ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO39

NANOSTRUCTURED TARGETS FOR ADVANCED BEAM DIAGNOSTICS

M. Siano*,[1], B. Paroli[1], C. Piazzoni, M. A. C. Potenza[1], Università degli Studi di Milano, Milan, Italy
U. Iriso, A. Nosych, E. Solano, L. Torino, ALBA-CELLS Synchrotron, Cerdanyola del Valles, Spain
D. Butti, T. Lefevre, S. Mazzoni, F. Roncarolo, G. Trad, CERN, Geneva, Switzerland
[1]also at Istituto Nazionale di Fisica Nucleare, Milan, Italy

Abstract

Transverse beam diagnostics with standard imaging techniques represent a challenge for next-generation accelerators and colliders due to the extremely small beam sizes, and X-ray interferometry offers an interesting method to overcome this challenge. In this regard, the X-ray Heterodyne Near Field Speckles (X-HNFS) technique has successfully been used to resolve few-micrometer beam sizes and at the same time attain a full 2D beam reconstruction. The method relies on diffracting the emitted X-ray radiation off a water suspension of spherical nanoparticles, which however pose several limitations for the full exploitation of the technique during normal operations. In this contribution we report on recent advances in the development of solid targets based on nanostructured materials with characteristics compatible with accelerator requirements. We present numerical and experimental results on the target design, prototyping and testing. Emphasis is given to the application as a transverse beam size monitor in the framework of the Feasibility Study of the Future Circular Collider (FCC) at CERN.

INTRODUCTION

Transverse beam profile monitors are fundamental tools in synchrotron light sources and particle colliders to infer the beam emittance, a key parameter that quantifies the performance of any accelerator. Direct imaging with an X-ray pinhole camera is routinely employed in storage rings to monitor the two-dimensional (2D) beam profiles [1]. However, diffraction effects limit its spatial resolution, thereby posing challenges for next-generation accelerators and colliders due to the extremely small beam sizes. In this context, X-ray interferometry is extensively being investigated as a possible approach to high-resolution transverse beam diagnostics [2].

Within the FCC collaboration among ALBA, CERN and Unimi, we are pursuing R&D activities on a Speckle-based Beam Size Monitor (SpBSM) to achieve few-μm beam size measurements [3]. The SpBSM is based on the interference patterns generated by a water suspension of spherical nanoparticles [4]. Such samples however undergo Brownian motions and sedimentation that limit the full exploitation of the technique during normal operations. In addition, the contrast of the interference patterns is low, especially at the high X-ray energies envisioned at FCC-ee [5]. Therefore, as part of these R&D activities, solid nanostructured targets are being investigated with characteristics compatible with long-term operations inside accelerator rings and specifically tailored to the FCC-ee requirements.

* mirko.siano@unimi.it

In this paper we report on recent advances in the development of solid nanostructured targets for advanced beam diagnostics with the SpBSM at FCC-ee, showing numerical and experimental results on the target design, prototyping and testing.

SPECKLE-BASED BEAM SIZE MONITOR

Figure 1 (top) shows the basic required components of the SpBSM: a magnetic structure to produce the X-ray synchrotron radiation, a monochromator (λ), a nanostructured sample and a camera. The SpBSM principle is based on the interference between the light diffracted by the nanostructured sample and the transmitted X-ray beam. Such interference generates random intensity modulations known as speckles (Fig. 1, bottom-left). Fourier analysis of these speckles (Fig. 1, bottom-center) provides direct access to the full 2D transverse coherence of the X-ray beam, hence the full 2D beam profile can be reconstructed [4, 6]. The method has been validated at the NCD-SWEET undulator beamline at the ALBA synchrotron light source, proving micron-size resolution [4, 6] as shown in Fig. 1 (bottom-right).

