Laser Generation of Near-GeV Low Emittance Positron Beams

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We report on the first spatial and spectral characterisation of near-GeV positron beams generated in a fully laser-driven configuration. The energy-resolved geometric emittance, source size and spectrum were simultaneously measured for electrons and positrons generated from a laser-wakefield accelerated electron beam impacting on a thin high-Z converter. More than 10⁵ positrons were observed within 5% of 600 MeV, with a source size smaller than 100 µm and sub-micron geometric emittance, in agreement with numerical modelling. We conclude that the positron emittance was dominated by the transverse size of the primary electron beam at the converter. Minimising the drift distance between the electron source and the converter would allow for the generation of GeV-scale positron beams with micron-scale source size and normalised emittance of a few microns, using a 150 TW laser system. It is proposed that beams with these characteristics are suited for experimental studies of positron acceleration in a plasma wakefield.

Laser-driven generation of ultra-relativistic positron beams has recently gathered significant attention from the research community with several landmark results already reported, including: positron energies in the region of 100 MeV [1–3], generation of high-density and quasi-neutral electron-positron beams [4], and first experimental observation of pair-plasma dynamics [5]. Besides the application of these beams to the investigation of phenomena of importance to laboratory astrophysics (see, for instance, Ref. [6]), these studies are motivated by the need for developing alternative positron acceleration schemes, especially for the next generation of electron-positron colliders [7, 8]. Plasma wakefield acceleration is one of the most promising approaches, thanks to the ultra-high acceleration gradients that they can sustain.

While wakefield acceleration of electrons has achieved a relatively high level of maturity, plasma acceleration of positron beams presents a fundamental challenge due to the asymmetry of accelerating and focusing fields in a non-linear plasma wakefield [9]. Several plasma acceleration schemes have been proposed [10–16] and first proof-of-principle experiments have demonstrated potential in this direction [17–21]. The slower pace in development of positron wakefield acceleration schemes is mainly due to scarcity of appropriate positron beam facilities, with only FACET [22] at SLAC National Accelerator Laboratory currently suited for this class of experiments.

For effective capture and acceleration in a plasma wakefield, the positron beam must be concentrated within the volume of the accelerating plasma structure. For example, quasi-linear acceleration in a plasma with a density of n_e = 10¹⁷ cm⁻³ (plasma wavelength λ_p = 2πe/ω_p ≈ 100 µm) [23], would require longitudinal and transverse beam dimensions of σ_z, σ_x ≲ 10 µm. Recently, it has been shown numerically that positron beams with these properties can be produced during the interaction of laser wakefield accelerated electron beams with a high-Z converter [24]. If realised, this would enable the study of positron acceleration with fully laser-driven experiments.

Here, we experimentally demonstrate that positron beams with properties suitable for capture and acceleration in a wakefield plasma accelerator can be produced in a compact and fully laser-driven configuration. GeV-scale nanocoulomb electron beams, generated by a laser wakefield accelerator (LWFA), interacted with a thin (∼ 1 mm) lead converter target to produce high-energy positrons. Numerical modelling agrees closely with the experimental data and indicates that the source size and emittance are dominated by the electron beam size at the entrance of the converter. Minimising the distance between the LWFA and the converter would allow a positron source size of a few microns and normalised emittance of tens of microns at 1 GeV, using a 100 TW-class laser systems.

The experiment was performed using the Gemini laser at the Central Laser Facility [25] (see supplemental material for setup figure). The laser pulses contained a mean (and RMS variation) of 7.9 ± 0.5 J in a FWHM pulse length of 48 ± 7 fs (peak power P₀ = 156 ± 9 TW) and a central wavelength of 800 nm. The pulses were focused with an f/40 off-axis parabola into a gas jet from a 15 mm exit diameter nozzle. The gas was a mixture of 2% nitrogen and 98% helium and had an electron density of n_e = (1.5 ± 0.2) × 10¹⁸ cm⁻³. The laser focal spot, measured in vacuum, was (37 ± 3) × (52 ± 4) µm in the trans-
verse \( x \) and \( y \) directions respectively (1/e² radius), giving a peak normalised vector potential of \( a_0 = 1.20 \pm 0.05 \). The laser was linearly polarised along the \( y \)-axis.

