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

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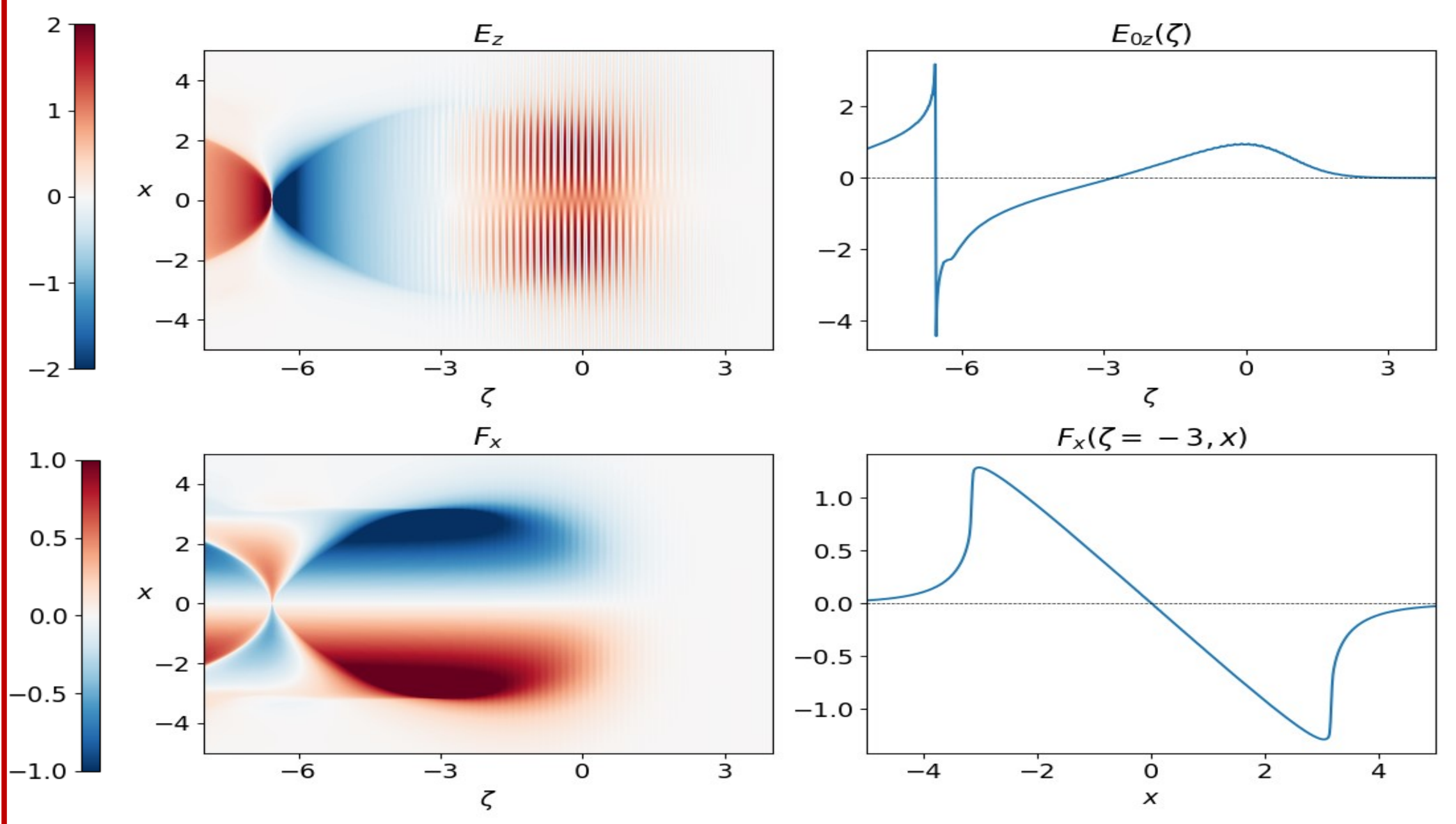
Motivations

