



Non-invasive Optical Diagnostics for Sustainable Operation of Next-Gen. Plasma Wakefield Accelerators

D. Ghosal^{1,2}, J. Wolfenden^{1,2}, A. Gilardi³, C. P. Welsch^{1,2}

¹. Department of Physics, University of Liverpool, L69 7ZE, UK

². The Cockcroft Institute, Warrington, WA4 4AD, UK

³. CERN, Geneva, 1217, Switzerland

Liverpool, July 10, 2026

Symposium: Innovations for a Sustainable Tomorrow

BACKGROUND & MOTIVATION

Beam Diagnostics

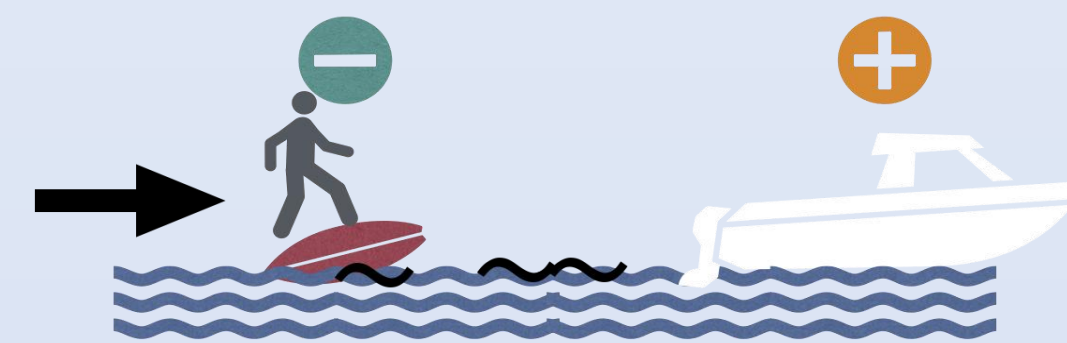
essential for accelerator operation: calibration, tuning, preserving beam quality. Next-gen. accelerators need higher beam quality (lower emittance, divergence values & higher brightness) → reducing operational cost, beam losses and unnecessary machine interventions.

AWAKE (Advanced Wakefield Experiment) → CERN's pioneering Plasma wakefield acceleration (PWA) [1] facility, a promising route towards compact, high-gradient particle accelerators. → far smaller and with far less material, energy, and infrastructure footprint than today's km-scale giant machines.

Any error in injection (or beam-transport) in position, angle, or beam size → emittance growth, reduced acceleration efficiency, or beam loss.



Typical size of a conventional large-scale facility [2] and (below) is the surfing analogy to wakefield acceleration



Available Tools:

Traditional diagnostics [3] have critical limitations: **invasiveness**, require **multiple shots** and **stable beams** = **less efficient**

