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Very High Energy Electrons with high charge and moderate energy spread from laser-wakefield acceleration

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Abstract

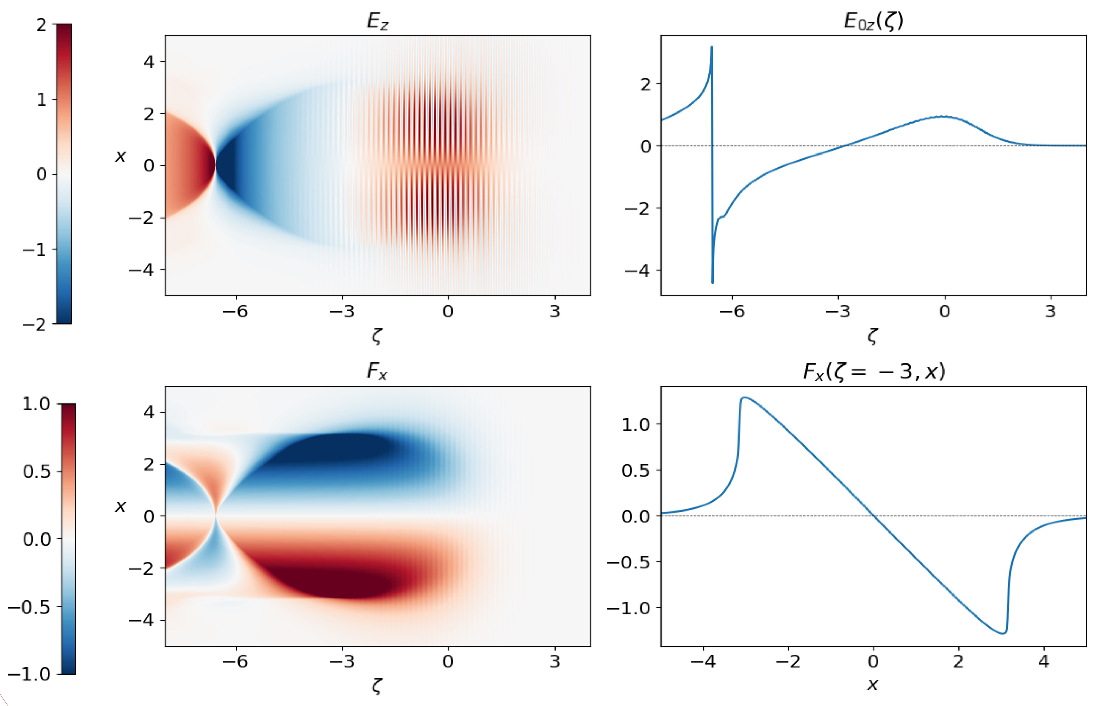
The use of Very High Energy Electrons (VHEE) for deep seated tumors treatment has been considered in the past as an alternative to photon irradiation[1]. More recently VHEE has been proposed in the context of FLASH radiotherapy[2]. In a recent work[3] we explored the use of laser-driven electron beams as an effective approach to VHEE radiotherapy. The high accelerating gradients of Laser Plasma Accelerators (LPA), in contrast to conventional Radio Frequency (RF) cavities, are well suited for the production of these electrons in terms of high peak dose rate, with energy ranging from ≃ 50 MeV up to ≃ 250 MeV to limit lateral dose spread. Overall, LPAs have the remarkable feature of being very compact in size, meeting cost-efficiency requirements for clinical purposes. In this context LPA-VHEE beams are well suited to meet the requirements of FLASH radiotherapy[4].
As pointed out in [3], the spectral features (high energy spread) and quality of the electron bunch affect the behaviour of dose deposition: these properties can be improved by several LPA schemes, usually at the cost of bunch charge. In this work we present the numerical study of an acceleration scheme in which a relative high charge (115 pC), ionization-injected electron bunch is accelerated by an intense laser-driven plasma "bubble" up to energy E = 220 MeV, with energy spread σ_E= 5.6%. A strategy for further increasing the bunch charge and to meet the requirements of VHEE-RT is outlined.

