Code benchmarking

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The experiment on proton driven plasma wakefield acceleration in CERN presents a real challenge for numerical simulations. Parameters of the experiment fall far beyond the area for which most codes were originally developed and tuned.

Proton beams are very long, up to several hundreds plasma wavelength. The excited wakefield is a result of an instability and depends on small amplitude seed perturbations.

At the same time, the design of the experiment relies mainly on simulation results rather than on other experiments.

Therefore, it is important to provide a thorough validation of available codes at test problems which contains the main physical effects involved.

Test 1: Long plasma wave

driven by the short unchanging proton bunch:

$$n_b = \begin{cases} 0.5\, n_{b0}\, e^{-r^2/2\sigma_r^2} \left[1 + \cos\left(\sqrt{\frac{\pi}{2}}\frac{\xi}{\sigma_z}\right)\right], & |\xi| < \sigma_z\sqrt{2\pi}, \\ 0, & \text{otherwise}, \end{cases}$$

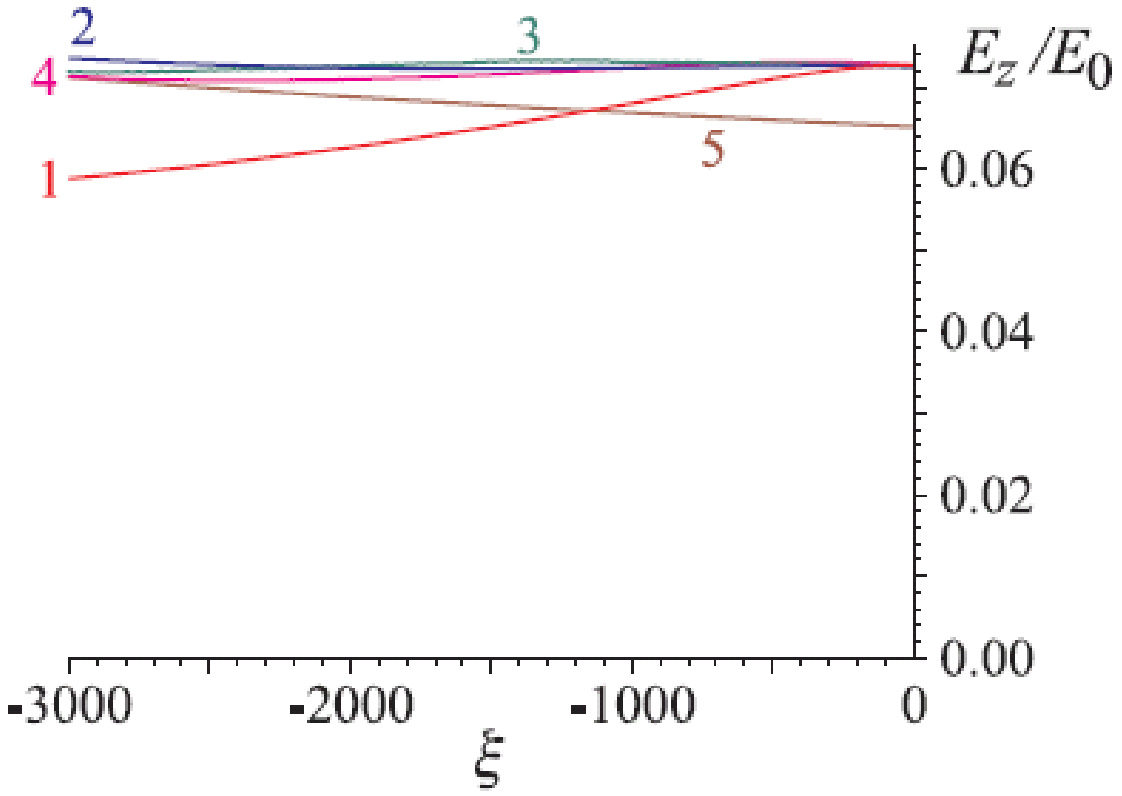
$$\xi = z - ct, \quad \sigma_r = c/\omega_p, \quad \sigma_z = c/\omega_p, \quad n_{b0} = 0.1\, n_0, \quad \omega_p = \sqrt{4\pi n_0 e^2/m},$$

We follow the excited wakefield up to the distance $3000\, c/\omega_p$ behind the driver

The driver (1) excites the wave of approximately the same amplitude as the self-modulating long proton beam. The distance $3000\, c/\omega_p$ is 5 rms lengths for the SPS-LHC proton beam in the plasma of the density $7 \times 10^{14}\mathrm{cm}^{-3}$. Compliance with this test is thus necessary for all kinds of PDPWFA simulations.