The use of Very High Energy Electrons (VHEE) for deep seated tumors treatment, with energies ranging between ≃50 MeV and ≃250 MeV, has been considered as an alternative to photon irradiation[1]. More recently VHEE has been proposed in the context of FLASH radiotherapy[2,3]. The dose rate needed for FLASH treatments requires high beam intensity, which is out of the range of operation of existing clinical electron accelerators. In a recent work[4] we explored the use of laser-driven electron beams as an effective approach to VHEE radiotherapy. Laser Plasma Accelerators (LPA) are well suited for the production of these electrons in terms of energy, thanks to the high accelerating gradients, and ultra-high instantaneous dose rate, due to the typical short duration of bunches. On the other hand, the spectral features (high energy spread) and quality of these electron bunches 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 enanched spectral features (energy spread σ_E= 5.6%). A strategy for further increasing the bunch charge and to meet the requirements of VHEE-RT is outlined.

Laser-plasma parameters and characterization



Laser parameters

- Linear polarization (x)
- $I \simeq 1.9 \times 10^{19}$ W/cm^2
- $\tau_{rms} = 37$ fs
- $w_0 = 19\ \mu$m

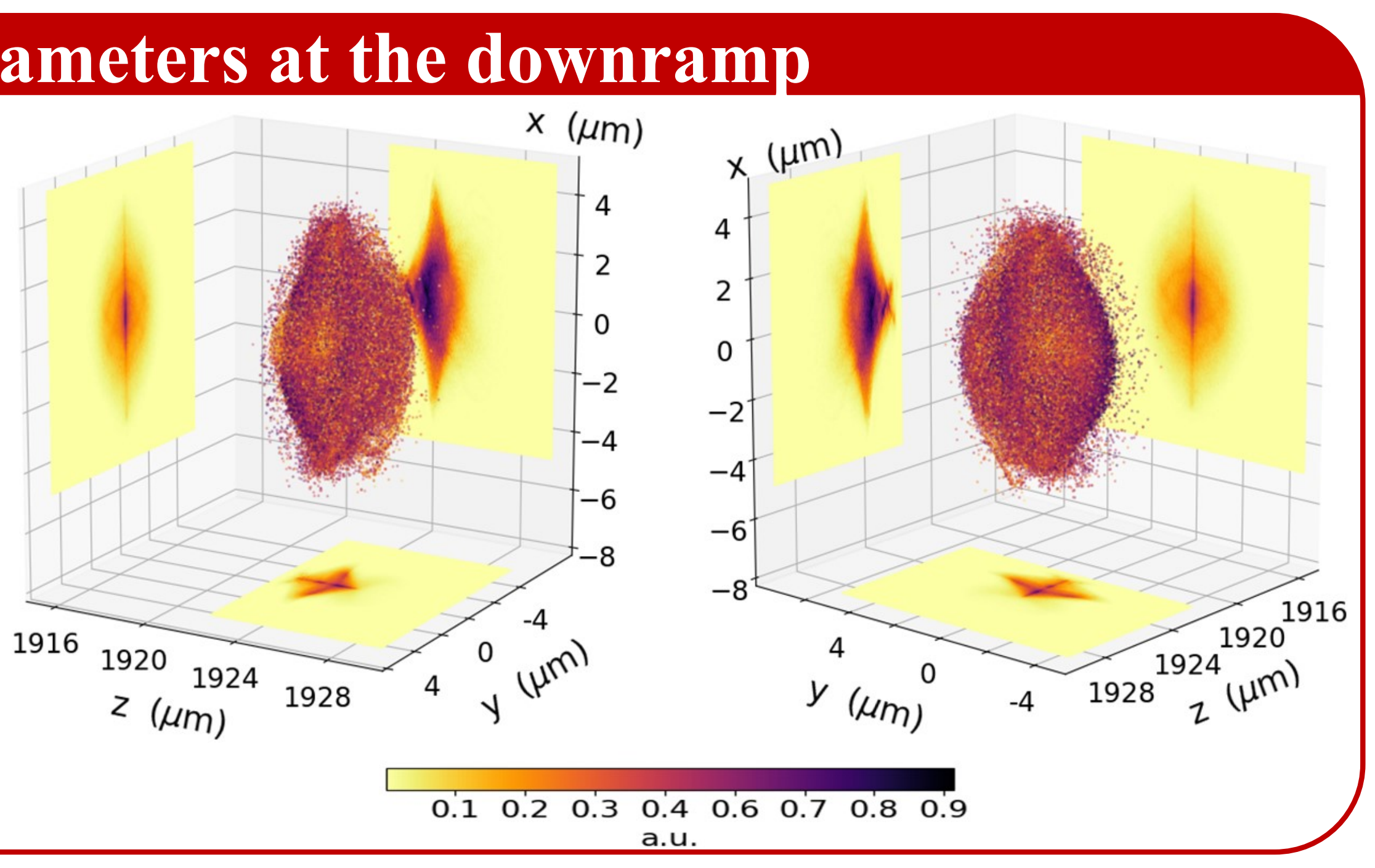
Fields are normalized to $E_0 \simeq 90$ GV/m, while coordinates are normalized to $k_p \simeq 0.18\ \mu$m^{-1}.