Motivations

The dose rate needed for FLASH treatments requires high beam intensity, which is out of the range of operation of existing clinical electron accelerators used for the treatment of deep seated tumors.
Electron beams able to deliver FLASH dose rates, for instance, have been obtained by standard medical accelerators, providing beams with a suitable quality for radiobiology and medical experiments but with typical energy up to ~ 20 MeV.
In this context, the use of Very High Energy Electrons (VHEE) in the range between 100 and 250 MeV is considered extremely promising for clinical applications and laser-driven particle accelerators are promising candidates to provide VHEE beams with the required characteristics for novel RT treatments exploiting the FLASH effect.
In this view we conducted a numerical study of an accelerating scheme in which a laser-driven plasma wave is excited in the so-called *bubble regime*. The strong fields associated to such plasma waves accelerate and focus electrons injected via ionization[5] of Nitrogen. To prevent beam degradation at the plasma exit we studied the effects of adiabatic defocusing in the plasma downramp, following Floetmann K.[6].

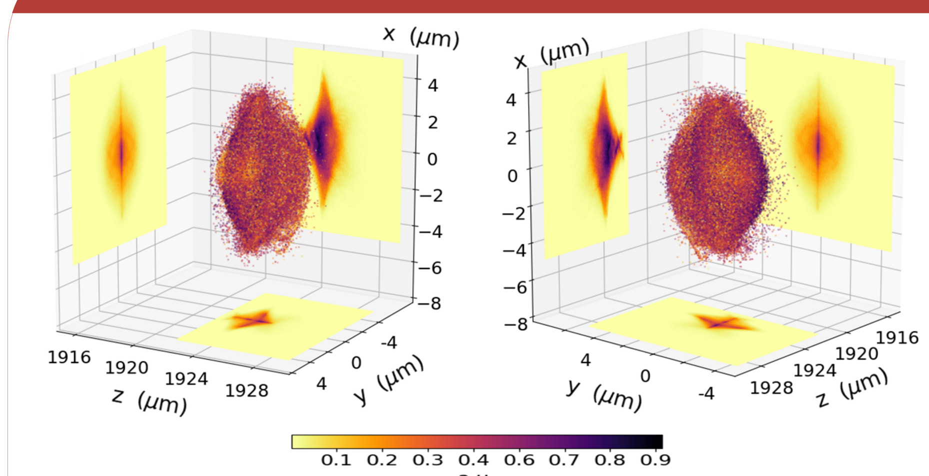
Laser-plasma parameters and characterization

Considering the matching conditions for a well-guided plasma bubble wakefield, the chosen laser driver is a Ti:Sa gaussian pulse with duration T_{rms} = 37 fs, waist w_0 = 19 μm and power P = 110 TW, *i.e.* an intensity on the target I ≃ 1.9 × 10^{19} W/cm ^{2}. This driver is able to guide a well defined "bubble" wakewave in a Helium plasma target 2 mm long whose electron background density is n_{0e} = 9× 10^{17} cm^{-3}, while in order to prevent an excess of trapped charge, which in turn modifies the accelerating field by *beam loading* effects, the Nitrogen is confined in a short strip 400 μm long. On the other hand, the concentration of Nitrogen in the He-N_2 mixture in the strip was set up to 1% of neutrals density (*i.e.* n_{N2}≃ 4.4 ×10^{15}cm^{-3}) to have the maximum trapped charge without incurring in beam loading (see ref.[5]).



The laser pulse propagates along the longitudinal direction z and is linearly polarized along the x direction.
In the figure on the left, in the first row the longitudinal accelerating field E_z normalized to $E_0 \simeq 90$ GV/m while in the second row the focusing force (calculated as the electromagnetic force on a relativistic electron) normalized to $E_0' \simeq 4$ TV/m .
$\zeta = z - ct$ is the longitudinal coordinate in the laser frame; coordinates are normalized to $k_p = \omega_p/c$ where ω_p is the *plasma frequency* associated to n_{0e} .