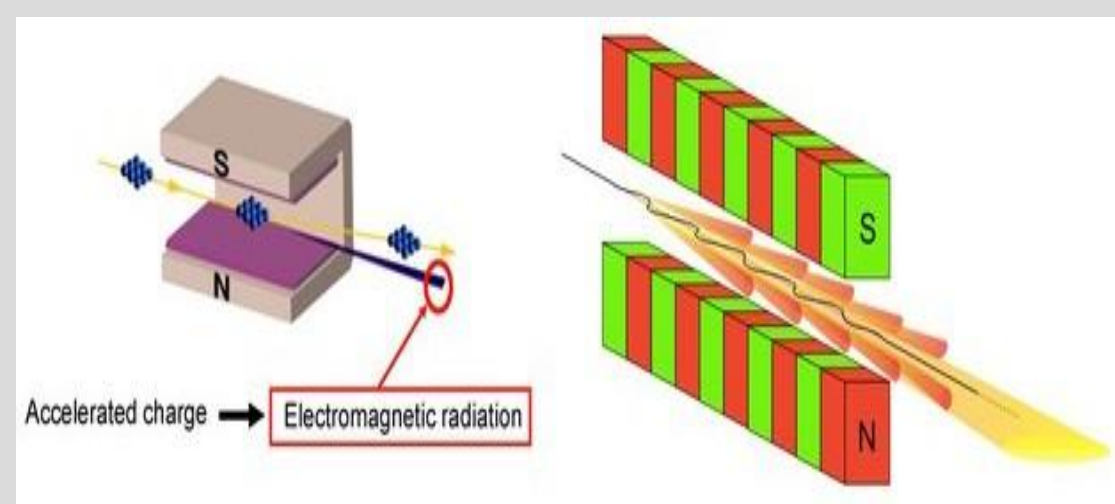


Optical Synchrotron Radiation (OSR) [3] - based **non-invasive** real-time beam monitoring → **single shot** characterization + helps to decode the beam prop. (e.g. *emittance*) → influence **acceleration efficiency**.

DIAGNOSTICS CONCEPT: OSR PHYSICS

Synchrotron Radiation (SR)

when relativistic charged particles are deflected in the presence of a magnetic field.



OSR

- highly **collimated**
- forward-peaked ($\theta \sim 1/\gamma$)
- Visible + near-UV
- **polarized** (σ and π components).

SR

Optical portion of SR

Engineering Challenges:

single-shot, non-invasive transverse profile measurement in geometrically-constrained beamline with a Dipole → photon yield & detection feasibility

Key Advantages:

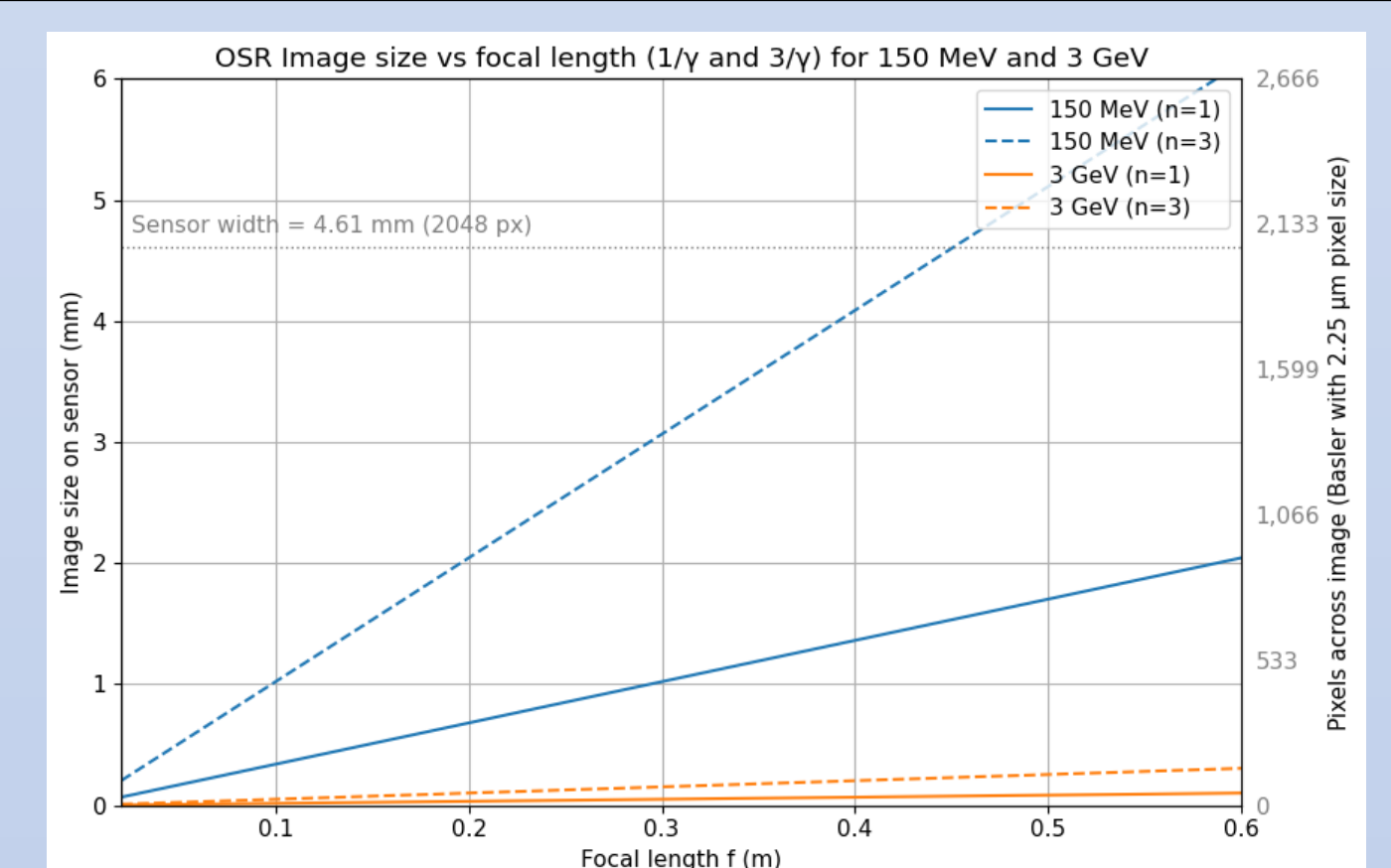
Non-invasive beam diagnostics, Single-shot stability monitoring, injection alignment verification, Faster machine optimization → online/automated feedback or virtual diagnostic, More efficient use of beamtime

