Generation of neutral and high-density electron-positron pair plasmas in the laboratory

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Electron-positron pair plasmas represent a unique state of matter, whereby there exists an intrinsic and complete symmetry between negatively charged (matter) and positively charged (anti-matter) particles. These plasmas play a fundamental role in the dynamics of ultra-massive astrophysical objects and are believed to be associated with the emission of ultra-bright gamma-ray bursts. Despite extensive theoretical modelling, our knowledge of this state of matter is still speculative, due to the extreme difficulty in recreating neutral matter-antimatter plasmas in the laboratory. Here we show that, by using a compact laser-driven setup, ion-free electron-positron plasmas with unique characteristics can be produced. Their charge neutrality (same amount of matter and anti-matter), high-density, and small divergence finally open up the possibility of studying electron-positron plasmas in controlled laboratory experiments.

INTRODUCTION

Electron-positron ($e^-/e^+$) plasmas are emitted, in the form of ultra-relativistic winds or collimated jets, by some of the most energetic or powerful objects in the Universe, such as black-holes [1, 2], pulsars [3], and quasars [4]. These plasmas are associated with violent emission of gamma-rays in the form of short-lived (milliseconds up to a few minutes) bursts, which are amongst the most luminous events ever observed in the Universe. These phenomena represent an unmatched astrophysical laboratory to test physics at its limit and, given their immense distance from Earth (some more distant than several billion light years), they also provide a unique window on the very early stages of our Universe [5,6]. Arguably, one of the most intriguing questions is how these gamma-ray bursts are produced. It is generally accepted that gamma-ray bursts must arise from synchrotron emission of relativistic shocks generated within an electron-positron beam [8, 9]. This radiative mechanism requires a strong and long-lived ($\tau \geq 1000\omega_p^{-1}$, with $\omega_p$ being the electron-positron plasma frequency) magnetic field; however, Weibel-mediated shocks generate magnetic fields that should decay on a fast time-scale ($\tau \approx \omega_p^{-1}$) due to phase-space mixing [9]. Also, diffusive Fermi acceleration, a proposed candidate for the acceleration of cosmic rays [9], requires magnetic field strengths that are much higher than the intergalactic average magnetic field ($\approx nT$) [10]. These and other questions could be addressed by ad-hoc laboratory experiments; however, the extreme difficulty in generating $e^-/e^+$ populations that are dense enough to permit collective behaviour [11, 12] is still preventing so and the properties of this peculiar state of matter are only inferred from the indirect interpretation of its radiative signatures and from matching numerical models. The intrinsic symmetry between negatively charged ($e^-$) and positively charged ($e^+$) particles within the plasma makes their dynamics significantly different from that of an electron-ion plasma or from a purely electronic beam. In the first case, the mass symmetry of the oppositely charged species induces different growth rates for a series of kinetic and fluid instabilities [13] and significantly affects the possibility of generating acoustic or drift waves [14]. In the second case, the overall beam neutrality forbids the generation of current-driven magnetic fields that would hamper the onset of transverse instabilities.

Different schemes have been proposed for the laboratory generation of $e^-/e^+$ plasmas: in large-scale conventional accelerators, the possibility of recombining high-quality electron and positron beams via magnetic chicanes [15] is envisaged and a different approach is foreseen in confining low-energy positrons using radioactive sources with Penning traps [11,16]. The proposed APEX experiment [12] builds on this idea, accumulating a large number of positrons in a multi cell Penning trap, before injecting into a stellarator plasma confinement device. The major challenge of these schemes is the recombination of these separate electron and positron populations. Alternative schemes have been proposed, in which electrons and positrons are generated in situ [17,19], thus
avoiding the aforementioned recombination issues. Despite the intrinsic interest of these results, the low percentage of positrons in the electron-positron beam (of the order, if not less, than 10%), and the low-density reported (collisionless skin depth much greater than the beam size, forbidding plasma-like behaviour) prevent their application to the laboratory study of $e^-/e^+$ plasmas. All these previous experimental attempts have thus not been able to generate $e^-/e^+$ beams that present charge neutrality and a plasma-like behaviour, both fundamental prerequisites for the laboratory study of this state of matter [10].

