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The Cockcroft Institute of Accelerator Science and Technology

Multi-proton bunch driven hollow plasma wakefield acceleration in the nonlinear regime

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Proton-driven plasma wakefield acceleration has been demonstrated in simulations to be capable of accelerating particles to the energy frontier in a single stage, but its potential is hindered by the fact that currently available proton bunches are orders of magnitude longer than the plasma wavelength. Fortunately, proton micro-bunching allows driving plasma waves resonantly. In this paper, we propose using a hollow plasma channel for multiple proton bunch driven plasma wakefield acceleration and demonstrate that it enables the operation in the nonlinear regime and resonant excitation of strong plasma waves. This new regime also involves beneficial features of hollow channels for the accelerated beam (such as emittance preservation and uniform accelerating field) and long buckets of stable deceleration for the drive beam. The regime is attained at a proper ratio among plasma skin depth, driver radius, hollow channel radius, and micro-bunch period.

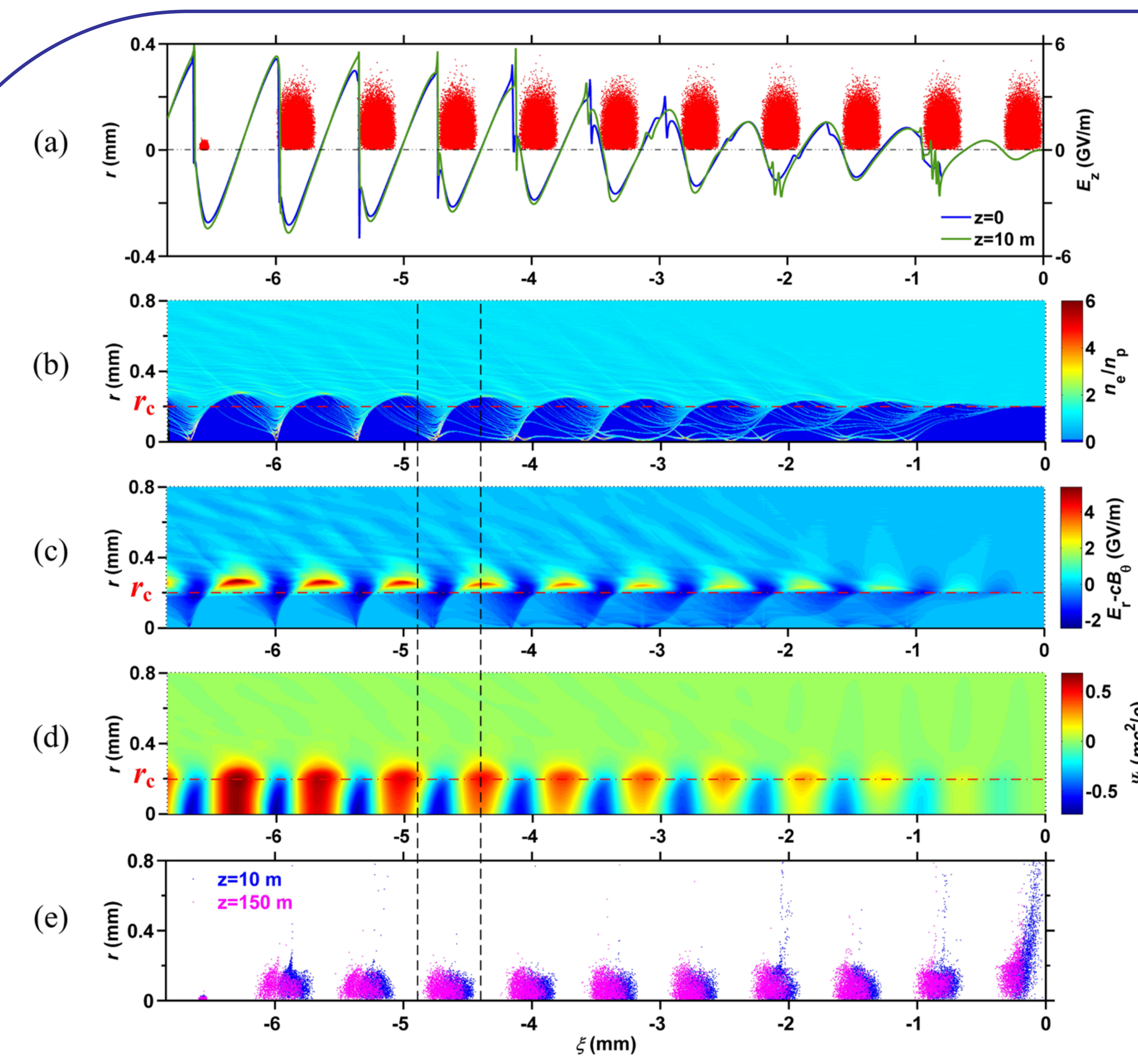

FIG. 1. (a) Initial distribution of 10 proton driving bunches and the witness electron bunch in the real space and the on-axis longitudinal electric fields. (b) The plasma electron density, (c) transverse plasma wakefields and (d) wakefield potential at z =10 m. (e) Snapshots of the driver and the witness bunches.