The residual laser exiting the LWFA was removed by reflection from a self-generated plasma mirror on the surface of a 125 \( \mu \)m polyimide tape which was replenished after every shot. A movable lead converter target (placed at a distance \( z_D = 50 \) mm from the LWFA exit plane of the gas jet) was used to generate electron-positron beams through a two-step bremsstrahlung induced Bethe-Heitler process [26]. The converter was a 45-degree wedge, such that translating it perpendicularly to the electron beam axis allowed the effective converter thickness to be varied continuously over the range \( 1 \geq L \geq 25 \) mm.

A shielding lead wall with an on-axis 10 mm diameter aperture was placed to allow only particles emitted from the converter within a 12.6 mrad half-angle to propagate to the detectors. A permanent magnetic dipole (integrated strength of \( B_{z} = 0.3 \) Tm) was placed behind the lead wall to sweep electrons and positrons onto the primary scintillator screens (Kodak LANEX), either side of the central axis. The screens were imaged with CCD cameras allowing observation of particles with kinetic energy \( E \geq 200 \) MeV. A second scintillator screen was placed 1000 mm behind the first in order to increase the measurement accuracy of the high energy electrons.

The electron spectra produced by the LWFA were first characterised without the converter in place. Ten shots were taken with nominally identical conditions, with variations in the electron spectrum due to the natural variation in laser and plasma source parameters. The five shots with the highest total beam energy are shown in figure 1a. The angularly integrated electron spectra for each of these shots are plotted in figure 1b along with their average. When analysing the electron-positron beams, shots with the brightest signals (3-8 shots out of 10) were used for each converter length, and so the average shown in figure 1b was taken as the expected LWFA spectrum for those shots. The average (and RMS variation) total beam charge for electron energies above 200 MeV was \( N_e = 1.4 \pm 0.2 \) nC and the total beam energy was \( W_b \approx 0.8 \pm 0.1 \) J, giving a laser-to-electron beam energy efficiency of \( \eta \approx 10\% \). The angular distribution of the energy integrated electron spectra (closely approximately by the square of a Lorentzian function) had a FWHM of \( \theta_x = 3.8 \pm 0.4 \) mrad.

To demonstrate energy selection of laser-driven positron beams, the lead converter was driven into the primary electron beam such that its path length was 5.0 mm (0.9 radiation lengths). A second magnetic dipole with a 25 mm wide lead slit placed at its entrance was positioned in the dispersed positron beam. The slit selected a narrow band of energies from the dispersed positron beam, which were collimated onto an additional scintillator screen by the magnetic field. The lead slit was translated along the dispersion axis of the magnetic dipole pair to change the selected energy band, resulting in the spectra shown in figure 2. For central energies of \( E > 500 \) MeV, the transmitted FWHM bandwidth was \( \Delta E/E \leq 5\% \), demonstrating that the positron beams are of sufficient quality for the capture and detection of a low bandwidth beamlet.

The electron and positron energy-resolved emittances were characterised using a 5.0 mm thick tungsten mask composed of horizontal slits with a period of 1100 \( \mu \)m (550 \( \mu \)m gaps), placed into the beam 290 mm behind the rear face of the converter (similar to the setup used in [2]). Particles hitting the solid bars of the mask were scattered to form a smooth background on the detector screen 1000 mm after the mask. The particles passing through the gaps of the mask resulted in a modulated beam profile as shown in figure 3. The modulation had a lower spatial frequency for lower energy particles, due to
the linear defocusing effect of perpendicular fringe fields as the electrons exit the main dipole field. Particles with $E \gtrsim 300\text{MeV}$ exited through the rear face and experienced only weak defocusing due to the coupling between the longitudinal fringe field ($B_z$) and the transverse momentum ($p_y$) accumulated in the main dipole field ($B_x$). For $E \lesssim 300\text{MeV}$, particles exited the side of the dipole field and experienced a much stronger defocusing as their longitudinal momentum ($p_z$) coupled with the transverse fringe field ($B_y$). In order to correct for the fringe field defocusing effect in the analysis, the measured signals were re-scaled in non-dispersion direction such that the magnification of the grid pattern was made constant for all energies.

