# Possibility of proton driven positron acceleration in the nonlinear regime in hollow plasma

Y. Li[1,*], G. Xia[1], K. Lotov[2], A. Sosedkin[2], K. Hanahoe[1], O. Mete-Apsion[1]

[1]The University of Manchester/Cockcroft Institute

[2]Budker Institute of Nuclear Physics/Novosibirsk State University

*yangmei.li@manchester.ac.uk

# Outline

- PD-PWFA

  Proton Driven Plasma Wakefield Acceleration

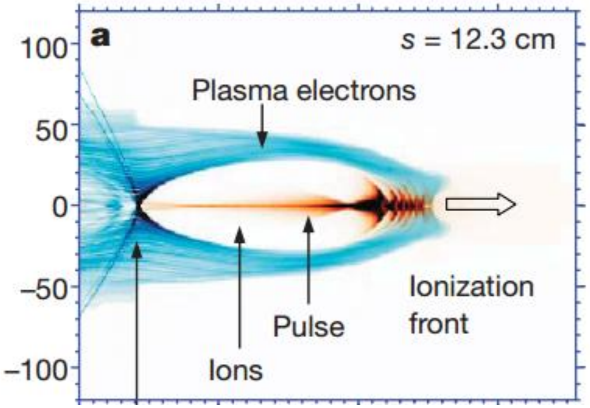
- Multiple PD-HPWFA in the nonlinear regime

  Proton Driven Hollow Plasma Wakefield Acceleration

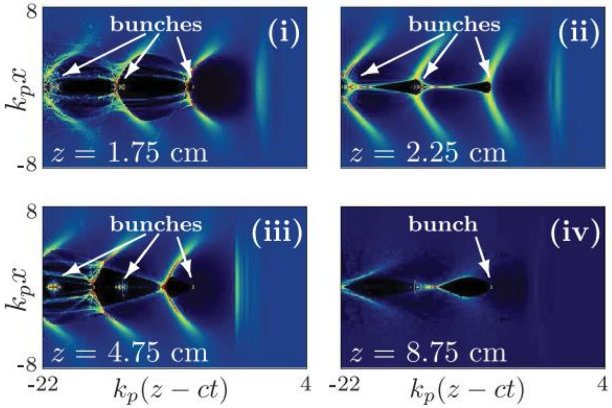
- Possibility of positron acceleration in this scenario
- Summary & Outlook

# Why PD-PWFA?

PWFA



LWFA



- Stanford Linear Accelerator Center [1]

85-cm-long column of lithium vapour
ne 2.7×$10^{17}$ cm$^{-3}$
42 GeV electron driver

⇩

85 GeV electrons
3×$10^{6}$ electrons per GeV

- Lawrence Berkeley National Laboratory [2]

9 cm long preformed plasma channel
plasma density 7×$10^{17}$ cm$^{-3}$
laser peak power 0.3 PW

⇩

4.2 GeV electrons; 6% rms energy spread;
6 pC charge; 0.3 mrad rms divergence

[1] Blumenfeld, I. *et al*. *Nature* **445,** 741-744 (2007).

[2] Leemans, W. P. *et al. Phys. Rev. Lett.* **113**, 245002 (2014).

# Why PD-PWFA?

## Limited energy content in e- bunches/lasers

- PWFA Transformer ratio $R = \frac{E_{\max}^{witness}}{E_{\max}^{drive}} \le 2 - \frac{N_{witness}}{N_{drive}}$
  - SLAC (50 GeV, 2e10 e/bunch) ~ 0.16 kJ
  - ILC (250 GeV, 2e10 e/bunch) ~ 0.8 kJ
  - SPS (400 GeV, 3e11 p/bunch) ~ 20 kJ
  - LHC (7 TeV, 1.15e11 p/bunch) ~ 130 kJ

**Single stage**

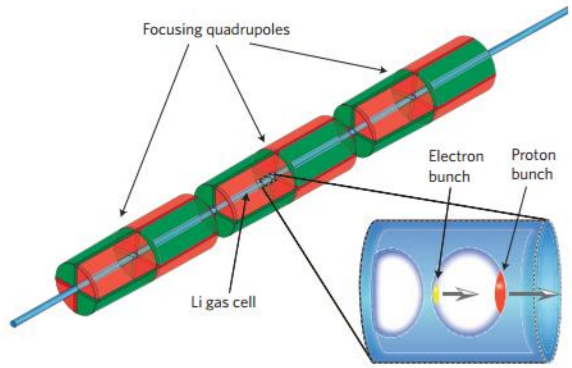
- LWFA
  - A PW laser, ~40 J.
  - 3D effect: Dephasing, Diffraction, Depletion

## Technically challenging multi-stage acc

- Tight synchronization and alignment requirements of the drive and witness bunches and of each accelerator module

