talbot oscillations appearing in the power spectrum, and $C(\Delta\vec{x}) = |\mu(\Delta\vec{x})|^2$ with $\mu(\Delta\vec{x})$ being the 2D Complex Coherence Factor (CCF) of the incoming X-ray radiation [7]. Therefore, we directly assess the 2D CCF of the incoming synchrotron light from the envelope of the Talbot oscillations. Notice in eq. (1) the spatial scaling $\Delta\vec{x} = z\vec{q}/k$. It maps spatial frequencies $\vec{q}$ into transverse displacements $\Delta\vec{x}$, thus enabling direct 2D coherence characterization [4-6]. It also consistently matches data from different z, since the envelopes of the Talbot oscillations perfectly superimpose upon the spatial scaling, as shown in fig. 1(d), (e) [4-6]. This makes the technique fully self-

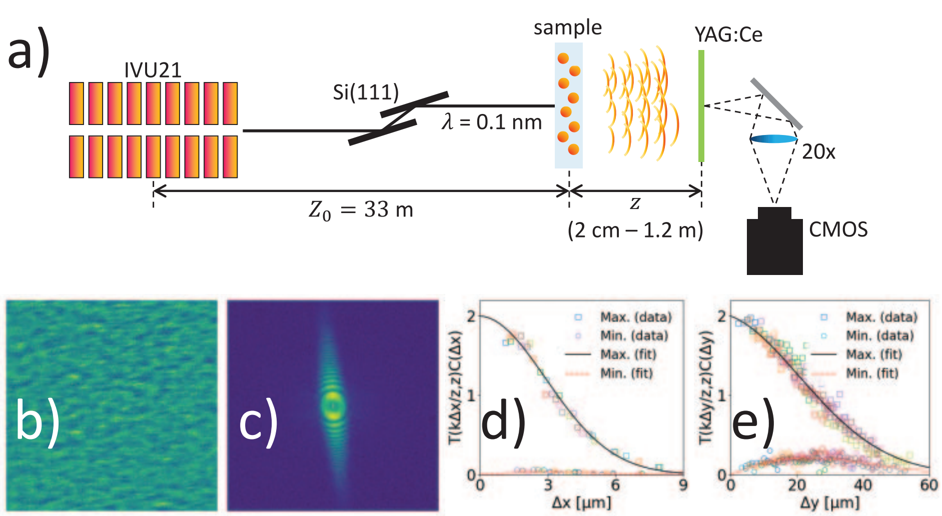

Fig. 1. – HNFS setup at the NCD-SWEET beamline (a). Example of X-ray speckle pattern (b) and corresponding 2D power spectrum (c). Data refer to $\kappa = 0.50\%$ at $z = 1.2\,\text{m}$. Horizontal (d) and vertical profiles (e) of Talbot oscillations upon spatial scaling (only Talbot maxima and minima are shown for visual purposes). Different colors correspond to different z.

consistent for what concerns coherence characterization. We then fit $C(\Delta\vec{x})$ by assuming a 2D Gaussian CCF with rms widths $\sigma_{\rm coh}^{H,V}$ along the horizontal and vertical directions, respectively. Finally, we retrieve the corresponding beam sizes $\sigma_{\rm beam}^{H,V}$ by means of pre-computed Look-Up Tables based on thorough simulations [8, 9].

3. – Results and discussion

A detailed description of the method and the fundamentals have been presented in a recent paper, where preliminary results obtained from the same data sets analyzed here are also reported [10].

The measured 2D power spectra are elongated along the vertical direction, as shown in fig. 1(c). This implies that the vertical beam size at the undulator location is much smaller than the horizontal one. Power spectra are actually rotated by 5 degrees, likely due to misalignment of the sensor axes. The overall rotation is constant during the coupling scan, thus evidencing that the beam orientation at the undulator location is not influenced by coupling.