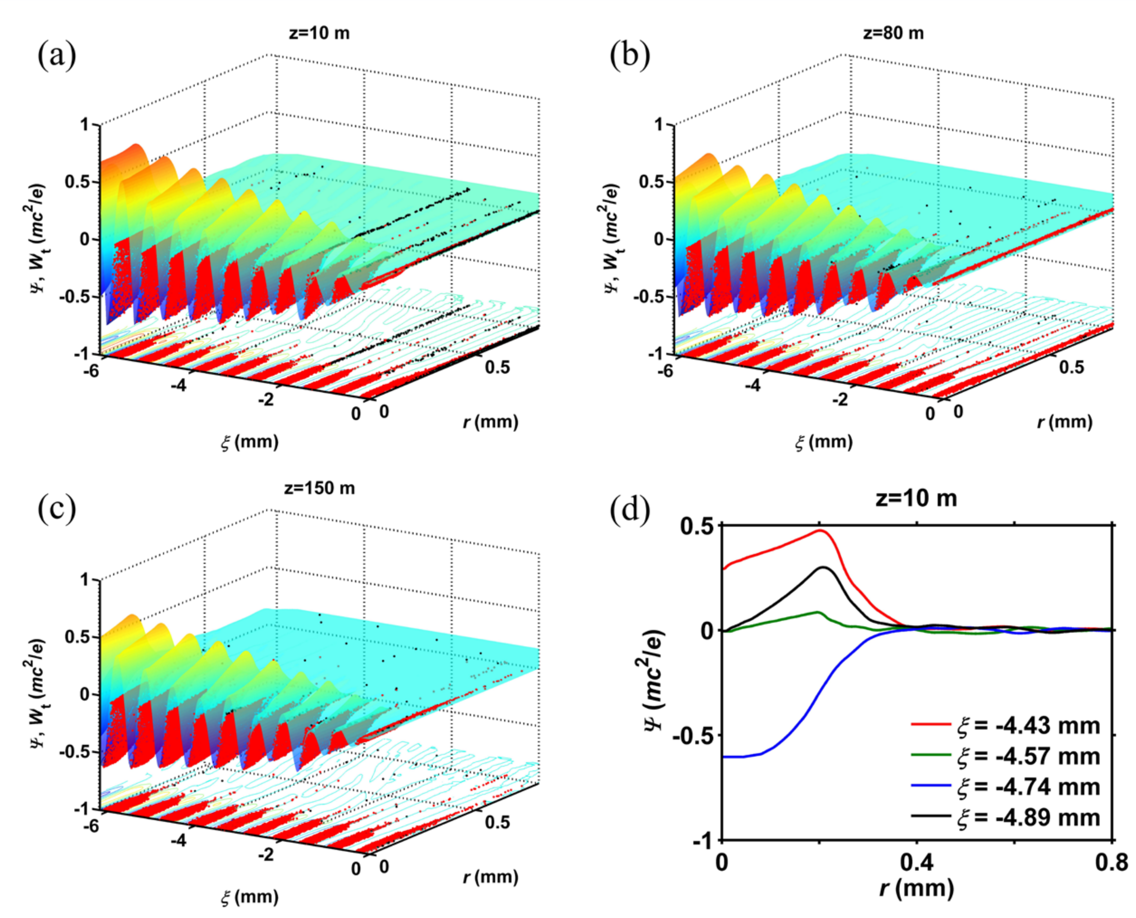

FIG. 2. (a, b, c) Spatial distributions of wakefield potential (surface) and driver protons (red dots for trapped and black for untrapped ones). (d) Radial dependencies of the potential at different ξ-positions (z=10 m) where the on-axis potential has local extrema or zero, i.e., ξ=-4.43 