ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO04

OPTICAL SYNCHROTRON RADIATION AS A NON-INVASIVE TOOL FOR EMITTANCE DIAGNOSTICS

D. Ghosal[1,2,*], J. Wolfenden[1,2], C. P. Welsch[1,2]
[1]Department of Physics, University of Liverpool, Liverpool, UK
[2]Cockcroft Institute, Warrington, UK

Abstract

As next-generation accelerators target higher brightness and lower emittance, conventional diagnostics may fall short. Optical Synchrotron Radiation (OSR), coupled with an optimized optical transport system, offers a scalable, high-resolution alternative. We apply a robust simulation framework for using OSR as a non-invasive tool to extract the transverse emittance of relativistic electron beams aiming for advanced accelerator facilities. The integrated simulation work of Synchrotron Radiation Workshop code and Zemax Opticstudio successfully handles modelling OSR emission and propagation through realistic optics, incorporating detector and transport effects. The feasibility of this emittance measurement study was assessed using a microlens array (MLA) system to capture angular beam distributions from the radiation. The method is benchmarked using beam conditions from the CLEAR facility at CERN, while also providing a base for extending OSR-based emittance diagnostics to other facilities.

INTRODUCTION AND MOTIVATION

The pursuit of higher beam quality in next-generation particle accelerators, including reduced emittance and enhanced brightness, imposes new demands on diagnostic tools. Emittance, a key parameter for beam quality, quantifies the spread of particle positions and angles in phase space, effectively determining how tightly a beam can be focused or transported. Precise, non-invasive diagnostics are essential for beam monitoring, not only for the calibration and tuning of the machines but also for preserving beam quality in advanced accelerator experiments.

Traditional invasive diagnostics [1, 2] require a stable and consistent beam profile (because they need multiple measurements) and are often insufficient at high repetition rates. As an alternative to multi-shot techniques, single-shot methods such as pepper-pot or slit-scan diagnostics can be used to reconstruct the transverse phase space and extract emittance value. However, these methods are typically limited to low-energy beams and remain inherently invasive. To overcome these limitations, researchers have explored optical radiation-based techniques that are non- or minimally invasive in nature. Among these, Optical Transition Radiation (OTR) [3], has been used to measure transverse beam profiles and angular distributions. But, OTR diagnostics are limited by the invasive nature [2], therefore Optical Synchrotron Radiation (OSR) has emerged as a superior option for non-invasiveness [4, 5]. While carrying valuable information about the transverse properties of the beam, such as divergence, size, and emittance, if properly captured and analyzed, OSR can provide detailed insight into beam phase space without interfering with beam propagation.

In this work, we present a robust simulation framework that combines electromagnetic field calculations with physical optics propagation (POP) to evaluate the viability of OSR as a diagnostic tool for emittance reconstruction. The methodology, described later in this paper, accounts for both the underlying radiation physics and the practical influence of beamline optics.

To benchmark and validate the method, beamline parameters from the CERN Linear Electron Accelerator for Research (CLEAR) facility [6] have been used. In particular, we evaluate the feasibility of using a microlens array (MLA) to sample the angular distribution of OSR and reconstruct the beam emittance from the resulting image. The simulation framework is not only adaptable to existing setups like CLEAR but is also extendable to more advanced and novel acceleration facilities [7], where single-shot, non-invasive emittance measurements is expected in a intense proton-driven plasma wakefield environment.

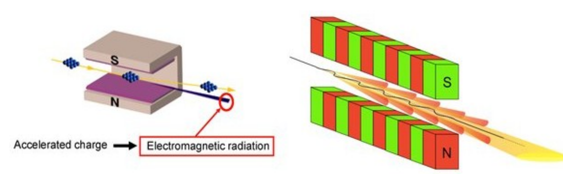

Figure 1: SR generated from a dipole (left), and a wiggler magnet (right) [8].

OSR AND EMITTANCE MEASUREMENT

When charged particles (e.g. electrons) are accelerated at relativistic speeds, they are deflected in the presence of a magnetic field, and emit synchrotron radiation (refer to Fig. 1). Due to relativistic beam effects, the radiation is highly collimated in the forward direction (a narrow cone of opening angle $\theta \approx 1/\gamma$) [9] and spans a broad spectral range. OSR refers to the specific portion of this radiation that falls within the optical range of the electromagnetic spectrum, encompassing the visible and ultraviolet ranges. The radiation field can be decomposed into two orthogonal polarization components: the π-polarization, lying in the propagation plane, which exhibits a strong, sharply forward-peaked distribution; and the σ-polarization, perpendicular to the plane, which shows a broader angular spread with a

* dghosal@liverpool.ac.uk

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO04

characteristic double-lobe structure [10]. This polarization dependence is a distinctive feature of OSR and enables the extraction of beam properties like- emittance from its angular and spatial distributions without interfering with the beam.

