High-quality positrons from a multi-proton bunch driven hollow plasma wakefield accelerator

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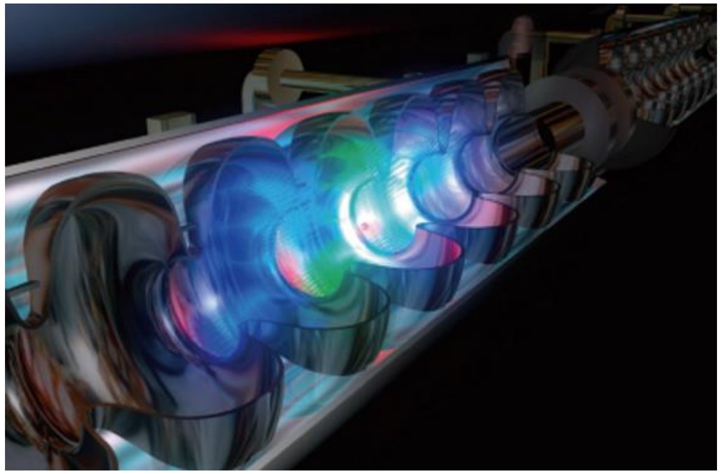
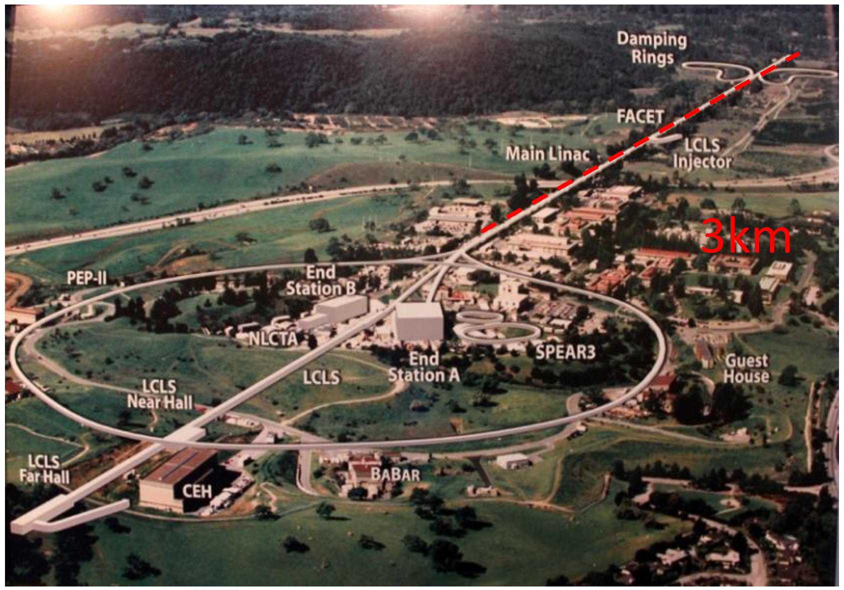
Thanks to K. V. Lotov, A. P. Sosedkin, Y. Zhao

Why plasma-based accelerators?