We report here on the first experimental evidence of the generation of a high-density and neutral electron-positron plasma in the laboratory. Its high density ($n_{e^-/e^+} \approx 10^{16}\text{cm}^{-3}$) implies that the collisionless skin depth in the plasma is smaller than the plasma transverse size effectively allowing for collective effects to occur. This characteristics, together with the charge neutrality, small divergence ($\theta_{e^-/e^+} \approx 10 - 20 $ mrad), and high average Lorentz factor ($\gamma_{e^-/e^+} \approx 15$) with a power-law spectral distribution, comparable to what observed in astrophysical jets [20] finally open up the possibility of studying the dynamics of $e^-/e^+$ plasmas in a controlled laboratory environment.

**EXPERIMENTAL SETUP**

The experiment (shown schematically in Fig. 1a) was carried out using the ASTRA-GEMINI laser system at the Rutherford Appleton Laboratory [21], which delivered a laser beam with a central wavelength $\lambda_L = 0.8\mu\text{m}$, energy on target $E_L \approx 14\text{ J}$ and a duration of $\tau_L = 42\pm 4\text{ fs}$. An $f/20$ Off-Axis Parabola focussed this laser beam onto the edge of a 20 mm wide supersonic He gas-jet, doped with 3.5% of $N_2$. A backing pressure of 45 bar was found to be optimum in terms of maximum electron energy and charge of the accelerated electron beam as resulting from ionization injection [22] in the gas-jet. Optical interferometry of the laser-gasjet interaction indicates this gas-pressure to correspond to a plasma density of $n_{pl} = (6.0 \pm 0.2) \times 10^{18}\text{ cm}^{-3}$. This interaction produced a reproducible electron beam (shot-to-shot fluctuation in charge and maximum energy below 10%) with a broad spectrum with maximum energy of the order of 600 MeV, half-angle divergence of 2 mrad and an overall charge of $(0.3\pm 0.1)\mu\text{C}$, corresponding to $(2.0\pm 0.6) \times 10^6$ electrons (see Fig. 1b for typical electron spectra and their average). This electron beam was then directed onto a Pb solid target of different thicknesses covering multiples of the material’s radiation length ($d=0.5, 1, 1.5, 2, 2.5, 3, 4\text{cm}$ given that the radiation length for Pb is $L_{\text{rad}} \approx 0.5\text{ cm}$ [19]). The electrons and positrons escaping from the rear side of the target were then separated and spectrally resolved by a magnetic spectrometer. The details of this detector can be found in the Methods section.

**EXPERIMENTAL RESULTS AND DISCUSSION**

A scan in target thickness was performed in multiples of its radiation length and the obtained positron spectra, each resulting from an average over five consecutive shots, are depicted in Fig. 2 (see Fig. 1c for the raw signal recorded on the LANEX screen for $d=0.5\text{cm}$). All spectra are in good agreement with the ones resulting from matching simulations using the Monte-Carlo scattering code FLUKA, which accounts for electromagnetic cascades during the passage of an electron beam through a solid target [21] (see Methods). A maximum positron energy of $E_{\text{MAX}} = 600\text{ MeV}$ is obtained for $d \approx L_{\text{rad}}$ (i.e. $5\text{mm}$, see Fig. 1a), whereas a maximum positron yield

![Figure 1](https://example.com/figure1.png)
is obtained for $d \approx 2L_{\text{rad}}$. For thicker targets, the maximum energy gradually decreases as it should be expected due to increased probability of energy loss during the propagation of the generated positrons through the rest of the solid target. For a similar reason, a thicker solid target allows a lower number of electrons and positrons to escape it. This is quantitatively shown in Fig. 3 which depicts the measured number of electrons and positrons (energy exceeding 120 MeV, see Methods) at the exit of a solid target, as a function of its thickness.

In order to quantitatively explain the observed trends, we have developed a simple analytical model for a quantum electrodynamic cascade which only includes the emission of photons by electrons and positrons via bremsstrahlung [25] and the creation of an electron-positron pair by a photon [26], both processes occurring in the field of a heavy atom. This model (see Methods) is able to reproduce the experimental trends well (dashed green curves in Fig. 3), provided that a constant re-scaling factor of 0.75 is adopted for the absolute yield of both the electrons and positrons. This underestimate is easily understood, as the latter does not take into account a number of energy loss mechanisms, such as Compton scattering and the ionisation of atoms [27] and it is however irrelevant for determining the ratio of electrons and positrons in the beam.

