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Electron-Positron Plasma Generation in Foam Targets

The creation of matter and antimatter by light is one of the most prominent predictions of quantum electrodynamics. While pair creation was experimentally demonstrated near nuclei, direct pair production via the interaction of two or more photons remains beyond current experimental capabilities. Numerous setups have been proposed to generate a large number of pairs with currently or near-future available laser facilities [1]. Nonetheless, due to the high energy required, generating a sufficient number of pairs to create an electron-positron plasma remains elusive.

Theory

The generation of electron-positron pairs from electrons is a two-step process, where a high-energy electron interacts with a strong field to emit a hard photon, which in turn can decay into an electron-positron pair. The strength of both processes is governed by the quantum nonlinearity parameter:

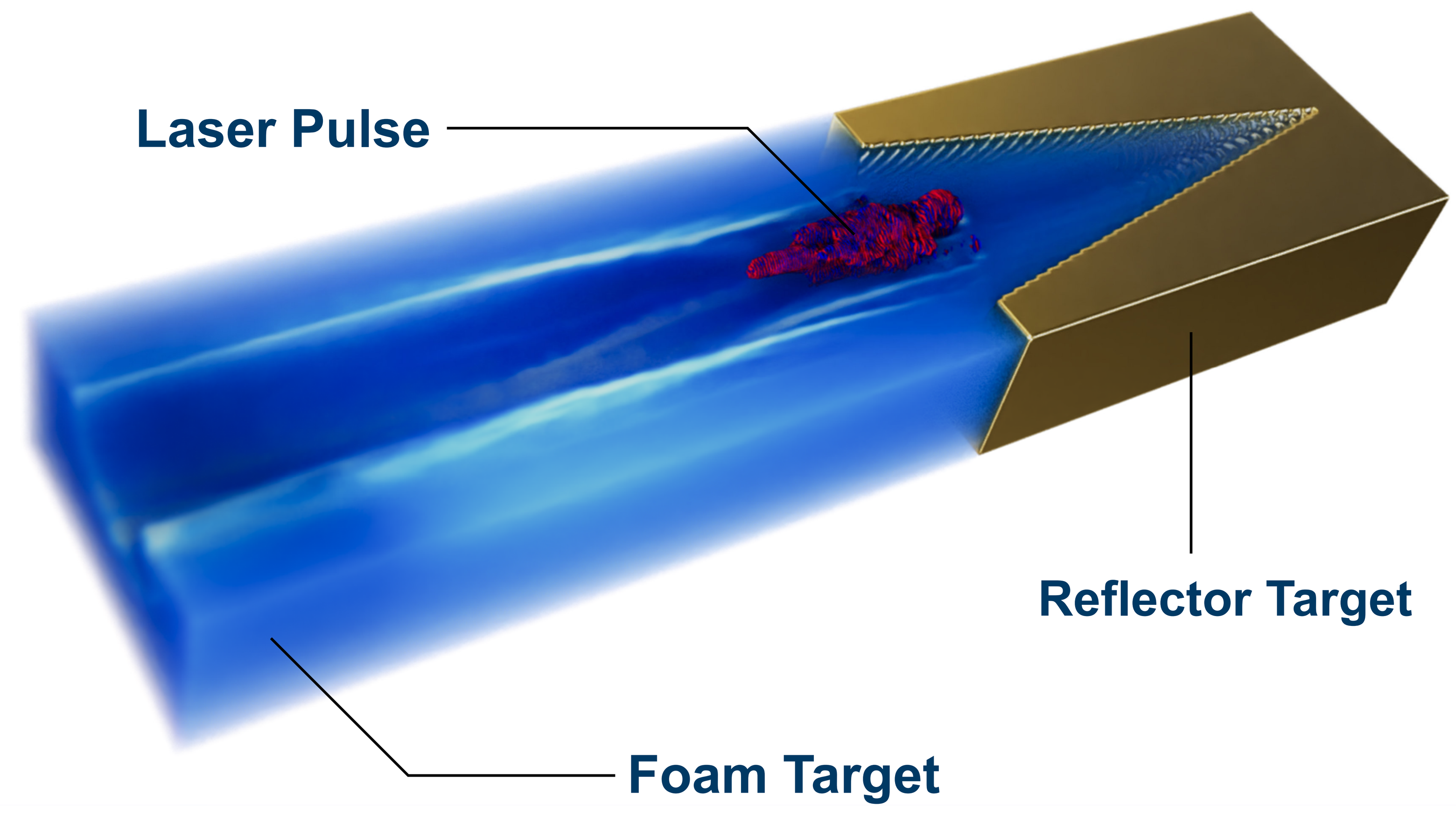
$$\chi = \frac{e\hbar}{m^3c^4}\sqrt{-\left(F_{\mu\nu}p^\nu\right)^2} = \frac{1}{E_s}\sqrt{(\boldsymbol{\gamma E} + \boldsymbol{p}\times\boldsymbol{B})^2 - (\boldsymbol{p}\cdot\boldsymbol{E})^2}.$$