EXTRACTION GEOMETRY & SIMULATION FRAMEWORK

- For the 150 MeV e^- beam and a dipole bending radius of about 1 m, the critical energy (E_c) ~ 7 eV, (155–177 nm).
- SR is naturally emitted in a narrow forward cone ($\frac{1}{\gamma} \sim 3.4$ mrad, with most of the radiation contained within $\frac{3}{\gamma} \sim 10$ mrad), allowing efficient optical collection.
- At a 45 cm distance from the source, the DN16 aperture subtends a half-angle ($\theta_{aperture}$) ~ 16.7 mrad → large enough to capture most of the synchrotron cone.
- SRW** (Synchrotron Radiation Workshop) [4] & **Zemax** OpticStudio [5] for the spectral-angular radiation distribution + propagation through beamline geometry and optics
- Wavelength dependent** transmission (varies with photon energy)

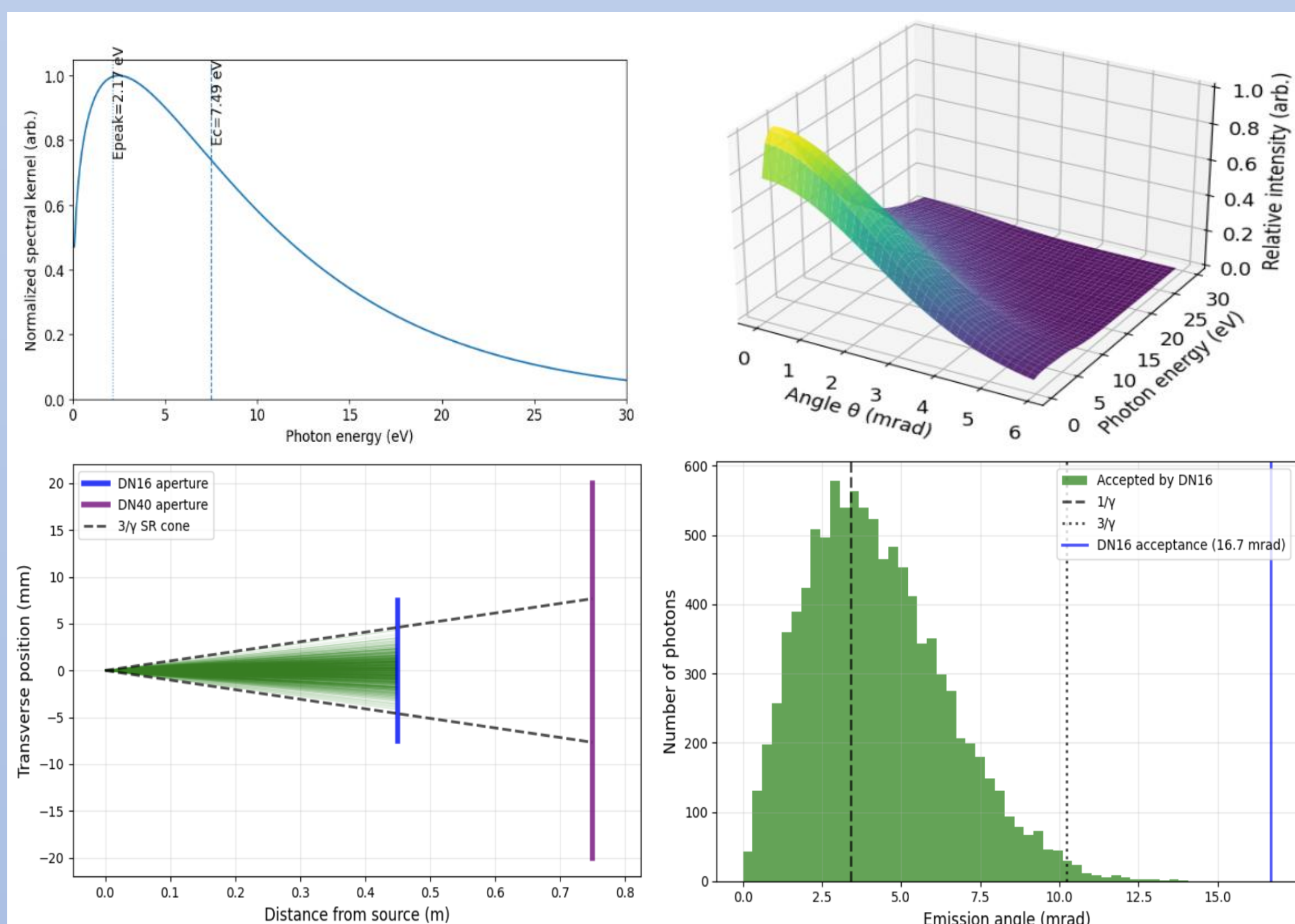
IMAGING SYSTEM & PHOTON STAT.

→ Camera system trade-off: **FOV, spatial resolution & photon collection efficiency.**
→ **f** and **M** to choose to well-sampled the OSR image on the detector.

