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Plasma Wakefield Acceleration: a parametric model for fast beam dynamics integration

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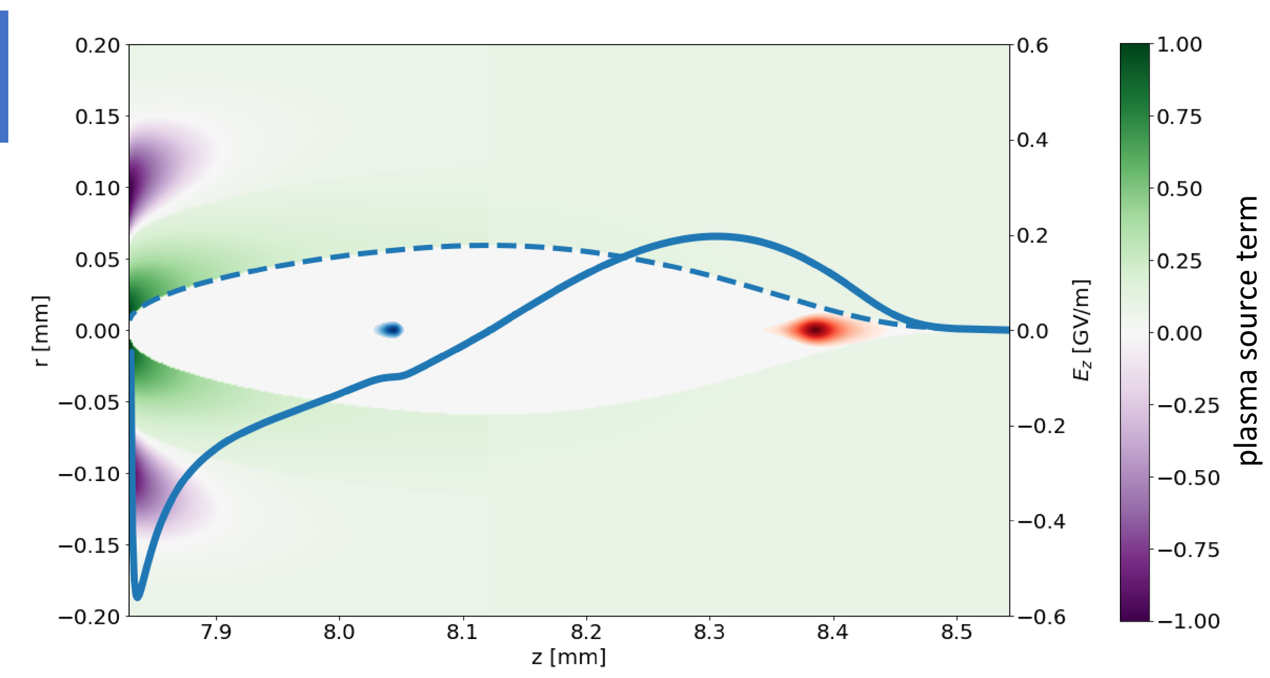
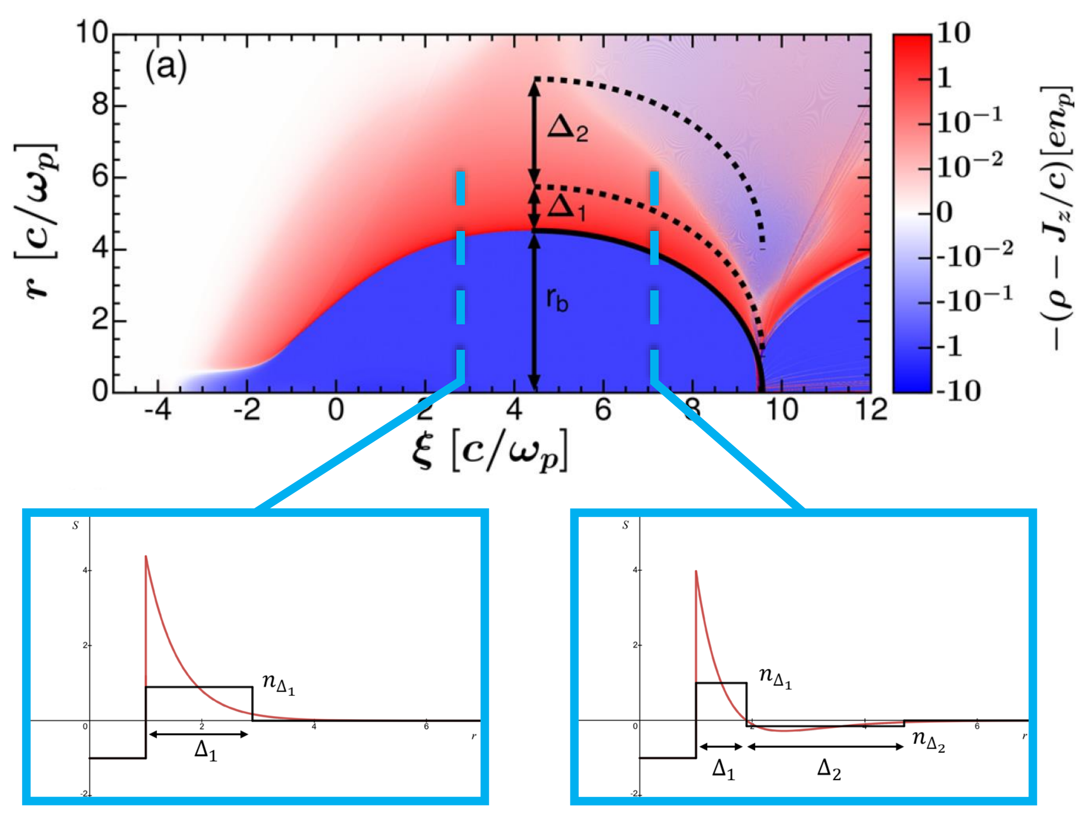
ABSTRACT