mm (maximum), ξ=-4.57 mm (zero), ξ=-4.74 mm (minimum), and ξ=-4.89 mm (zero).

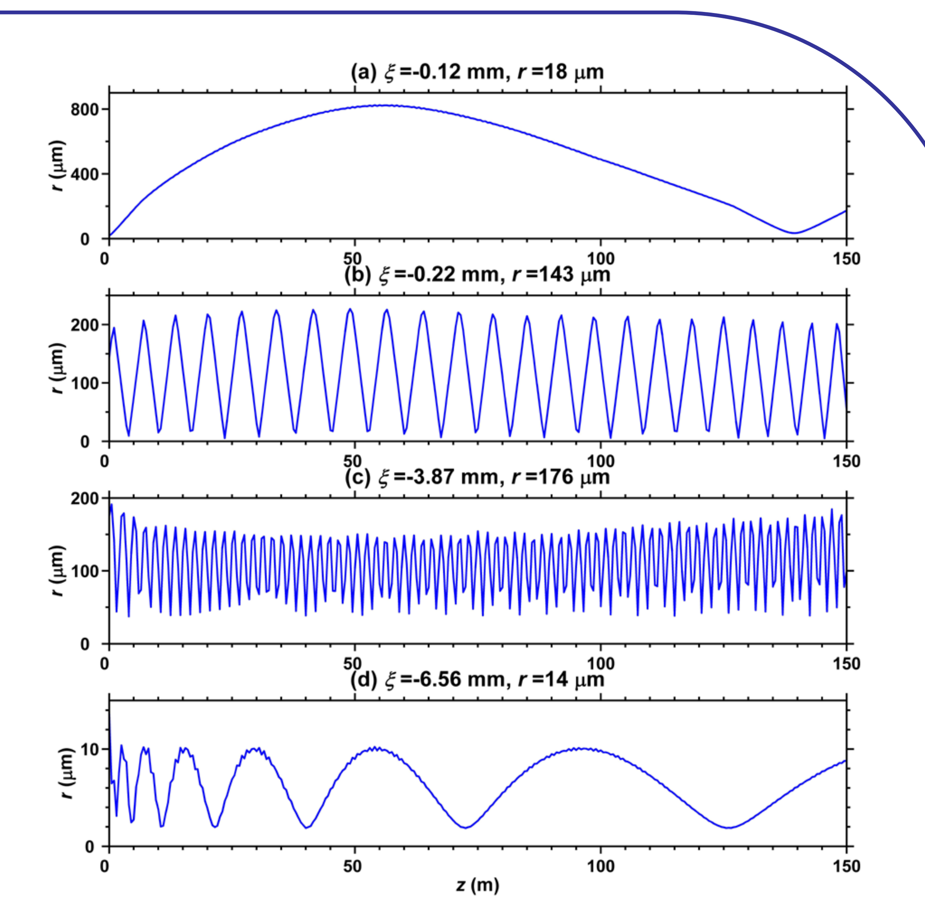

FIG. 3 Trajectories of protons initially located at the head (a) and back (b) of the first driving bunch and at the front (c) of the seventh driving bunch and the trajectory of the witness electron (d).

