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Collimated x-rays emitted through laser-driven plasma lensing

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Abstract. The Laser wakefield accelerator (LWFA) can be used as a powerful x-ray source, with diverse applications, such as medical imaging, tomography and x-ray absorption spectroscopy for warm dense matter. However, due to the large x-ray divergence, typically on the order of tens of milliradians at full width at half maximum, an effective beam transport to the sample and subsequent detection becomes challenging which limits the signal to noise ratio. By using a laser-plasma lens of high density positioned a few millimetres downstream from the LWFA, x-ray radiation with only a few milliradians divergence is produced. The lens consists of nitrogen gas ionised by the drive laser, within which a wake is excited mainly by the LWFA electron bunch. As the LWFA electrons propagate through this second plasma they generate strong transverse fields, which focuses the beam and produces bright x-rays. In this work, the preliminary parametric study of the x-ray lens radiation is presented.

1. Introduction

Over the past decades, the Laser Wakefield Accelerator (LWFA) has proven able to deliver electron bunches in the energy range of hundreds of MeV over just a few millimetres. In the so-called bubble regime [1], the strong radial fields cause the off-axis accelerating electrons to oscillate transversely to the propagation direction. These betratron oscillations [2], can cause emission of x-ray radiation with characteristics similar to that produced in an undulator. The wiggler parameter, K, for which the divergence of the x-ray beam depend on through $\theta_\beta = K/\gamma$, where γ is the Lorentz factor of the electrons, is typically on the order of 10-20 for the LWFA presented here. For 100 MeV electrons, this leads to an x-ray divergence on the order of magnitude of tens of mrad. These x-rays typically have a pulse duration in the femtosecond regime and are inherently synchronised with the drive laser, which makes the LWFA an attractive source for pump-probe experiments, for example probing ionisation states of warm dense matter [3, 4], and ultra-fast x-ray absorption measurements [5, 6]. The small source size makes it ideal for applications such as high-resolution phase-contrast imaging [7], and tomography of atomising sprays [8]. However, for most applications the signal-to-noise ratio (S/N) is limited by the photon flux from a LWFA at the sample and detection plane. Improvement of the S/N is possible in many cases by averaging over several measurements, but imaging small structures require the sample to be positioned close to the radiation source for adequate resolution. For these cases placing the x-ray source closer to the sample or reducing the divergence would add more flexibility to the experimental setup. In a previous study [9], a passive plasma lens [10, 11]

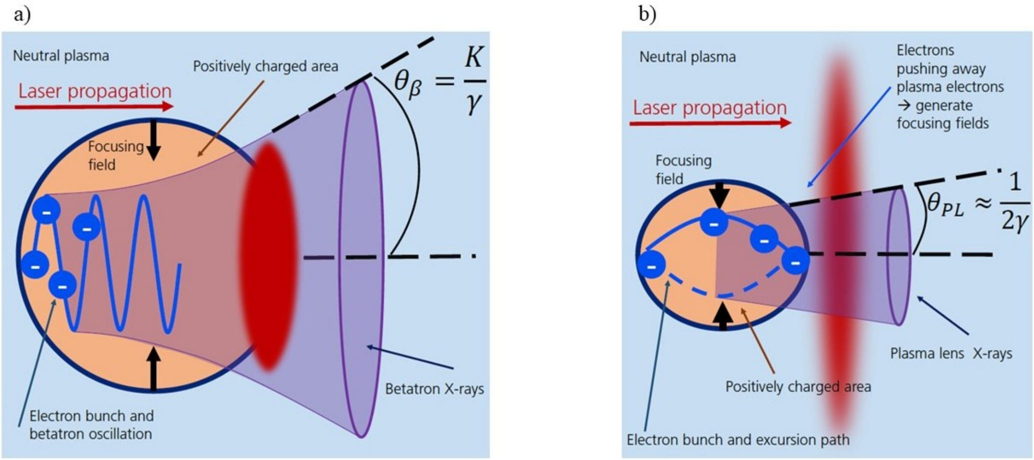

Figure 1. Conceptual sketch of betatron radiation from a) a LWFA and b) a laser-plasma lens. θ_β refers to the x-ray divergence of the betatron radiation from the LWFA while θ_{PL} is the x-ray divergence of the plasma lens betatron radiation.