# PD-PWFA

- Proton driven plasma wakefield acceleration



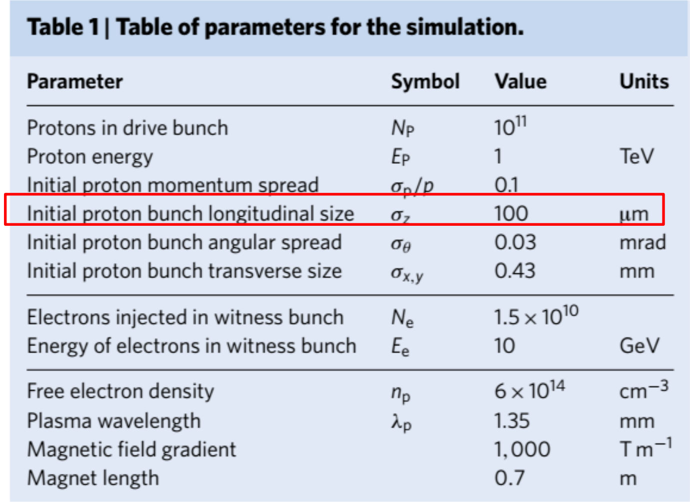
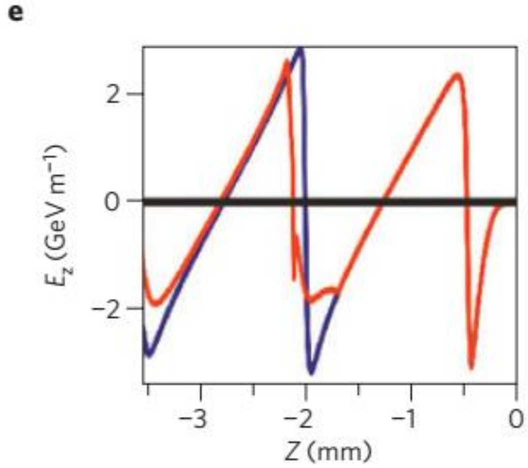
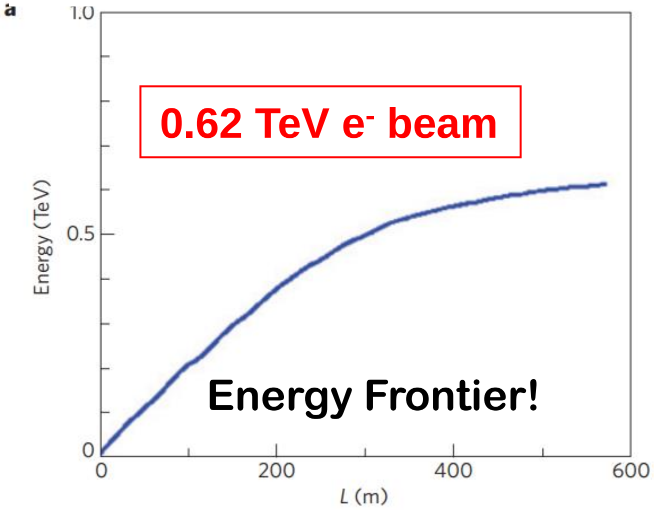


**Table 1 | Table of parameters for the simulation.**

| Parameter | Symbol | Value | Units |
|---|---|---|---|
| Protons in drive bunch | $N_P$ | $10^{11}$ | |
| Proton energy | $E_P$ | 1 | TeV |
| Initial proton momentum spread | $\sigma_p/p$ | 0.1 | |
| Initial proton bunch longitudinal size | $\sigma_z$ | 100 | μm |
| Initial proton bunch angular spread | $\sigma_\theta$ | 0.03 | mrad |
| Initial proton bunch transverse size | $\sigma_{x,y}$ | 0.43 | mm |
| Electrons injected in witness bunch | $N_e$ | $1.5\times10^{10}$ | |
| Energy of electrons in witness bunch | $E_e$ | 10 | GeV |
| Free electron density | $n_p$ | $6\times10^{14}$ | $cm^{-3}$ |
| Plasma wavelength | $\lambda_p$ | 1.35 | mm |
| Magnetic field gradient | | 1,000 | $T\,m^{-1}$ |
| Magnet length | | 0.7 | m |





**0.62 TeV $e^-$ beam**

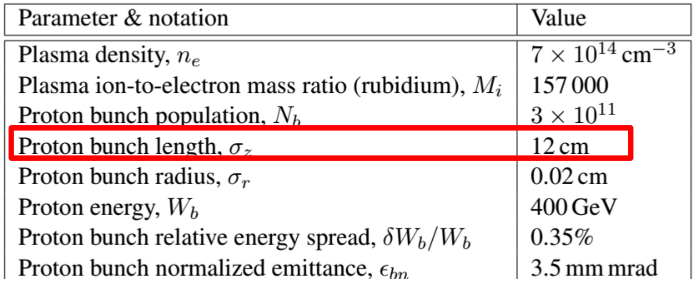
**Energy Frontier!**

A. Caldwell, et al., Nature Phys. **5**, 363 (2009).

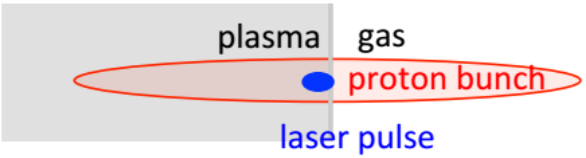
# AWAKE at CERN

- Compression of currently available proton bunches to plasma wavelength by a factor of several orders of magnitude is technically challenging.

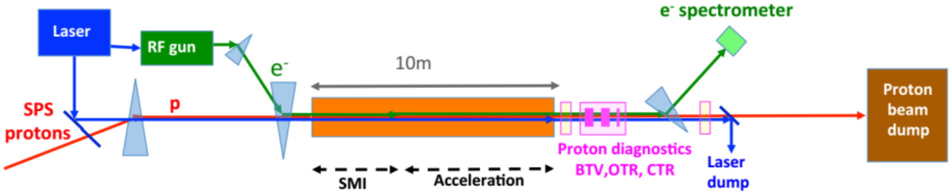
Table 1: Baseline parameters of the AWAKE experiment.