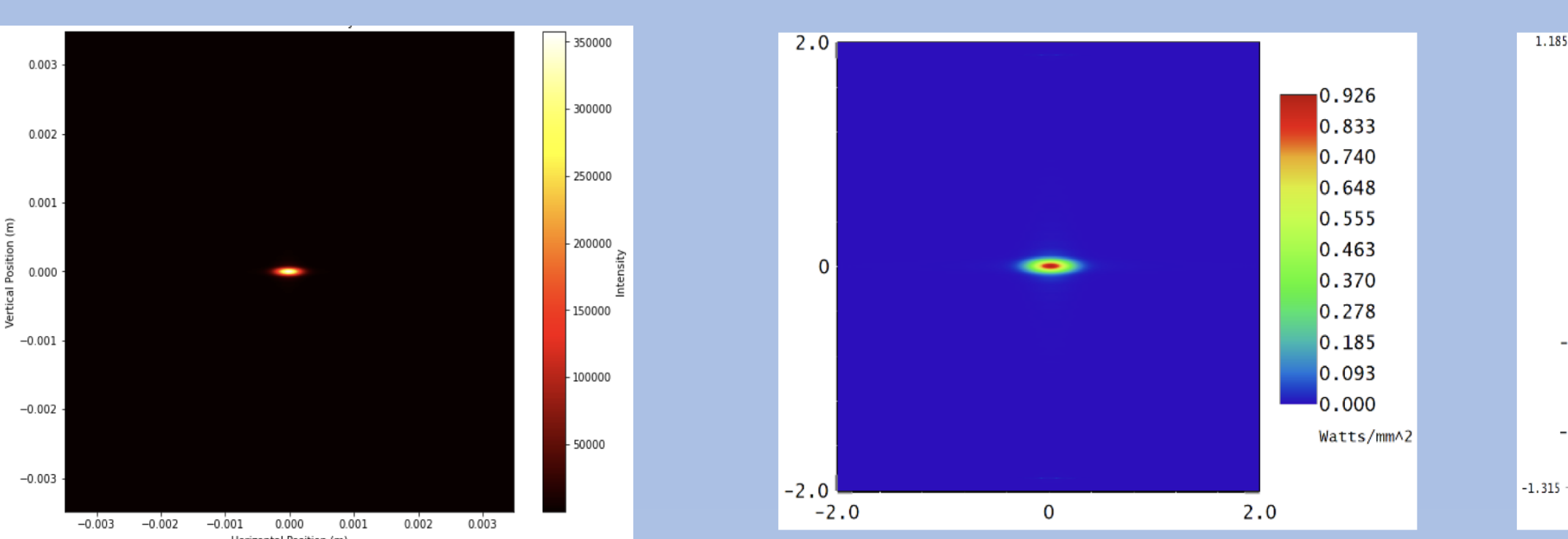


- For a nominal bunch charge of 100 pC: $N_{\gamma, optical} \sim 10^8 - 10^9$
- Large detection ($N_{detected} \sim 10^7 - 10^8$).
- High enough photon count per bunch to overcome shot noise $\sqrt{N}$.
- Fair signal for emittance + beam profiling even at lower E @ **110 MeV**

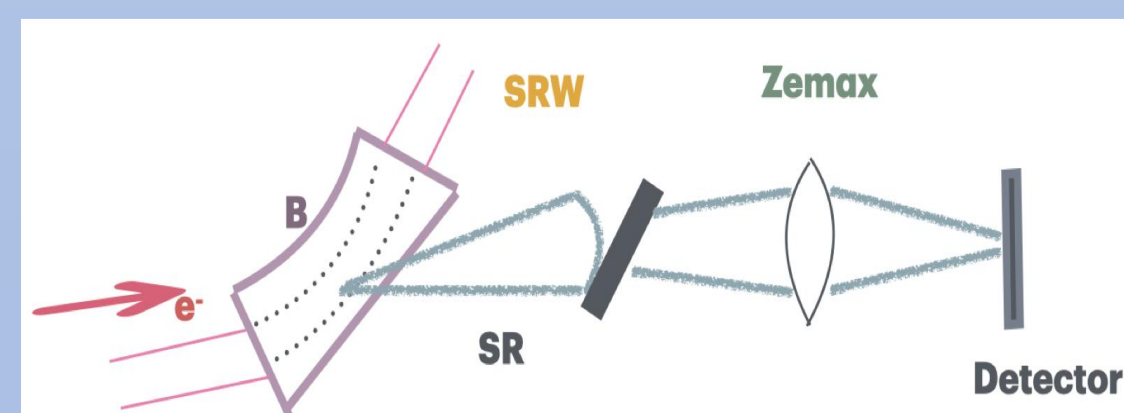
RESULTS: PERFORMANCE ASSESSMENT & DISCUSSION



photon energy scan and the 3D Ang. distribution; (below) Accepted photons propagation through the apertures and the angular distribution of them