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The geometric emittance of a particle beam is 

$$
\epsilon = \sqrt{\langle x'^2 \rangle \langle y'^2 \rangle - \langle x' \rangle^2 \langle y' \rangle^2},
$$

where $\langle x'^2 \rangle$ is the angle-position correlation term. In the drift space before the LWFA, the primary electron beam develops a strong correlation term before it enters the converter. However, the relatively large scattering angles quickly removes this correlation and the plane at which the correlation term vanishes is $100 - 200\mu\text{m}$ from the back of the converter. Therefore, the correlation term was neglected and the geometric emittance was calculated as the product of the measured divergence and source size, i.e., $\epsilon = \sigma_x \sigma_\theta$.

The electron and positron beam properties were retrieved as functions of energy for converter lengths $L = 1.0, 2.0, 4.0, 8.0\text{mm}$ ($0.2, 0.4, 0.7$ and $1.4$ radiation lengths) and are plotted in figure 4. The number of observed electrons was seen to decrease with converter thickness (figure 4a), while the number of positrons was maximised for $L = 4.0\text{mm}$. The electron and positron source size (figure 4b) was observed to be approximately $100\mu\text{m}$, and to be weakly dependent on energy. The electron and positron RMS divergence (figure 4c) was approximately constant at $\sigma_\theta \approx 5\text{mrad}$, as it was limited by the aperture in the lead wall. Due to the fixed beam divergence, the emittance trends were largely determined by the variation in source size. As seen previously at lower energies [2] the positron geometric emittance (figure 4d) was consistently lower than for the electrons. The positron geometric emittance exhibited a gradual linear decrease as a function of energy with values of $\epsilon = 690\text{nm}$ at $E = 100\text{MeV}$ and $\epsilon = 460\text{nm}$ at $E = 600\text{MeV}$ for a $1.0\text{mm}$ converter. The results had an RMS variation of $\approx 43\%$ in the spectrum and $\approx 20\%$ in emittance, due to the shot-to-shot variation in the primary electron beam generated by the LWFA.

In order to ascertain the effect of the beam-line geometry on the measured positron beam characteristics, simulations were performed using the particle physics Monte-Carlo code FLUKA [27, 28]. Electrons were initialised from the LWFA electron spectrum approximation shown in figure 1, using $10^6$ primary electrons for each converter thickness. The momenta and position of all electrons and positrons were recorded as they exited the rear surface of the converter. The divergence of the primary LWFA electron beam was modelled by applying randomised shifts (matching the measured LWFA divergence) to the position and propagation angles of each generated particle. The transverse particle positions were also modified according to the expected LWFA electron source size of $1\mu\text{m}$ [29–31], although this contribution was negligible. The effect of the aperture in the beamline was simulated by removing all particles which had radial positions greater than $5\text{mm}$ at the aperture plane.

The results of the numerical simulation with converter thickness $L = 1.0\text{mm}$ are shown in figure 5 for (1) zero drift before converter ($z_D = 0\text{mm}$) (black lines), (2) finite drift distance ($z_D = 50\text{mm}$) (dashed cyan lines), and (3) finite drift ($z_D = 50\text{mm}$) plus the aperture in the lead wall (blue lines). The experimentally measured positron beam properties generated by the $1\text{mm}$ lead converter are then plotted alongside the simulation results in figure 5, showing good agreement (RMS average difference for all converter lengths of $15\%$, $3.5\%$, $2.8\%$ and $0.5\%$ for the spectrum, emittance, source size and divergence, respectively).
FIG. 4. Retrieved electron and positron beam properties as functions of particle energy. The a) spectra, b) source size, c) divergence and d) geometric emittance are given for each converter length as shown by the color-bars at the side of the figure. The lines are the average of 4,6,3 and 8 shots for converter lengths of 1.0,2.0,4.0 and 8.0 mm respectively. Each line results from a Gaussian weighting of each measurement point using a kernel width of $\sigma_E = 25$ MeV.

FIG. 5. Positron beam a) spectrum, b) source size, c) divergence and d) geometric emittance plotted for a 1.0 mm thick lead converter. The experimental data (red) is plotted alongside FLUKA simulations for: an idealised zero divergence and source size primary electron beam (black); including the effects of finite primary electron beam divergence and source size (cyan dashed); also clipping the beam with a 12.6 mrad aperture (blue).