- RF accelerators



RF breakdown threshold: 100MV/m



SLAC: accelerating e-/e+ to 50 GeV

LHC: accelerating protons to 7 TeV

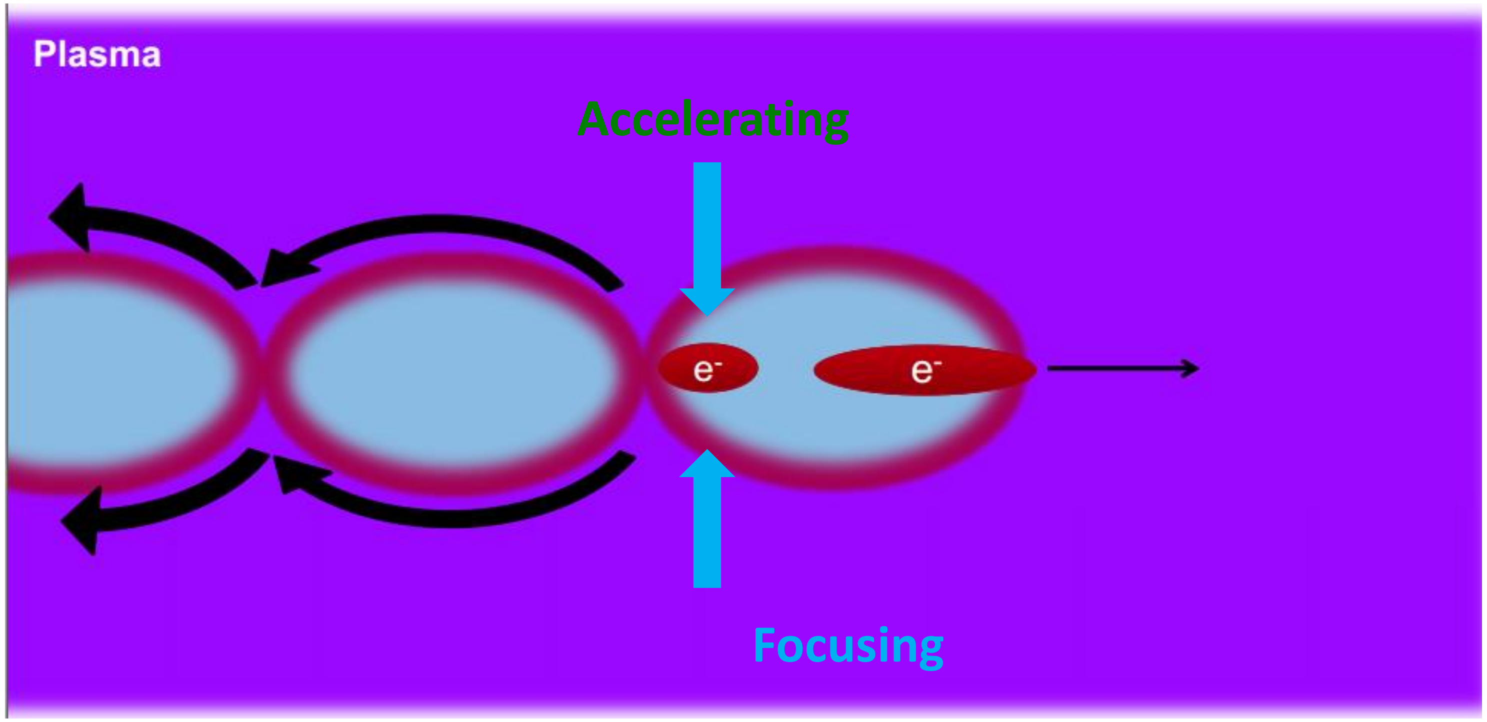
Why plasma-based accelerators?

- Plasma wave-breaking field

$$E_{wb}[\mathrm{V/m}] = mc\omega_p / e = 96\sqrt{n_e\ (\mathrm{cm}^{-3})}, \quad \omega_p = \sqrt{e^2 n_e / \varepsilon_0 m_e}$$

e.g. $n_e = 10^{18}\ \mathrm{cm}^{-3}$, $E_{wb} \approx 100\ \mathrm{GV/m}$

Three orders of magnitude larger acceleration gradients!



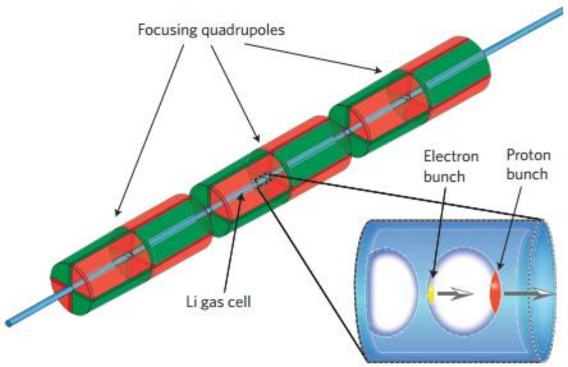
Size shrunk a thousand times

Affordable

Compact

Why Proton driven plasma wakefield acceleration

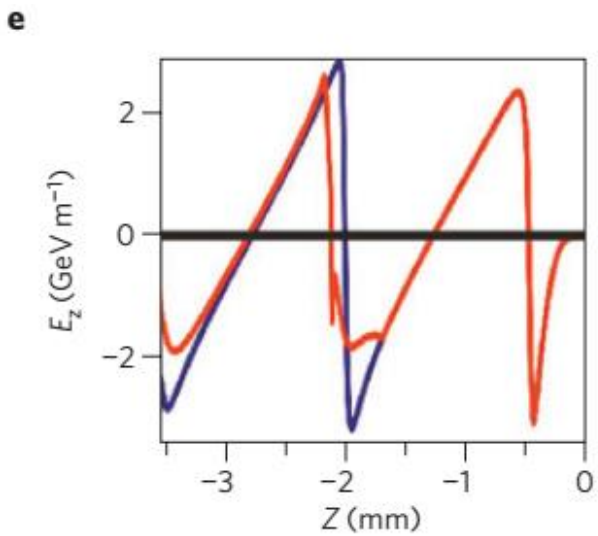
- Limited energy content in e- bunches/lasers