Emittance is a fundamental quantity describing the spread of particles in position-momentum phase space. It provides a measure of beam quality, with lower emittance indicating a more focused and brighter beam, critical for applications requiring high luminosity. Measuring emittance in high-energy, space-constrained beamlines with single-shot capability is challenging, while maintaining minimal interference with the beam. To exploit OSR's potential to extract this information, one requires an optical system that can resolve both spatial and angular content in a single exposure. This can be realized by placing an MLA at the image plane, where each microlens samples the local angular distribution while preserving spatial information. An MLA consists of a grid/array of evenly spaced high-precision micro-lenses on a single substrate [11].

In a typical measurement setup, the radiation is first spatially imaged onto the surface of the MLA. Each micro-lens then focuses the light from its specific region of the image, breaking it up and creating a unique spot pattern. This spot array, which represents the angular distribution of the radiation as a function of its spatial position, is subsequently reimaged onto a camera. By simultaneously analyzing the spot patterns from all the lenses, the local angular spread of the beam can be inferred. This technique enables a single-shot reconstruction of the beam's emittance, with the resolution and accuracy of the method dependent on both the emission characteristics of the source and the performance of the optical transport system.

SIMULATION FRAMEWORK

A complete simulation pipeline has been developed to evaluate the feasibility of using OSR for transverse emittance diagnostics. This integrates Synchrotron Radiation Workshop (SRW) [12] for physical modeling of the emitted radiation with Zemax OpticStudio [13] for POP analysis through the optical transport system.

Modelling in SRW

For a given magnetic field, the trajectory of a relativistic electron can be calculated by solving the differential equation of the Lorenz force with a set of initial conditions [14]. To compute the near-field SR emission by a single electron in frequency domain, an approach based on retarded potentials is applied [15]. From Fourier transformations of the potentials, one can obtain the following expression for the electric field of radiation emitted by the electron:

$$\vec{E} = iek \int_{-\infty}^{+\infty} \left[\vec{\beta} - \vec{n}\left(1 + i(kR)^{-1}\right)\right] R^{-1} e^{ik(c\tau+R)}\, d\tau, \quad (1)$$

where k is a wave number, $\vec{\beta} = \vec{\beta}(\tau)$ is the instant relative velocity of the electron, $\vec{n} = \vec{n}(\tau)$ is the unit vector directed from the instant electron position to an observation point, $R = R(\tau)$ is the distance from the electron to the observation point, c is the speed of light, and e is the charge of the electron.

In SRW, only transverse components of the electric field of radiation is considered, assuming $kR >> 1$. The propagation of the computed synchrotron field from the source point through the optical system was handled using scalar diffraction theory, applying the Huygens-Fresnel principle in the paraxial approximation [15]. To account for the finite transverse emittance of the beam, the single-electron intensity maps were convolved with a 2D Gaussian distribution representing the beam's transverse spatial and angular spread. Here SRW's CalcElecFieldSR and CalcIntFromElecField modules were used to compute intensity (total and individual π and σ components).

Zemax Optical Propagation

To assess how the simulated OSR field would behave in a realistic optical diagnostic system, the radiation was further propagated through a ray-tracing model in zemax. While SRW models the field propagation and calculate the radiation profile, zemax enables detailed optical system optimization, accounting for geometric optics, component tolerances, ray tracing etc. The built-in analysis tools of zemax, such as- Physical Optics Propagation, Beam File Viewer, Spot Diagram, Ray tracing footprints, transfer map visualizations etc. were used for these purposes.

CLEAR BEAM PARAMETERS FOR SIMULATION

The integration of OSR-based diagnostics into next-gen accelerator facilities presents unique challenges like- comparatively shorter length dipole with high beam energy, limited extraction space (on-axis Vs off-axis scenario) [16], radiation environment etc. For this, CERN's CLEAR facility was selected as a testbed to explore the viability of such a system, enabling both simulation validation and initial proof-of-concept measurements under controlled conditions. Based on the available operation modes of the CLEAR beamline, Table 1 contains the used beam parameters for simulation and test configuration.