Characterization of bunch and extraction with adiabatic defocusing

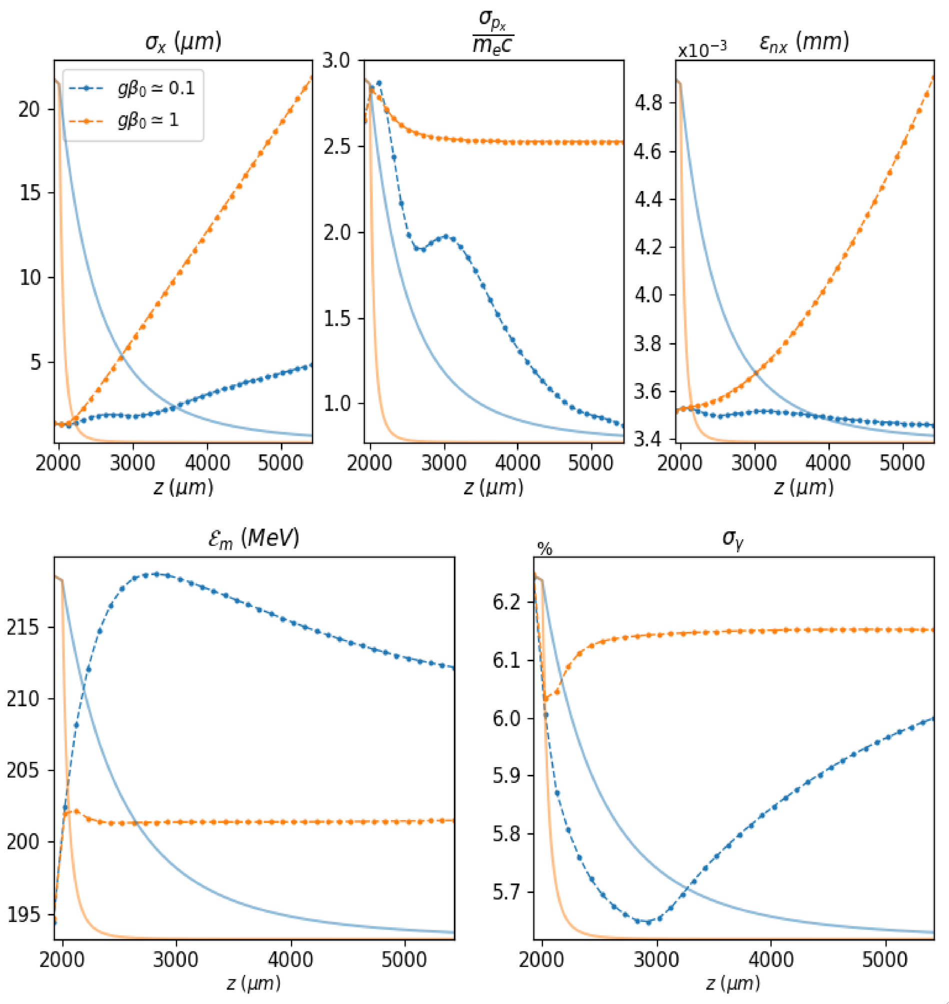


Before entering the downramp section the injected charge is Q = 115 pC with mean energy E_m = 195 MeV and energy spread σ_E = 6%. On the right a tri-dimensional reconstruction of the bunch in real space with colormap indicating the concentration of charge: as can be seen the bunch is asymmetric, squeezed along the x direction. This is due to the linear polarization of laser which gives more momentum in the polarization direction to the particles during the ionization.

In the table some bunch parameters, where ε_{nx} is the normalized emittance and σ_x, σ_{px} are the second order central moments of the phase space distribution of bunch electrons along the x direction: we notice that in the case of the density gradient there is an improvement of the momentum spread, which is helpful for the extraction of the bunch from the acceleration stage.

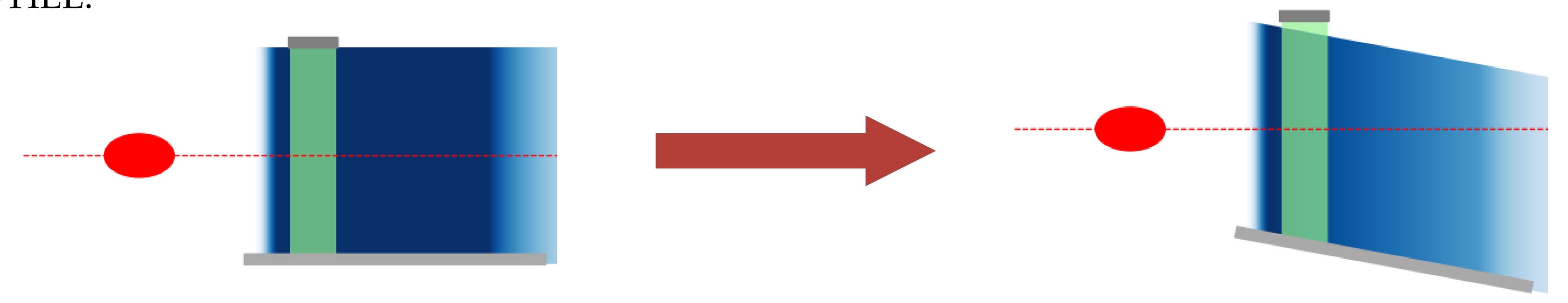
	ε_{nx} ($\times 10^{-3}$ mm)	σ_x (μm)	$\sigma_{p_x}/m_e c$
plateau	3.55	1.14	3.12
ramped	3.51	1.33	2.65

