ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPMO40

DEVELOPMENT OF AN IMAGING PROTOCOL FOR LASER DRIVEN X-RAY SOURCES

E. Kiely*,[1], M. A. Williams, J. M. Warnett, WMG, University of Warwick, Coventry, UK
K. Fedorov, O. Finlay, A. Bhardwaj, C.D. Armstrong, D. R. Symes, STFC, Oxford, UK
J. Giles-Friend[1], Swansea University, Swansea, UK
A. Bennett[1], University of Nottingham, Nottingham, UK
[1]also at Central Laser Facility, STFC, Oxford, UK

Abstract

The Extreme Photonics Applications Centre (EPAC) being built at the Central Laser Facility in the UK will utilise a 10 Hz Laser Wakefield Accelerator (LWFA) to produce a directional, tuneable X-ray source, with energies ranging from 3 keV up to 10s of MeV while maintaining a micron-scale source size and ultra-short pulse duration. A combination of such characteristics opens an opportunity for cutting-edge high-resolution industrial imaging of dense materials: battery packs, historical artefacts and dynamic processes: fluid flows, motor engines running. The primary challenge for imaging with LWFA X-ray sources stems from shot-to-shot instabilities of flux, energies and pointing. Using simulations and real-world data these effects are shown, with different methods for accounting for each demonstrated and discussed.

INTRODUCTION

Diagnostic X-ray imaging is a powerful multi-disciplinary tool for non-destructive inspection of objects that require internal viewing without disassembly. Current X-ray sources (X-ray tubes, synchrotrons, and linear accelerators (LINACS)) used in computed tomography provide the range of energies and X-ray characteristics that are needed to image objects with a range of sizes and for objects requiring low keV up to multi-MeV X-rays to penetrate. Each has its own limitations, and the brightest and most powerful among them such as LINACs and synchrotrons are not readily available to most users. Laser wakefield accelerators (LWFA) are capable of overcoming some of the challenges seen with conventional sources, producing both monochromatic and polychromatic X-rays from a few keV up to 10s of MeV with a micron-scale source size. LWFAs can also be designed for lab-scale use making it possible to have a synchrotron-like light source readily available at multiple facilities. As the technology for using LWFA is relatively new, there are characteristic effects of LWFA that need to be addressed to make these sources commercially viable for industrial imaging. This includes instabilities in the X-ray flux, the position of the X-ray source jittering shot-to-shot, and the X-ray source having a 3D structure.

The Central Laser Facility has a dedicated experimental area (Gemini TA2) for developing a high repetition LWFA where the facility can test the diagnostics, protocols and equipment that will be used at the Extreme Photonics Applications Centre (EPAC), which is due to open to users in 2027. Currently the experimental area has focused on characterising the stability of the accelerator and the factors that affect electron acceleration. With the addition of an X-ray camera suitable for the energies generated and frame rates that meet the 5 Hz repetition rate of the laser, the focus can shift towards characterising and developing protocols for X-ray imaging.

This paper aims to outline the effect that the characteristics of LWFA sources have on their imaging capabilities and to propose methods to limit their influence.

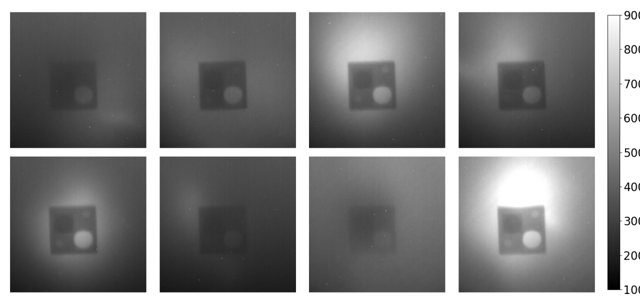


Figure 1: Images taken using MeV X-rays generated by inverse Compton scattering at the GEMINI TA3 target area. The images shown demonstrate the flux instabilities seen using LWFA for generating X-rays.

X-RAY FLUX INSTABILITIES

While the brightness of LWFA x-ray sources is extremely high, their average flux is limited by the laser repetition rate, typically producing a total flux of 10^7-10^{11} photon/s [1, 2] depending on the generation mechanism. This is low compared to conventional sources that have a flux ranging from 10^{13}-10^{16} photons/s [2–4]. This means that for imaging at very high resolution, or with strong absorption, multiple shots might be needed to obtain high-contrast, low-noise radiographs. This can be trivial for some applications as only the acquisition time per radiograph is affected, but the flux shot-to-shot from LWFA is also unstable, as seen in Fig. 1. To address these issues two approaches are being tested. First is to attempt to stabilise the flux between shots and the second is to optimise the X-ray flux from the LWFA.