I. By employing hollow plasma we enable the operation of multiple proton bunch driven PWFA in the blowout regime.
II. Up to half a wakefield period is applicable to each proton bunch in terms of long-term and stable deceleration and maintenance.
III. Up to 90% of TeV protons survive and bring the witness electrons to 0.47 TeV with low energy spread (1.3%) and well-preserved norm. emittance.
IV. The betatron radiation of witness electrons can be foreseen to be modest.

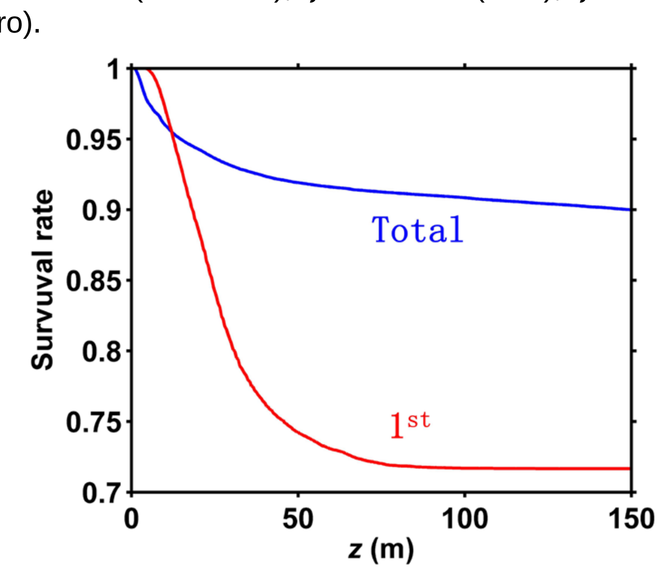

FIG. 4. Survival rates for the whole proton driver and the first driving bunch, respectively.

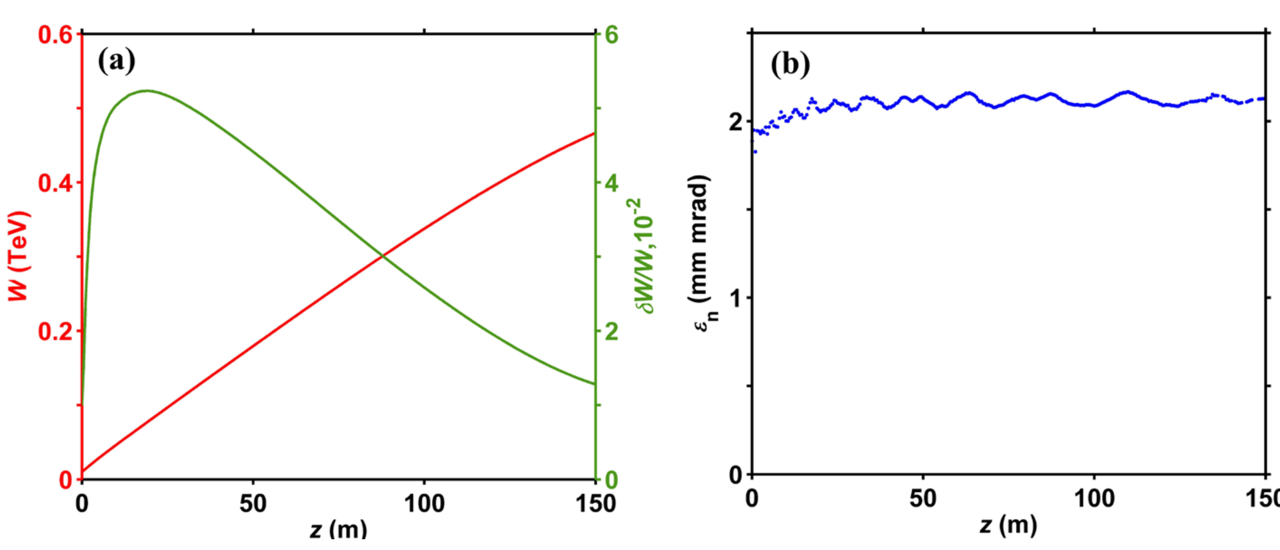

FIG. 5. (a) Energy (red line) and correlated energy spread (green line); (b) normalized emittance (blue points) of the witness bunch with respect to the acceleration distance.