Let us now turn our attention to the total positron fraction in the jet $[N_{e+}/(N_{e+} + N_{e-})]$ as a function of the target thickness (plotted in Fig. 3c). For $d \approx L_{\text{rad}}$.

Figure 3. a. Measured (blue circles) and simulated (red crosses) number of positrons ($E_{e+} > 120$ MeV) as a function of the Pb thickness ($N_{e+\text{EXP}}$, see main text). The green dashed line represents the analytical prediction (discussed in the text). b. Measured (blue circles) and simulated (red crosses) number of electrons ($E_{e-} > 120$ MeV) as a function of the Pb thickness ($N_{e-\text{EXP}}$, see main text). The green dashed line represents the analytical prediction (discussed in the text). For these two frames error bars lie within the size of the squares. c. Percentage of positrons in the leptonic jet: measured (full blue circles), simulated (red crosses) and analytical prediction (green dashed lines). For all panels, the error bars represent shot-to-shot fluctuations. FLUKA simulations indicate that the overall number of relativistic electrons and positrons ($E_e \geq 1$ MeV) behave in a similar manner. The percentage of positrons in the beam reaches 50% for $d > 2.5$ cm $\approx 5L_{\text{rad}}$. 

Figure 2. Measured positron spectra, as resulting from the average over five consecutive shots, (solid lines) compared with what obtained from FLUKA simulations (dashed lines) for $d = 5$ mm (a.), $d = 2$ cm (b.), and $d = 4$ cm (c.). In this latter case, also the spectrum of the electrons escaping the target is plotted. Its similarity with the positron spectrum is a clear indication of the generation of a neutral electron-positron pair beam. The inset in panel a. shows the simulated positron spectrum at low energy for $d = 5$ mm.
the positrons account for approximately 8 - 10% of the overall beam, due to the fact that most of the primary electrons are able to escape the target (consistently with the results reported in Ref. [19]). However, as we increase the target thickness, this ratio increases up to a point were the positrons account for almost 50% of the leptonic jet \((d \geq 2.5 \text{cm})\), see Fig. 3c). In this case, not only the integrated number of electrons and positrons is similar, but also their spectrum (see Fig. 3c), further indication that almost all the electrons and positrons escaping the target arise from pair production. Charge neutrality is preserved also if the target thickness is increased: however we will focus our attention only on \(d = 2.5 \text{ cm}\), since it provides the highest density of the neutral \(e^-e^+\) beam. Simulations confirm that the majority of positrons are generated with energies of the order of a few MeV following a Jüttner-Synge distribution, which is commonly assumed for relativistic thermalised plasmas [25] (see, as an example, the inset in Fig. 2a). We thus refer to the experimentally measured number of \(e^-\) and \(e^+\) \((E_{e^\pm} > 120 \text{ MeV})\) with the subscript \(N_{\text{EXP}}\), whereas we will refer to their simulated number \((E_{e^\pm} > 2m_e c^2 \approx 1 \text{ MeV})\) with the subscript \(N_{\text{FLUKA}}\). For \(d = 2.5 \text{ cm}\) we thus have \(N_{e^-}\text{EXP} \approx N_{e^+}\text{EXP} \approx 3 \times 10^7\) and \(N_{e^-}\text{FLUKA} \approx N_{e^+}\text{FLUKA} \approx 1.2 \times 10^9\) (see Fig. 3a). Taking the appropriate moment of the distribution function, the averaged Lorentz factor of the beam is typically of the order of a few tens \((\gamma_{\text{AV}} \approx 15\) for \(d = 2.5 \text{ cm}\)). FLUKA simulations indicate a divergence of the beam to be energy-dependent, in a range of \(5-20 \text{ mrad}\) [25].