was used to create a second radiation step [9, 12]. The LWFA drive laser was used to ionise the background plasma of the lens, and the wakefield was driven mainly by the electron bunch itself. The divergence of the x-ray pulses radiated from the plasma lens was shown to be significantly lower than the betatron radiation from a single stage LWFA. In Figure 1, conceptual drawings of the betatron radiation of a LWFA and the plasma lens is shown. Upon entering the plasma in the lens, downstream from the LWFA, the electron bunch excites a strong wake, and the focusing fields therein collimate or focus the initially divergent electron bunch. For nominal focusing conditions, only a partial betatron oscillation occurs, and the electron bunch envelope has a single crest inside the lens. Close to the crest of the bunch envelope, the transverse acceleration of the bunch electrons is simultaneously the largest, which causes the smaller bunch divergence at this location to imprint on the divergence of the emitted x-rays (as long as the electron energy is sufficiently high). This easily implemented low-divergence x-ray source thus expands the capabilities of a fully LWFA-driven x-ray source. In this paper, we show the preliminary results of the so-called plasma lens radiation.

2. Method

The experiment was conducted at Lund Laser Centre, using the multi-TW Ti:Sapphire laser, delivering 1 J at a nominal pulse duration of 38 fs and 800 nm centre wavelength, focused with an f/13 off-axis parabola. A schematic of the gas targets used is shown in Figure 2. Two supersonic gas jets are positioned opposing each other such that they can be brought together with a small separation between the opening orifices. The first jet, jet 1, is used as a LWFA and has an opening orifice with a diameter of 1.5 mm. The gas composition used is helium doped with 1% of nitrogen. Thus, the laser pulse is focused at the beginning of jet 1, and the electrons are injected to the accelerating gradients of the wakefield through ionisaton of the K-shell electrons of nitrogen, in the so-called ionisation injection scheme [13]. The second jet, jet 2, has an opening orifice of 1 mm and the gas target is pure nitrogen, and is placed 1 mm above the laser axis. For each jet, the background density and position in the three spatial coordinates can be varied independently.

Throughout the experiment, the conditions of jet 1 are kept constant. For jet 2, the backing pressure, hence the background density, n_{e}, and the relative distance from jet 1, Δs are varied.

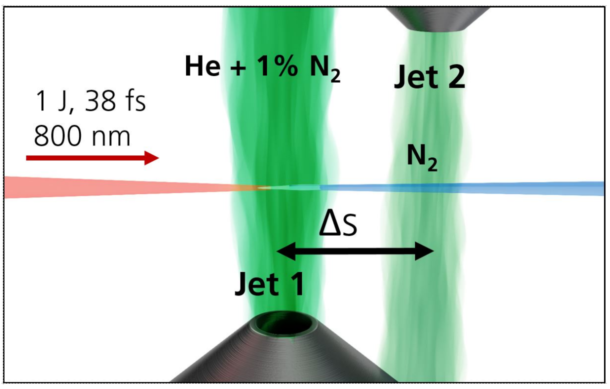

Figure 2. The experimental set-up. Jet 1 is the LWFA, and jet 2 provides the laser-plasma lens. Δs refer to the centre-to-centre distance between the two jets.

The x-ray transverse beam-profile is detected in line of sight using a deep-depletion back-illuminated 16-bit CCD camera. The electrons are deflected using a 0.8 T dipole magnet onto a phosphorous screen and the scintillation is recorded with a 16-bit CMOS camera.