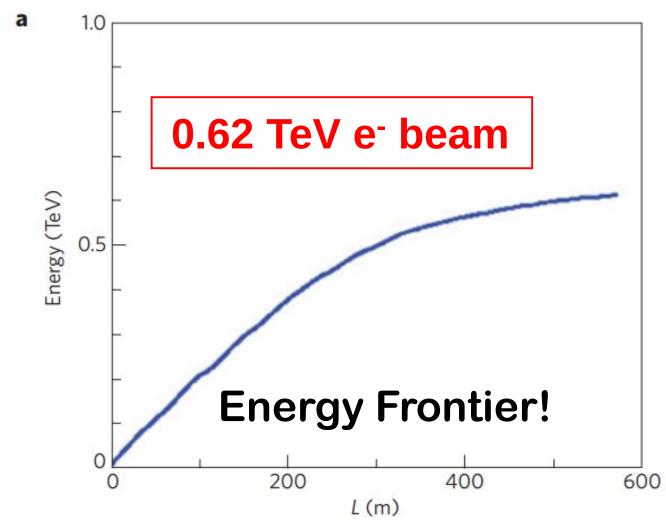


- **SLAC (50 GeV, 2e10 e/bunch) ~ 0.16 kJ**
- **ILC (250 GeV, 2e10 e/bunch) ~ 0.8 kJ**
- **A PW laser, ~40 J.**
- **SPS (400 GeV, 3e11 p/bunch) ~ 20 kJ**
- **LHC (7 TeV, 1.15e11 p/bunch) ~ 130 kJ**

Table 1 | Table of parameters for the simulation.

Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	N_e	1.5×10^{10}	
Energy of electrons in witness bunch	E_e	10	GeV
Free electron density	n_p	6×10^{14}	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1,000	$T\,m^{-1}$
Magnet length		0.7	m