A fundamental requisite for the laboratory study of \(e^-/e^+\) plasmas is that the generated \(e^-/e^+\) beams must present collective behaviour in their dynamics. Collective (i.e., plasma-like) effects are likely to occur in the beam only if its transverse size \(D_B\) is larger than the collision-less skin depth \((l_{\text{skin}} \approx c/\omega_{\text{prop}},\) with \(\omega_{\text{prop}}\) being the relativistic plasma frequency). The beam density is determined by the temporal duration of the beam (that relates to its longitudinal extent) and its transverse size. The primary electron beam exits the gas-jet with a typical temporal duration comparable to half the plasma period within the gas [30]; \(\tau_{pl} \approx (13.0 \pm 0.3) \text{ fs}\). The semi-analytical model for the quantum cascade inside the Pb indicates an average temporal spreading across different spectral components of the beam of the order of \(1-3\) fs, resulting in a beam duration of \(\tau_{e^-/e^+} \approx 15 \pm 2\) fs. As intuitively expected, the lower energy electrons and positrons will escape the solid target in a wider area if compared to their higher energy counterparts. FLUKA simulations confirm this expectation and indicate, for \(d = 2.5\) cm, a maximum transverse size of the beam of the order of \(D_B \approx 200 \pm 30 \mu\text{m}\). For these parameters we thus obtain a particle density in the laboratory reference frame of the order of \(n_e \approx (1.8 \pm 0.7) \times 10^{16} \text{ cm}^{-3}\) implying a beam proper density of \(n_{\text{prop}} = n_e/\gamma_{\text{AV}} \approx (1.5 \pm 0.5) \times 10^{15} \text{ cm}^{-3}\) (see Fig. 4b). The relativistically corrected collisionless skin depth of the beam is thus \(l_{\text{skin}} \approx c/\omega_{\text{prop}} \approx (160 \pm 30) \mu\text{m}\). This value is smaller than the beam transverse size, indicating that the generated particle beam is a neutral \(e^-/e^+\) plasma. It is interesting to note that the occurrence of collective behaviour (i.e the situation in which \(D_B/l_{\text{skin}} \geq 1\)) does not depend on the beam transverse size \(D_B\) since, based on the considerations presented above, it can be expressed as: \(D_B/l \approx 4.1 \times 10^{-4} \sqrt{N/(\gamma_{\text{AV}} \tau_{pl}[fs])} \approx 1.4\) for our experimental parameters.

\(e^-/e^+\) PLASMA DYNAMICS

The presented characteristics of the \(e^-/e^+\) plasmas generated in our experiment are appealing for the laboratory study of the dynamics of this exotic state of matter. As an example, a particularly active area of research in this direction is the determination of the growth and evolution of kinetic instabilities, which are extensively modelled in order to interpret peculiar astrophysical observations such as the emission of gamma-ray bursts [31][32]. It is widely accepted that these ultrabright bursts result from synchrotron radiation generated via relativistic shocks triggered during the propagation of
In order to check the validity of our estimates, we have carried out 3-dimensional Particle-In-Cell simulations using the particle-in-cell (PIC) code OSIRIS [37] (see Methods). Simulation results are illustrated in Fig. 5. During its propagation through a denser $e^−/e^+$ plasma, the $e^−/e^+$ is subject to the Weibel/current filamentation instability leading to the formation of electron and positron filaments with thicknesses of the order of the beam skin depth. The electron and positron filaments spatially separate each other leading to net localised currents and the generation of the corresponding azimuthal magnetic field structures with maximum amplitudes of the order of 40 T in the middle of the bunch. At early times, the simulations show that the transverse scale length of the filaments is even shorter than the beam skin depth. To further understand the impact of charge neutrality on the instability onset, additional three-dimensional simulations were performed using a purely electronic bunch of same characteristics. In this case, the electron bunch generates plasma wake-fields, and neither filamentation of the beam (insets in Fig. 5c) nor the generation of strong magnetic fields (inset Fig. 5d) are observed. These results corroborate the expectation that current filamentation instability growth can be controlled by changing the beam overall total charge and it is maximised for a purely neutral $e^−/e^+$ plasma.

On the other hand, the beam is also susceptible to longitudinal instabilities [32, 38], which would induce a broadening of the $e^−/e^+$ spectrum and generation of strong fields in the background plasma. For $d = 4$ cm (neutral beam) the measured electron and positron spectra are indeed flatter than the ones predicted by FLUKA, which does not include collective behaviour of the beam particles (see Fig. 2c). For $d = 0.5$ cm (highly charged beam) simulations and experiments agree much more closely. The spectral flattening may also be produced by kinetic self-focusing of the beam [39, 40].