A Ti:Sa laser pulse with power P = 110 TW propagates in a 2mm long Helium plasma with electron density $\boldsymbol{n_{0e} = 9 \times 10^{17}}$**cm**$^{-3}$, exciting a *bubble* wake. The electrons to be trapped are extracted by means of ionization[5] of Nitrogen N_2 confined in a 400 μm long He-N_2 strip to have the maximum trapped charge without incurring in *beam loading.* The N_2 concentration in the strip is 1% of the mixture.

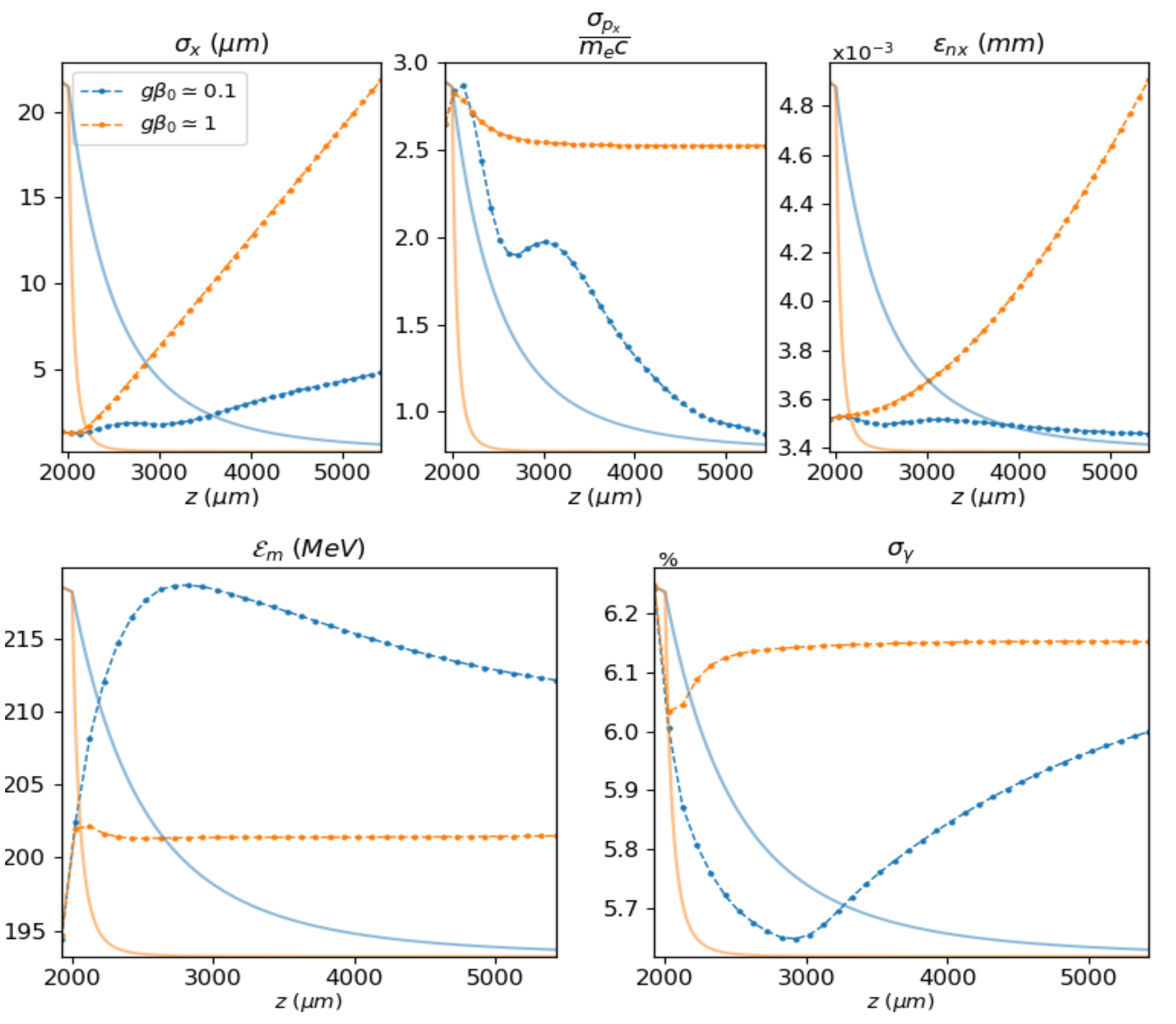
Bunch parameters at the downramp

	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