Parameters

Parameters	Values	Units
Initial proton beam:		
Population of a single bunch, N_b	1.15×10^{10}	
Energy, W_{d0}	1	TeV
Energy spread	10%	
Single bunch length, σ_z	63	μm
Beam radius, σ_r	71	μm
Bunch train period	631	μm
Initial witness electron beam:		
Population	2×10^9	
Energy, W	10	GeV
Energy spread, $\delta W/W$	1%	
Normalized emittance, ε_n	2	mm mrad
Unperturbed hollow plasma:		
Plasma density, n_p	6×10^{15}	cm^{-3}
Hollow channel radius, r_c	200	μm
External quadrupole magnets:		
Magnetic field gradient, S	0.5	T/mm
Quadrupole period, Lq	0.9	m

Acknowledgements

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Discussion

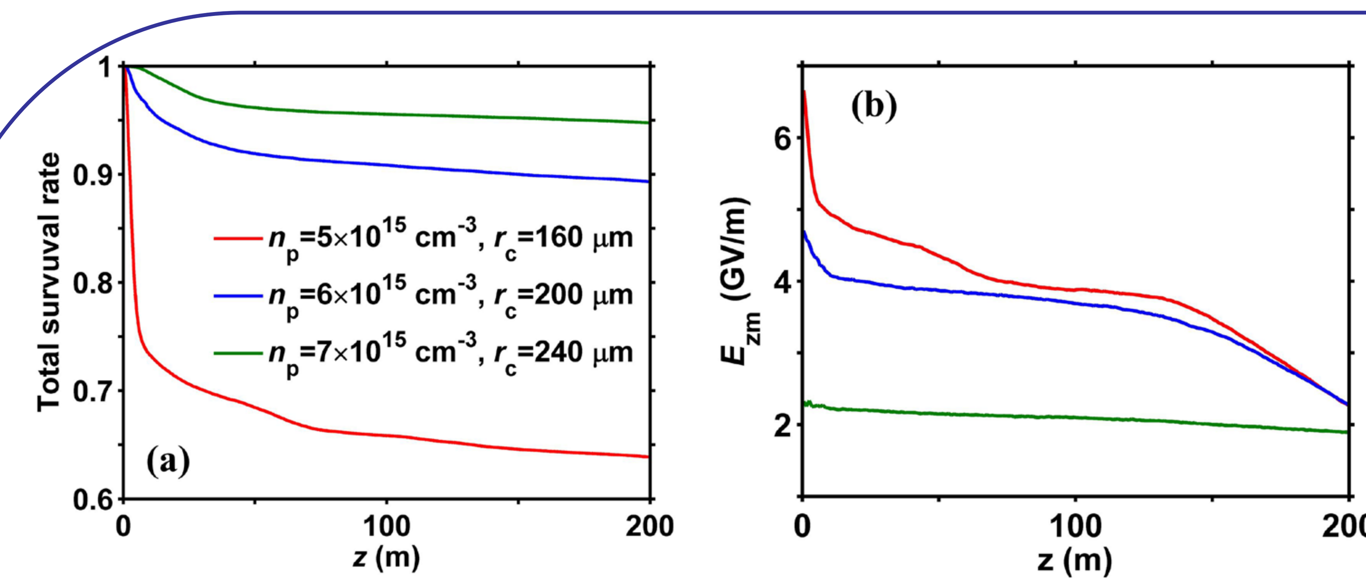

FIG. 6. Driver survival rates (a) and maximum longitudinal wakefield amplitudes (b) for different plasma structures.