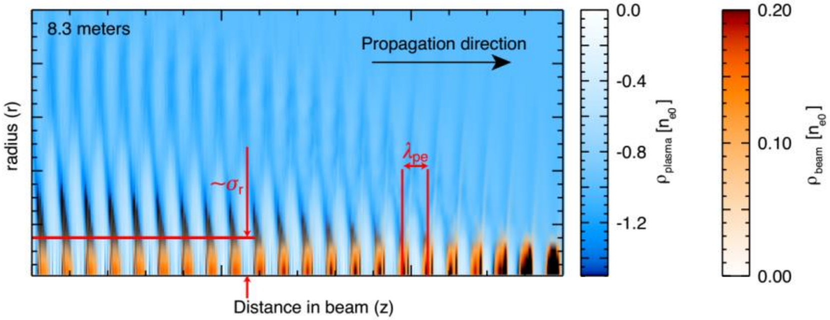


| Parameter & notation | Value |
|---|---|
| Plasma density, $n_e$ | $7 \times 10^{14}\,\mathrm{cm}^{-3}$ |
| Plasma ion-to-electron mass ratio (rubidium), $M_i$ | 157 000 |
| Proton bunch population, $N_b$ | $3 \times 10^{11}$ |
| Proton bunch length, $\sigma_z$ | 12 cm |
| Proton bunch radius, $\sigma_r$ | 0.02 cm |
| Proton energy, $W_b$ | 400 GeV |
| Proton bunch relative energy spread, $\delta W_b / W_b$ | 0.35% |
| Proton bunch normalized emittance, $\epsilon_{bn}$ | 3.5 mm mrad |



SMI enables multi-microbunch driven plasma wakefield acceleration.





A. Caldwell, et al. AWAKE design report: a proton-driven plasma wakefield acceleration experiment at CERN. No. CERN-SPSC-2013-013. (2013).

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# Multiple PD-HPWFA in the nonlinear regime

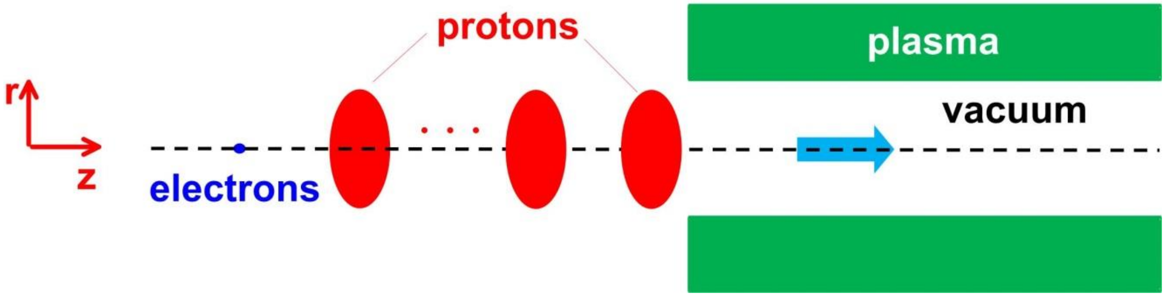
- SMI of the long proton bunch in the uniform plasma limits the beam-plasma interaction to the linear or weakly nonlinear regimes.

if NOT

- Wave period elongates
- Most of the bunch defocuses

if SO

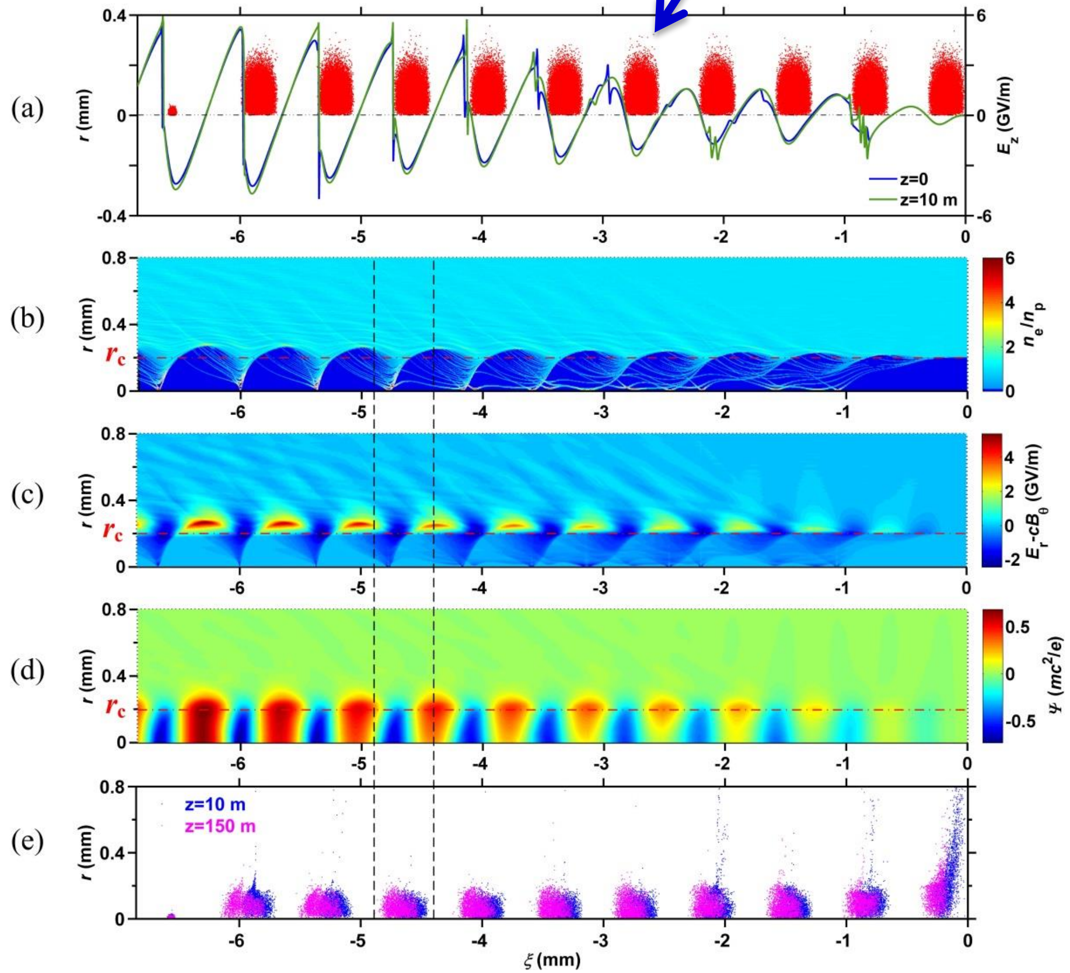
- Nonlinear plasma focusing both across and along the witness bunch
- Radially nonlinear accelerating fields