Before entering the downramp section the injected charge is **Q=115 pC** with mean energy $\mathbf{E_m}$ **=195 MeV** and energy spread $\boldsymbol{\sigma_E = 6\%}$.



Extraction with adiabatic defocusing

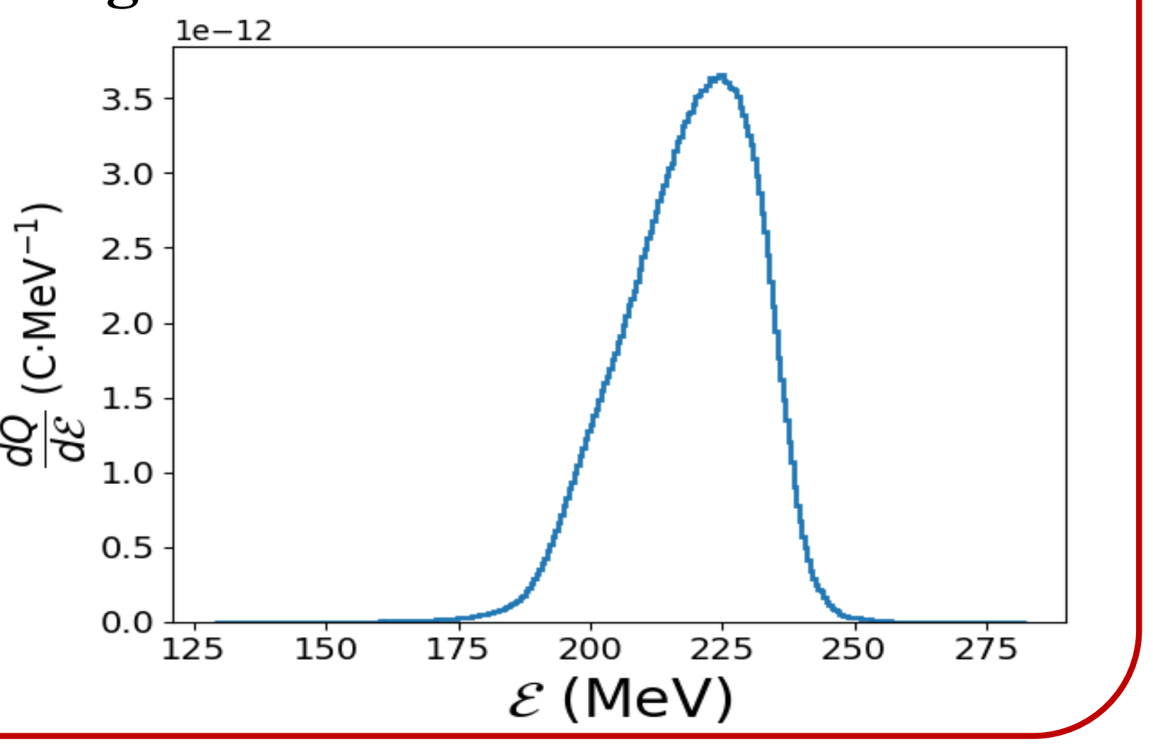


The bunch defocusing can be controlled via an **adiabatic density transition**, providing a downramp profile (see ref.[6]) in the form

$$\frac{n_e}{(1+gz)^4}$$

(adiabaticity is assured by $g\beta_0 \ll 1$, where $\beta_0 \simeq 0.19$ mm is the bunch Twiss parameter at the downramp). This allows the **reduction of bunch divergence without emittance degradation**.