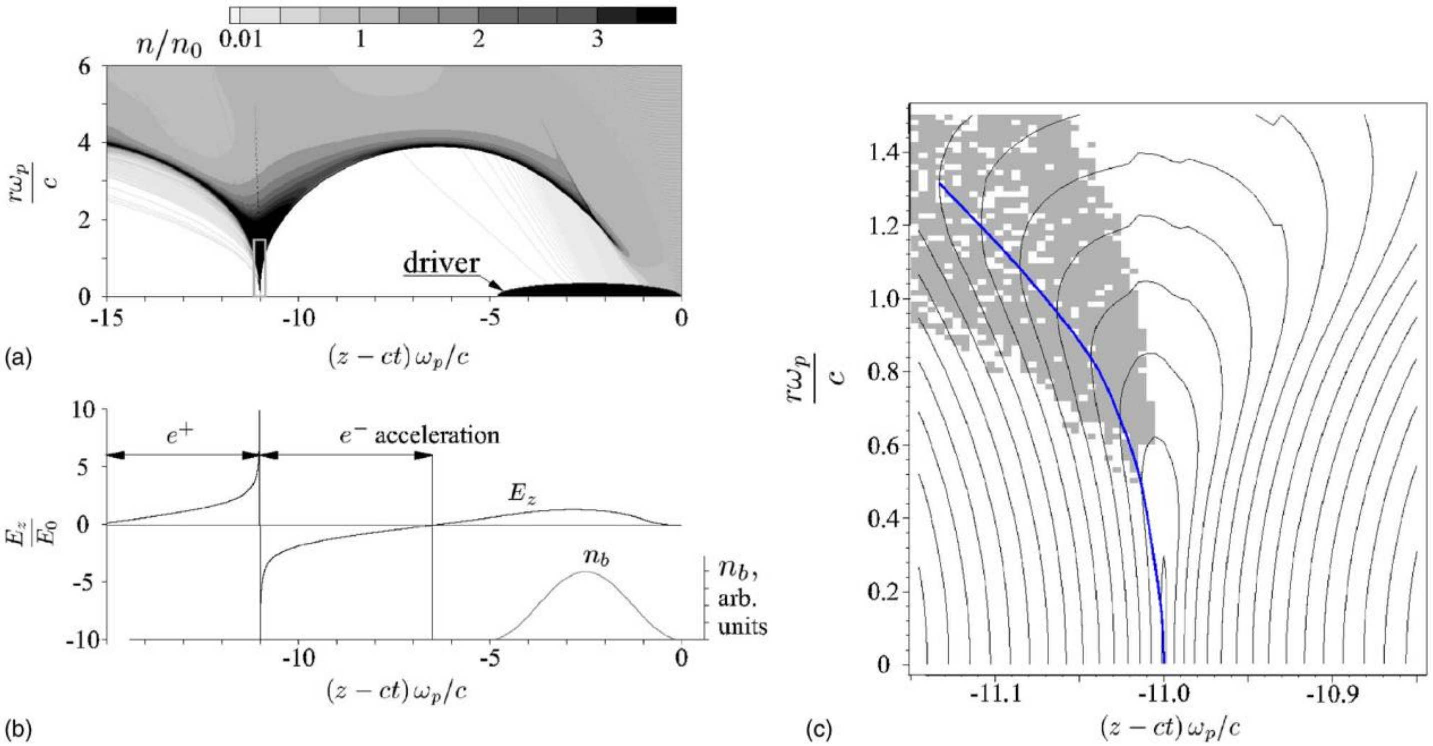




A. Caldwell, et al., Proton-driven plasma-wakefield acceleration. Nature Phys. **5**, 363 (2009).

Obstacle in positron acceleration

- Lack of stable acceleration regime for positrons in PWFA as the accelerating structure is strongly charge dependent in nonlinear regime.