Due to the lower initial divergence for higher energy particles, the aperture transmits a larger fraction of higher energy positrons, modifying the detectable spectrum (figure 5a). The aperture also constrains the beam divergence to an approximately constant value of $\sigma_\theta \approx 5$ mrad (figure 5c). Including the finite divergence of the LWFA does not affect the positron spectrum or divergence but has a strong effect on the source size (figure 5b) and, subsequently, the emittance of the positron beam (figure 5d). Using a beam transport system to minimise the electron beam size on the converter, or alternatively by placing the converter closer to the exit of the LWFA would allow for a significant reduction of the positron source size. In the latter case, a replenishing tape (such as the one used for this experiment) could be used to extract the post-plasma laser pulse and protect the converter from damage. For the measured LWFA electron beam FWHM divergence of 3.8 mrad and a typical beam waist at the LWFA source of 1 $\mu$m, the positron source size could be reduced to 5 $\mu$m by placing a 1 mm converter directly at the LWFA exit. In this case the positron beam would have a divergence of 8 mrad, a geometric emittance of 15 nm, and a normalised emittance $\bar{\epsilon} = \gamma \beta_z \epsilon = 18$ $\mu$m at 600 MeV. The simulations also show a longitudinal RMS spreading of 0.2 $\mu$m for positrons within a 5% bandwidth of 600 MeV implying that the positron beam duration will be similar to that of the primary electron beam ($\sigma_z \lesssim \lambda_p/2 = 14$ $\mu$m for $n_e = 1.5 \times 10^{18}$ cm$^{-3}$).

With the reduction in drift length, the positron beam characteristics are well suited for efficient capture and post-acceleration as a witness beam in a plasma wakefield accelerator. For example, Silva et al. [16] numerically demonstrated plasma acceleration for a positron bunch with a radius of $\sigma_x = 5$ $\mu$m and a normalised emittance of 10 $\mu$m using an electron beam driver, while Vieira et al. [12] numerically demonstrated effective wakefield acceleration of a $\sigma_x = 6$ $\mu$m positron beam in a Laguerre-Gaussian laser mode. Experimental demonstrations of wakefield acceleration of positrons reported in the literature [17–20], used witness positron beams with similar geometric emittance to our inferred beam properties, though at a higher energy (see Table I), demonstrating the suitability of the positron source reported here to provide witness beams for wakefield acceleration studies, such as proposed for EuPRAXIA [32].

Increasing the energy of the primary electron beam...
| E (GeV) | σx (µm) | σz (µm) | ε (nm) | ε (µm) |
|--------|---------|---------|--------|--------|
| 0.6    | 100     | -       | 460    | 540    |
| 0.6    | 5       | ≲ 14    | 15     | 18     |
| 28.5   | 25      | 730     | 390 × 80 | 200 × 50 |
| 20.3   | <100    | 30 - 50 | 5 × 1  | 300    |
| 20.3   | 50      | 540     |        |        |

**TABLE I.** Summary of measured and inferred positron parameters, compared with sources used for previously reported positron wakefield acceleration experiments.

is expected to further improve the positron beam characteristics. Single stage LWFA has been demonstrated beyond 5 GeV [33], which along with a minimised drift distance for the LWFA electrons is expected to provide nm-scale geometric emittances and a normalised emittance of 10 µm at 3 GeV [34].

In conclusion, comprehensive spatial and spectral characterisation of GeV-scale laser-driven positron beams is reported. Experimental results show a geometric emittance of ε = 0.46 µm for 600 MeV positrons, with the source size of σx = 100 µm largely dominated by the primary electron beam size at the converter. The positron beam normalised emittance can be reduced to the micron-scale by eliminating the LWFA-to-converter vacuum drift section and by using a higher primary electron energy. This positron generation mechanism opens up the possibility of studying laser wakefield acceleration of positrons, using the dual beam capabilities of existing and future laser facilities [35]. Laser generation of high quality positron beams could also be added to beam driven wakefield facilities with laser capabilities (e.g. FLASHForward [36] and SPARC.LAB [37]) to study beam-driven methods, without the need for an emittance dumping storage ring.

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1 Experimental setup

The setup for the experiment described in this paper is shown in figure 1.

Figure 1: Schematic of the experimental setup. The laser is focused into the gas jet to drive the Laser-Wakefield Accelerator which generates the primary electron beam. This electron beam generates electron-positron pairs in the converter which then propagate through an aperture in the lead wall. The primary dipole disperses the electron and positron beams (positrons shown in blue) onto the spectrometer screens. The emittance mask can be placed into the beam to measure the electron and positron beam spatial properties. A secondary electron spectrometer screen is used to improve the accuracy of the electron spectrum measurement. The secondary dipole and positron spectrometer screen is used to perform energy selection.