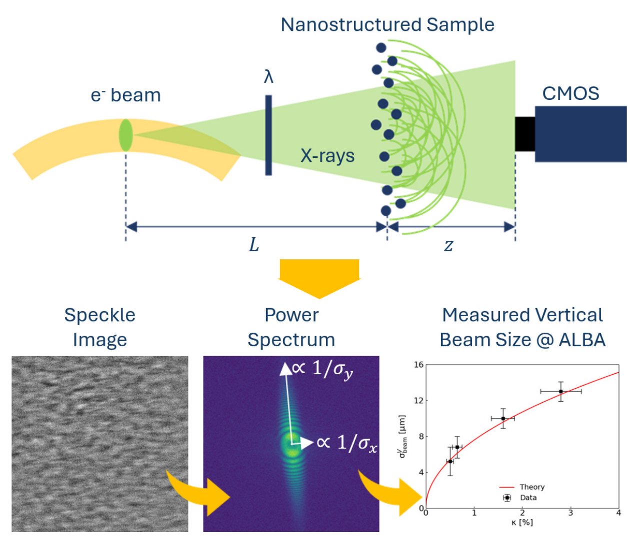

Figure 1: (Top) Basic required components of the SpBSM: a radiation source, a monochromator (λ), a nanostructured sample, a camera. L = 33 m in [4], L = 100 m in a typical FCC-ee extraction line [3]. In the current SpBSM, z = 1 m. (Bottom) Operating principles of the SpBSM: Fourier analysis of the speckle images allows retrieving the 2D beam profile. The current SpBSM enables resolving beam sizes as small as 4 μm at ALBA, corresponding to 12 μm at FCC-ee due to the different L.

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO39

The properties of the nanostructured targets, such as their characteristic size, shape and material, affect the speckle signal according to the so-called form factor $S(q)$, being q the radial coordinate in Fourier space [7]. Its amplitude $S(0)$ is related to the overall speckle signal, while its shape contributes to the decay of the power spectrum at larger q, thereby limiting the smallest beam size that can be resolved [4]. As a consequence, we aim at developing and producing nanostructured targets exhibiting a form factor as high as possible to increase the speckle signal, and as broad and flat as possible to preserve the sensitivity of the technique.

NANOSTRUCTURED TARGETS UNDER INVESTIGATION

Options for solid nanostructured targets are shown in Fig. 2 and include spherical nanoparticles (NPs) suspended in water, nanoclusters (NCs) deposited onto solid substrates, nanostructured membranes, and nanoporous gold.

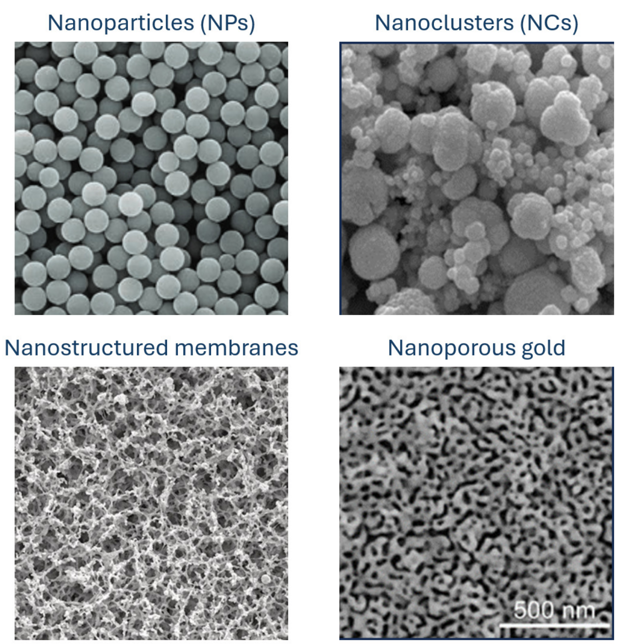

Figure 2: Nanostructured targets under investigation for the SpBSM at FCC-ee: nanoparticles (NPs), nanoclusters (NCs), nanostructured membranes, nanoporous gold.