Table 1: CLEAR Beam Parameters

Parameter	Values
Beam energy	~205 MeV
Energy spread	1 –1.5 %
Transverse beam size	100 s of μm to mm
Repetition rate	0.8 to 10 Hz
Charge per bunch	~100 pC to 1.5 nC
Bunches per train	1 to 80

RESULTS AND DISCUSSION

In SR diagnostics, the spectral intensity profile refers to the photon flux (or intensity) as a function of photon energy

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO04

(or equivalently wavelength) at a given observation point. Using SRW, these curves were generated for specific beam energies and observation angles, providing insight into the optimal detection wavelength range for the optical system. Figure 2 shows two such computed spectra emitted in case of CLEAR beamline for different cases.

To account for realistic bunch effects, simulations were

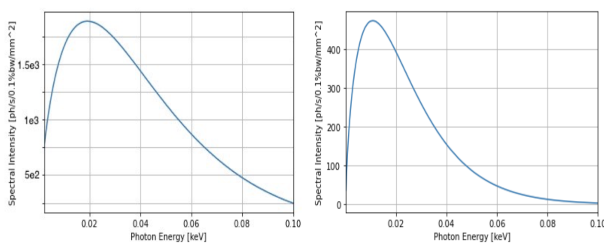

Figure 2: Simulated OSR spectral intensity profiles at CLEAR; the left plot is the total intensity (sum of π and σ components) profile while the right one shows only for one polarization component with a different divergence value.

extended to include multi-electron radiation. Figure 3 shows the simulated multi-energy OSR intensity (π polarization) at the image plane for the CLEAR beamline. The left 2D map indicates the intensity distribution of the electron; the corresponding horizontal and vertical 1D projections are exhibited in the adjacent subplots respectively.

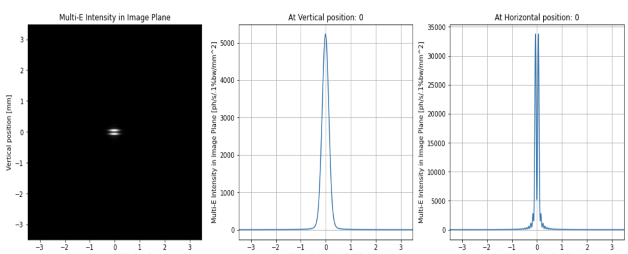

Figure 3: 2D and 1D multi-electron intensity distribution.

The far-field OSR distributions generated in SRW were exported and used as source inputs in zemax for optical transport modelling. The interface was implemented by converting the SRW-calculated complex electric field maps into zemax-compatible source zbf file formats [17], ensuring correct spatial scaling, polarization preservation, and wavelength sampling. As can be seen, Fig. 4 confirms that end-to-end integration is successful preserving the spatial and angular feature of the OSR pattern.

The fitted MLA spot centroids (following the post-processed zemax output) were mapped into trace space (x, x') and (y, y'). Confidence ellipses constructed from their second-moment covariance matrices (as can be seen in the example plots in Fig. 5) provide a compact representation of the reconstructed beam phase space, enabling extraction of emittance and Twiss parameters. Importantly, these ellipses represent statistical correlations of the centroids. With the SRW-Zemax pipeline established, a series of parametric scans (with varying beam parameters) have been performed to quantify the sensitivity of the OSR-MLA diagnostic.

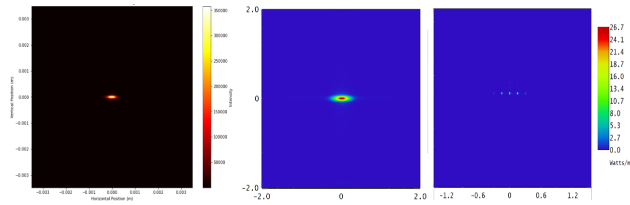

Figure 4: The first subplot is the spatial intensity profile as the output of SRW, which is intact in Zemax (2nd subplot) for the image plane, while the 3rd subplot shows the MLA spot pattern in the focal plane (i.e. the angular profile).

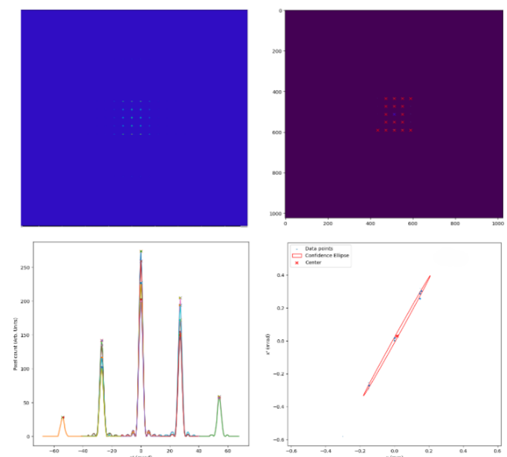

Figure 5: Emittance reconstruction: MLA spot arrays (top left) are first identified properly (top right), followed by analyzed to extract beamlet centroids (bottom left), which are mapped into phase space, enabling reconstruction of the horizontal phase space with fitted emittance ellipses (bottom right).