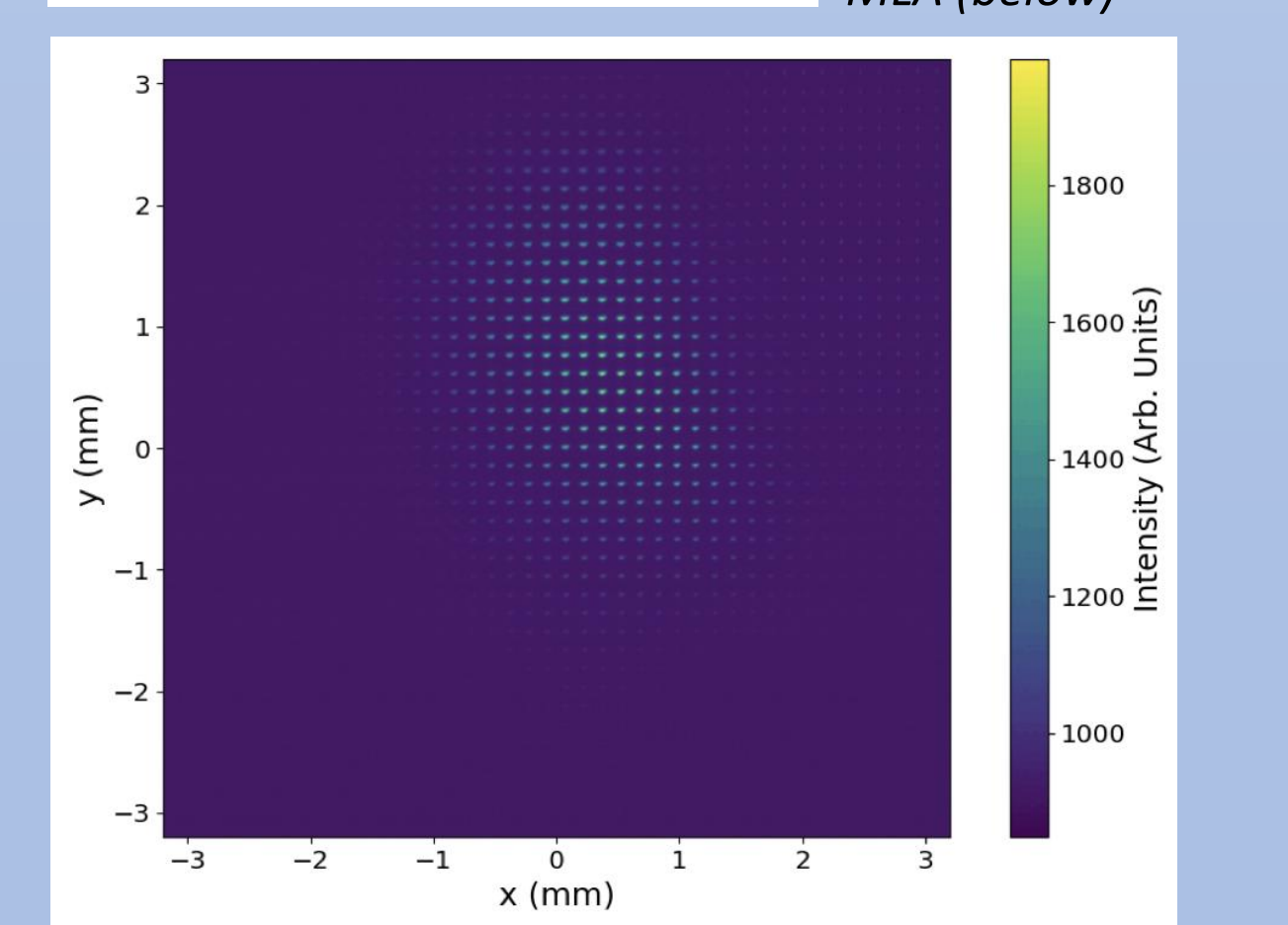