Comparison with an almost "free-drift" downramp: 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%**



FBPIC simulation

Simulations were performed using the FBPIC code[8], 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) μm^2 with 10 particles per cell**, while the temporal resolution of the PIC-loop is Δ **t = 0.08 fs**

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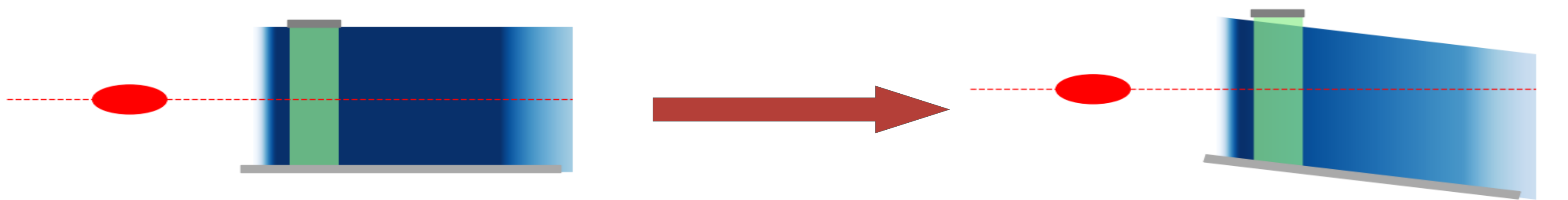
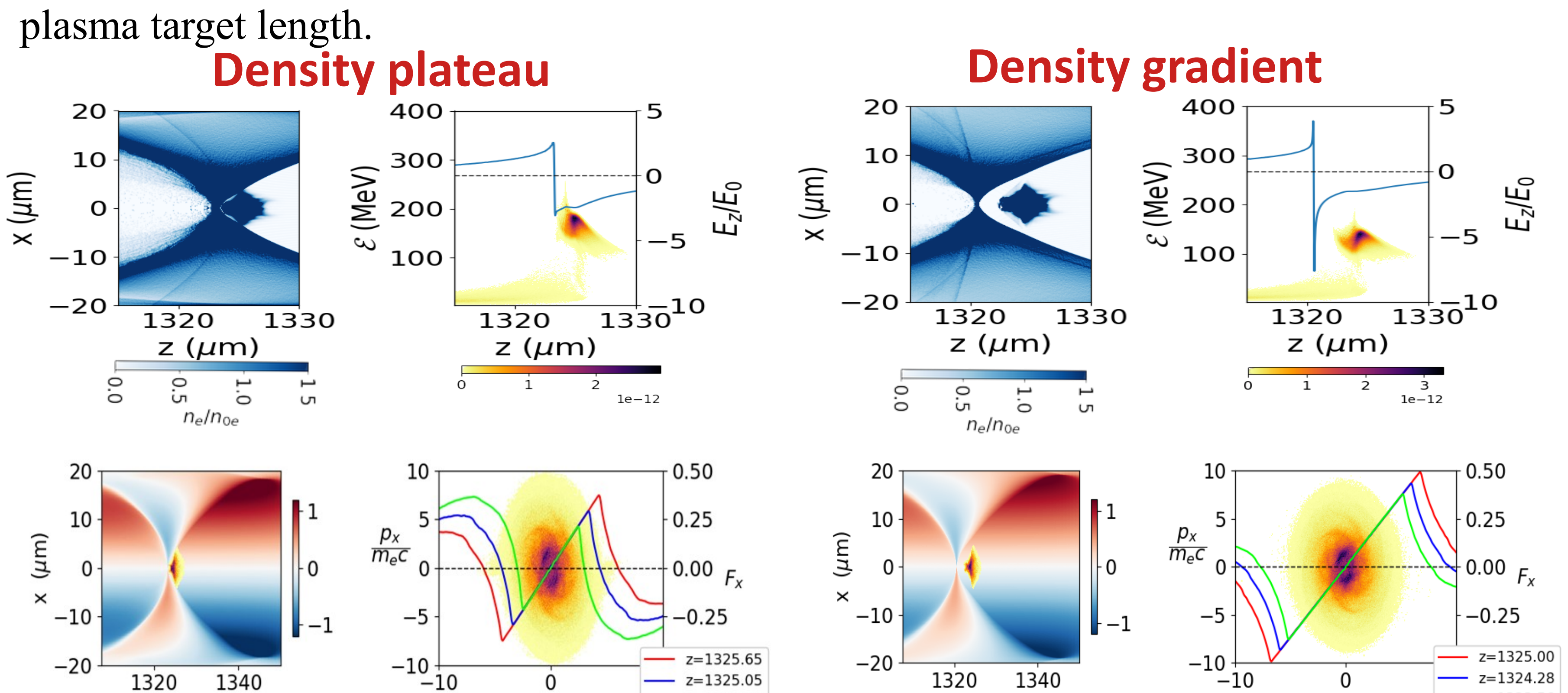
Wavelength lengthening via density gradient



