# Potential of laser-driven VHEEs toward FLASH radiotherapy: Monte Carlo dosimetric study of single-field pencil beam scanning of a brain tumor

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Supplementary Materials

## 1 Particle-In-Cell (PIC) simulations

We briefly provide in the following the main details of the PIC simulations carried out for our work. As mentioned in the text, the main purpose of our study, from the LWFA source point of view, was to find an acceleration regime yielding, using a 100TW class laser, a spectrum featuring a strong component in the VHEE region.

The driver laser (Ti:Sapphire linearly polarized laser pulse with wavelength $\lambda = 800$ nm, 3 J energy and pulse duration $\tau = 30$ fs FWHM) was supposed to be focused onto a gas-jet target down to a spot size $w_0 = 20$ $\mu$m, resulting in $a_0 = 2.7$ and peak intensity $I = 1.6 \times 10^{19}$ W/cm$^2$.

The neutral gas target, consisting in a mixture of 99% of Helium (He) and 1% of Argon (Ar), has a density of $n_n = 4.5 \times 10^{17}$ cm$^{-3}$. In the above conditions, the laser trailing edge is intense enough to fully ionize Helium up to $He^{2+}$ state, while Argon is partially ionized up to $Ar^{12+}$ state; in these conditions, the background plasma features an electron density of $n_e = 9.4 \times 10^{17}$ cm$^{-3}$. In the simulations, the plasma target is a cylinder with a longitudinal extent of $\simeq 3$ mm and a radius of $\simeq 0.05$ mm; the up-ramp and down-ramp of plasma stage were modeled with a sine-like profile.

The injection mechanism we rely upon in these conditions is mainly ionization injection. In particular, electrons injected are obtained from the tunneling ionization [1] of inner bound electrons of the $Ar^{12+}$ state. As known, electrons are mainly ionized by the driver electric field peak and those which are extracted at a proper phase inside the laser pulse[2, 3] are reached out by the accelerating phase of the plasma wave, getting trapped in its potential.

PIC simulations were performed with the *Fourier-Bessel Particle in Cell* code (FBPIC) [4]; the code implements a pseudo-spectral, quasi-cylindrical PIC algorithm. Such a kind of algorithm exploits the symmetry of the laser-plasma stage, using an azimuthal Fourier decomposition of field components, and uses a *Pseudo-Spectral Analytical Time Domain* (PSATD) scheme to solve Maxwell equations in Fourier spectral space. The azimuthal decomposition, which can be truncated at low order, reduces a full three dimensional problem to an actual two dimensional simulation (one 2D grid for each azimuthal mode) without loss of information, while using the PSATD scheme avoids several spurious numerical artifacts.

In the simulations, we used a 2D $z \times r$ simulation box made up by a window moving at velocity of laser driver inside the plasma, with spatial dimensions $75 \times 48$ $\mu m^2$ and resolution $0.025 \times 0.08$ $\mu m^2$ ($32 \times 10$ points per $\lambda$). The decomposition of fields was truncated to the second order in azimuthal modes and the temporal resolution of PIC-loop was $\delta t = 0.08$ fs, with a total interaction time $T \simeq 10$ ps.

Figures from 1 to 4 show the electron $z - \mathcal{E}$ phase space, the energy spectrum, the $x - x'$ (polarization direction) phase space, and the $y - y'$ phase space at the electron exit from the LWFA stage, respectively.

The electron bunch, carrying a total charge of $\sim 120$ pC, has a mean energy $\mathcal{E} \simeq 217$ MeV, when particles with energy greater than 100 MeV are selected, with energy spread $\sigma_{\mathcal{E}} \simeq 21\%$. The linear polarization of the laser results in the bunch exhibiting an asymmetrical structure in the phase space, with larger root-mean-square (rms) dimension in the polarization direction ($\sigma_x \simeq 1.67$ $\mu$m) rather than in the orthogonal one ( $\sigma_y \simeq 0.99$ $\mu$m). The total rms divergence on the solid angle is $\sigma_s \simeq 3.39$ mrad.