In order to generate a large number of pairs, it requires a combination of high-energy electrons and strong fields. The rate of coherent pair production can be estimated as [2]:

$$W_{CP} \approx \frac{\alpha m_e^2 c^4}{\hbar\gamma}\begin{cases} 0.23\,\chi\exp\left(-\dfrac{8}{3\chi}\right), & \chi \ll 1 \\ 0.38\chi^{2/3}, & \chi \gg 1 \end{cases}$$

Setup

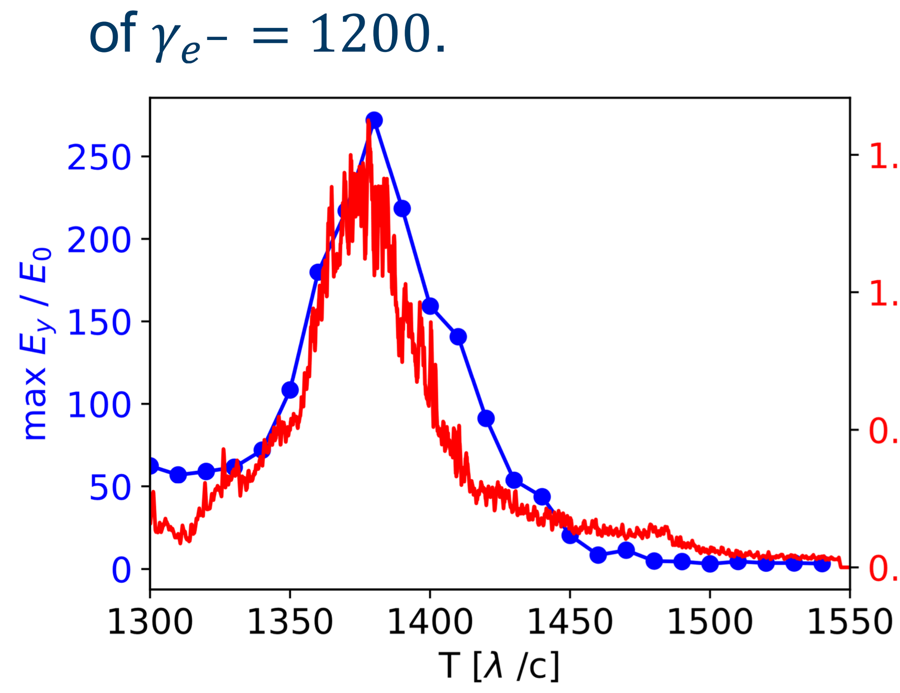
We consider a single-laser setup, where the laser acts as both the accelerator of electrons via direct laser acceleration (DLA) and as the background field after colliding with a reflector target.
We utilize a 1.5 kJ laser pulse, with wavelength $\lambda = 800\,\mathrm{nm}$, a waist radius $\sigma = 2.5$ μm and length $T = 150$ fs [3]. This results in a laser parameter of $a_0 \sim 200$.