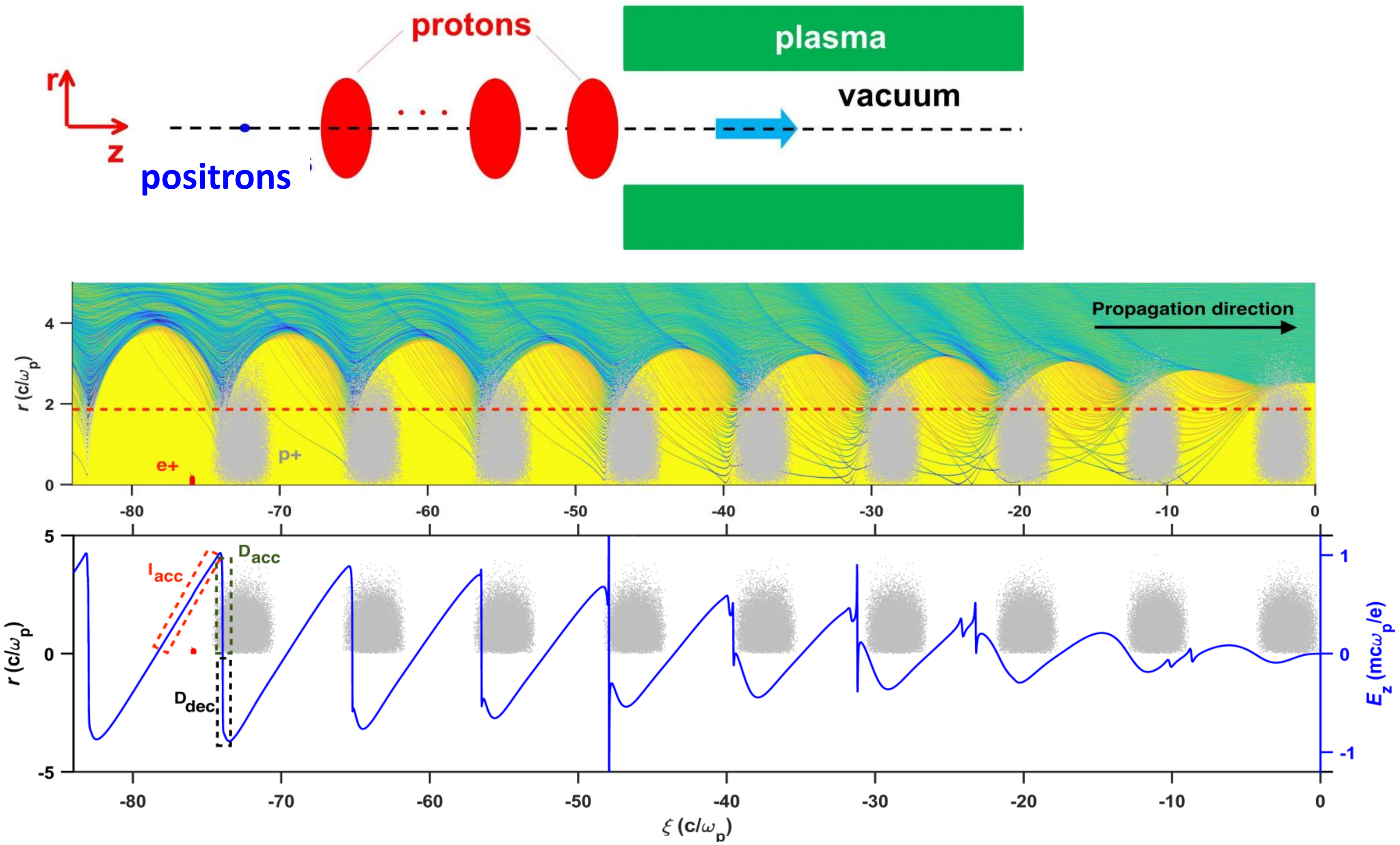


- The focusing region for positrons is confined to the narrow region where the plasma electrons collapse on axis, the plasma density is nonuniform and the fields vary strongly.
- Energy spread increase and drastic emittance growth.

K, Lotov. Acceleration of positrons by electron beam-driven wakefields in a plasma. Phys. Plasmas 14 (023101), 2007 .

◻ Hollow plasma channel

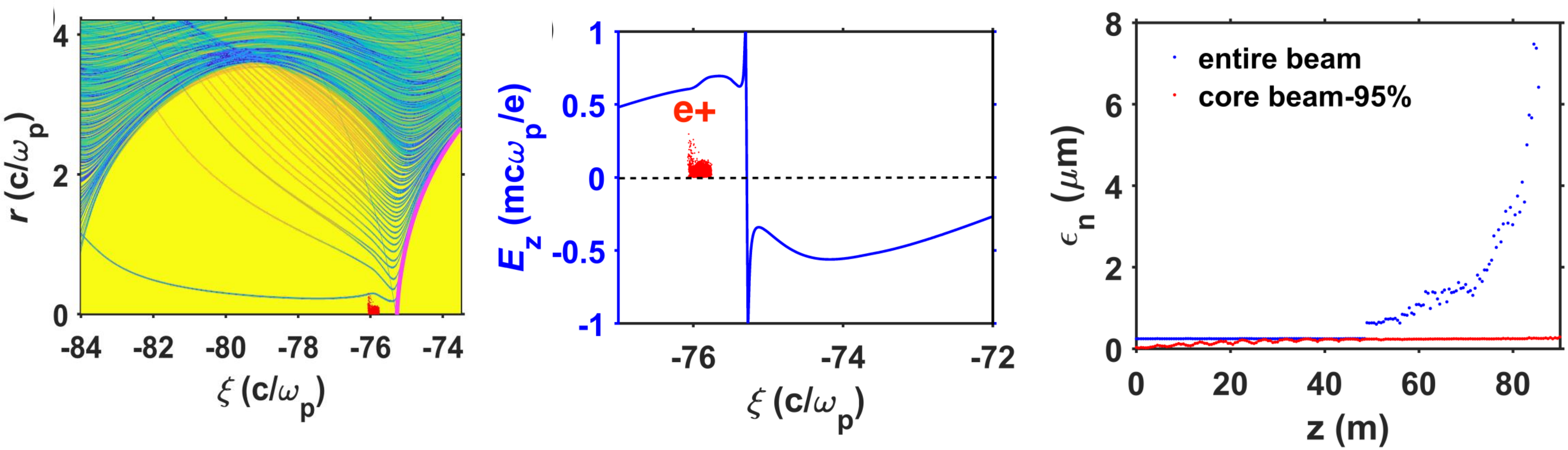
✓The hollow plasma eliminates the defocusing from background ions within the channel.



Discrepancy in positron acceleration between the normalized emittance and the energy spread