Spherical NPs, as well as nanostructured membranes and nanoporous gold samples, are commercially available and retrievable from suppliers, while NCs are entirely produced in house at the Physics Department of Unimi in collaboration with CIMAINA. These targets are produced with a technique called Supersonic Cluster Beam Deposition (SCBD) [8]. It consists in the ablation of a metallic rod by a plasma ignited at the injection of a high-pressure pulse of an inert gas (typically He or Ar). The resulting species then coalesce due to the collisions with the inert gas, thus forming the NCs. The cluster beam then passes through a nozzle, is focused by aerodynamical lenses and is directed onto the substrate.

NUMERICAL RESULTS FOR TARGETS BASED ON SPHERICAL NANOPARTICLES

Numerical studies are possible for targets composed by spherical NPs based on the exact Mie solution to the scattering of electromagnetic waves from small spheres [9]. Spherical NPs are of interest as they provide a first-order approximation to other types of targets, see for example the NCs and the voids in the nanostructured membranes in Fig. 2. In addition, they yield useful insights into the general X-ray scattering properties of nanostructured targets in general.

We report in Fig. 3 the results for SiO_2 NPs and Au NPs with different diameters ranging from 1 nm up to 2 µm. The sample used in [4] (a water suspension of SiO_2 spheres with 500 nm diameter) is highlighted in red for a direct comparison. It also serves as a reference for the development of new targets.

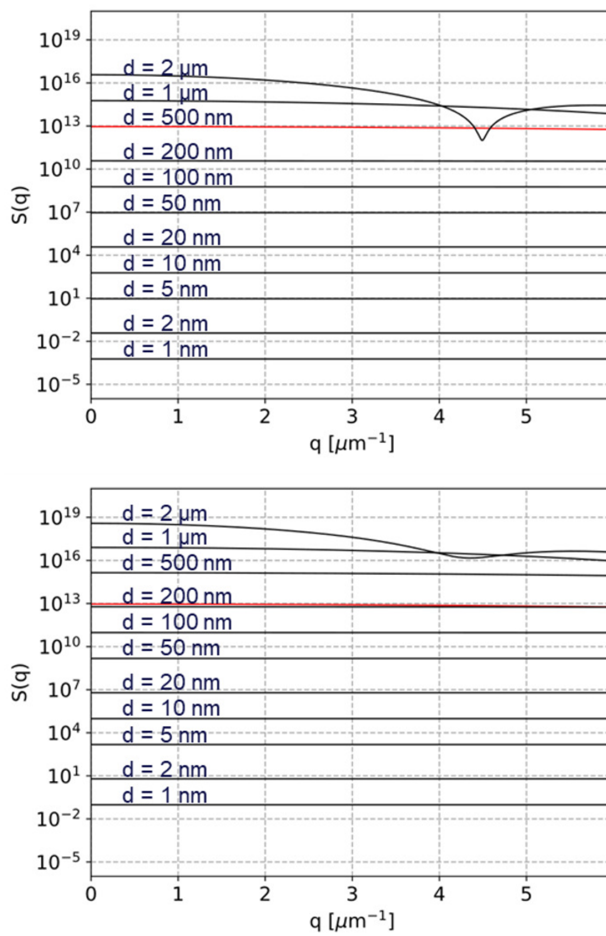

Figure 3: Form factors of SiO_2 (top) and Au (bottom) NPs with sizes between 1 nm and 2 µm. Results for the sample used in [4] are reported in red for direct comparison. Data refer to 12.4 keV X-rays.

In general, we find that the amplitude of the form factor increases with the size of the NPs, but at the same time $S(q)$ also starts to exhibit a rapid decay and to develop deep oscillations. The best compromise is found for a characteristic size of the NPs between 1 µm and 2 µm.

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO39

The increase of $S(0)$ with the characteristic size of the NPs follows a power law of the type $S(0) = c \cdot d^{\alpha}$, as shown in Fig. 4. The fitted exponent α is always close to 6, thus implying a quite strong dependence of $S(0)$ on the size of the NPs. The dependence on the NP material and on the radiation wavelength is weaker and is described by the parameter c. In particular, the speckle signal is enhanced by elements with higher atomic numbers. For example, notice from Fig. 4 that $S(0)$ for Au NPs is roughly two orders of magnitude larger than the corresponding $S(0)$ for SiO_2 NPs.