	Code & parameters	period, c/ω_p
1.	LCODE fluid, grid size $(0.05\, c/\omega_p)^2$, with artificial viscosity	6.2832
2.	LCODE fluid, grid size $(0.02\, c/\omega_p)^2$, with artificial viscosity	6.2852
3.	QUICKPIC, grid size $0.002\, c/\omega_p \times 0.1\, c/\omega_p$	6.2851
4.	LCODE fluid, grid size $(0.05\, c/\omega_p)^2$, no artificial viscosity	6.2838
5.	H-VLPL3d, $0.05\, c/\omega_p \times (0.06\, c/\omega_p)^2$	????

Test 1: Long plasma wave



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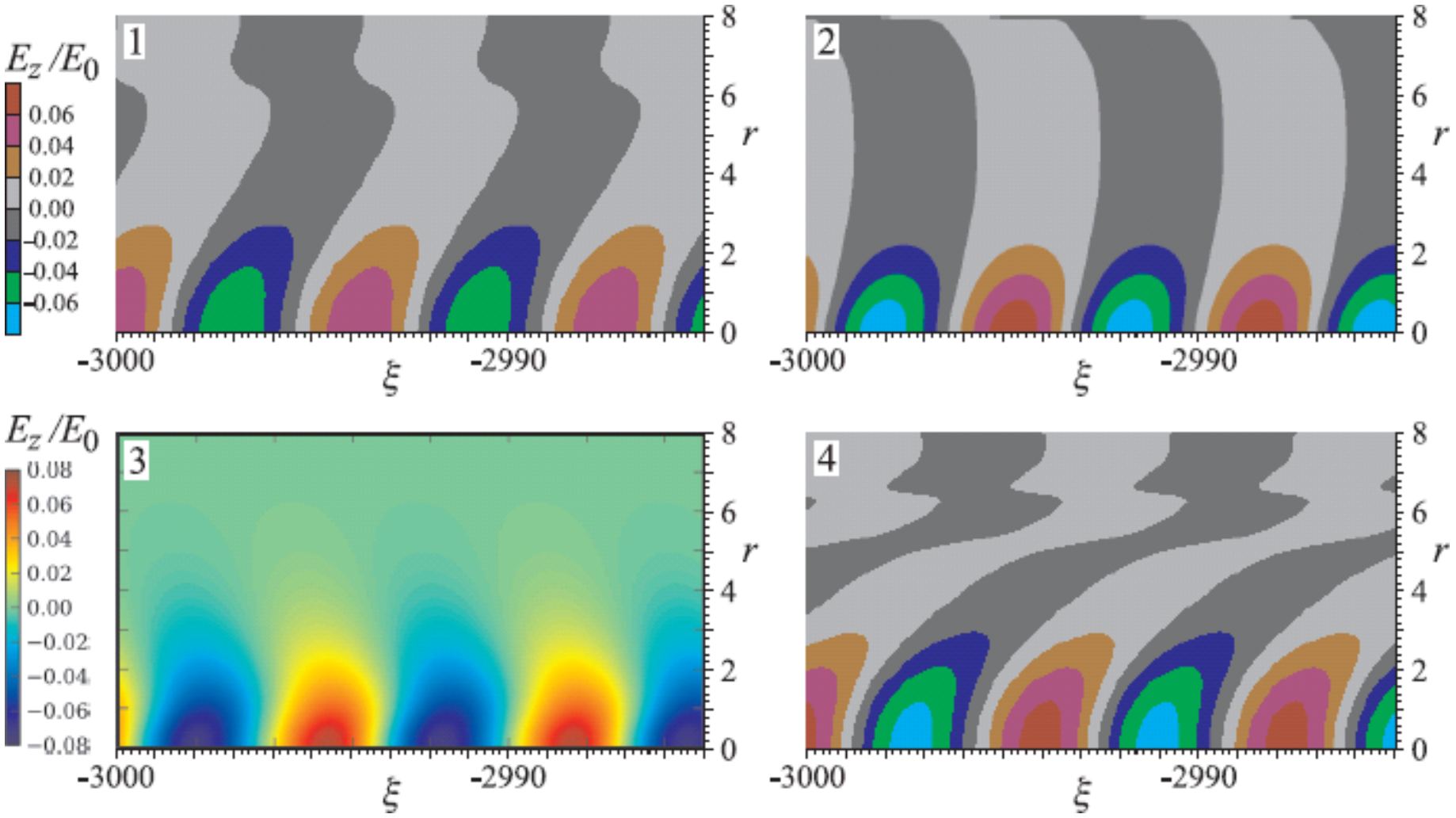