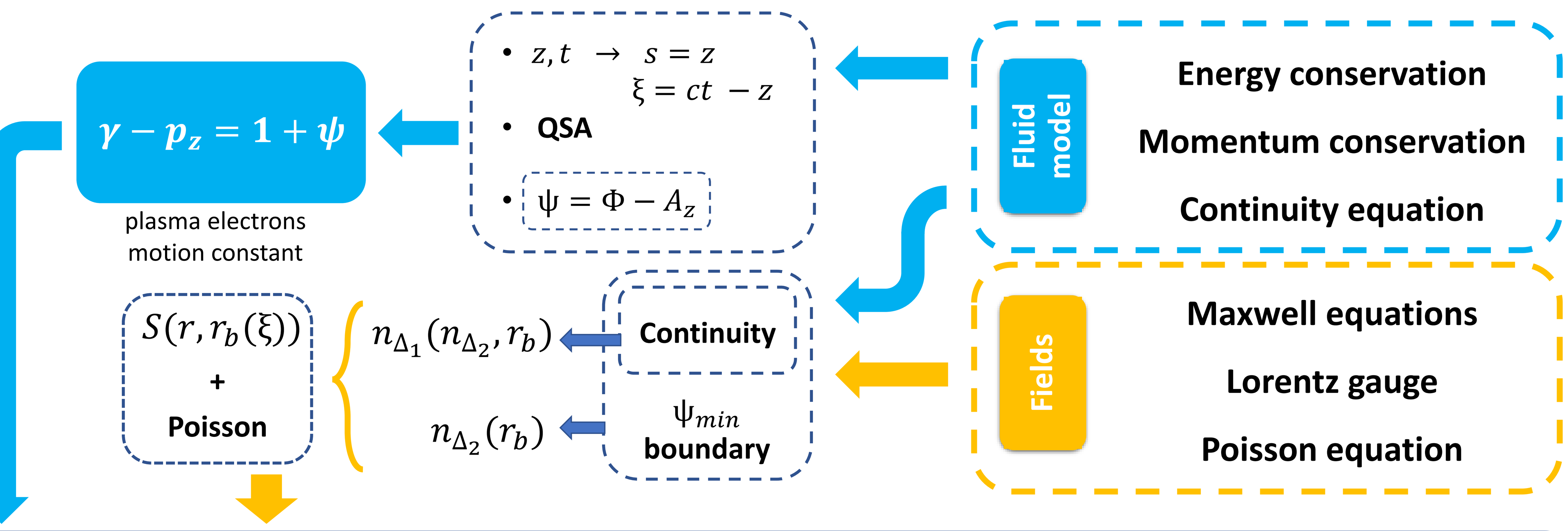
The state of the art in terms of Plasma Wakefield Acceleration simulation accuracy are Particle in Cell (PIC) codes, based on kinetic models which require hard numerical integration and execution times of hundreds of hours on processors clusters for centimeter-long simulations. During my Master's thesis a computationally lighter model was developed, able to accurately reproduce the most significant aspects of the process in shorter execution times, setting a starting line for identification of work points and optimal beam injection conditions. The code lays on a multi-fluid superposition plasma model (Lu et al. [1], Dalichaouch et al. [2]): charge density and currents are calculated via continuity equation through a semi-empirical parametrization of fluid regions ratios, tuned by fit on PIC simulation results. Under quasi-static approximation, plasma response and wakefields are calculated at each time step for a given beam profile and used to compute beam slices evolution. Beam energy, emittance and energy spread evolution were validated on PIC simulation and linear model results, featuring high accuracy and showing model ability to reproduce nonlinearities and to range in different plasma response regimes. The code can be run on a laptop, giving execution times four orders of magnitude shorter than a PIC code executed on a processors cluster.