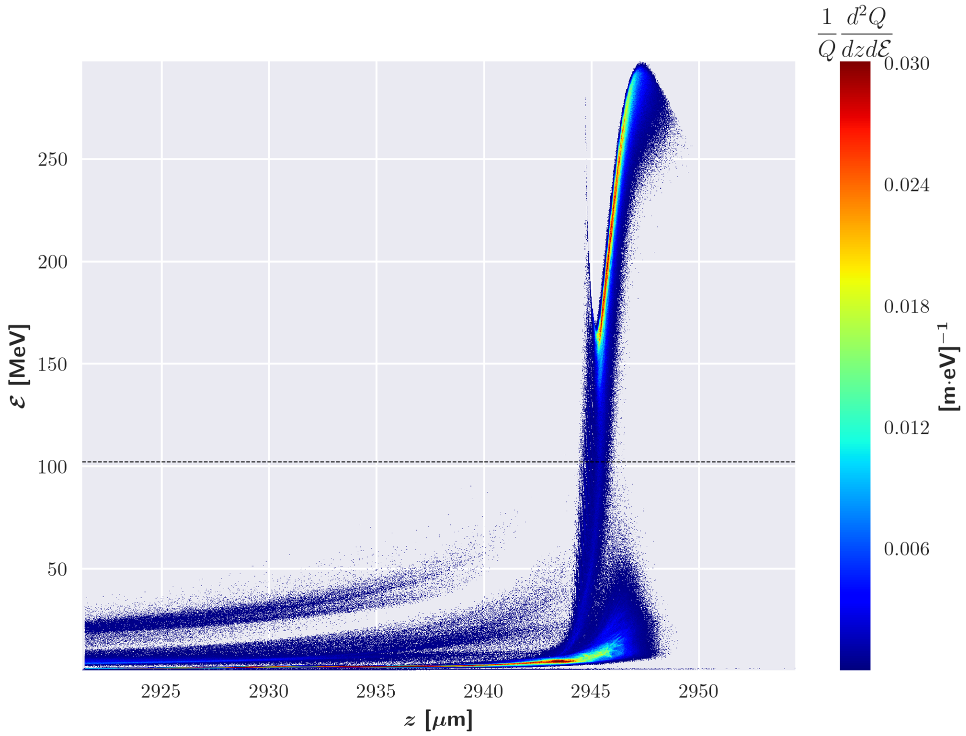


Figure 1: Bunch distribution in $z - \mathcal{E}$ phase space, out of plasma; black dashed line denotes the 100 MeV energy cut used in the paper.

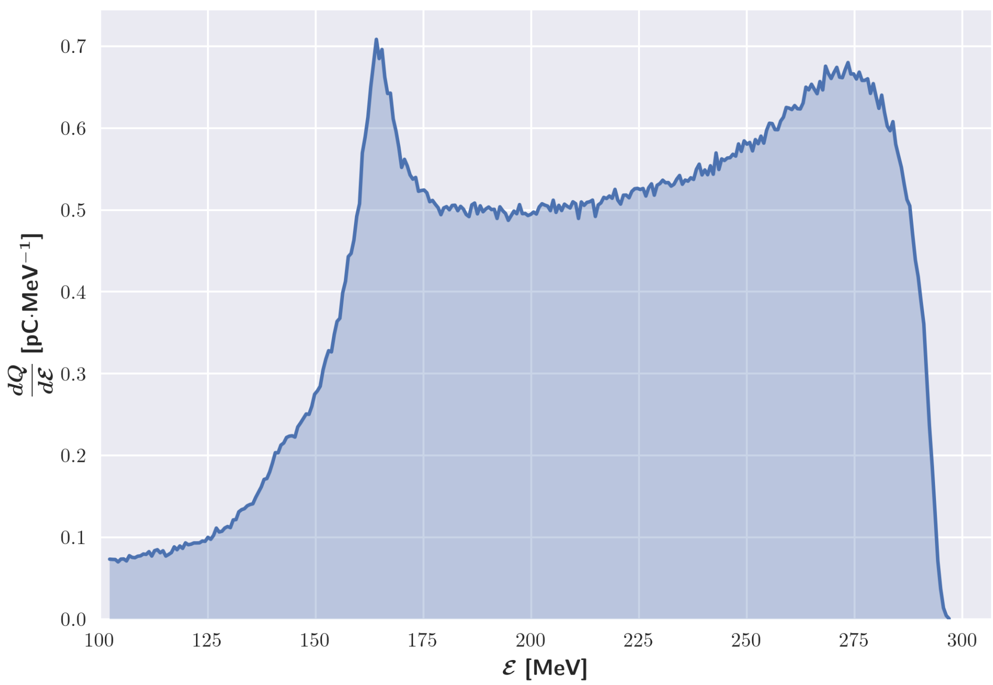


Figure 2: Energy spectrum with energy cut at 100 MeV. Mean energy is 217 MeV, with energy spread $\sigma_{\mathcal{E}} = 21\%$. Total carried charge $Q \simeq 120$ pC.