# Multiple PD-HPWFA in the nonlinear regime

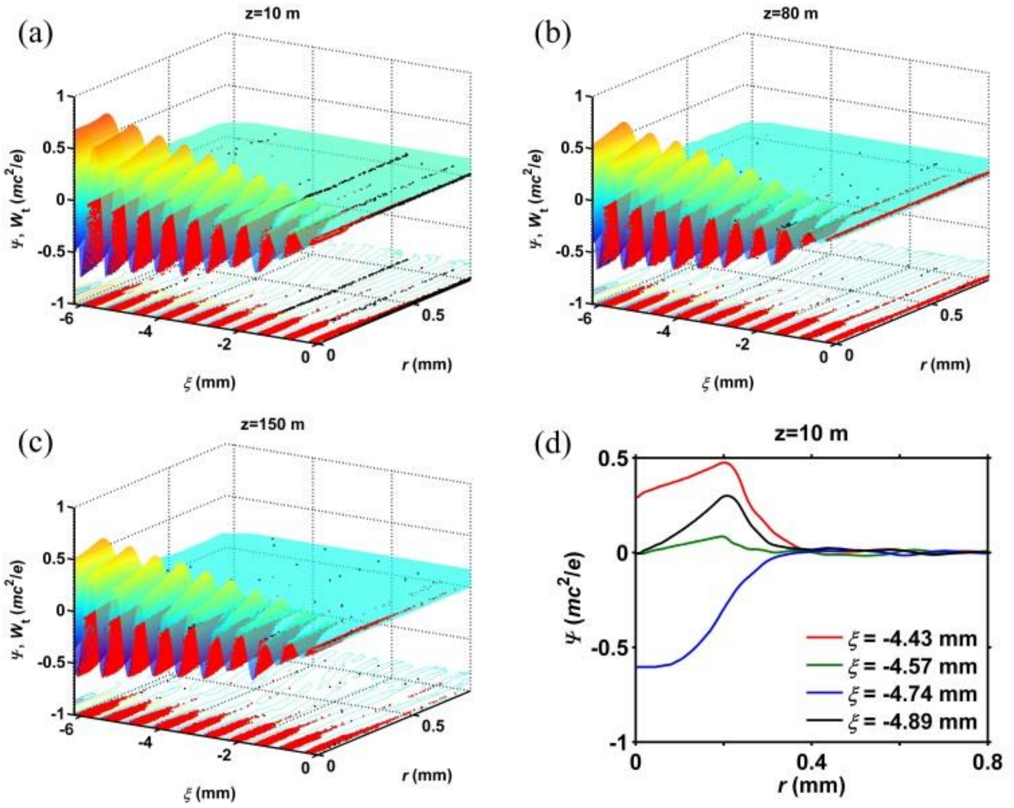
## Simulation Parameters

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



**Half wake period**

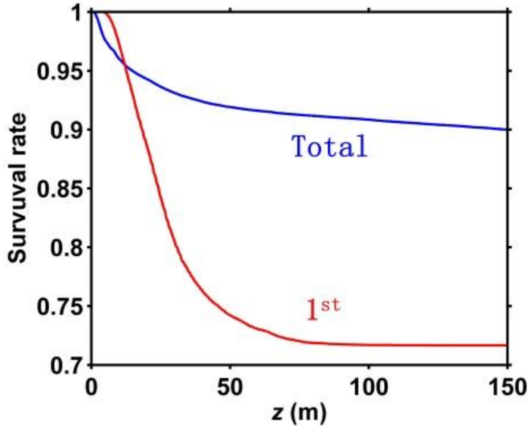
# Characteristics of proton bunches



Spatial distributions (a, b, c) of wakefield potential and driver protons (red dots for trapped and black for untrapped ones). (d) Radial dependencies of the potential at different $\xi$-positions.