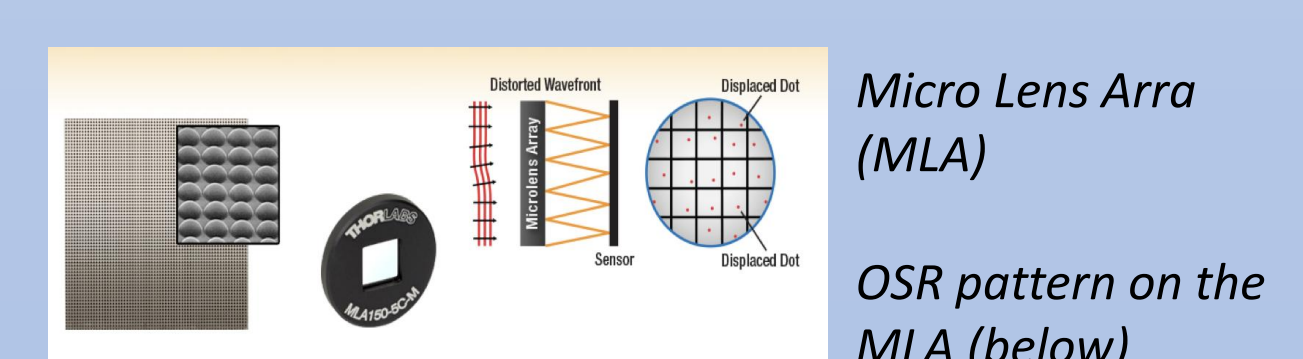
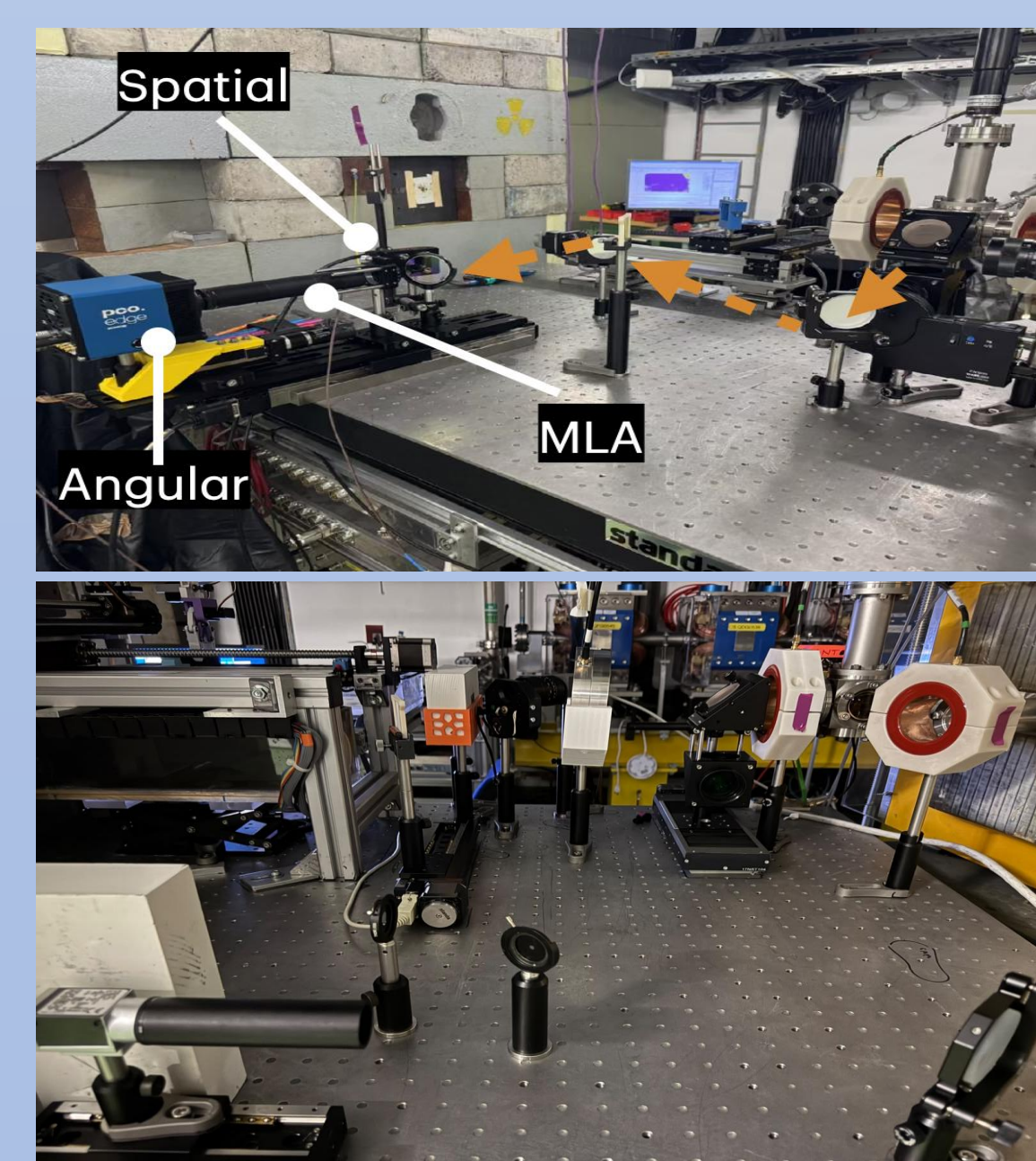