Test 2: Seeded instability

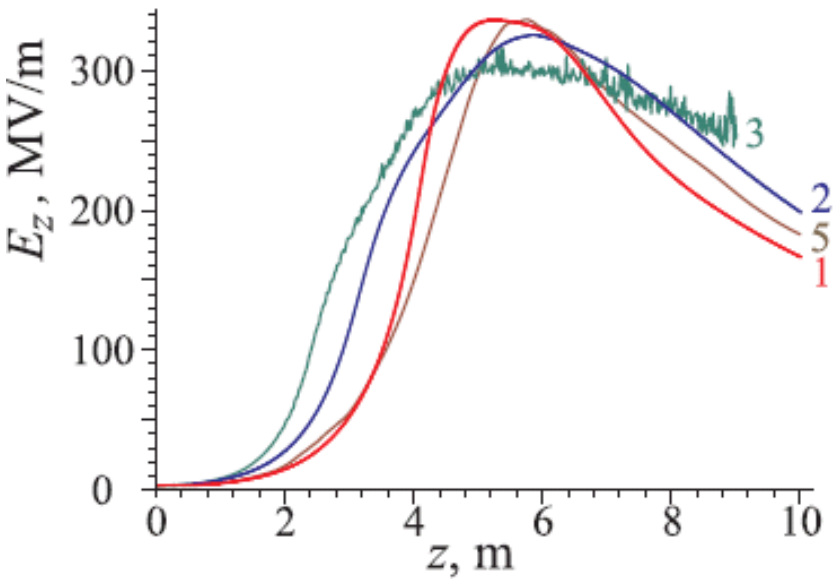
Half-cut SPS-LHC bunch:

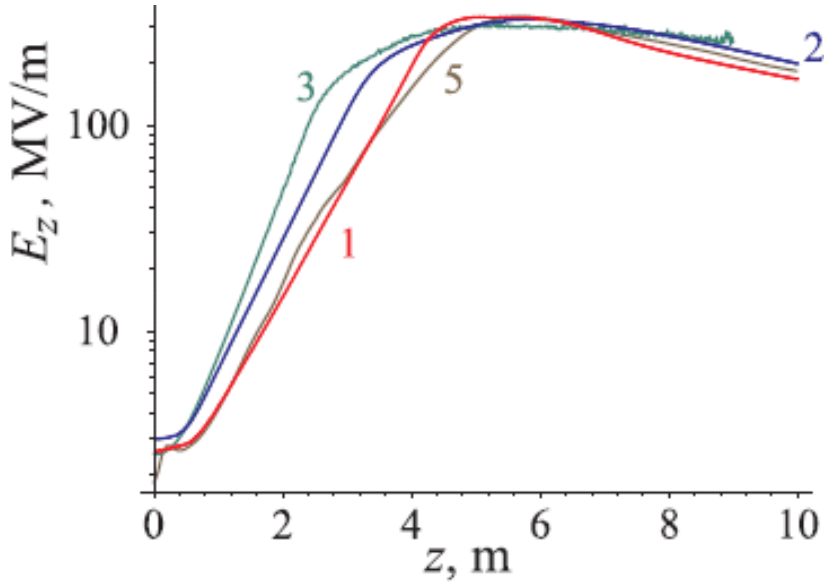
$$n_b = \begin{cases} 0.5\, n_{b0}\, e^{-r^2/2\sigma_r^2} \left[1 + \cos\left(\sqrt{\frac{\pi}{2}}\frac{\xi}{\sigma_z}\right)\right], & -\sigma_z\sqrt{2\pi} < \xi < 0, \\ 0, & \text{otherwise.} \end{cases}$$

Parameter & notation	Value	In plasma units
Plasma density, n_0	$7 \times 10^{14}\,\mathrm{cm}^{-3}$	1
Plasma skin depth, c/ω_p,	$\mathbf{0.02}\,\mathrm{cm}$	1
Wavebreaking field, $E_0 = mc\omega_p/e$,	$2.54\,\mathrm{GV/m}$	1
Population, N_b	$\mathbf{1.15 \times 10^{11}}$	1.15×10^{11}
Length, σ_z	$\mathbf{12}\,\mathrm{cm}$	$598\,(c/\omega_p)$
Radius, σ_r	$\mathbf{0.02}\,\mathrm{cm}$	$1\,(c/\omega_p)$
Maximum beam density, n_{b0}	$1.52 \times 10^{12}\,\mathrm{cm}^{-3}$	$0.00217\,(n_0)$
Energy, W_b	$450\,\mathrm{GeV}$	$\mathbf{880\,000}\,(mc^2)$
Energy spread, δW_b	$135\,\mathrm{MeV}$	$\mathbf{264}\,(mc^2)$
Emittance, ϵ	$8\,\mu\mathrm{m\,mrad}$	$4 \times 10^{-5}\,(c/\omega_p)$
Angular spread, $\delta\alpha = \epsilon/\sigma_r$,	$\mathbf{4 \times 10^{-5}}$	4×10^{-5}

