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Positron acceleration in transversely tailored plasmas

FACET-II Science Workshop 2019
10/31/2019

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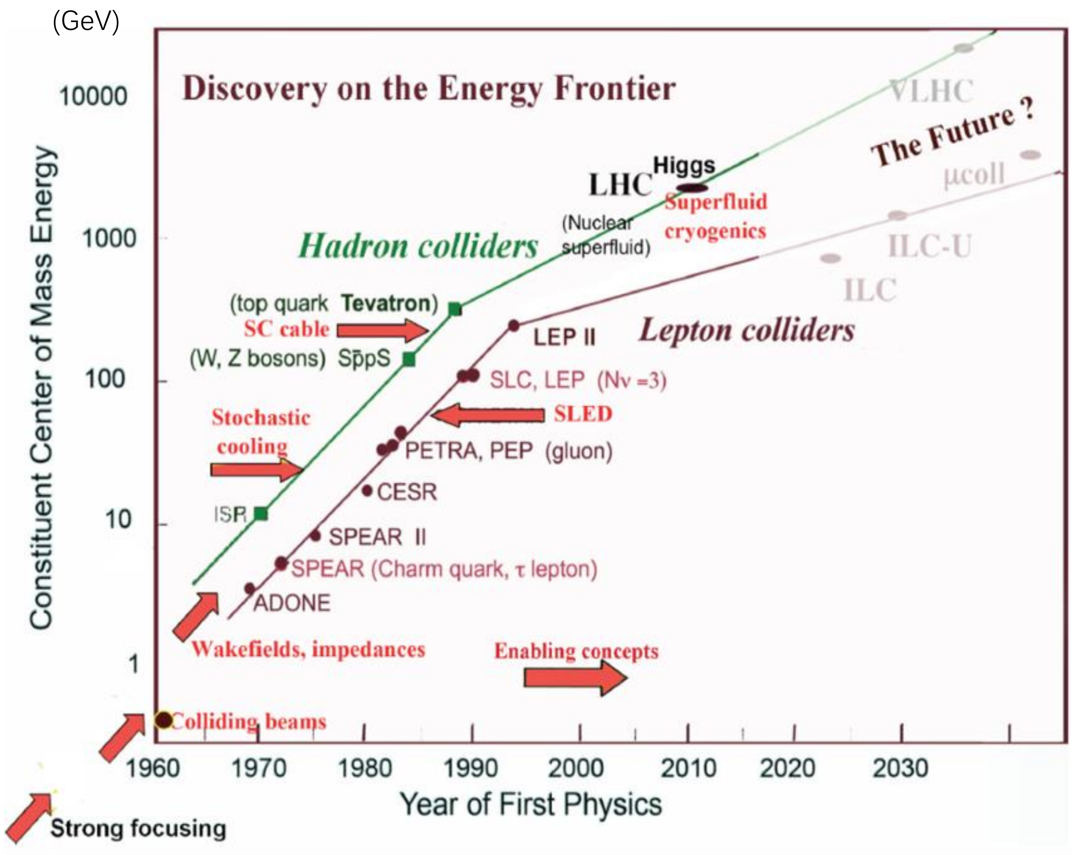
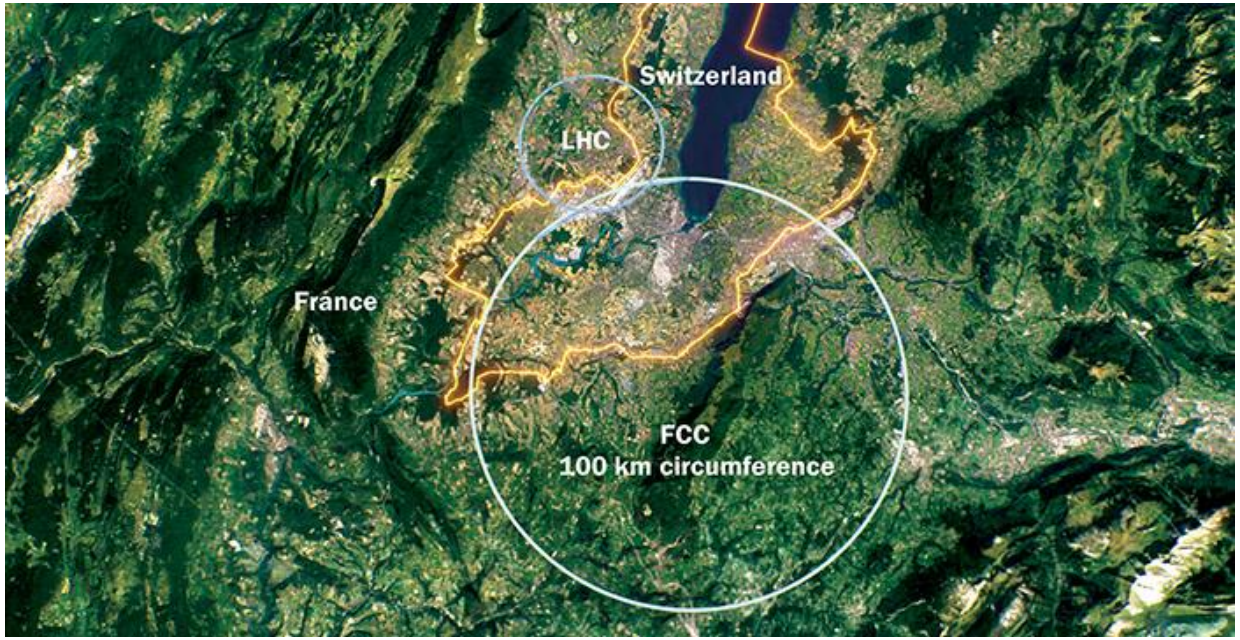
Why do we need wakefield positron acceleration?