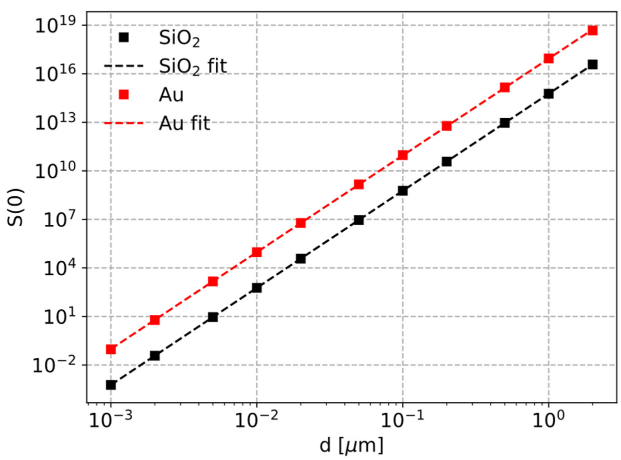

Figure 4: Dependence of $S(0)$ on the size of the NPs for both SiO_2 and Au targets. Data refer to 12.4 keV X-rays.

SAXS RESULTS AT NCD-SWEET (ALBA)

We perform SAXS measurements at the NCD-SWEET undulator beamline at ALBA to experimentally characterize the form factors of the different nanostructured targets. We use SiO_2 NPs in water (the sample used in [4]) as a reference, and test high-Z NCs (Zr, Mo, W, Au) on different solid substrates, two different nanostructured membranes with different pore sizes, and one nanoporous gold sample.

Results are reported in Fig. 5, alongside with a comparison to theoretical predictions for the spherical geometry when meaningful. Data below $q = 20\ \mu m^{-1}$ are not accessible due to the presence of a beam stop.

Results for spherical NPs show a remarkable agreement with numerical predictions based on the Mie scattering theory. The comparison between data and simulations also show that NCs are well described by spherical objects with a characteristic size between 10 nm and 15 nm. However, the peak at $q = 100\ \mu m^{-1}$ is distinctive of peculiar physical phenomena occurring during the deposition process, namely surface diffusion of smaller NCs and subsequent nucleation around the larger ones. Extrapolating data at $q = 0\ \mu m^{-1}$ based on the best-fitted Mie curves also evidence that $S(0)$ for the NCs is roughly six orders of magnitude smaller with respect to the NPs. Based on the dependence of $S(0)$ on the size of the targets (see also Fig. 4), this implies that the size of the NCs should be increased by roughly a factor 10 to

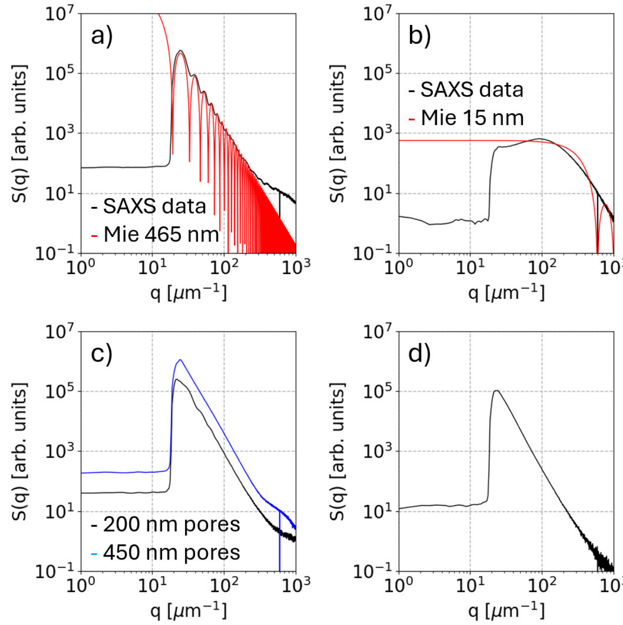

Figure 5: SAXS characterization of the form factor of SiO_2 NPs (a), Au NCs (b), two nanostructured membranes with different pore sizes (c), and nanoporous gold (d).

match the signal generated by the reference sample. The two nanostructured membranes and the nanoporous gold sample, on the other hand, generate higher signals and are therefore good candidates as solid targets for the SpBSM.