The measured horizontal and vertical beam sizes are shown in fig. 2(a), (b), respectively. We also report a comparison with theoretical expectations based on the nominal machine parameters at the undulator location [11]. Results are also summarized in table I. The measured horizontal beam size is constant regardless of the beam coupling, with an average value of $124 \pm 3\,\mu$m. This implies that the horizontal beam size at the undulator location is not affected by coupling. Contrarily, the vertical beam size increases with coupling from roughly $5\,\mu$m at $k = 0.50\%$ up to $13\,\mu$m at $k = 2.80\%$.

We notice that the nominal vertical emittance at NCD-SWEET, ranging from 20 pm at $\kappa = 0.50\%$ up to 130 pm at $\kappa = 2.80\%$, matches the expected performances of next-generation facilities [12]. This evidences that current undulator sources along the vertical direction actually operate as fourth-generation SLS. This similarity is also reinforced by recent numerical investigations on fourth-generation SLS [12]. Simulations predict a transverse coherence length of roughly 90 μm at a distance of 30 m from a $4.5\,\mu$m electron beam for X-rays with $\lambda = 0.1$ nm [12]. Remarkably, these parameters closely resemble our measurements at NCD-SWEET for $\kappa = 0.50\%$.

Finally, it is worth mentioning that "correlation functions for synchrotron radiation close to the diffraction limit cannot be factorized in the two transverse directions" in fourth-generation SLS [12]. Therefore, next-generation facilities explicitly demand for 2D coherence mapping techniques. The HNFS method answers this call.

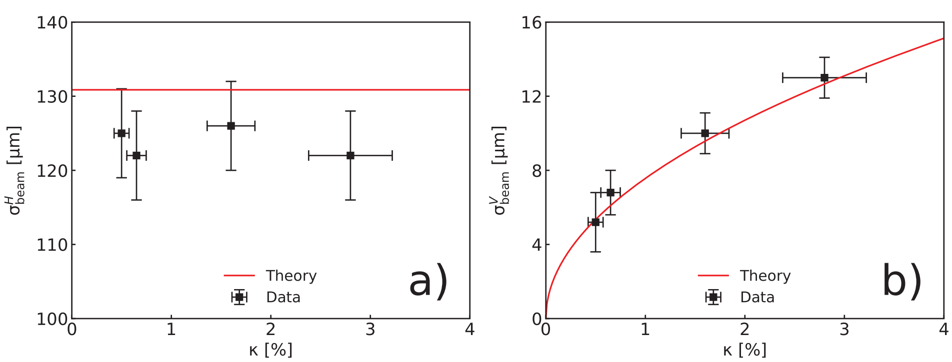

Fig. 2. – Measured horizontal (a) and vertical beam sizes (b) at the NCD-SWEET beamline.

TABLE I. – *Summary of the results obtained at the NCD-SWEET beamline.*

κ [%]	σ^H_{coh} [μm]	σ^V_{coh} [μm]	σ^H_{beam} [μm]	σ^V_{beam} [μm]
0.50	4.2 ± 0.2	93.4 ± 29.6	125 ± 6	5.2 ± 1.6
0.65	4.3 ± 0.2	71.6 ± 12.6	122 ± 6	6.8 ± 1.2
1.60	4.1 ± 0.2	49.7 ± 5.6	126 ± 6	10.0 ± 1.1
2.80	4.3 ± 0.2	39.0 ± 3.2	122 ± 6	13.0 ± 1.1

4. – Conclusions

We have shown full 2D electron beam diagnostics with the HNFS technique. This method has been validated at the NCD-SWEET undulator beamline at ALBA, where we have characterized the beam orientation and the horizontal and vertical beam sizes as a function of the machine coupling. We have measured beam sizes as small as $5\,\mu$m, proving for the first time that the used technique is compatible with ultra-low emittance electron beams. Finally, this method is intrinsically 2D, thus compliant with future fourth-generation light sources explicitly demanding for 2D coherence mapping techniques.

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