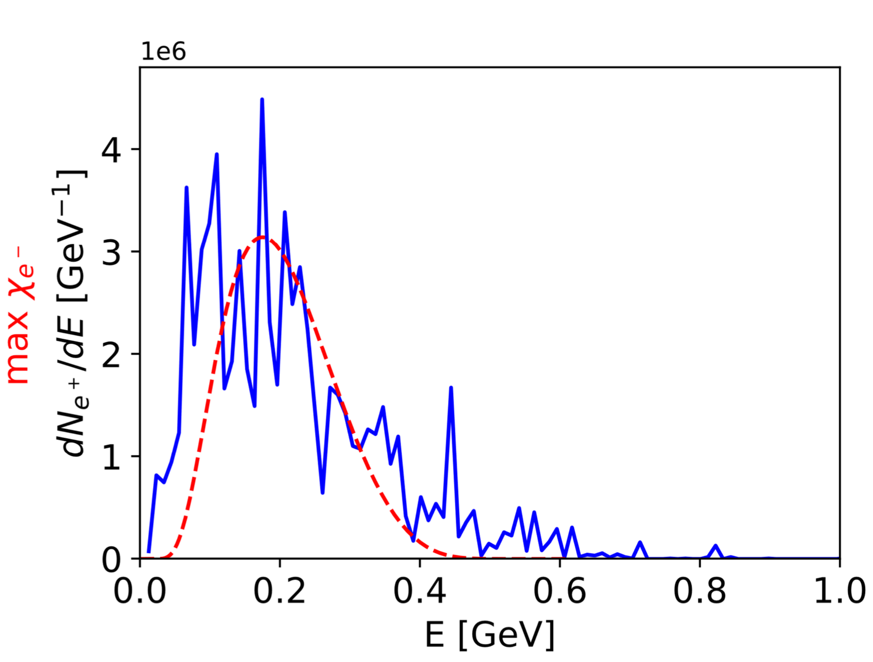


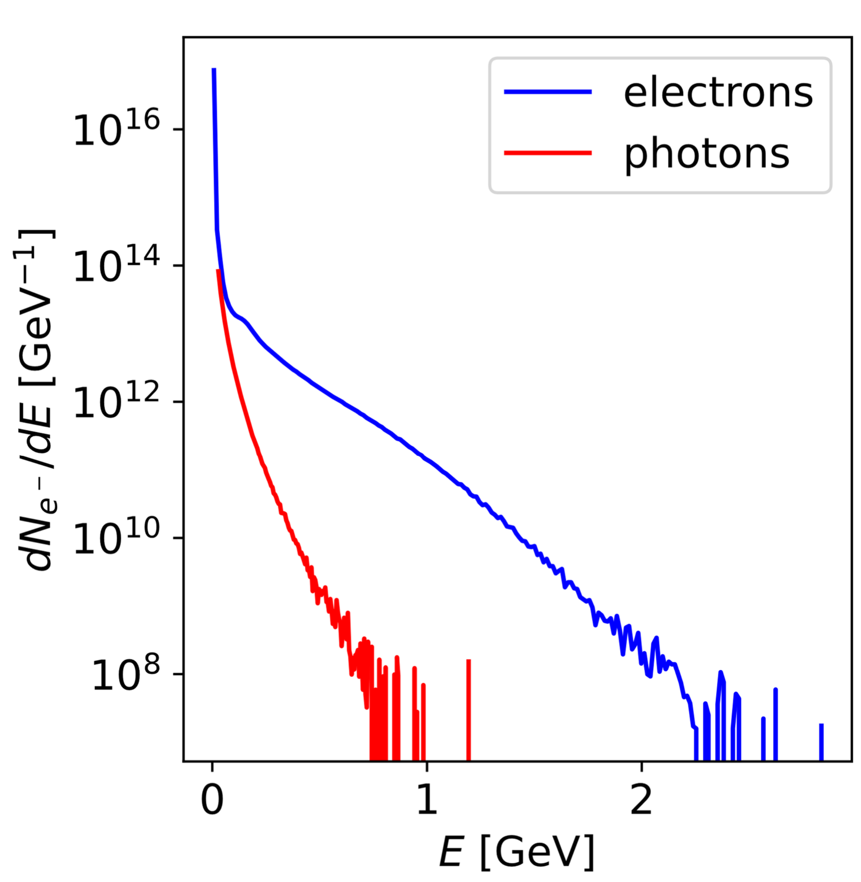
We consider a pre-ionised foam target with a Gaussian channel at the optical axis for better laser guidance. After the foam target is a gold reflector target with a conical cavity to amplify the laser fields at the reflection point.