2 Two-screen electron spectrometers

Two screens were placed in the electron beam after the magnetic dipole, with some drift space in-between. The signal seen on each screen is due to the energy and angular spectra of the electron beams generated in the plasma. It is assumed that all electrons were generated at a fixed point at the exit of the LWFA. Electrons with kinetic energy in the range of $100 \geq \gamma m_e c^2 \geq 2500$ MeV and propagation angles relative to the design axis of $-15 \geq \theta_y \geq 15$ mrad were numerically tracked through the magnetic field of dipole, and the location of their intersections with the LANEX screens was recorded. This was used to produce a look-up table which gave the particle energy as a function of its position on each screen and its initial propagation angle $\theta_y$. The electron beam spectrum was determined by finding the coefficients of a third-order polynomial.
function $\theta_y(\gamma)$ that minimised the mean squared difference between the retrieved angularly integrated electron spectra from each screen.

Charge calibration of the electron spectrometers were performed by measuring electron spectra on an image plate placed in front of the second LANEX screen and comparing to the images recorded on the CCD over the same shots. The image plate used was BAS-TR2040, with a sensitivity of 1 PSL per 350 electrons. The first electron screen was then calibrated by matching the angularly integrated spectra recorded on each screen. A retractable LANEX detector was placed close to the exit of the first dipole magnet so that it could observe both the positron and electron beams with a single CCD. This was used to measured the relative yield of positrons and electrons at the same time as observing the signals on the primary electron and positron screens. The relative yield was then used to cross-calibrate the charge sensitivity of the primary positron screen.

3 Lepton source size, divergence and emittance retrieval

The beam profile after the beam aperture was modelled as a azimuthally symmetric clipped Gaussian distribution, such that only particles with $x_{i,\text{ap}}^2 + y_{i,\text{ap}}^2 \leq R^2_{\text{ap}}$ were transmitted, where $x_{i,\text{ap}}$ and $y_{i,\text{ap}}$ are the transverse spatial coordinates of the $i^{th}$ particle at the aperture plane $z_{\text{ap}}$, with aperture radius $R_{\text{ap}}$. This profile was dispersed according to the individual particle energies onto the spectrometer screen. The particle distribution $S'_y(x)$ was measured at the detector plane $z_{\text{det}}$ where $x$ and $y$ are transverse coordinates perpendicular and parallel to the dispersion plane of the spectrometer respectively. Due to the combination of energy spread and divergence, the profile $S'_y(x)$ is due to particles over a range of different energies where their initial propagation angle $\theta_{i,y}$ and energy $E_i$ result in the particle intersecting the detector plane at the position $y$. With the assumption that the spectrum $N(E)$ is slowly varying, then each slice measurement $S'_y(x)$ represents the integral of the beam profile over $y$, i.e.,

$$S'_y(x) = \frac{2A_{y,0}}{\sqrt{\pi}R} \int_0^\sqrt{R^2-x^2} \exp\left[ -\frac{x^2 + y^2}{2\sigma^2} \right] dy$$

$$S'_y(x) = \sqrt{2\pi A_{y,0}\sigma_x} \text{erf}\left( \frac{\sqrt{R^2-x^2}}{2\sigma_x^2} \right) \exp\left[ -\frac{x^2}{2\sigma_x^2} \right]$$

where $A_{y,0}$ is the amplitude of the particle distribution, $R = R_{\text{ap}}z_{\text{det}}/z_{\text{ap}}$ is the projected size of the aperture at the detector plane and $x \leq R$. The functional form of equation 1 was used to fit the amplitude of the modulated signal $S'_y(x)$ when retrieving the apertured beam properties as described below.

Several steps were followed to extract the particle emittance from the spectrometer signals. Firstly, a variable threshold filter was used to remove hard-hits caused by stray photons hitting the CCD directly. Secondly, the defocusing of the effect of the magnetic dipole fringe fields was removed by re-scaling the measured signal in non-dispersion direction such that the spatial frequency of the grid pattern was made constant for all energies. Then vertical slices were taken through the resultant image, averaging over 4 mm in the dispersion direction to produce the signal modulation $S'_y(x)$ as a function of $x$ at a given $y$-position. The scattered particles from the grid formed a smooth background on the detector which was removed by fitting a Gaussian to the values at the minima of the observed modulations. The envelope of the signal was similarly found by fitting the beam profile function (equation 1) to the signal maxima. The RMS width of the fitted envelope was then divided by the source-to-screen distance to obtain the beam divergence $\sigma_y$.