CONCLUSION AND OUTLOOK

This study demonstrates that OSR, when combined with optimized optical transport and image analysis, can serve as a robust, non-invasive diagnostic tool for measuring transverse beam emittance. The integration of SRW and zemax in a modular simulation framework enables precise modeling of the emission and detection capability.

Benchmarking the method with CLEAR beamline parameters is to confirm the feasibility and resolution limits. The framework also acts as a base to further implement and adapt with the existing challenges at AWAKE-like future proton-driven plasma wakefield environments.

ACKNOWLEDGEMENTS

This work was supported by the AWAKE-UK phase II project funded by STFC under grant No. ST/X005208/1. We also thank Pierre, Antonio, Alex, Alfred and Catherine for beamtime support and valuable discussions.

REFERENCES

[1] M. Wendt, ”Challenges in Accelerator Beam Instrumentation”, in *Proc. DPF-2009*, Detroit, MI, Jul. 2009.

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO04

https://lss.fnal.gov/archive/2009/conf/fermilab-conf-09-670-ad.pdf

[2] H. Zhang, ”Beam diagnostics (destructive methods)”, *AVA school on Low Energy Antimatter Physics*, CERN, Jun. 2018. https://indico.cern.ch/event/677170/contributions/2772376/attachments/1674153/2687096/beam_diagnostic_destructive_method.pdf

[3] O. Sedlacek *et al.*, ”Optical transition radiation measurements of a high intensity low energy hollow electron beam on electron beam test facility”, in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 3952–3955. doi:10.18429/JACoW-IPAC2023-THPA002

[4] R. H. A. Farias *et al.*, “Optical Beam Diagnostics for the LNLS Synchrotron Light Source”, in *Proc. PAC'97*, Vancouver, Canada, May 1997, paper 8P060, pp. 2238–2240. doi:10.1109/PAC.1997.751168

[5] R. Thurman-Keup *et al.*, ”Synchrotron radiation based beam diagnostics at the fermilab tevatron”, *J. Instrum.*, vol. 6, 2011. doi:10.1088/1748-0221/6/09/T09003

[6] CLEAR, CERN, https://clear.cern/

[7] R. Ramjiawan *et al.*, ”Design of the proton and electron transfer lines for AWAKE Run 2c”, *Nucl. Instrum. Methods Phys. Res. A*, Vol. 1049, 2023. doi:10.1016/j.nima.2023.168094

[8] S. Oğur, ”Linac and Damping Ring Designs of the Future Circular $e^{+}e^{-}$ Collider of CERN”, Ph.D. thesis, Boğaziçi University, Turkey, May 2019. doi:10.13140/RG.2.2.12312.21761

[9] A. Hofmann, ”Diagnostics with synchrotron radiation”, *CERN report*, CERN, Switzerland, 2005. https://cds.cern.ch/record/1058091/files/p295.pdf

[10] M. Dohlus *et al.*, ”Application of Accelerators and Storage Rings”, *Particle Physics Reference Library*, pp. 661–795, May 2020. doi:10.1007/978-3-030-34245-6$_$11

[11] Thorlabs Micorlens Array, https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=2861

[12] ESRF-SRW, https://www.esrf.fr/Accelerators/Groups/InsertionDevices/Software/SRW

[13] Ansys Zemax, https://www.ansys.com/products/optics/ansys-zemax-opticstudio?

[14] S. Kongtawong *et al.*, ”Simulation of synchrotron radiation from electron beams affected by vibrations and drifts”, *Phys. Rev. Accel. Beams*, vol. 25, 024601, 2011. doi:10.1103/PhysRevAccelBeams.25.024601

[15] O. Chubar *et al.*, ”Accurate and efficient computation of synchrotron radiation in the near field region”, in *Proc. EPAC'98*, Stockholm, Sweden, Jun. 1998, pp. 1177-1179. https://accelconf.web.cern.ch/e98/papers/THP01G.pdf

[16] D. Cooke *et al.*, ”Measurement of the emittance of accelerated electron bunches at the AWAKE experiment”, Nov. 2024, arXiv:2411.08681 [physics.acc-ph]. doi:10.48550/arXiv.2411.08681

[17] Zeemax Beam File, https://optics.ansys.com/hc/en-us/articles/23239731653139-ZBF-Import-Export