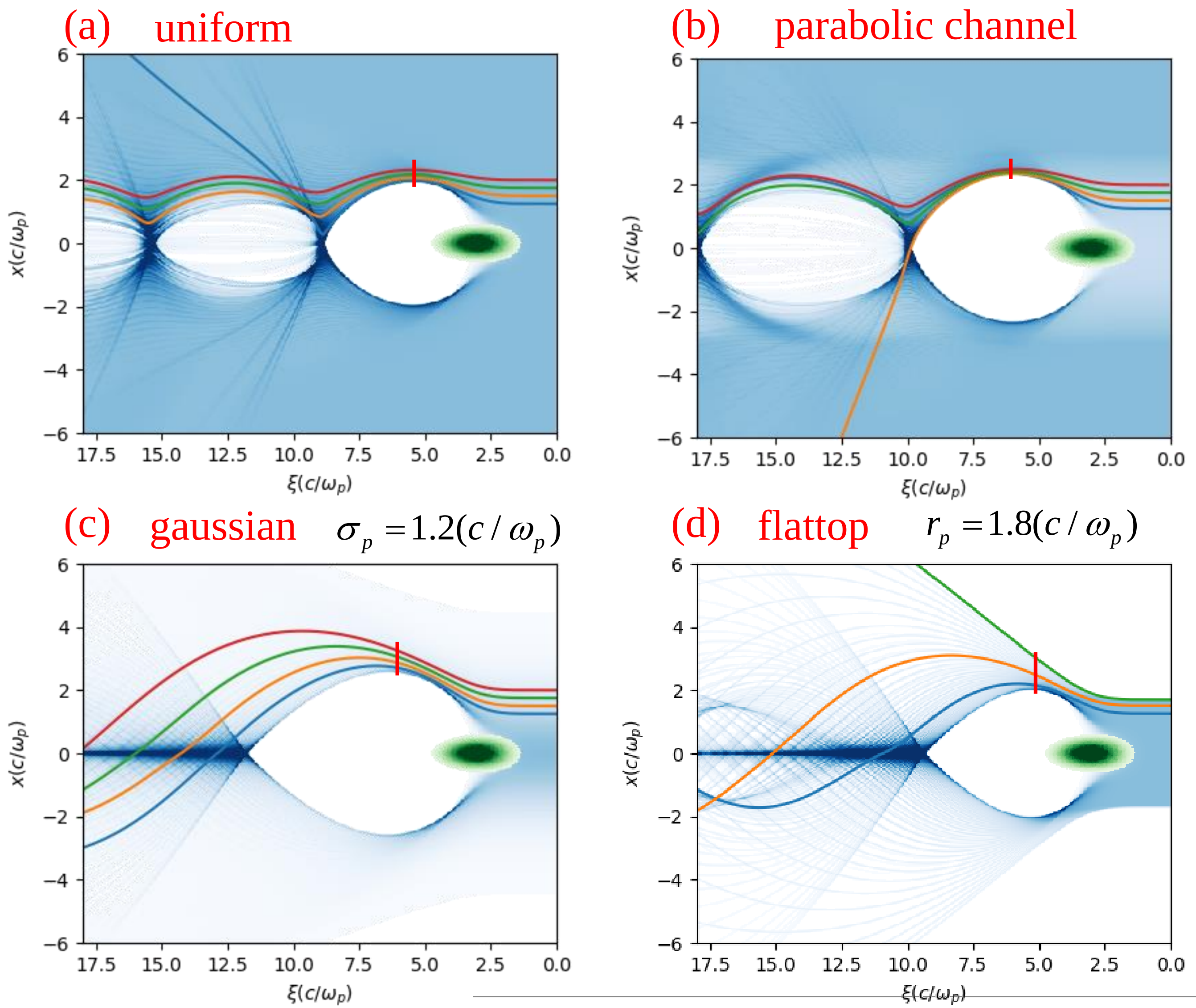


Livingston plot



LHC & FCC ?

Different transverse profiles



$n_p = 10^{16} cm^{-3}$ $\Lambda = \frac{n_{b0}}{n_p}\sigma_r^2 = 1$

Tracking plasma electrons with initial radial coordinate of 1.25, 1.5, 1.75, 2 (c/ω_p).

- Sheath width matters
- For narrow sheath, most plasma electrons do not come back to the axis, so there's a series of bubbles.