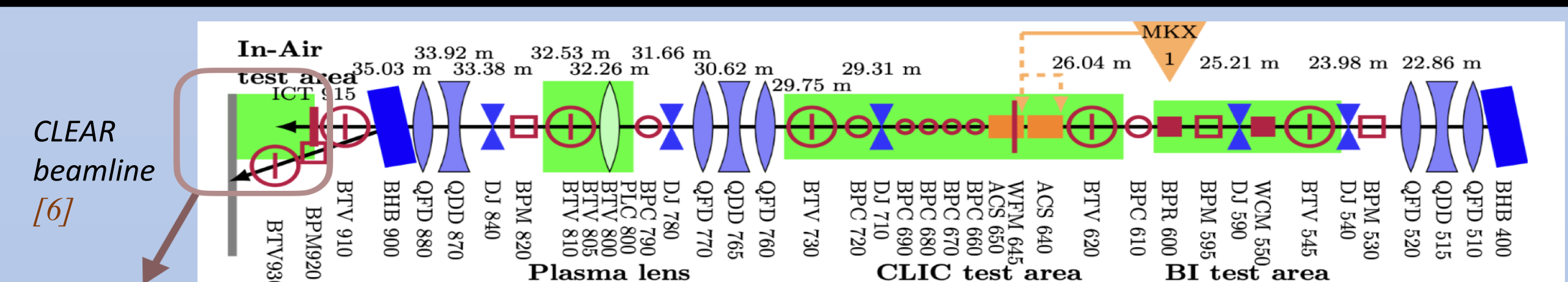