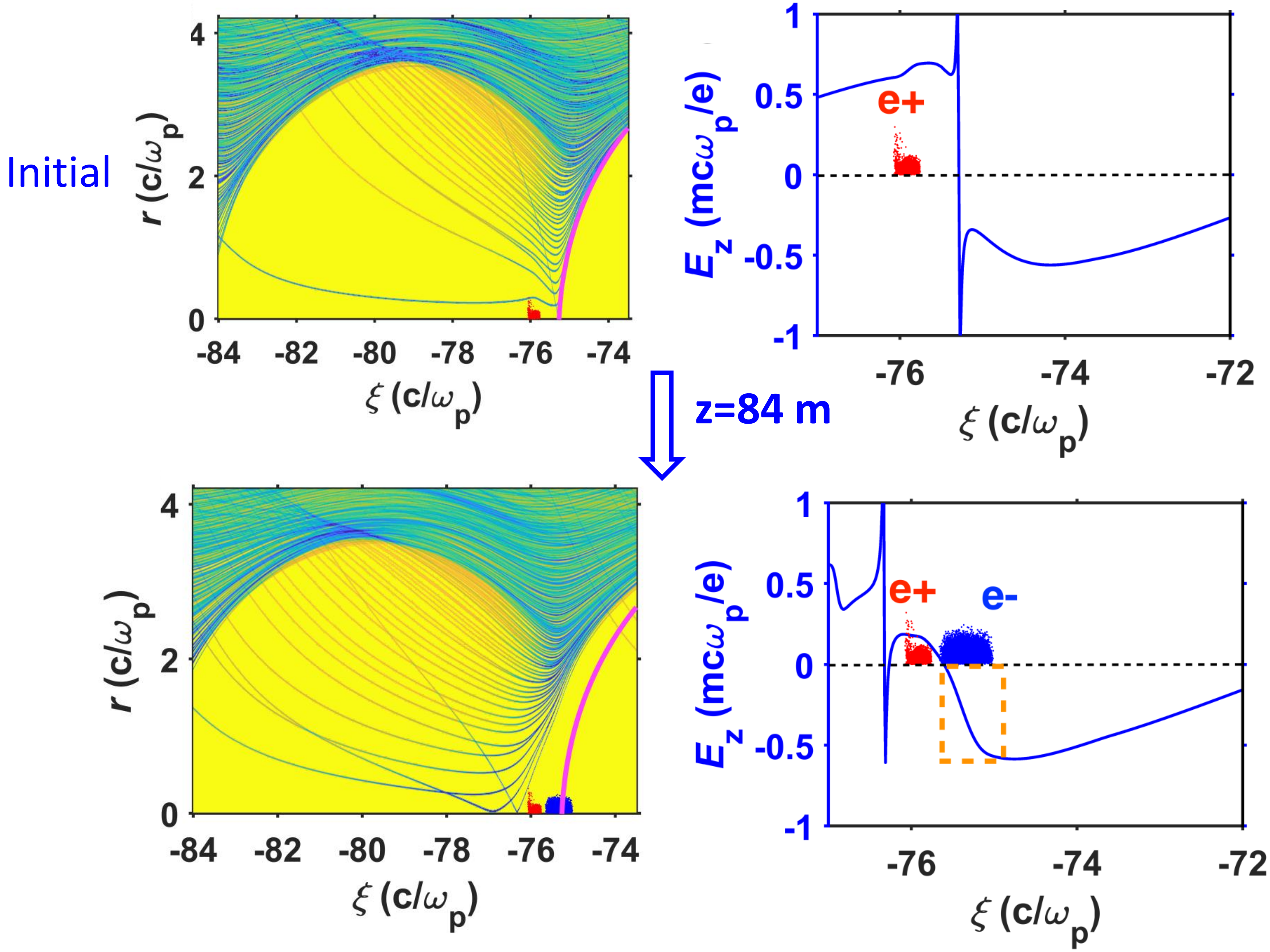
Plasma electrons within the channel dilute the positron bunch

Dephasing between protons (or wake phase) and positrons due to large γ difference.