- For wide sheath, most plasma electrons will be back to the axis, thus form an electron column.

Dawson ring model

It is to describe the motion of plasma electrons.

There are 2 basic assumptions.

- There's no trajectory crossing.
- The total force is due to the electrostatic force. (non-relativistic limit)

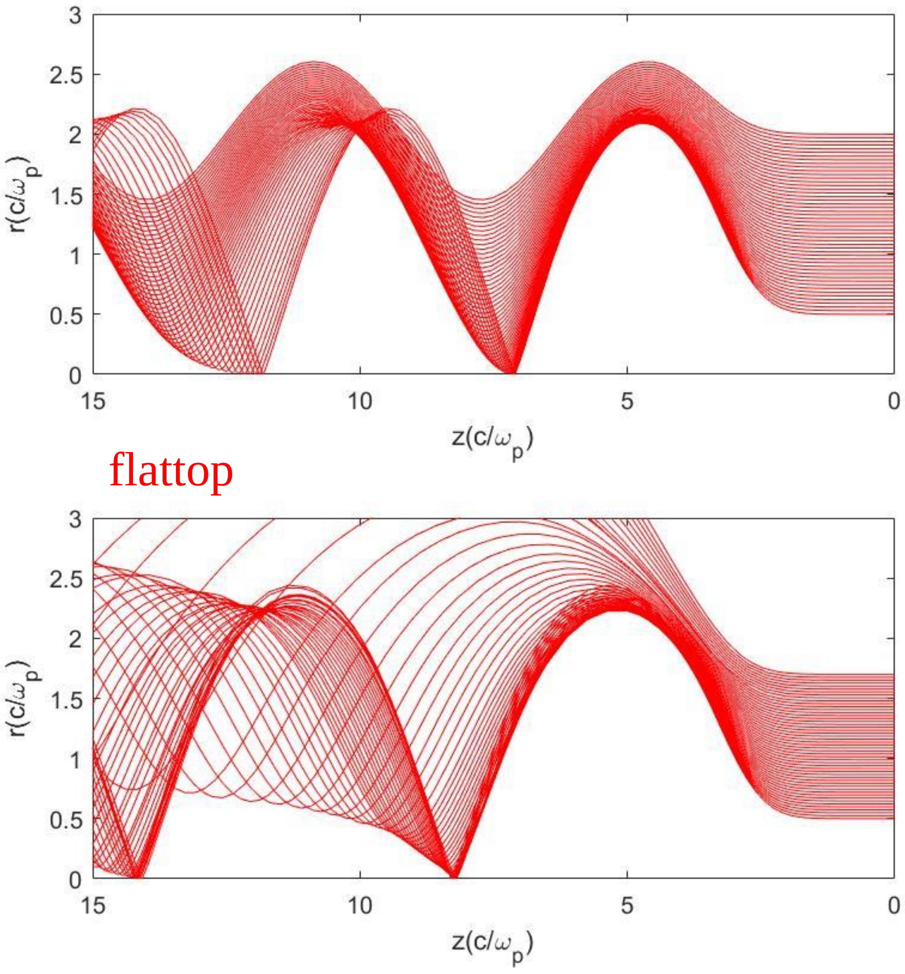
In uniform plasma: $$\frac{d^2r}{d\xi^2} = -\frac{1}{2}r + \frac{1}{r}[\frac{1}{2}r_0^2 + \int_0^r n_b(r',\xi)dr']$$