Parametric model ouput render. Color variable: plasma source term. Dashed line: calculated blowout region profile. Solid line: longitudinal wakefield.



PHYSICAL MODEL



hybrid model

$$A(r_b)\frac{d^2 r_b}{d\xi^2} + B(r_b) r_b \left(\frac{dr_b}{d\xi}\right)^2 + C(r_b) r_b = \frac{\lambda(\xi)}{r_b}$$

blowout radius equation

$$\psi(r,\xi) = \frac{r_b^2(\xi)}{4}\left(1+\beta(\xi)\right) - \frac{r^2}{4}$$

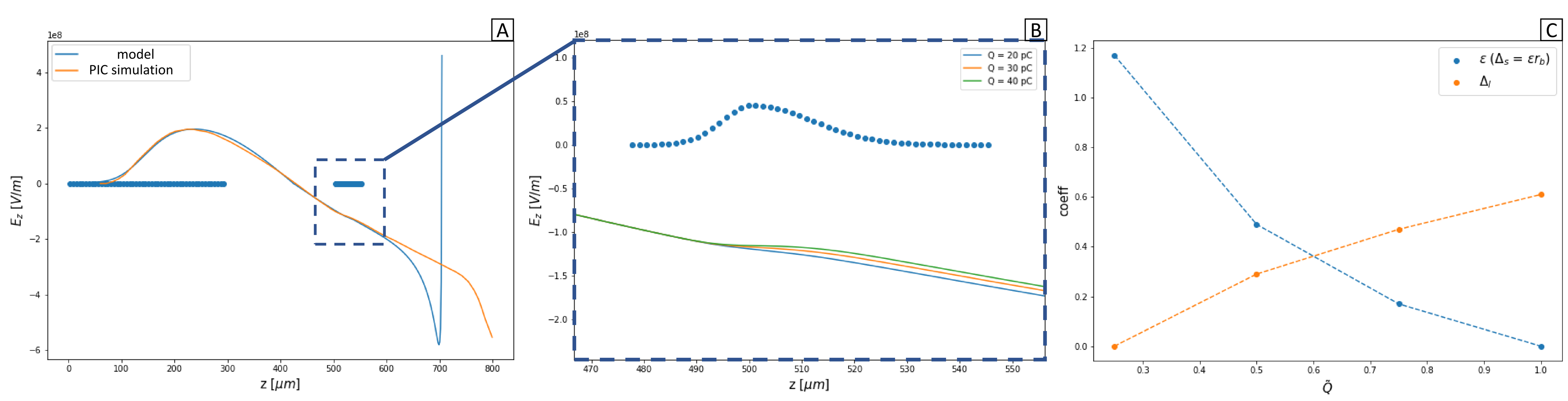
pseudopotential

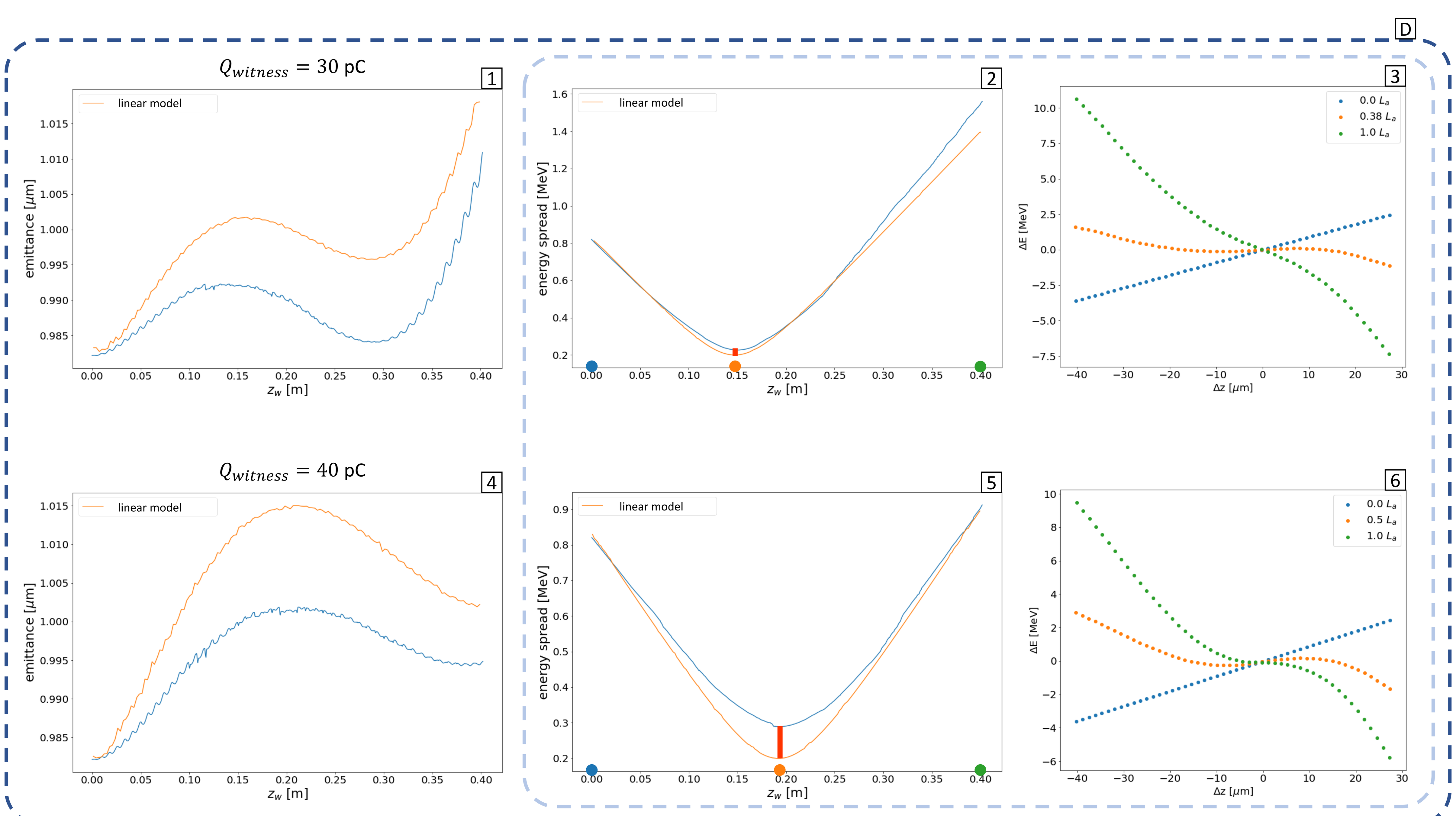
+

$$\sigma_x'' + \frac{\gamma'}{\gamma}\sigma_x' + \frac{k_{ext}}{\gamma m_0 c^2}\sigma_x = \frac{\varepsilon_{x,n}^2}{\sigma_x^3\gamma^2} + \frac{k_{sc}}{\sigma_x \gamma^3}$$