In conclusion, we have reported on the first creation of a neutral electron-positron plasma in the laboratory. Its overall charge neutrality and plasma-like behaviour are an absolute novelty in the field of experimental physics and, in conjunction with the small divergence and high energy of these plasmas, finally allow for the laboratory study of this unique state of matter.

Methods
The electron-positron spectrometer: The magnetic spectrometer comprised a pin-hole entrance with a diameter of approximately 15 mm through 5 cm of plastic followed by 5 cm of lead. This plastic-lead wall was indeed necessary in order to shield the particle detectors from noise generated during the electron beam impact onto the solid target. After this, a pair of permanent magnets \((B = 0.8 \text{ T}, \text{length of 10 cm})\) was inserted to spectrally resolve the electrons and the positrons, which were recorded by two LANEX screens \([41]\). This arrangement allowed us to resolve particle energies from 120 MeV to 1.2 GeV. The LANEX screens were cross-calibrated using absolutely calibrated Imaging Plates \([42]\). The small difference in stopping power (of approximately 2\% \([43]\) between electrons and positrons was taken into account in calibrating the LANEX screens. Every electron or positron spectrum shown in the manuscript results from an average over five consecutive shots. The energy resolution of the spectrometer can be approximated, in the ultra-relativistic limit, as:

\[
\frac{\delta E}{E} \approx \frac{(D_s + D_t)R\theta_s}{(D_t - L_m/2)L_m},
\]

(1)

Where \(D_s\) is the pinhole-magnet distance (10cm), \(D_t\) is the magnet-detector distance (1m), \(R \approx E/(mcB)\) is the radius of curvature of the particle with energy \(E\) and charge \(e\) in the magnetic field \(B\), \(\theta_s = 15\) mrad is the angular acceptance of the detector, and \(L_m\) (10cm) is the length of the magnet. For the energies of interest in our experiment \((120 \leq E[\text{MeV}] \leq 300)\), the energy resolution is between 10\% and 20\%.

FLUKA simulations: FLUKA is a nuclear physics Monte-Carlo scattering code, which accounts for electromagnetic cascades during the passage of an electron beam through a solid target \([24]\). The numerical model for the quantum electromagnetic cascade is routinely checked and constantly improved to take into account any refinement in cross-section measurements in conventional accelerators. As an input for the simulation, we assume an electron beam with the spectral shape depicted in Fig. 1b (brown solid line). \(10^8\) iterations were used in order to achieve a good statistical representation in the Monte-Carlo method. Every numerical result reported originates from an average over five identical runs in order to minimise any stochastic error arising from the random seed generator of the code. The results of the simulations, obtained in units of particles per initial electron, were then rescaled with the measured number of primary electrons, giving a good quantitative agreement with the experimental data.

Semi-analytical model for the quantum cascade: We assume a quantum electrodynamics cascade shower involving only electrons, positrons, and photons at energies much larger than the electron rest energy \(m\) (units with \(h = c = 1\) are assumed hereafter). We thus neglect additional electron and positron energy losses as resulting, for instance, from Compton scattering with the electrons of the atoms and from the ionisation of the atoms themselves. The only processes to be included in the kinetic equations are thus the emission of photons by electrons and positrons via bremsstrahlung and the creation of an electron-positron pair by a photon, both processes occurring in the field of a heavy atom. By setting the target thickness \(d\) in units of the radiation length \(L_{rad}\), i.e. \(\ell = d/L_{rad}\), the electron/positron distribution functions \(f_{\pm}(E, \ell)\) and the photon distribution function \(f_\gamma(E, \ell)\) satisfy the kinetic equations \([27]\):

\[
\frac{\partial f_{\pm}}{\partial \ell} = -\int_0^1 \frac{dv}{v} \psi_{\text{rad}}(v) \left[ f_{\pm}(E, \ell) - \frac{1}{1-v} f_{\pm}(E, 1-v, \ell) \right] + \int_0^1 \frac{dv}{v} \psi_{\text{pair}}(v) f_\gamma \left( \frac{E}{v}, \ell \right),
\]

