Spectral and spatial characterisation of GeV-scale laser-driven positron beams

Contact *g.sarri@qub.ac.uk*

M.J.V. Streeter, N. Cavanagh, T. Audet, L. Calvin, G. Sarri
Queen's University Belfast , BT7 1NN, Belfast United Kingdom

C. Colgan, E. Los, B. Kettle, S.P.D. Mangles, Z. Najmudin
The John Adams Institute for Accelerator Science, Imperial College London, London, SW7 2AZ, UK

A.F. Antoine, M. Balcazar, J. Carderelli, Y. Ma, A.G.R. Thomas
Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48109-2099, USA

H. Ahmed, P.P. Rajeev, D.R. Symes
Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot OX11 0QX, UK

Abstract

We report on the first spatial and spectral characterisation of near-GeV positron beams generated in a fully laser-driven configuration. More than 10^5 positrons within 5% of 600 MeV were generated from the electron beam of a laser driven plasma wakefield accelerator. The positron beams had a source size of 100 microns and normalised emittance of 500 microns, diagnosed via a one-dimensional pepper-pot technique.

Introduction

Laser-driven generation of ultra-relativistic positron beams has recently achieved several landmark results, including: positron energies in the region of 100MeV [1–3], generation of high-density and quasi-neutral electron-positron beams [4], and first experimental observation of pair-plasma dynamics [5].

These beams are not only of fundamental importance for the investigation of phenomena of relevance to laboratory astrophysics (see, for instance, Ref. [6]), but also for the development of alternative positron acceleration schemes, especially towards the next generation of electron-positron colliders [7, 8]. Plasma-based systems based on wakefield acceleration show some promise, thanks to the ultra-high acceleration gradients that they can sustain. However, they pose stringent requirements on the spatial and spectral properties of the positron beams to be injected in the accelerator.

For example, for the effective capture and acceleration in a plasma wakefield, the positron beam must have longitudinal and transverse beam dimensions of the order of, if not less than, 10 µm, to be captured in the narrow wakefield region that provides acceleration of positively charged particles. 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 [9]. Generating positron beams of this kind in a laser-driven configuration would thus represent a steppingstone towards the realisation of facilities dedicated to experimental studies of wakefield acceleration of positrons, something that as of today can only be in principle carried out at FACET at the SLAC National Accelerator Laboratory. When realised, positron beams of this kind can be used more widely as witness beams, in a facility such as the one proposed at EuPRAXIA [10], one of the facilities included in the ESFRI roadmap in Europe.

Here, we experimentally demonstrate that positron beams of this kind can be generated, and comprehensively characterized, using a 150 TW laser system, enabling the possibility to exploit these beams for positron wakefield acceleration studies.

Experimental setup

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

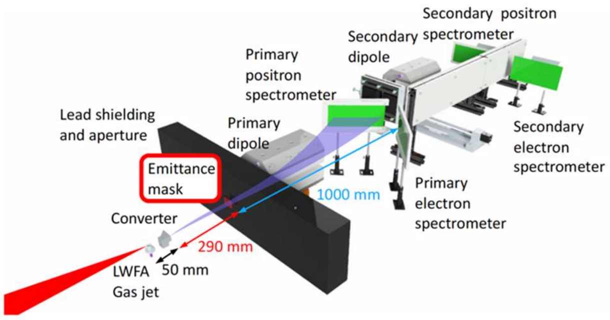

Figure 1: Schematic of the experimental setup. The laser is focused into the gas jet to drive the Laser-Wakefield Accelerator which generates the primary electron beam. This electron beam generates electron positron pairs in the converter which then propagate through an aperture in the lead wall. The 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 be perform energy selection.

The experiment was performed using the Gemini laser at the Central Laser Facility. The laser pulses had a mean energy (and RMS variation) of 7.9 ± 0.5 J in a pulse length of 50 fs. The pulses were focused with an f/40 off-axis parabola to a normalized laser intensity of $a_0 = 1.14 \pm 0.05$ onto a gas jet filled with a mixture of 2% nitrogen and 98% helium. A lead converter target was used to generate electron-positron beams through bremsstrahlung induced pair production. A permanent magnetic dipole was placed behind the lead wall to sweep electrons and positrons onto the primary LANEX scintillator screens. A second scintillator screen was placed 1 m behind the first 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. The electron beams presented an overall charge (electrons with an energy greater than 200 MeV) of $N_e = 1.4 \pm 0.2$ nC and a broad energy spectrum ranging from 200 MeV (minimum energy detectable by the magnetic spectrometer) and 900 MeV.

The energy-resolved emittance of the generated electron and positron beams was characterised using a 5 mm thick tungsten mask composed of horizontal slits with a period of 1100 μm, placed into the beam 290 mm behind the rear face of the converter (similar to the setup used in [2]).

Main Results

An exemplary lineout of the positron signal at the scintillator screen after propagation through the emittance mask is shown in Fig. 2, together with the fitting required for the beam parameters retrieval.