envelope equation

RESULTS





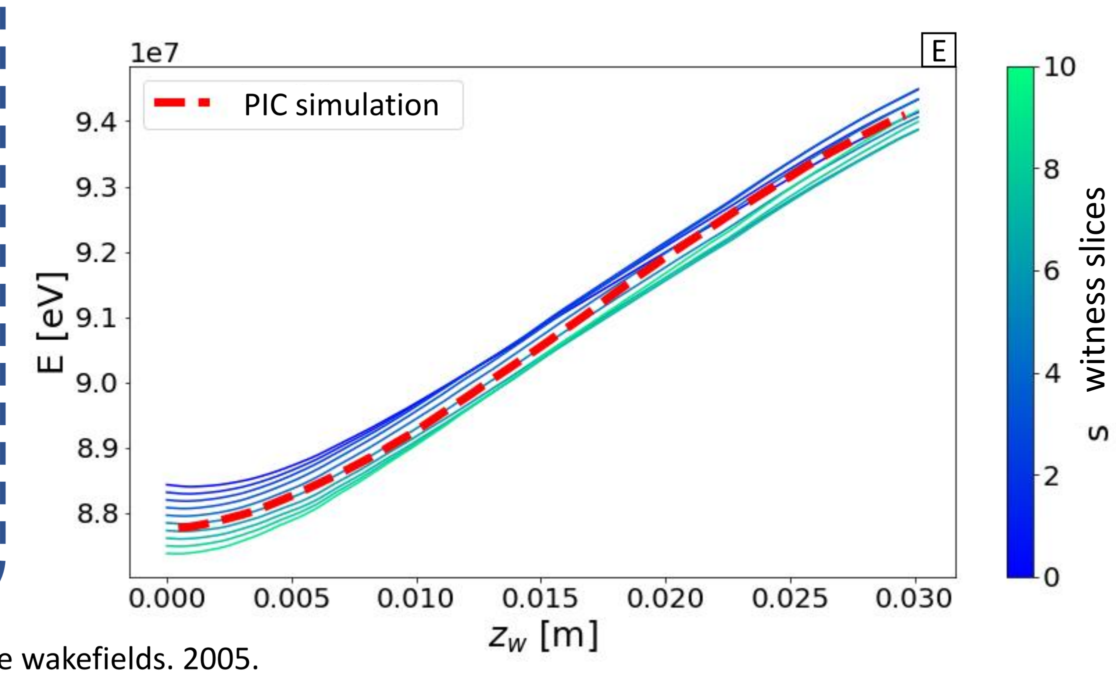
A: longitudinal field, comparison with PIC simulation results [4]. Thick blue lines show driver (left) and witness (right) beams slices positions. Blowout region size is underextimated due to oversimplified model for bubble's rear part.

B: beam loading effect detail. Dotted line shows adimensional witness charge density profile. Longitudinal field nonlinearity grows with beam charge.

C: model parameters best fit for different $\tilde{Q}$ values. Fits were performed on PIC smulation results [3]. Ranging from linear to nonlinear regime, the model adapts showing a neat trend for the fluid regions parameters.

D: witness beam quality evolution, transverse emittance and longitudinal energy spread. Simulation results for witness charge 30pC (1,2,3) and 40pC (4,5,6). Emittance discrepancies with reference linear model simulations [4] are $\leq 1\%$ (1,4). Energy spread minima (orange spots) and trends coincide with linear model output (2,5), showing higher minima values thanks to the nonlinear character of the implemented model: energy spread nonlinearity increases with acceleration length and with witness charge (3,6).

E: witness beam transverse slices energy evolution, comparison with PIC simulation [4]. Transverse distribution second moments envelope equations and motion equations were indipendently integrated for each beam slice.



[1] W. Lu, C. Huang, M. Zhou, M. Tzoufras, F. S. Tsung, W. B. Mori, and T. Katsouleas. A nonlinear theory for multidimensional relativistic plasma wave wakefields. 2005.
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[3] M. Ferrario, S. Atzeni, and A. Marocchino. Comparisons of time explicit hybrid kineticfluid code architect for plasma wakefield acceleration with a full pic code. *Journal of Computational Physics*, 327, 2016.
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