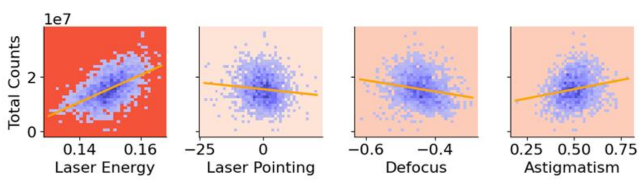
Shot-to-shot fluctuations are difficult to correct for without changing the structure of the laser being used, which can

* evan.kiely@warwick.ac.uk

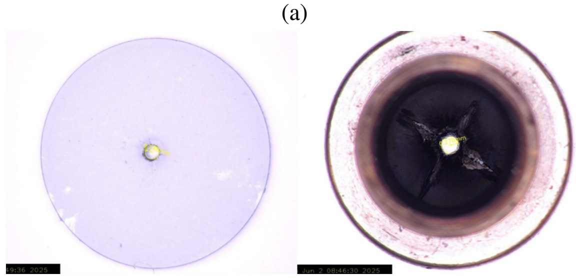
ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPMO40

be challenging for older systems. Alternatively, consideration is given to the stabilisation of drifts over a user-defined burst length. To achieve this, parameters that have the greatest impact on the generated flux need to be identified. Initial work performed in the Gemini TA2 target area has focused on studying the correlation between laser parameters and the electron charge generated by the LWFA. Figure 2(a) demonstrates this with a correlation matrix plotting total counts from an electron spectrometer vs different laser parameters. The highest correlation is seen from the laser energy, showing that stabilising this parameter should be a high priority.

To stabilise the laser energy, Gaussian process regression (GPR) models [5] are planned to be tested in TA2. The model stabilises a parameter by predicting how it might drift and correcting for it before the drift occurs. This is preferred to a reactive correction such as a PID controller as the stabilisation corrects before an experiment can be affected by the drift. These algorithms are currently being tested by stabilising the laser energy entering the TA2 experimental area.



(a)



(b)

Figure 2: (a) A correlation matrix showing how the laser properties affect the total counts seen on the electron spectrometer. (b) Images of gas cell apertures before (left) and after (right) shooting with the laser. The aperture size increased from 140 µm to 270 µm.

Another effect observed is the damage to the apertures of the gas cell caused by instabilities in the laser's pointing direction; examples of this damage can be seen in Fig. 2(b). This reduces the plasma density by allowing more gas to escape the cell, which affects the generated electron charge. Currently, a PID controller has been implemented for pointing stabilisation as this is currently sufficient, and further work is being done on improving the apertures' lifetime.

To optimise the X-ray flux, Bayesian optimisation algorithms have been implemented in the past by Shalloo et al. 2020 [6] to improve the electron charge and X-ray flux from an LWFA. Initial tests in the experimental setup have shown promising results in optimising the electron charge when controlling the wavefront of the incident laser as can be seen in Fig. 3. With the addition of the 5 Hz X-ray camera, attention now turns to optimising the X-ray flux at high rep rate.

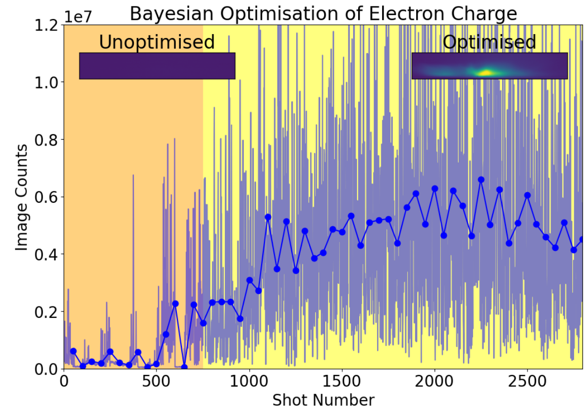


Figure 3: Using Bayesian optimisation to optimise the electron charge at 5 Hz shot rate from a LWFA. The light blue is the shot-to-shot total counts from an image of the electron spectrometer, and the dark blue is the average value of the last burst of 50 shots. The two electron spectrometer images are taken from the first 100 shots (unoptimised) and the last 100 shots (optimised).