Compliance with this test is necessary for reliable simulations of the seeded instability.

Test 2: Seeded instability





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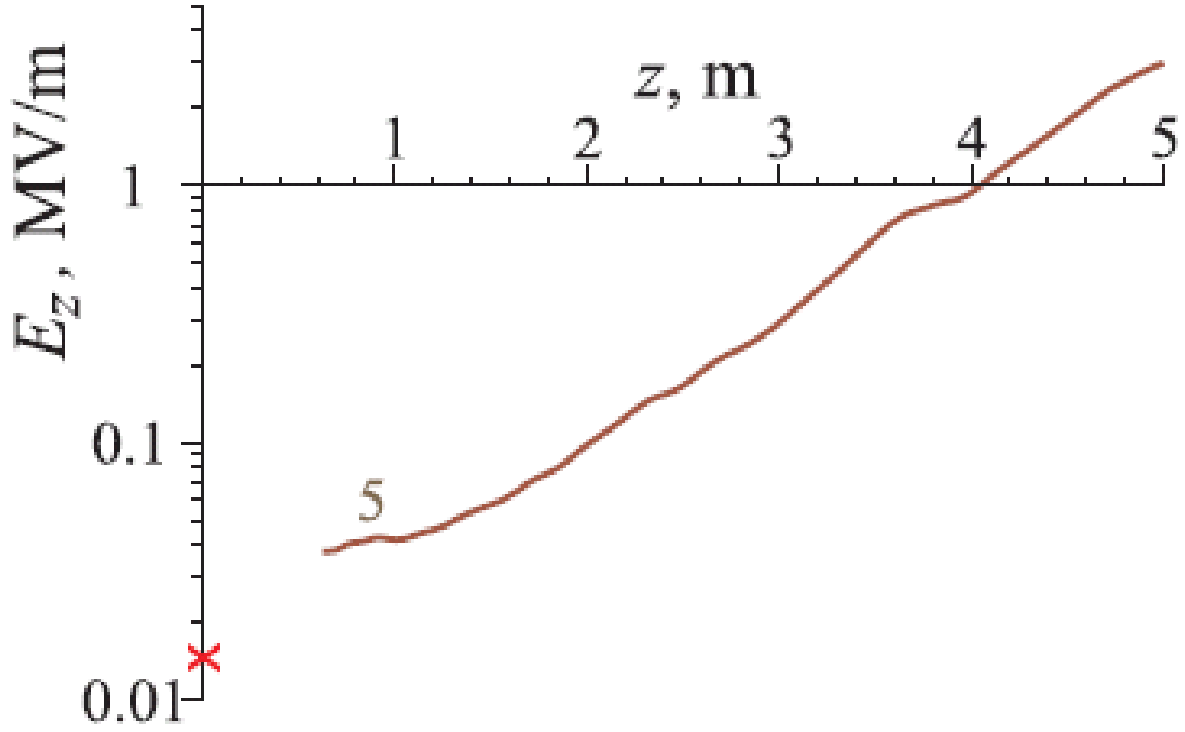
Test 3: Unseeded instability

Full SPS-LHC bunch:

$$n_b = \begin{cases} 0.5\, n_{b0}\, e^{-r^2/2\sigma_r^2} \left[1 + \cos\left(\sqrt{\frac{\pi}{2}}\frac{\xi}{\sigma_z}\right)\right], & |\xi| < \sigma_z\sqrt{2\pi}, \\ 0, & \text{otherwise.} \end{cases}$$

The code must reproduce the natural wakefield noise at the very beginning of the plasma, which expectation is 13 kV/m for the amplitude of the on-axis field E_z.



Test 4: Ion motion

Test 5: Wavebreaking regime (half-cut SPS optimal bunch)

Test 6: Electron trapping (by wakefield of half-cut SPS optimal bunch

Test 7: Gas ionization

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Codes are welcome to participate