Basin-like radial profile of the wakefield potential in the channel.

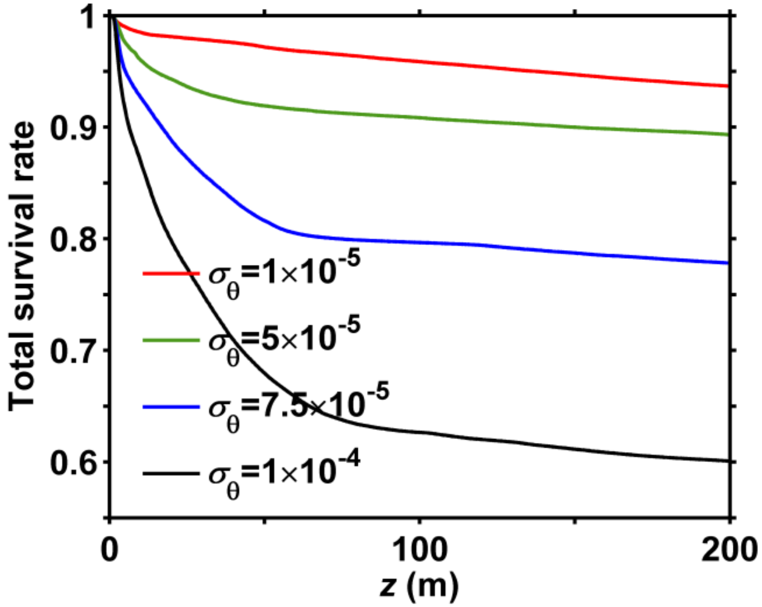
$$W_t = p_r^2/(2\gamma_b) + \Delta\psi(r,\xi)$$



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

# Proton survival rate vs. Initial angular divergence

$$W_t = p_r^2/(2\gamma_b) + \Delta\psi(r,\xi)$$



- Self-modulation results in large radial momenta of the protons.
- Other methods to generate bunches (longitudinal modulation?)

A. Petrenko and I. Sheinman, “High-energy micro-buncher based on the mm-wavelength dielectric structure,” in 25th Russian Particle Accelerator Conference (RuPAC’16), St. Petersburg, Russia, 21–25 November 2016

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- We simply introduce a positron bunch to the accelerating phase in the multiple PD-HPWFA case.

| Parameters | Values | Units |
|---|---|---|
| **Positron bunch:** | | |
| Bunch charge | 160 | pC |
| Energy, $W$ | 10 | GeV |
| Energy spread | 1% | |
| Bunch length, $\sigma_z$ | 15 | µm |
| Beam radius, $\sigma_r$ | 5 | µm |
| Normalized emittance, $\varepsilon_n$ | 1 | µm |

Lq is the quadrupole period, W is the beam energy, S is the magnetic field gradient, $\varepsilon_p$ is rms emittance.

- With S =0.5 T/mm and Lq=0.9 m, it gives W>>3.1 GeV.
- $\sigma_{r\_eq}$=5.4 µm

- ➢ Quadrupole focusing period is much shorter than the period of transverse particle oscillations.

$$L_q \ll 2\pi\sqrt{\frac{W}{eS}}$$

- ➢ The average quadrupole focusing corresponds to the betatron function:

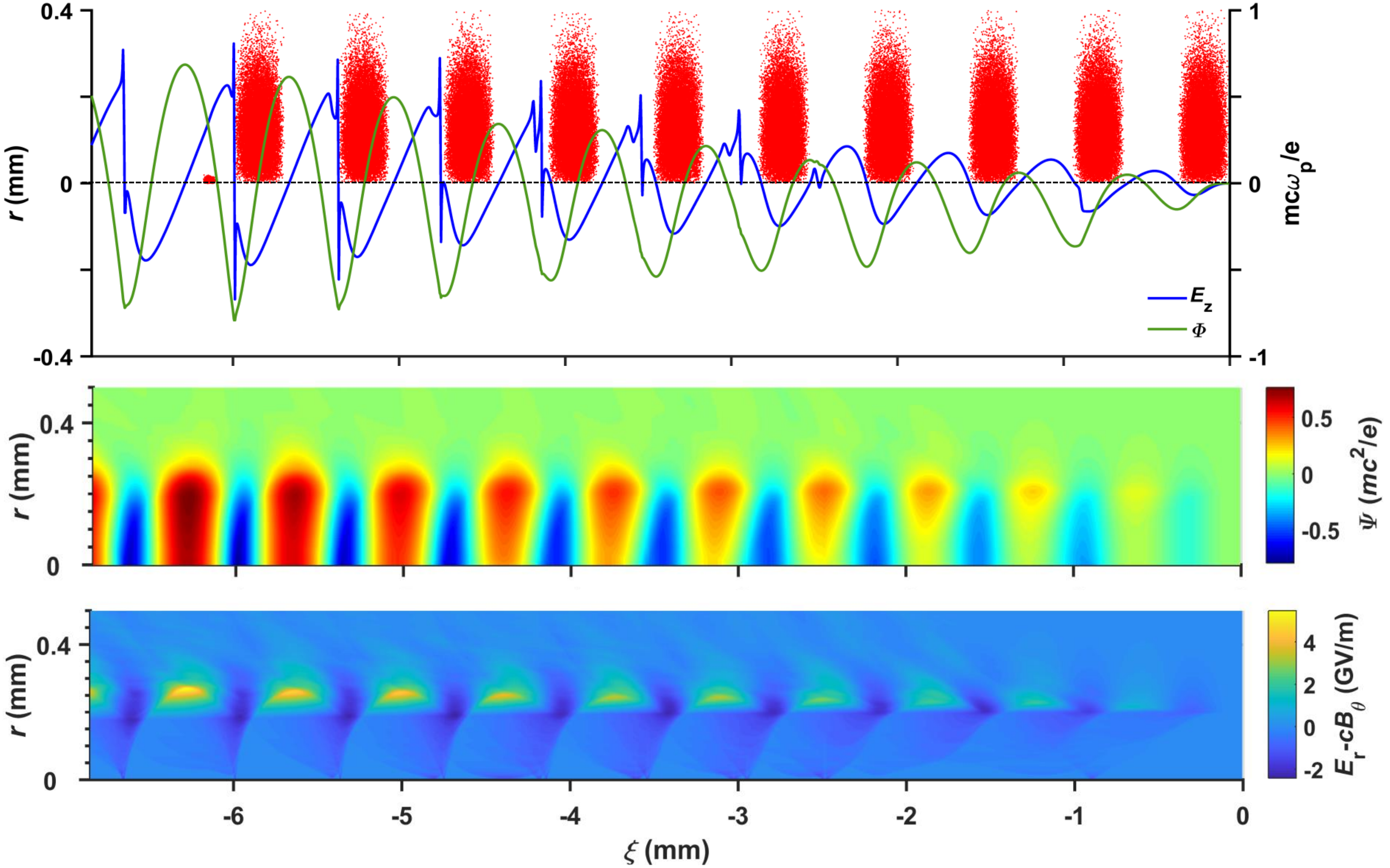
$$\beta = \sqrt{\frac{rW_P}{F_q}} = \frac{2\pi\sqrt{2}W_P}{SL_q e\sqrt{\kappa}}$$

- ➢ The equilibrium radius:

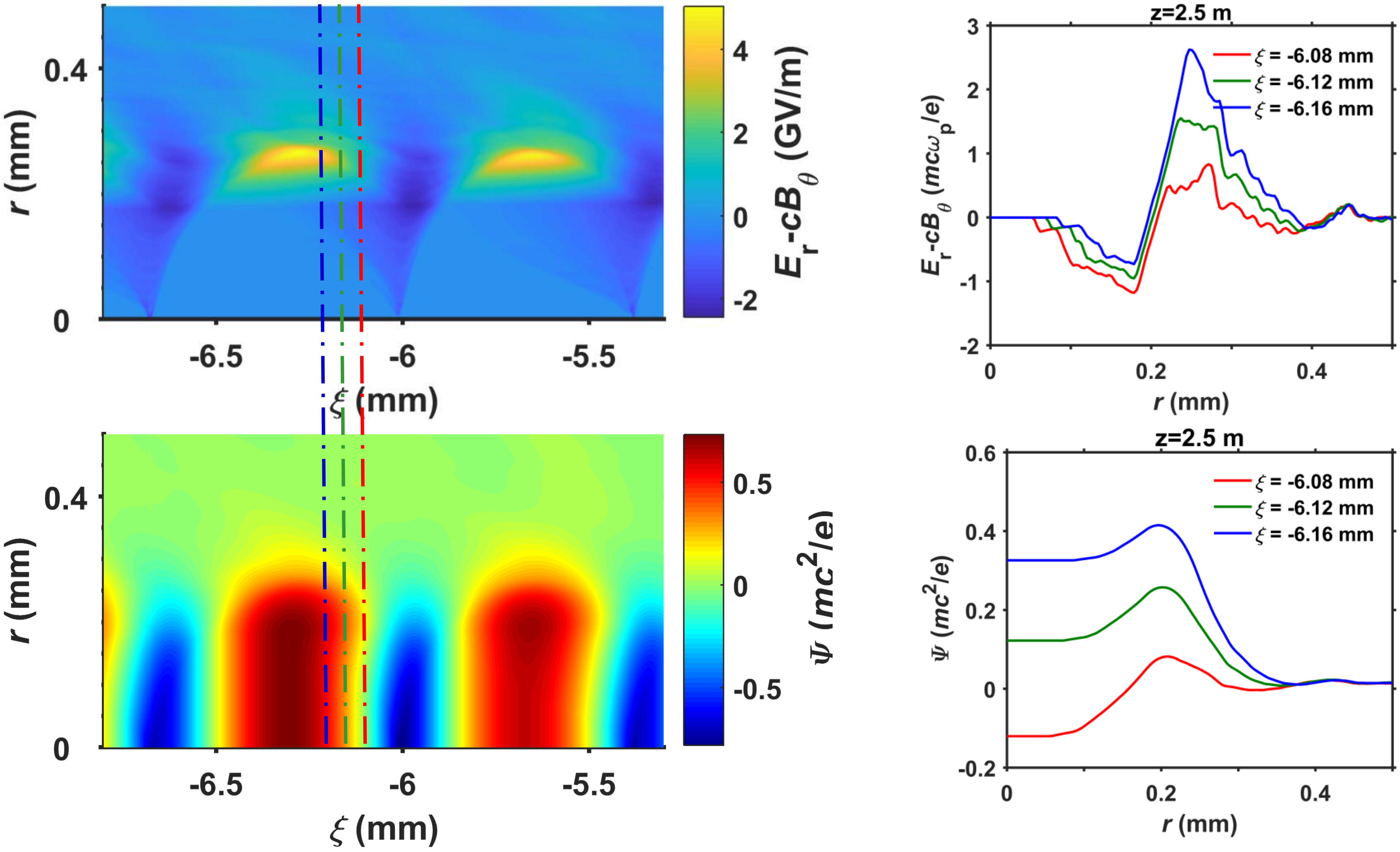
$$\sigma_r = \sqrt{\epsilon_P \beta}$$

# Multiple proton bunch driven e+ acc in hollow plasma

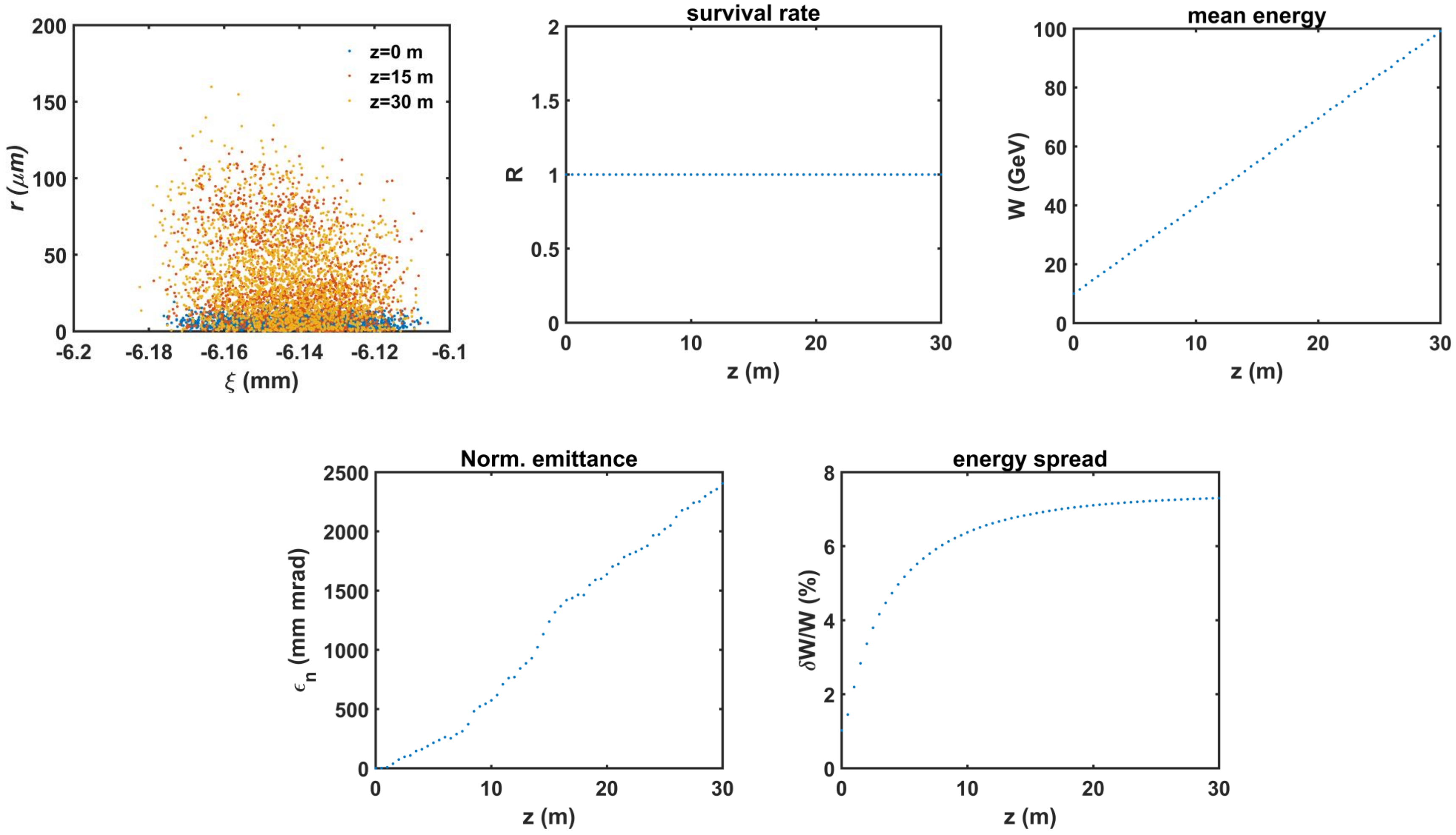
z= 0 m



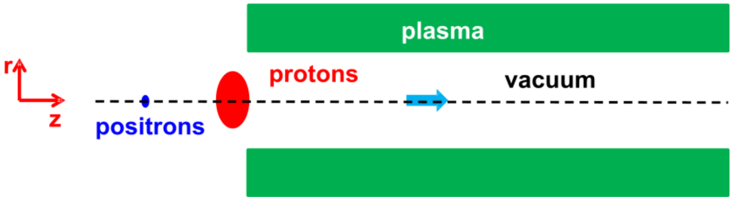
# Transverse dynamics

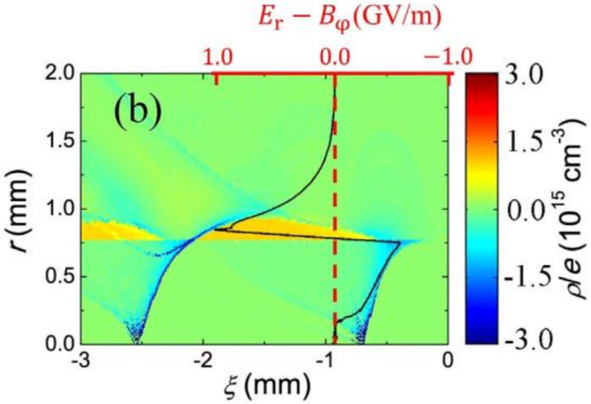


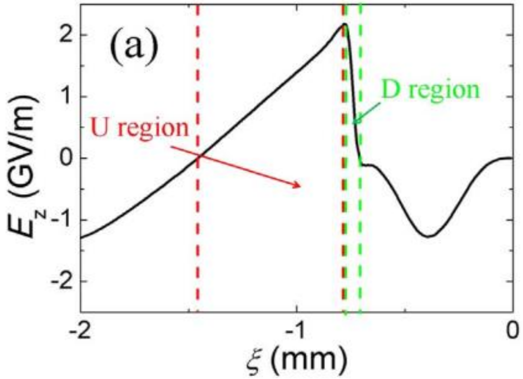
# Acc characteristics and beam quality

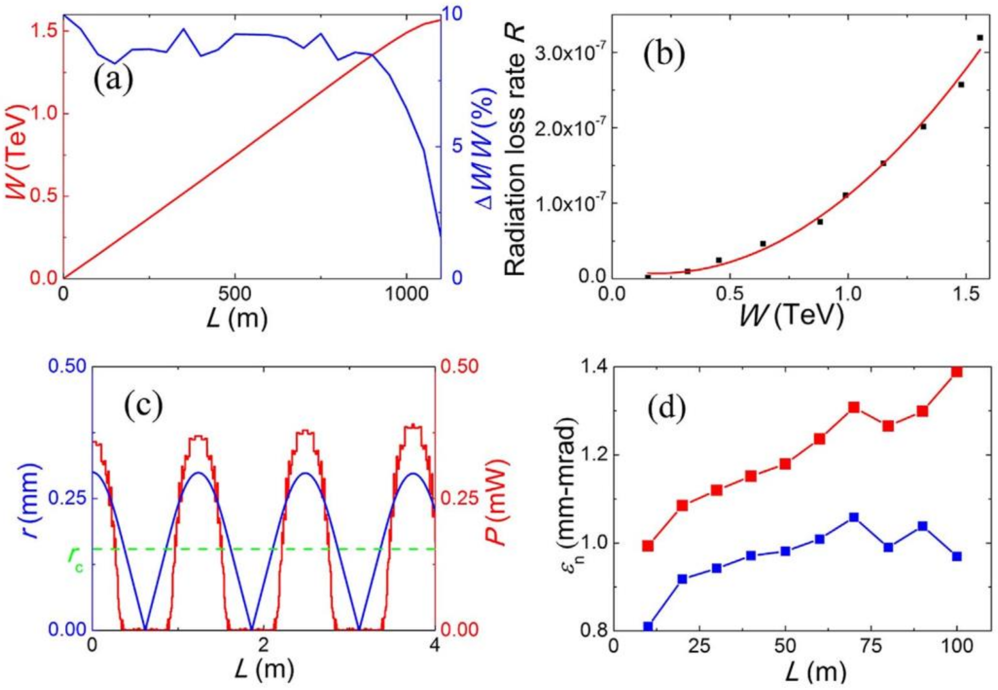


# More exciting published results









- ✓ Good radial confinement
- ✓ Novel effect in reducing energy spread
- ✓ Low radiation losses
- ✓ Emittance preservation

L. Yi *et al.*, Positron acceleration in a hollow plasma channel up to TeV regime, Sci. Rep. 4, 4171 (2014).

# Summary & Outlook

- The hollow plasma eliminates the defocusing from background ions within the channel; broadens the region where the protons can stay; enables the operation of multiple PD-PWFA in the blowout regime.
- The majority of protons survive after a long distance;
- Multiple proton bunches are more likely yielded through long realistic proton drivers.
- With proper parameter optimization, a favorable region for both positron acceleration and quality conservation is possible.
- Experimental implementation of a long and stable hollow channel is still a challenge.

# References

- Y. Li *et al.*, Multi-proton bunch driven hollow plasma wakefield acceleration in the nonlinear regime, Phys. Plasmas **24**, 103114 (2017).
- Y. Li *et al.*, High-quality electron beam generation in a proton-driven hollow plasma wakefield accelerator, Phys. Rev. Accel. Beams **20**, 101301 (2017).
- L. Yi *et al*., Scheme for proton-driven plasma-wakefield acceleration of positively charged particles in a hollow plasma channel, Phys. Rev. ST Accel. Beams 16, 071301 (2013).
- L. Yi *et al*., Positron acceleration in a hollow plasma channel up to TeV regime, Sci. Rep. 4, 4171 (2014).

Thank you for your attention!