VARYING SOURCE POSITION

A shifting source can in some cases be benign, but only where the jitter in the source position is less than the minimum resolution of the imaging setup. Outside of this case it will have significant impacts when imaging. For integrating shots due to insufficient signal or for CT reconstruction, we need to be able to align images or know how the source position changes shot-to-shot. This can be done by placing fiducials within the field-of-view and then either aligning the fiducials in the radiographs or using them to measure the shift in the source position. For aligning images, the fiducial should be placed at the same distance from the source as the object to ensure the images align correctly. This method is the simpler option, but if the source shift is high enough, the resolution in the resulting radiographs could be affected with angular shifts in the source position, causing features to not only move laterally in the images but also slightly rotate.

Tracking the movement of the source can be more accurate, as the CT reconstruction algorithm can be told the position of the source for each individual shot and account for it when reconstructing. This can be done using fiducials (such as spheres) in the scene and tracking how they move shot-to-shot. A shifting source has been simulated using gVXR [7] to evaluate the accuracy of this measurement. Results of these simulations can be seen in Fig. 4. To measure how the source shifts, four 100 µm diameter spheres have been placed 1100 mm from the X-ray source and the detector at 2000 mm from the source. Each sphere is placed so that

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPMO40

it occupies the four corners of the radiograph. The centroid position of each sphere is determined for each radiograph, and the centre position between all 4 spheres is found. By measuring how the centre position shifts shot-to-shot, the source position deviations can then be calculated. The zero position of the source is assumed to be the average of the calculated centre positions across shots taken. Then, a position based on the deviations can be input into the reconstruction algorithm based on the determined zero reference position.

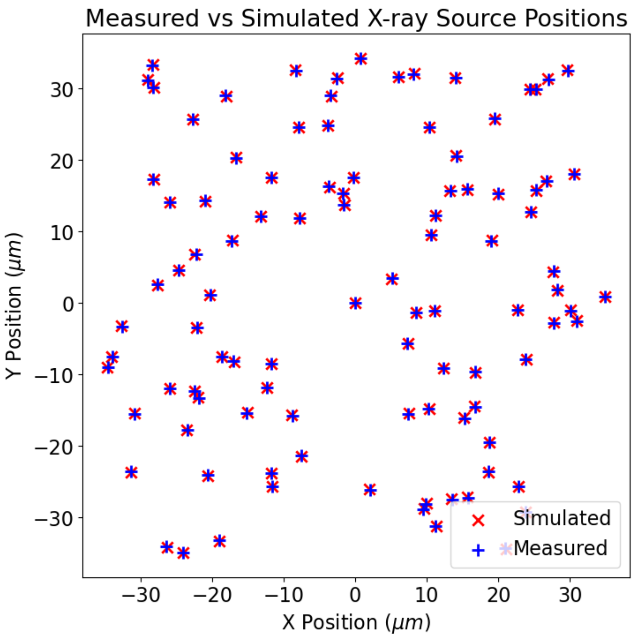


Figure 4: Results of measuring the source position from simulated radiographs.

3D X-RAY SOURCE

The most challenging characteristic of LWFA to account for is the 3D nature of the X-ray source. The X-rays can be emitted along the length of the gas cell, and the emission length of this source causes blurring in the peripherals of the image, an example of this can be seen in Fig. 5. Synchrotrons circumvent this issue by placing the end station far from the undulators, ensuring that the object is sufficiently close to the detector, thereby eliminating the need for magnification from the imaging setup. LWFAs do not have sufficient flux to allow for the detectors and objects to be placed far from the source. With the source position also shifting shot-to-shot, using specific detectors to improve imaging resolution, as on synchrotrons, is difficult. This requires LWFA to use geometric magnification to image structures that are close to the X-ray source size, making understanding the emission length behaviour of the LWFA being used important to maximise the available field-of-view and the maximum magnification achievable.

The emission length can be measured using a granulated pattern such as sandpaper, as demonstrated by Senthilkumaran et al. [8]. Determining the effect on the resultant image allows for post-processing to crop the image to a region of interest where the emission length has little to no effect. The latter of these requires the source jitter to be sufficiently large, or the manual shifting of the object to stitch the images together. The former is easier, but for CT imaging the user must ensure that their region of interest is contained in the unblurred region of the radiograph. With the emission length measured, the object can be moved to a magnification where the effect it has on the image is mitigated, but this will come at the cost of reduced image resolution.

Another possible method for dealing with the emission length is to tailor the plasma density profile. The X-ray flux in the betatron regime has been shown to increase using tailored plasma density gradients [9–11]. By varying the position of these features it's possible that the emission length can be tuned. Simulations and practical experiments are required to measure the effect that varying the position of these features has on both the emission length and the X-ray flux. The expected result is that users will need to balance flux and emission length in this case for imaging purposes.