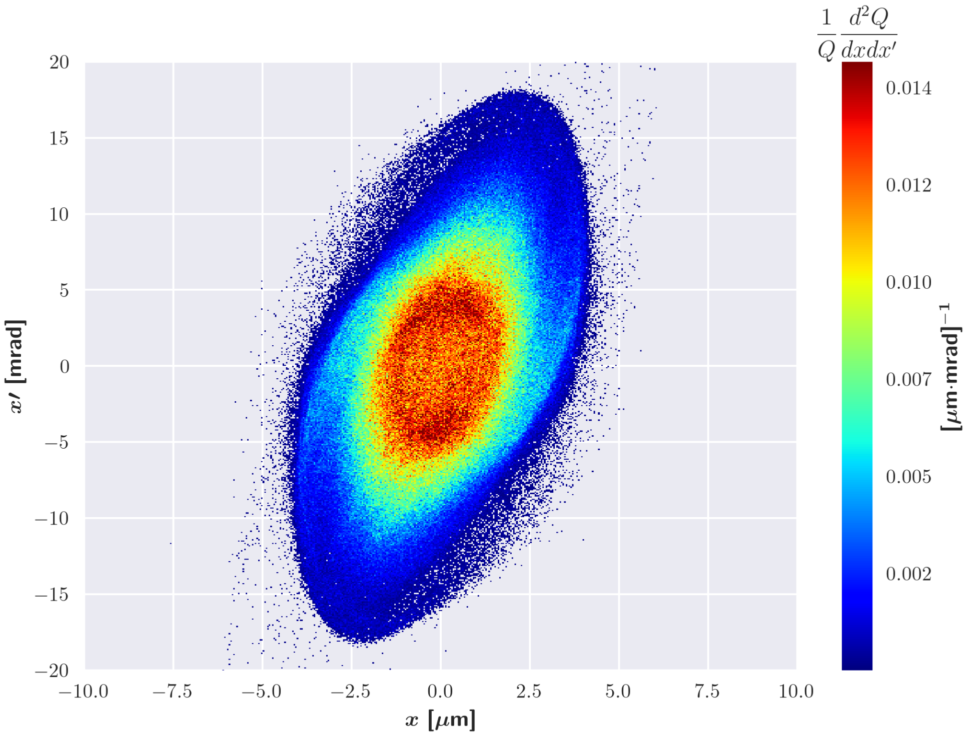


Figure 3: Transverse trace space $x - x'$. Rms bunch size $\sigma_x = 1.67$ $\mu$m and rms divergence $\sigma_{x'} = 5.89$ mrad.

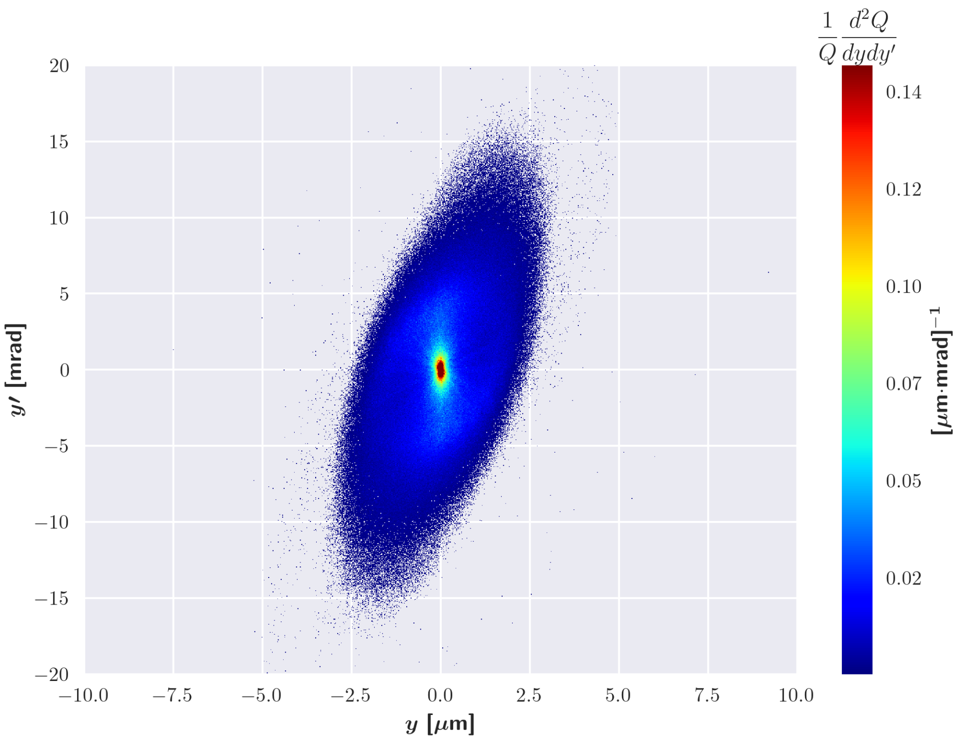


Figure 4: Transverse trace space $y - y'$. Rms bunch size $\sigma_y = 0.99$ $\mu$m and rms divergence $\sigma_{y'} = 4.44$ mrad.

# References

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