In order to be sent to a usual beam transport line, where a large beam size and a small divergence are required, accelerated bunches at the exit of a plasma need a transition downramp section which allows a controlled beam expansion without emittance degradation.
In the case of bubble regime, when the forces are linear, the defocusing can be easily controlled via density transition. Providing a de-focusing (see ref.[6]) in the form $n_{0e}/(1+gz)^4$, where g is a tapering parameter and adiabaticity is assured by $g\beta_0 \ll 1$ (β_0 is the bunch Twiss parameter at the downramp) the adiabatic de-focusing compensate the emittance pressure on the bunch, allowing a reduction of its divergence and avoiding emittance degradation. With $\beta_0 \simeq 0.19$ mm at the end of the acceleration section, in the figure on the right is shown a comparison with an almost "free-drift" downramp. As result, in the adiabatic case emittance is conserved and the bunch is further accelerated to mean energy ~220 MeV with a minimum energy spread of 5.6%



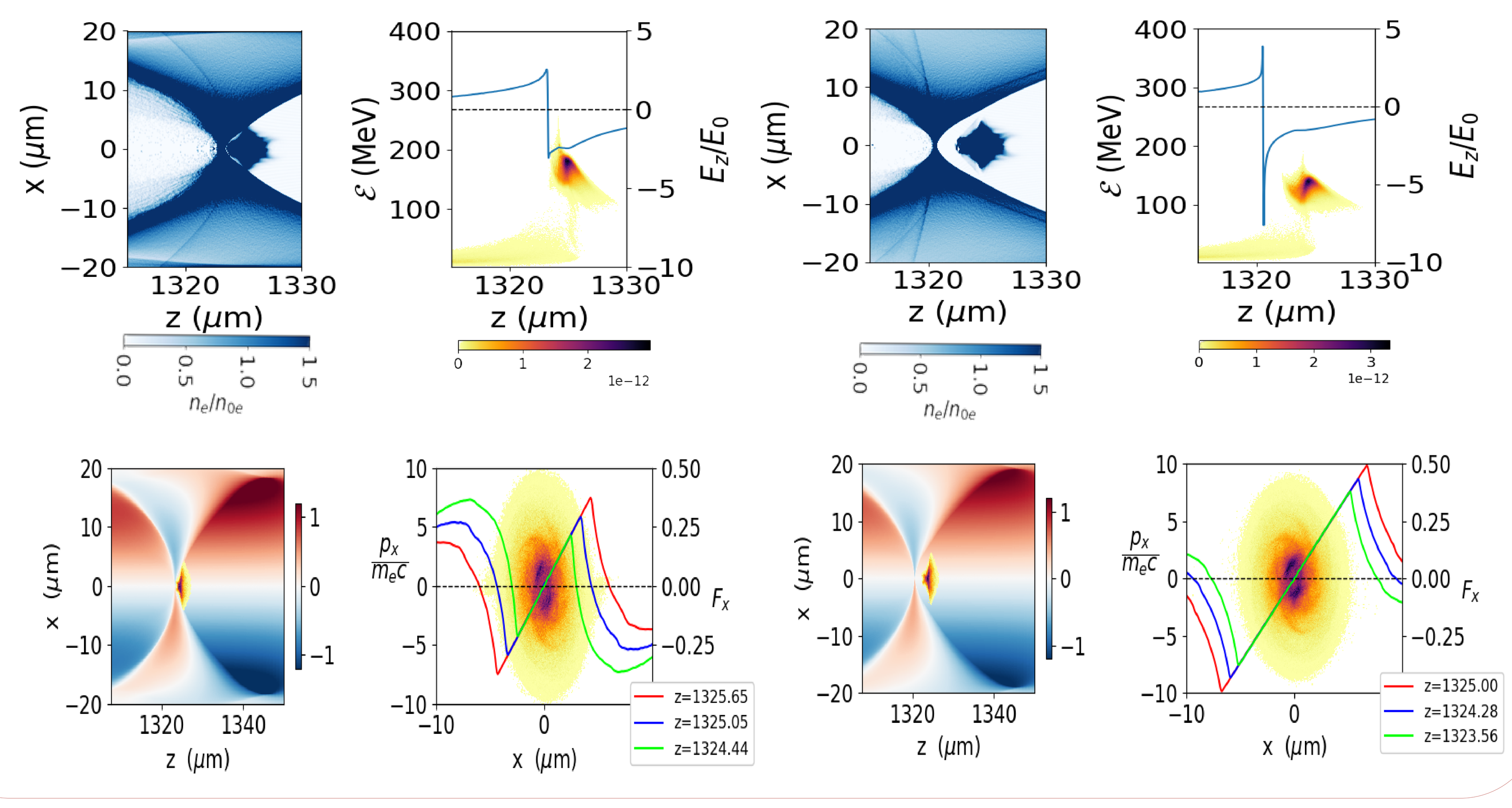
Density gradient of plasma target

During the acceleration the injected bunch stays in phase with the rear of the bubble, where the longitudinal accelerating field dramatically "falls" to high accelerating values in length-scale comparable with the longitudinal dimensions of the bunch ($\sim 3\,\mu m$), so there are "tail" bunch electrons that acquire more energy than the "head" ones: this causes a tilting of the energy distribution of bunch electrons, increasing the energy spread. Besides the longitudinal electric field is more sensible to beam loading at the bubble rear.
To solve this problem an "artificial" dephasing between the bubble rear and the bunch is introduced with a negative density gradient of the background plasma which elongates the *plasma wavelength* (approximately equal to the diameter of the bubbke): this gradient has to be smooth enough to do not trigger any injection of plasma background electrons. As countepart the bunch gains less energy, but remaining in the ranging of VHEE.