An "artificial" dephasing between the bubble rear and the bunch is introduced with a **negative plasma density gradient**, which elongates the *plasma wavelength,* smooth enough to do not trigger any injection from density transitions. In this way we assure an **homogeneous accelerating field** along the bunch length and **linear focusing forces** across the bunch width for all bunch slices. The density is reduced of the 25% over the plasma target length.



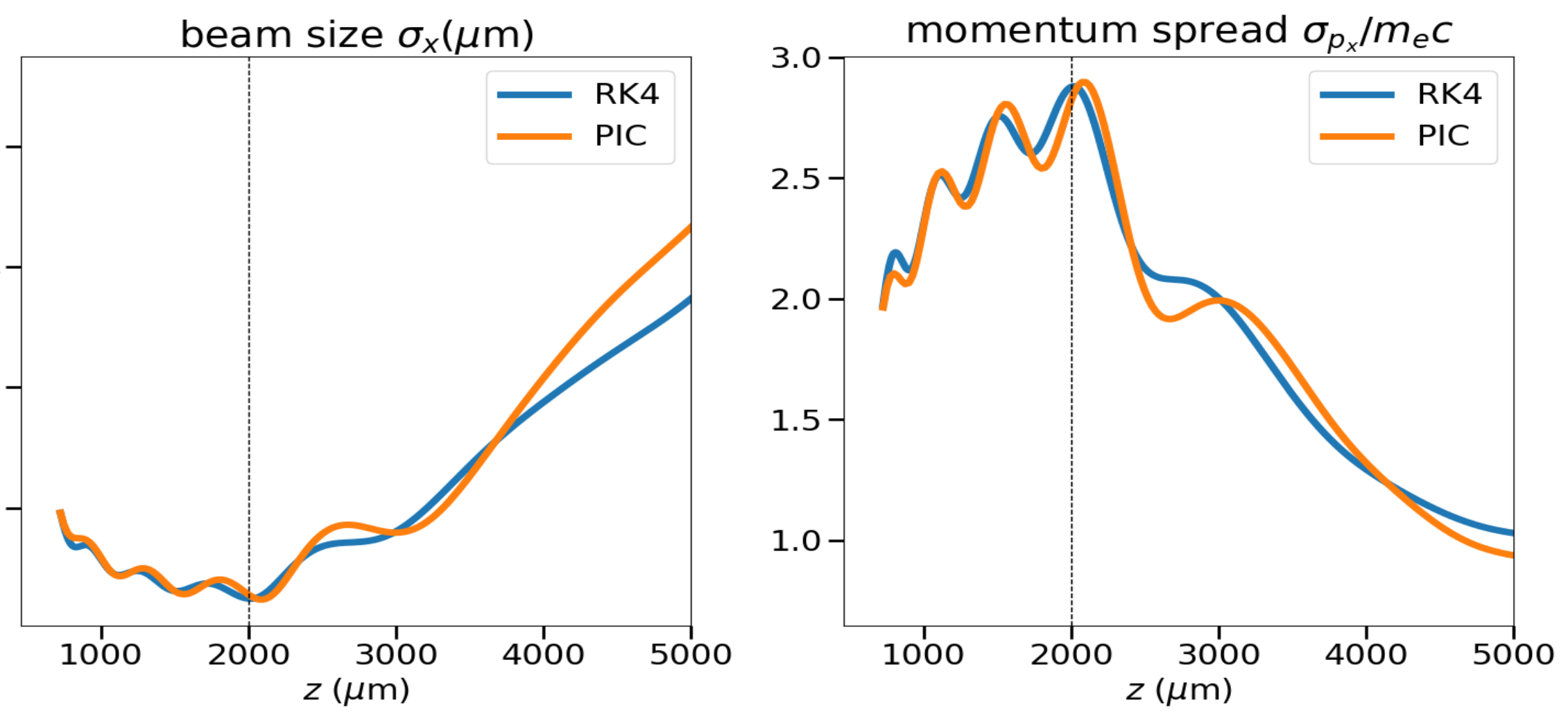
Invariant envelope model

The motion of a particle beam in a simultaneously accelerating and focusing system, such as a plasma bubble, can be studied by means of ***envelope equation***[7] for the bunch size σ_x (we focus only on the laser polarization direction).

$$\sigma_x'' + \frac{\gamma'}{\gamma}\sigma_x' + \frac{k_p^2}{2\gamma}\sigma_x = \frac{\varepsilon_n^2}{\gamma^2\sigma_x^3}(1+\hat{\rho})$$

where γ is the bunch mean energy and the focusing $k_p^2/2\gamma$ depends on z, through density profiling. In our case the bunch propagates in *thermal regime* ($\hat{\rho} \ll 1$) and its energy distribution has negligible energy spread; along with the ***invariant envelope*** **transormation** $\sigma_x \rightarrow \widehat{\sigma_x} = \sigma_x\sqrt{\gamma}$ and the **equation for mean energy evolution** we have the following ODE system:

$$\boxed{\begin{aligned} \frac{d\widehat{\sigma_x}}{dz} &= \widehat{\sigma_x}' \\ \frac{d\widehat{\sigma_x}'}{dz} &= \frac{\varepsilon_{nx}^2}{\widehat{\sigma_x}^3} - \frac{\widetilde{k_p}^2}{2\gamma}\widehat{\sigma_x} \\ \frac{d\gamma}{dz} &= -\frac{e}{m_e c^2}\langle E_z\rangle \end{aligned}}$$