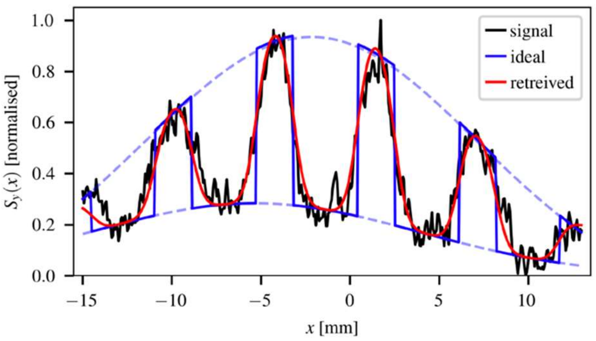

Figure 2: Example signal modulation fitting for beam parameters retrieval. The signal (black line) is taken for a central positron energy of 420MeV with a converter thickness of 8 mm. An ideal beam (zero source size) would produce a rectangular profile pattern (blue line) between the scattered signal and the beam amplitude (blue dashed lines). Deviations from this ideal behaviour allow one to extract the beam source size.

In line with previously published results at lower energy and numerical predictions [2,9], the positron beam is observed to exhibit an energy dependent source size and divergence, with both quantities monotonically decreasing with increasing energy. At 600 MeV, the positron beam was observed to have a source size of 100 microns and a normalized emittance of 540 mm mrad. Energy selection of the positron beam indicates the possibility of extracting more than 10^5 positrons in a 5% bandwidth centered around near-GeV energies.

Crucially, the source size is strongly dependent on the electron beam size at the converter entrance indicating the necessity of minimizing the distance between the gas-jet and the converter target. By eliminating this drift space, the positron beam would have a micron-scale source size and a geometrical emittance of the order of 15 nm (normalized emittance of 18 μm). While not directly measured, the longitudinal length of the positron beam is estimated to be smaller than 15 μm.

Conclusions

In conclusion, we report on detailed spectral and spatial characterization of laser-driven positron beams generated using the Gemini laser. Results indicate that positron beams with near-GeV energies and micron-scale normalized emittance can be produced by commercially available high-power laser systems. 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. Laser generation of high-quality positron beams could also be added to beam driven wakefield facilities with laser capabilities (e.g. FLASHForward [11] and SPARC LAB [12]) to study beam-driven methods, without the need for emittance damping storage ring.

Acknowledgements

The authors wish to acknowledge support from EPSRC (grant No: EP/V044397/1, EP/N027175/1), STFC (ST/V001639/1), US NSF (grant #2108075) and from the staff of the Central Laser Facility.

References

[1] G. Sarri, W. Schumaker, A. Di Piazza, M. Vargas, B. Dromey, M. E. Dieckmann, V. Chvykov, A. Maksimchuk, V. Yanovsky, Z. H. He, B. X. Hou, J. A. Nees, A. G. Thomas, C. H. Keitel, M. Zepf, and K. Krushelnick, Physical Review Letters 110, 255002 (2013).

[2] A. Alejo, G. M. Samarin, J. Warwick, C. Mccluskey, G. Cantono, T. Ceccotti, S. Dobosz DufrÅLenoy, P. Monot, and G. Sarri, Plasma Physics and Controlled Fusion 62 (2020), 10.1088/1361-6587/ab7e81.

[3] S. Li, G. Li, Q. Ain, M. S. Hur, A. C. Ting, V. V. Kulagin, C. Kamperidis, and N. A. Hafz, Science Advances 5 (2019), 10.1126/sciadv.aav7940.

[4] G. Sarri, K. Poder, J. M. Cole, W. Schumaker, A. Di Piazza, B. Reville, T. Dzelzainis, D. Doria, L. A. Gizzi, G. Grittani, S. Kar, C. H. Keitel, K. Krushelnick, S. Kuschel, S. P. Mangles, Z. Najmudin, N. Shukla, L. O. Silva, D. Symes, A. G. Thomas, M. Vargas, J. Vieira, and M. Zepf, Nature Communications 6, 6747 (2015).

[5] J. Warwick, T. Dzelzainis, M. E. Dieckmann, W. Schumaker, D. Doria, L. Romagnani, K. Poder, J. M. Cole, A. Alejo, M. Yeung, K. Krushelnick, S. P. Mangles, Z. Najmudin, B. Reville, G. M. Samarin, D. D. Symes, A. G. Thomas, M. Borghesi, and G. Sarri, Physical Review Letters 119, 185002 (2017).

[6] N. Shukla, J. Vieira, P. Muggli, G. Sarri, R. Fonseca, and L. O. Silva, Journal of Plasma Physics 84, 905840302 (2018).

[7] ALEGRO collaboration, arXiv (2019), 10.48550/arxiv.1901.10370.

[8] Advanced Accelerator Development Strategy Report: DOE Advanced Accelerator Concepts Research Roadmap Workshop, Tech. Rep. (USDOE Office of Science (SC) (United States), 2016).

[9] A. Alejo, R. Walczak, and G. Sarri, Scientific Reports 9, 5279 (2019).

[10] R. Assman et al., European Physical Journal: Special Topics 229, 3675 (2020).

[11] A. Aschikhin et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 806, 175 (2016).

[12] M. Ferrario et al, Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms 309, 183 (2013).