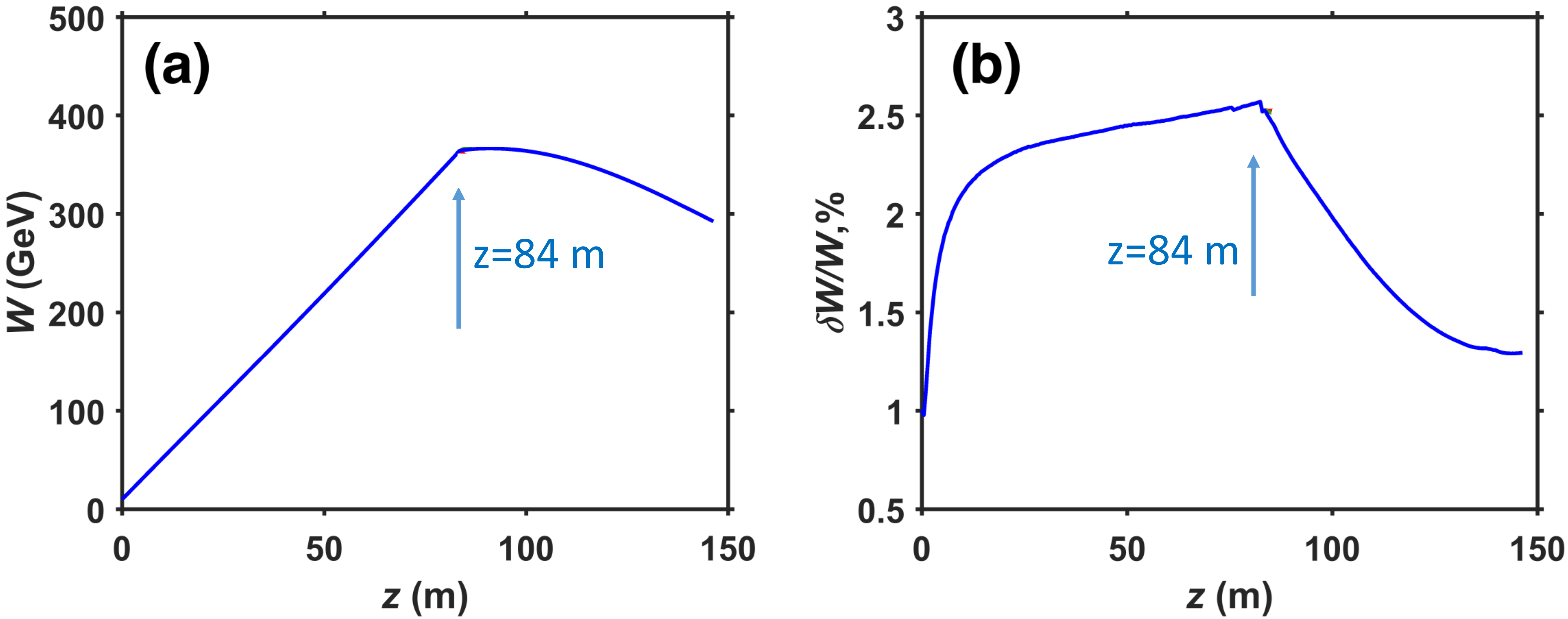
- Positrons gain energy in "I_{acc}" region with preserved norm. emittance but an increasing energy spread.
- With energy depletion and elongation of proton bunches, the wake excitation is weaker and plasma electrons penetrate into the positron region, leading to its emittance growth.

□Decreasing plasma density from n_0 to $0.95n_0$ + loading an extra electron beam with a population 1×10^{10}



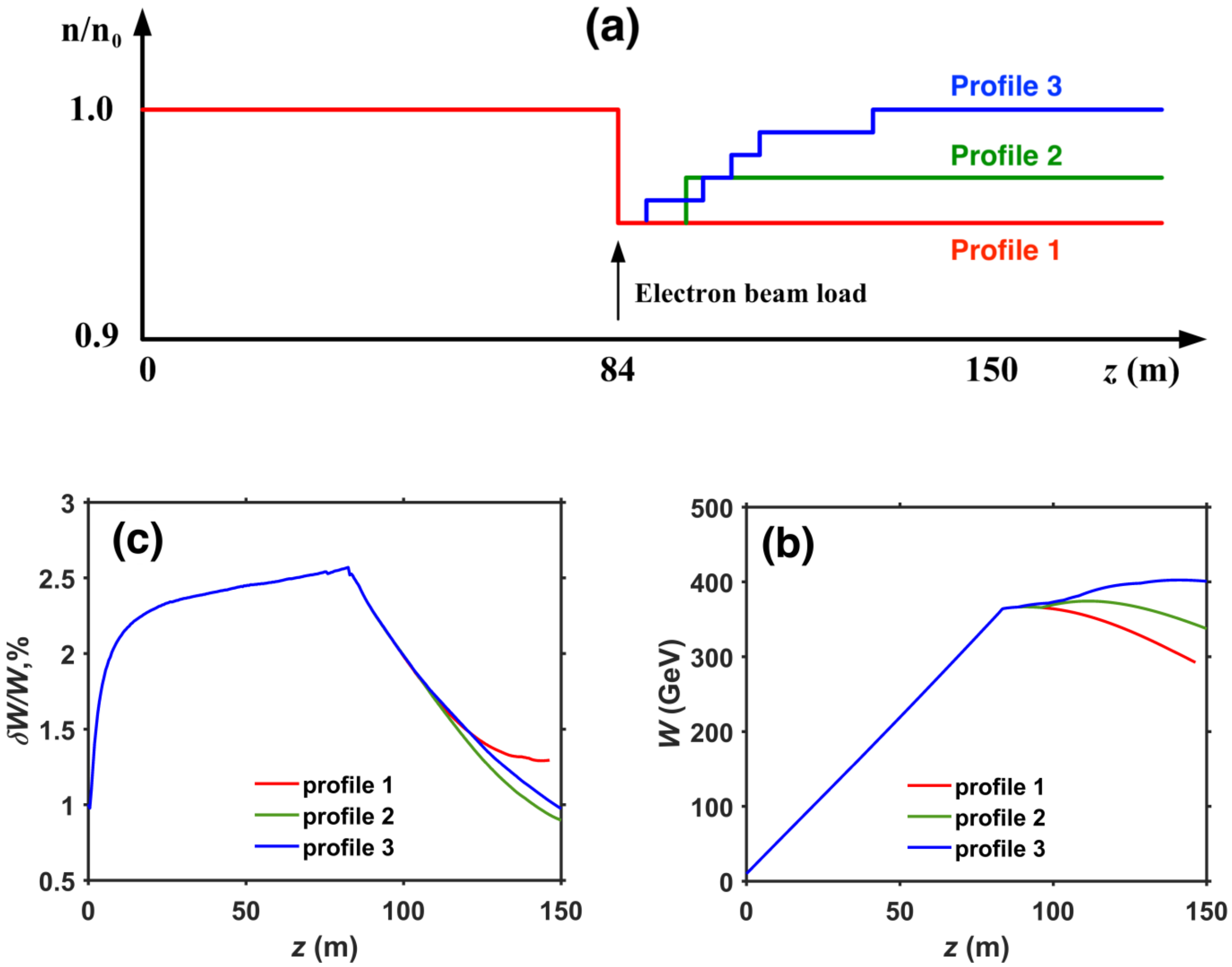
- ✓ With extension of wake wavelength, the "D_{acc}" region with a sharp slope is shifted to the positron bunch.
- ✓ Extra electrons remove the interference of plasma electrons with positrons.