3. Results and discussion

The laser-plasma lens acts on the electron beam, as seen in Figure 3 a). Jet 1 is optimised such that a strong lens-radiation is observed after propagation through jet 2. To efficiently couple the electron bunch from jet 1 to jet 2, the transverse bunch divergence is firstly reduced by a down ramp at the end of jet 1 [14]. The down ramp is created by placing the first jet 2 mm below the optical axis (leading to a Gaussian-like density profile). The laser pulse propagates together with the electron bunch from jet 1. Diffraction of the laser pulse after exiting jet 1 causes an increase in the divergence such that the laser pulse intensity decreases, to approximately 10^{18} W/cm^2 at the plasma-vacuum interface. The laser pulse therefore generates the plasma by ionising nitrogen only to the fifth degree and excites a linear wake in jet 2. The electron bunch then generates the radially focusing fields in jet 2 such that jet 2 acts as a laser-plasma lens. At densities on the order of magnitude of 10^{20} cm^{-3} in jet 2, the electrons are focused for high energies (here at 160 MeV), and strongly defocused for energies below 100 MeV. The mean bunch charge after jet 1 is approximately 250 pC, and unchanged after jet 2. Along with this strong overfocusing of electrons of low energies, an x-ray beam with a low divergence is observed, shown in 3 b), with a FWHM divergence in the y direction $\theta_\mathrm{y} \approx 5$ mrad at lowest. When jet 2 is off, typical observed divergences are $\theta_\mathrm{y} = 20$ mrad FWHM. This means that the plasma lens radiation has an x-ray divergence which is a factor of four smaller than the radiation from the LWFA. The theoretically smallest x-ray divergence, as discussed in Ref. [9], depend on the electron energy through $\theta_\mathrm{PL} \approx 1/2\gamma$. For the 160 MeV electrons the FWHM divergence becomes 3.4 mrad (1.6 mrad r.m.s.), which is close to the experimentally observed divergence. In reality, due to the energy spread, the lower energy electrons are also contributing to the radiated x-rays and because of the inverse dependency on γ, less energetic electrons give rise to more divergent x-rays. The electron beam's characteristics, such as emittance, divergence, and betatron oscillation are imprinted on the emitted x-ray radiation. Scaling regarding the plasma density of jet 2 and the jet separation is therefore expected to directly influence the observed x-ray radiation. Thus, the laser-plasma lens is an effective method for producing low divergent x-rays, while maintaining a compact setup. These results, together with previous results [9], proves that the lens radiation can be generated from a wide range of electron bunch drivers, thus making it straightforward to set up.