\[
\frac{\partial f_\gamma}{\partial \ell} = \int_0^1 \frac{dv}{v} \psi_{\text{rad}}(v) \left[ f_\gamma(1, \ell) + f_\gamma(E/v, \ell) - \mu_0 f_\gamma(E, \ell) \right],
\]

where the functions

\[
\psi_{\text{rad}}(v) = \frac{1}{v} \left[ 1 + (1-v)^2 - (1-v) \left( \frac{2}{3} - 2b \right) \right],
\]

\[
\psi_{\text{pair}}(v) = v^2 + (1-v)^2 + v(1-v) \left( \frac{2}{3} - 2b \right),
\]

with \(\mu_0 = 7/9 - b/3\) and \(b = 1/18 \log(183/Z^{1/3})\), are related to the cross section of bremsstrahlung and pair photo-production in the field of a heavy atom with charge number \(Z\) (see \([27]\) for details). By numerically solving these equations, we are able to reproduce the experimental trends well (dashed green curves in Fig. 3 of the manuscript), provided that a constant re-scaling factor of 0.75 is adopted for the absolute yield of both the electrons and positrons. The overestimation of the experimental results by this simplified model is easily understood, as the latter does not take into account a number of braking mechanisms, such as Compton scattering and the ionisation of atoms \([27]\). Such braking mechanisms essentially do not distinguish between relativistic electrons and positrons, as it results from the fact that the same overall coefficient allows to fit the results of both electrons and positrons. Starting from a simple model, where each electron/positron (photon) after a radiation length emits a photon (transforms into an electron-positron pair) with half of the energy of the initial electron (with the electron and positron sharing half of the energy of the initial photon), it can also be shown that the maximum yield of positrons with an energy exceeding \(E\) can be estimated to occur for a target thickness \(d_{\text{opt}} \sim L_{\text{rad}} \log((E_e)/E)/\log(2)\) \([27]\), where \((E_e)\) is the average energy of the initial electron distribution (see Fig. 1b of the manuscript). In our case, it results \((E_e) \approx 456\) MeV and \(d_{\text{opt}} \sim 1.1\) cm, in good agreement with the experimental results.

The Particle-In-Cell simulations: The simulations were performed with the fully relativistic, massively parallel, particle-in-cell (PIC) code OSIRIS \([37]\). OSIRIS has been extensively used to explore relativistic beam plasma interaction scenarios, and has been widely
applied to model the Weibel Instability in various configurations (see, for instance, refs. [13] [15] [37] [44]). In OSIRIS, the electric and magnetic fields are defined in a grid. The trajectory of each simulation particle is determined through the relativistic equations of motion, by interpolating the grid fields to the position of the particle. Current density is deposited onto the grid, and used to advance the electric and magnetic fields through Maxwell’s equations discretised using a finite-difference scheme. In this section, we give the numerical parameters for the simulations. Simulations used a moving window with dimensions 1.5 × 100 × 100 (c/ωp)3 divided into 75 × 1000 × 1000 cells with 2 × 1 × 1 particles per cell for plasma electrons and for beam particles. Here ωp is the plasma frequency of the background electron-proton plasma, which has a density of n0 = 1016 cm−3. A charge-neutral beam constituted by electrons and positrons was initialized at the entrance of the plasma. The density profile for electrons and positrons is given by

\[ n_b = n_{b0} \exp \left( -\frac{\xi^2}{\sigma_e^2} - \frac{r^2}{\sigma_r^2} \right) \]

where \( n_{b0} = 10 \times n_0 = 10^{17} \text{ cm}^{-3} \), \( \sigma_e = 0.22 \ c/\omega_p = 11.7 \ \mu\text{m} \) and \( \sigma_r = 10 \ c/\omega_p = 530 \ \mu\text{m} \) are the bunch peak density, length and transverse waist respectively. The particles’ Lorentz factor is initialised to be \( \gamma = 700 \).

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Authors’ contributions
GS and MZ conceived the experiment, which was performed by GS, KP, JC, WS, DD, and MV, with input from LAG, DS, GG, and SK. GS carried out the data analysis and interpretation with theoretical support provided by ADP, CHK, and BR. Particle-In-Cell simulations and their analysis were performed by JV, NS, and LOS. The manuscript was written by GS, in collaboration with BR, MZ, ADP, CHK, ZN, AGRT, LAG, SPDM, and KK.

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