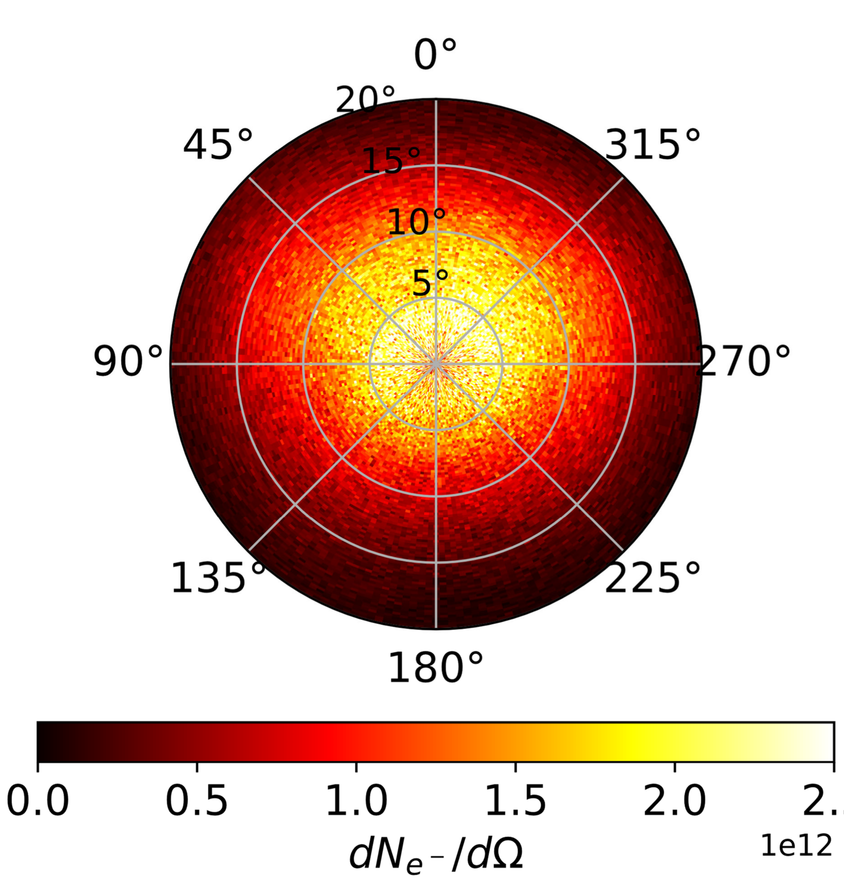
Simulation Results

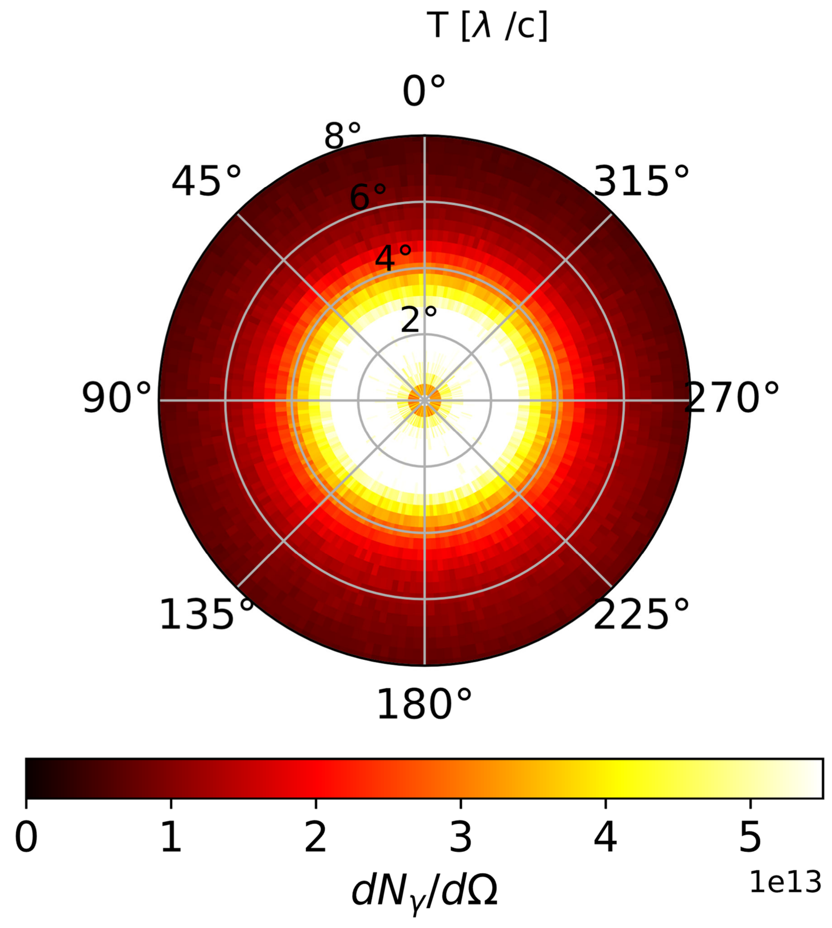
We performed full 3D-PIC simulations using VLPL [4]. We consider an inner density of $n_0 = 0.3\,n_c$ and outer density $n_1 = 1\,n_c$ for the foam with a radius $\sigma = 5.5$ μm. High-energy electrons are generated via DLA, producing a burst of isotropic high-energy photons. At the reflection point, the residual electromagnetic fields are amplified by more than a factor of 3, resulting in a quantum nonlinearity parameter $\chi > 1$, which enables electron-positron pair production, resulting in $\sim 10^6$ pairs. The obtained positron energy spectrum shows qualitatively good agreement with theoretical predictions for $\chi = 1.2$ and an initial electron Lorentz factor of $\gamma_{e^-} = 1200$.











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