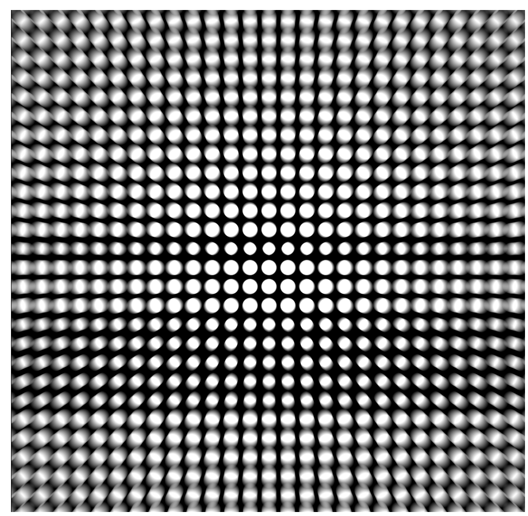


Figure 5: An example of how the emission length can effect a radiograph where the centre is sharper and the peripherals are blurring.

CONCLUSION

In this paper, the challenges of imaging with X-rays generated by LWFA are discussed. Issues with flux and source jitter can be reduced using different optimisation and measurement techniques that can either remove the issues or allow you to compensate for them while imaging. The emission length of the generated X-rays is the most difficult property to account for, as it limits the maximum magnification achievable by an LWFA beamline. Methods for reducing this effect are discussed above, but further testing needs to be performed to see if the emission length can be adjusted or if there are other methods for correcting for it in a similar manner to the source jitter.

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPMO40

REFERENCES

[1] A. Döpp *et al.*, "Quick x-ray microtomography using a laser-driven betatron source", *Optica*, vol. 5, no. 2, pp. 199–203, Feb. 2018. doi:10.1364/OPTICA.5.000199

[2] W. Sun *et al.*, "Review of high energy x-ray computed tomography for non-destructive dimensional metrology of large metallic advanced manufactured components", *Rep. Prog. Phys.*, vol. 85, no. 1, p. 016102, 2022. doi:10.1088/1361-6633/ac43f6

[3] A. W. Stevenson and F. Di Lillo, "Estimating the absolute flux distribution for a synchrotron X-ray beam using ionization-chamber measurements with various filters", *J. Synchrotron Radiat.*, vol. 24, no. 5, pp. 939–953, Sep. 2017. doi:10.1107/S1600577517009274

[4] R. Behling and F. Grüner, "Diagnostic X-ray sources — present and future", *Nucl. Instrum. Methods Phys. Res. A*, vol. 878, pp. 50–57, 2018. doi:10.1016/j.nima.2017.05.034

[5] C. E. Rasmussen, "Gaussian processes in machine learning", in *Summer school on machine learning*. Heidelberg: Springer, 2003, pp. 63–71. doi:10.1007/978-3-540-28650-9_4

[6] R. J. Shalloo *et al.*, "Automation and control of laser wakefield accelerators using bayesian optimization", *Nat. Commun.*, vol. 11, no. 1, p. 6355, 2020. doi:10.1038/s41467-020-20245-6

[7] F. P. Vidal and P.-F. Villard, "Development and validation of real-time simulation of X-ray imaging with respiratory motion", *Comput. Med. Imaging Graph.*, vol. 49, pp. 1–15, 2016. doi:10.1016/j.compmedimag.2015.12.002

[8] V. Senthilkumaran *et al.*, "Laser-driven betatron x rays for high-throughput imaging of additively manufactured materials", *Rev. Sci. Instrum.*, vol. 95, no. 12, 2024. doi:10.1063/5.0221606

[9] R. Rakowski *et al.*, "Transverse oscillating bubble enhanced laser-driven betatron x-ray radiation generation", *Sci. Rep.*, vol. 12, no. 1, p. 10855, 2022. doi:10.1038/s41598-022-14748-z

[10] M. Kozlova *et al.*, "Hard x rays from laser-wakefield accelerators in density tailored plasmas", *Phys. Rev. X*, vol. 10, no. 1, p. 011061, 2020. doi:10.1103/PhysRevX.10.011061

[11] B. Guo *et al.*, "Enhancement of laser-driven betatron x-rays by a density-depressed plasma structure", *Plasma Phys. Control. Fusion*, vol. 61, no. 3, p. 035003, 2019. doi:10.1088/1361-6587/aaf613