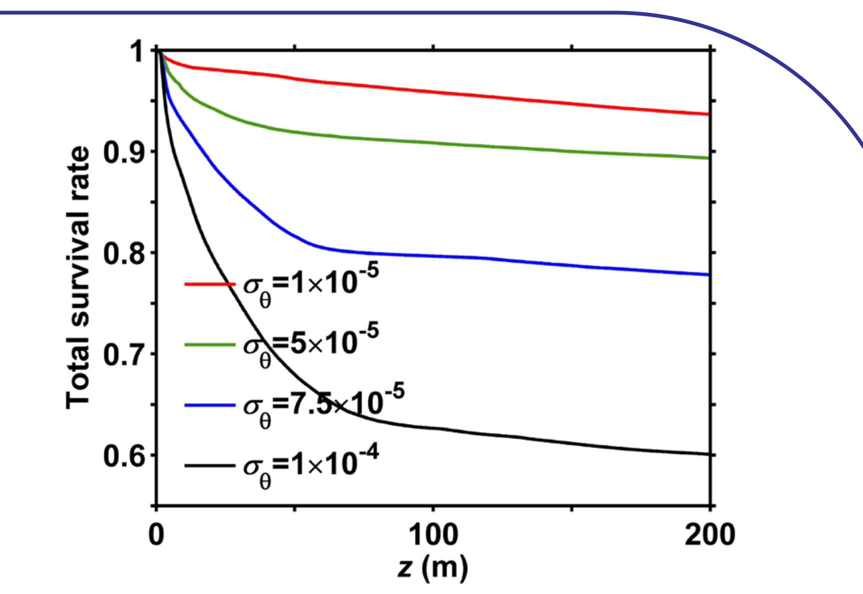

FIG. 7. Total survival rates concerning the whole proton driver with different initial angular spreads.