where $\langle E_z\rangle$ is the mean longitudinal field on the bunch and $\widetilde{k_p}^2 = k_p^2 + \frac{\gamma'^2}{2\gamma} - \gamma''$. Providing $n_p \gg \frac{\varepsilon_0\langle E_z\rangle^2}{2m_e\gamma c^2} + \frac{\varepsilon_0}{e}\langle E_z\rangle'$ ($n_p = n_i - n_e$ is the effective background density at bunch position) we can approximate $\widetilde{k_p} \approx k_p$ and solve the system with a 4th-order Runge-Kutta (RK) method, with the normalized emittance ε_{nx}, the effective density n_p and $\langle E_z\rangle$ evaluated from PIC simulation. There is agreement between the RK solution and PIC results untill $z \simeq 4$ mm, where the bunch can be considered out of the plasma.

Conclusions

In view of using laser-driven VHEE beams for FLASH radiotherapy, **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. With bunches like ours a minimum repetition rate of ~100 Hz is needed. A further increase of charge will reduce the required repetition rate: with our scheme the **injected charge can be increased extending the N_2 strip** of by a few hundreds μm and slightly **raising the concentration**. Our scheme provides bunches with **relative low emittance**, which enables controlled beam transport and focusing and controlled dose delivery, and **moderate energy spread**, which assures a more reliable control of beam stability and longitudinal dose deposition.

References

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