- Most usable signal in the VIS and near-UV range, (favorable detector response).
- $E_c \sim 7-8$ eV: the midpoint of the radiated power distribution
- Capturing most of the useful radiation (aperture acceptance covers nearly the full synchrotron cone).
- Beamline geometry does not suppress the diagnostic signal.



SRW-to-Zemax end-to-end Simulation chain

Proof-of-Concept TEST @CLEAR (CERN)



Key Sustainable takeaways

- **85% Geometric acceptance** + Large detected photons (10^7-10^8 /bunch)
- SNR comfortably above 100 → **single-shot imaging.**
- Suitability for **non-invasive & continuous operation**

CONCLUSION

- The performance study shows that OSR is feasible for **non-invasive, single-shot** diagnostics in the AWAKE-like novel accelerator beamlines.
- Despite geometric constraints and lower beam energy, the expected photon statistics remain strong.
- The method is suitable for beam alignment checks, shot-to-shot stability monitoring, and future feedback-based optimization.
- Better beam alignment **reduces beam loss and unnecessary tuning time.**
- The approach supports **more efficient accelerator operation** + aligns with the broader goals of **sustainable research infrastructure.**

REFERENCES

- M. Litos et al., "High-efficiency acceleration in a plasma wakefield accelerator", *Nature*, vol. 515, 2014
- D. Ghosal, "The AWAKE Experiment", *EuPRAXIA Camp-II, Lisbon, July, 2025*
- R. Thurman-Keup et al., "Synchrotron radiation based beamdiagnostics at the fermilab", *J. Instrum.*, vol. 6, 2011
- ESRF-SRW, <https://www.esrf.fr/Accelerators/Groups/InsertionDevices/Software/SRW>
- CLEAR, (<https://clear.cern/>).

ACKNOWLEDGEMENT

This work is a part the AWAKE-UK phase II project, funded by STFC under grant No. ST/X005208/1. We would like to thank Wilfrid, Collette, Marlene, Michele, Patric, Edda.

<https://www.cockcroft.ac.uk/>
dghosal@liverpool.ac.uk



SCAN ME