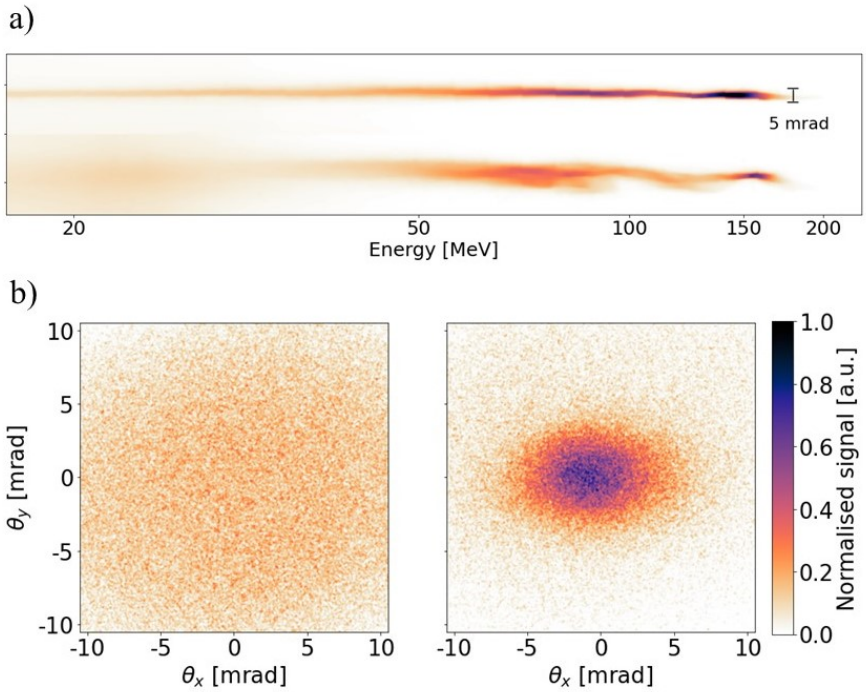

Figure 3. The influence of jet 2 on the electron bunch in a), and the detected x-ray radiation in b). The vertical bar in a) shows a reference for 5 mrad. It can be seen that the plasma lens focuses electron energies at 160 MeV, but strongly defocus lower energies. The left figure in b) shows a reference x-ray beam profile, i.e., jet 2 is off. To the right is the beam profile of the x-ray beam when jet 2 is on.

4. Conclusion

The laser-plasma lens can be used to produce betatron x-rays with a significantly lower divergence than the betatron x-rays from a LWFA. The lens can be constructed such that the set-up maintains its simplicity and remains compact. This type of laser-plasma lens provides an increased flexibility in applications requiring an inherently low-divergent x-ray beam.

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References

[1] Pukhov A, Gordienko S, Kiselev S and Kostyukov I 2004 *Plasma Physics and Controlled Fusion* **46** B179–86
[2] Rousse A, Phuoc K T, Shah R, Pukhov A, Lefebvre E, Malka V, Kiselev S, Burgy F, Rousseau J P, Umstadter D *et al.* 2004 *Physical Review Letters* **93** 135005
[3] Mo M Z, Chen Z, Fourmaux S, Saraf A, Kerr S, Otani K, Masoud R, Kieffer J C, Tsui Y, Ng A *et al.* 2017 *Physical Review E* **95** 053208
[4] Mahieu B, Jourdain N, Ta Phuoc K, Dorchies F, Goddet J P, Lifschitz A, Renaudin P and Lecherbourg L 2018 *Nature Communications 2018 9:1* **9** 1–6
[5] Behm K, Hussein A E, Zhao T Z, Baggott R A, Cole J M, Hill E, Krushelnick K, Maksimchuk A, Nees J, Rose *et al.* 2020 *High Energy Density Physics* **35** 100729
[6] Kettle B, Gerstmayr E, Streeter M, Albert F, Baggott R, Bourgeois N, Cole J, Dann S, Falk K, Gallardo González I *et al.* 2019 *Physical Review Letters* **123** 254801

[7] Svendsen K, González I G, Hansson M, Björklund Svensson J, Ekerfelt H, Persson A and Lundh O 2018 *Optics Express* **26** 33930

[8] Guénot D, Svendsen K, Lehnert B, Ulrich H, Persson A, Permogorov A, Zigan L, Wensing M, Lundh O and Berrocal E 2022 *Physical Review Applied* **17** 064056

[9] Björklund Svensson J, Guénot D, Ferri J, Ekerfelt H, Gallardo González I, Persson A, Svendsen K, Veisz L and Lundh O 2021 *Nature Physics* **17** 639–45

[10] Kuschel S, Hollatz D, Heinemann T, Karger O, Schwab M B, Ullmann D, Knetsch A, Seidel A, Rödel C, Yeung M *et al.* 2016 *Physical Review Accelerators and Beams* **19** 071301

[11] Doss C E, Adli E, Ariniello R, Cary J, Corde S, Hidding B, Hogan M J, Hunt-Stone K, Joshi C, Marsh K A *et al.* 2019 *Physical Review Accelerators and Beams* **22** 111001

[12] Ferri J, Corde S, Döpp A, Lifschitz A, Doche A, Thaury C, Ta Phuoc K, Mahieu B, Andriyash I A, Malka V *et al.* 2018 *Physical Review Letters* **120** 254802

[13] Pak A, Marsh K A, Martins S F, Lu W, Mori W B and Joshi C 2010 *Physical Review Letters* **104** 025003

[14] Dornmair I, Floettmann K and Maier A 2015 *Physical Review Special Topics - Accelerators and Beams* **18** 041302