Experimentally this can be obtained tilting the gas target noozle with respect to the laser propagation direction.
Moreover, considering the focusing forces along the trasverse directions, the transverse dimensions of the bunch are such that parts of the bunch are subjected to non-linear components of the focusing force which warp the transverse phase space distribution and compromising the quality of the bunch in terms of emittance and momentum spread.

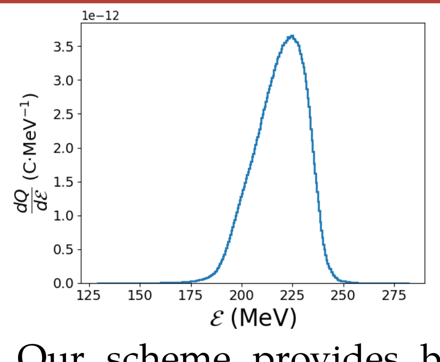
Density plateau **Density gradient**



Simulations

Simulations where performed using the FBPIC code[7], a spectral, quasi-cylindrical particle in cell code which exploits the cylindrical symmetry of laser-plasma systems to reconstruct the tridimensional behaviour using bidimensional (r, z) grids, one for each azimuhal mode (m = 0,1 in our case): the cell resolution is (0.067 x 0.023) μm² with 10 particles per cell, while the temporal resolution of the PIC-loop is Δt = 0.08 fs

Conclusions



In the view of using VHEE for FLASH radiotherapy, which usually requires dose rates of 40 Gy/s, high charge bunches are beneficial to reduce the number of bunches needed to achieve the therapeutic dose in the FLASH temporal window of 200 ms, thus relaxing the repetition rate of operation. With bunches like ours a minimum repetition rate of ~100 Hz is needed, but an increase of injected charge can further relax this repetition rate: in this sense, using our scheme, the injected charge can be increased extending the N_2 strip of few hundreds μm and slightly raising the concentration.

Our scheme provides bunches with relative low emittance and moderate energy spread. The low emittance enables controlled beam transport and focusing and controlled dose delivery. This can be achieved using an adiabatic transiction section at the exit of the acceleration stage. Moreover, a moderate energy spread assures a more reliable control of beam stability and longitudinal dose deposition.

References

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