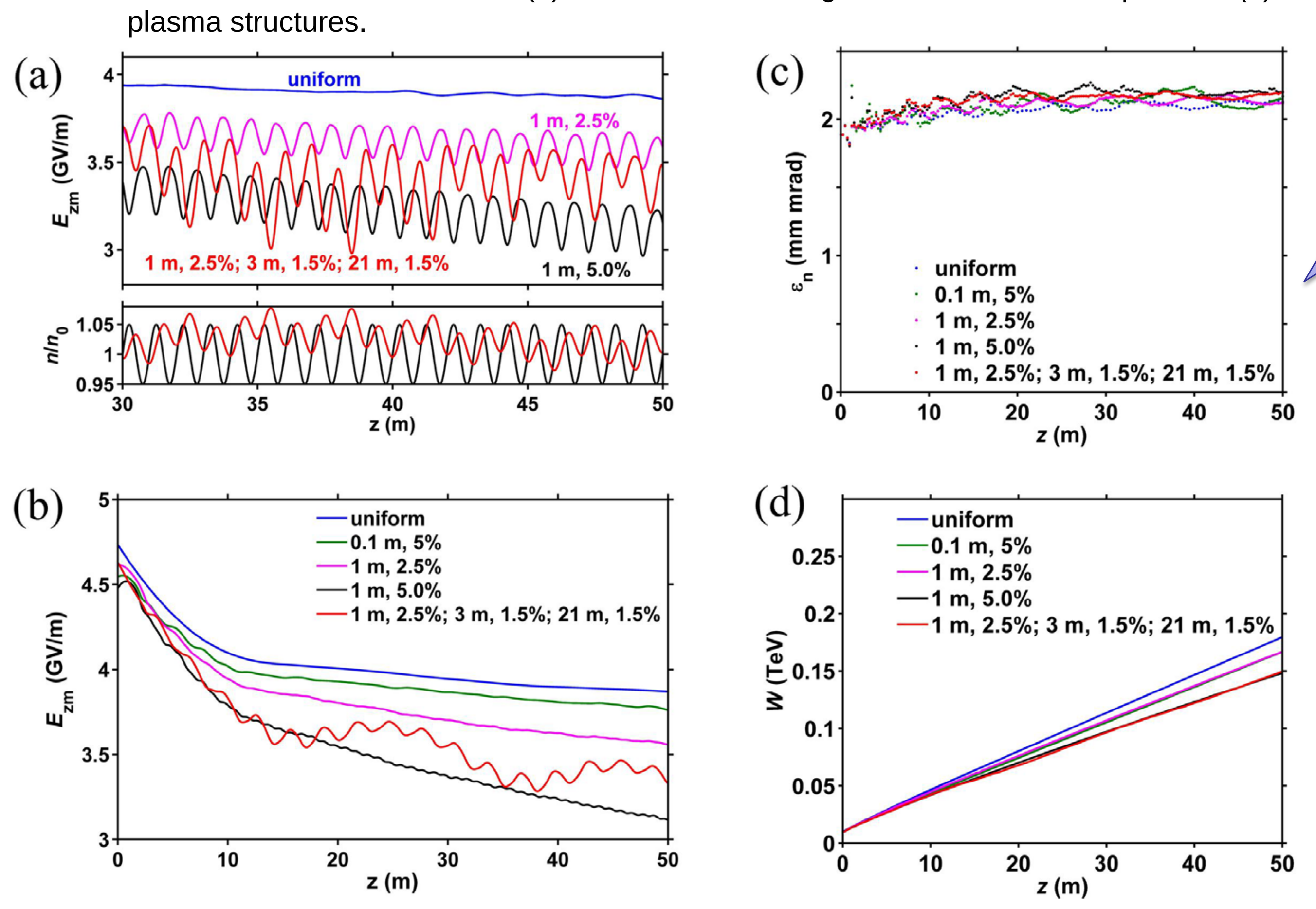

FIG. 8. (a) Maximum longitudinal electric fields excited in axially non-uniform plasmas. The lower plots represent the corresponding plasma density profiles.(b) Maximum longitudinal electric field amplitudes of different cases of plasma inhomogeneity. (c) Normalized emittance of the witness beam in different cases. (d) Mean energy of the witness beam. Note that the "uniform" in the legends denotes the hollow channel with axially uniform plasma.

- regular plasma density non-uniformity $n = n_0(1+\delta n\sin(\frac{2\pi z}{L}))$, δn perturbation amplitude, L perturbation period
- irregular plasma density non-uniformity $n = n_0(1+0.025(1-\cos(\frac{2\pi z}{1\,\mathrm{m}}))+0.015\sin(\frac{2\pi z}{3\,\mathrm{m}})+0.015\sin(\frac{2\pi z}{21\,\mathrm{m}}))$

I. The optimal ratio between the driver radius and the hollow channel radius comes from a compromise between the survival rate of the protons and the accelerating field amplitude.
II. The survival rate of protons is essentially determined by the relation between their radial momenta and the potential well depth
III. The proposed scheme can tolerate a regular density perturbation up to a level of 5% and is slightly more sensitive to the irregular perturbation.
IV. A "clean" accelerating region for the witness beam can still be kept under the plasma density perturbation and thereby its normalized emittance is well preserved.
V. The limitation on tolerable density perturbations comes from decreasing the acceleration rate, rather than degrading the witness quality as in the case of uniform plasmas

Summary & Outlook

This work expands the concept of proton driven PWFA. Assuming the micro-bunching techniques will be developed in the frame of AWAKE project, the hollow channels would open the path to emittance-preserving accelerating structures for future high-energy physics facilities. The least developed part of the concept is the production of long hollow channels, which is far from maturity. However, the channel could be sectionalized into multiple plasma cells with almost no decrease of the longitudinal fields, provided that the gap between cells is shorter than the betatron period of driver particles. It also can sustain relatively large eigenfrequency fluctuations (at the level of 5%). All of these lower the precision requirements in producing the desired hollow plasma channel.