An ideal zero source size beam would produce a sharp step-function within the bounds of the scattering signal and the beam envelope, with the spatial period of the magnified grid size. Blurring of this pattern was observed due to contributions of the finite spatial resolution of the diagnostic (215 $\mu$m) and the source size $\sigma_z$ of the beam, which was found by iterative minimisation of the mean squared error between the measured signal and the calculated signal for a given source size. The geometric emittance was calculated as the product of the measured divergence and source size, i.e. $\epsilon = \sigma_x\sigma_y$. An example measured signal and retrieved modulation signal is shown in figure 2.

In order to benchmark the retrieval process, synthetic data was created by numerically propagating results from a FLUKA simulation and removing particles that would hit the solid bars of the emittance
Figure 2: Example signal modulation fitting for beam parameters retrieval. The signal (black line) is taken for a central positron energy of 420 MeV with a converter thickness of 8 mm. The retrieved signal (red line) corresponds to a source size of 127 µm. An ideal beam (zero source size) would produce a rectangular profile pattern (blue line) between the scattered signal and the beam amplitude (blue dashed lines).
measurement grid. The dispersion of the magnet was added by shifting the particles transversely according to their energy using the same dispersion function as for the experimental spectrometer. To create the modulated signal $S_x(y)$ for a given energy band, the particles are selected according to their position on the spectrometer. Due to the significant beam divergence, there is some trajectory crossing such that some particles of different energies are selected, and some of the correct energy are omitted, as illustrated in figure 3.

![Figure 3: Example synthetic positron spectrometer particle distribution. Particles that pass through the grid were propagated ballistically onto the detector plane, and then dispersed according to their energy. Taking a slice along the y-axis mixes some particle energies together due to the effect of the beam divergence. Particles label 'energy band' have energies within 450-550 MeV. Selected particles have x positions corresponding to the expected position for zero-divergence particles within the same energy range. The signal $S_x(y)$ is generated by making a histogram of selected particle y coordinates.](image)

The synthetic signals were analysed with the same procedure as for the experimental data and compared to the values directly calculated from the particle distributions, as shown in figure 4. The retrieved beam properties closely agree with the directly computed values for the apertured beam, verifying the analysis procedure.

4 FLUKA simulations

Simulations of the bremsstrahlung induced pair-production process were performed using the particle physics Monte-Carlo code FLUKA with the EM-cascade defaults. Electrons were initialised with zero source size and transverse momentum from an energy distribution chosen to match the experimentally measured average LWFA spectrum. A lead converter of variable thickness $L$ was placed in the path of the electrons, and the momenta and position of all electrons, positrons and photons were recorded as they exited the rear surface of the converter. The simulations were performed for $10^6$ primary electrons for each converter thickness.

In order to simulate the effects of the finite divergence of the electron beam, each particle was assigned random angular shifts $\Delta x'_i$ and $\Delta y'_i$ from the probability density function $f(x') = f_0[(x'/\theta_w)^2 + 1]^{-2}$,
Figure 4: Comparison of retrieved positron beam a) spectrum, b) emittance c) source size and d) divergence with values computed directly from the particle distributions. Properties are plotted for: the synthetic diagnostic data (red line); the FLUKA particle distribution including the effects of finite primary electron beam divergence and source size (cyan dashed line); the FLUKA particle distribution also clipping the beam with a 12.6 mrad aperture (blue line). The FLUKA simulation used a 1 mm thick lead converter.
which was seen to approximate the experimentally transverse profile of the primary electron beam with $\theta_w = 2.9 \pm 0.3$ mrad ($f_0$ is the normalisation constant). The particle transverse momenta and positions were then altered according to these shifts and using the experimental drift length between the LWFA exit and the converter rear face of 50 mm. The transverse particle positions were also modified according to the expected LWFA electron source size of 1 $\mu$m, although this contribution was negligible. Each particle was shifted 10 times from the value taken from the FLUKA simulation, with the shifted particle properties recorded each iteration to produce a final list with 10 times the number of particles as were produced by the FLUKA simulations. Particle distribution properties were then calculated at the longitudinal plane for which the correlation term $\langle xx' \rangle$ was minimised (typically fractionally inside the rear surface of the converter).