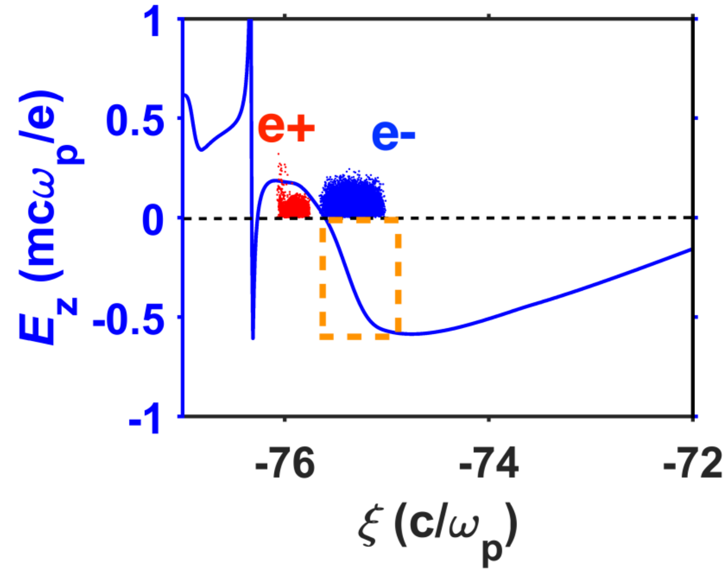
Energy gain & Energy spread



Discussion

Different longitudinal plasma profiles





- ✓ Due to wake phase shift, positrons will gradually slide into the ”D_{dec}" region.
- ✓ Increasing the plasma density can shift the “D_{acc}" region back to the positron bunch.
- ✓ Also while wake wavelength decreases, the extra electron bunch moves towards a smaller acceleration gradient and extracts less energy from the plasma wave.
- ✓ It is feasible to obatin positive net energy gain and the decreased energy spread.

Summary

- The hollow plasma channel enables multiple proton bunches working the nonliear regime and acceleration of the positron bunch.
- The plasma electrons providing focusing to the multiple proton bunches dilute the positron bunch.
- By loading an extra electron bunch to repel the plasma electrons and meanwhile reducing the plasma density slightly to shift the accelerating phase with a conducive slope to the positron bunch, the positron bunch can be accelerate to 400 GeV (40% of the driver energy) with an energy spread as low as 1% and well preserved normalized emittance.
- This work expands the concept of positron acceleration driven by multiple proton bunches or single less intense proton bunches.

Y. Li, et al. High-quality positrons from a multi-proton bunch driven hollow plasma wakefield accelerator. arXiv:1809.04922, 2018.