CONCLUSIONS AND PERSPECTIVES

In this contribution we have presented numerical and experimental results regarding the development of solid targets based on nanostructured materials for advanced transverse beam diagnostics. These include targets based on nanoclusters (NCs), nanostructured membranes and nanoporous gold. While the size of NCs still requires optimization, the two nanostructured membranes and the nanoporous gold are good candidates as solid targets for a Speckle-based Beam Size Monitor (SpBSM), and will be tested soon at the new FE21 beamline at ALBA. FE21 is already equipped with a pinhole camera to enable direct comparison and cross calibration of the two techniques. The new beamline will therefore serve as a scaled version of a typical FCC-ee extraction line. Future R&D activities will also be devoted to the investigation of high-Z metallic targets for operations with photon energies up to ≈100 keV.

ACKNOWLEDGEMENTS

M. Siano, B. Paroli, and M. A. C. Potenza acknowledge support from the MUSA – Multilayered Urban Sustainability Action – project, funded by the European Union – NextGenerationEU, under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment Line 1.5: Strengthening of research structures and creation of R&D “innovation ecosystems”, set up of “territorial leaders in R&D”.

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO39

REFERENCES

[1] G. Kube, "Review of Synchrotron Radiation based Diagnostics for Transverse Profile Measurements", in *Proc. DIPAC'07*, Venice, Italy, May 2007, pp. 6–10, 2007. https://jacow.org/d07/papers/MOO1A03.pdf

[2] N. Samadi, X. Shi, L. Dallin, and D. Chapman, "Source size measurement options for low-emittance light sources", *Phys. Rev. Accel. Beams*, vol. 23, no. 2, p. 024 801, 2020. doi:10.1103/PhysRevAccelBeams.23.024801

[3] S. Mazzoni *et al.*, "Overview of the FCC-ee beam instrumentation R&D", in *Proc. IBIC'24*, Beijing, pp. 1–4, 2024. doi:10.18429/JACoW-IBIC2024-TUAC2

[4] M. Siano *et al.*, "Two-dimensional electron beam size measurements with X-ray heterodyne near field speckles", *Phys. Rev. Accel. Beams*, vol. 25, no. 5, p. 052 801, 2022. doi:10.1103/PhysRevAccelBeams.25.052801

[5] S. Mazzoni *et al.*, "CERN's beam instrumentation R&D study for FCC-ee", in *Proc. IPAC'23*, Venice, Italy, pp. 4653–4656, 2023. doi:10.18429/JACoW-IPAC2023-THPL088

[6] M. Siano *et al.*, "Two-dimensional electron beam size measurements with X-ray Heterodyne Near Field Speckles", in *Proc. IPAC'23*, Venice, Italy, pp. 2594–2598, 2023. doi:10.18429/JACoW-IPAC2023-WEYD1

[7] M. Siano, B. Paroli, and M. A. C. Potenza, "Heterodyne Near Field Speckles: from laser light to X-rays", *Adv. Phys.: X*, vol. 6, no. 1, p. 1 891 001, 2021. doi:10.1080/23746149.2021.1891001

[8] E. Barborini, P. Piseri, and P. Milani, "A pulsed microplasma source of high intensity supersonic carbon cluster beams", *J. Phys. D: App. Phys.*, vol. 32, no. 21, p. L105, 1999. doi:10.1088/0022-3727/32/21/102

[9] H. C. van De Hulst, *Light scattering by small particles*. New York, US: Dover Publications, Inc., 1981.