- The total force has 3 components, the plasma ion, the plasma electron inside the ring and the electron driver.

In flattop plasma: $$-\frac{1}{2}r \rightarrow \begin{cases} -\frac{1}{2}r, r \le r_p \\ -\frac{1}{2}\frac{r_p^2}{r}, r > r_p \end{cases}$$

uniform

flattop

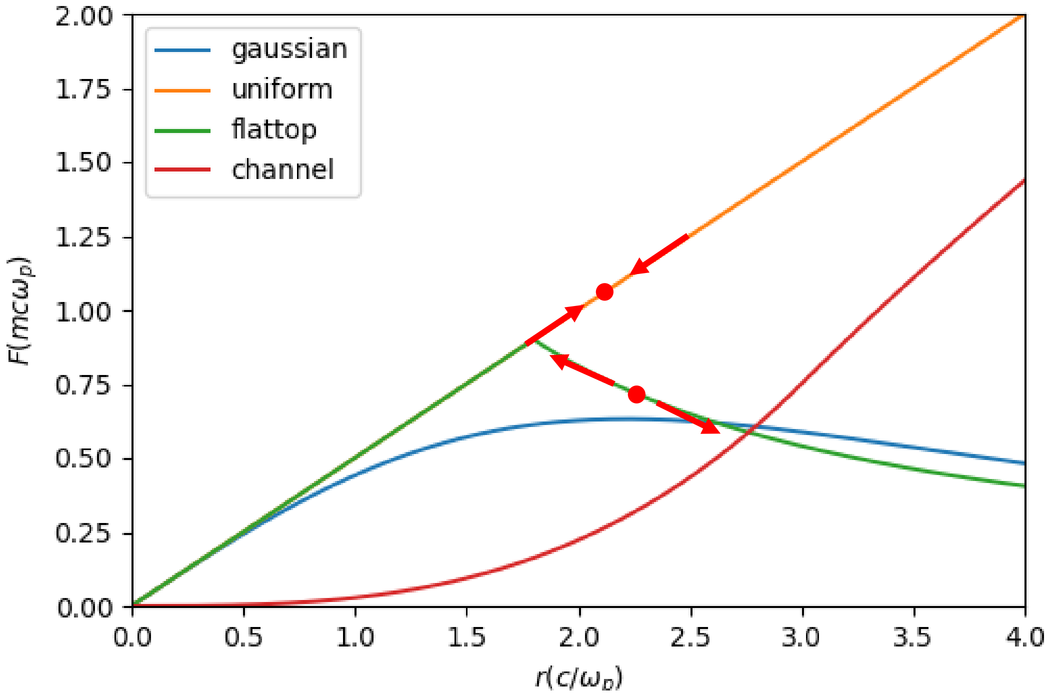


W. Lu et al. Physics of Plasmas **13**, 056709 (2006)

Further simplified

Observation: after the driver, the major term is from the focusing force of the plasma ions.

Focusing force from ions



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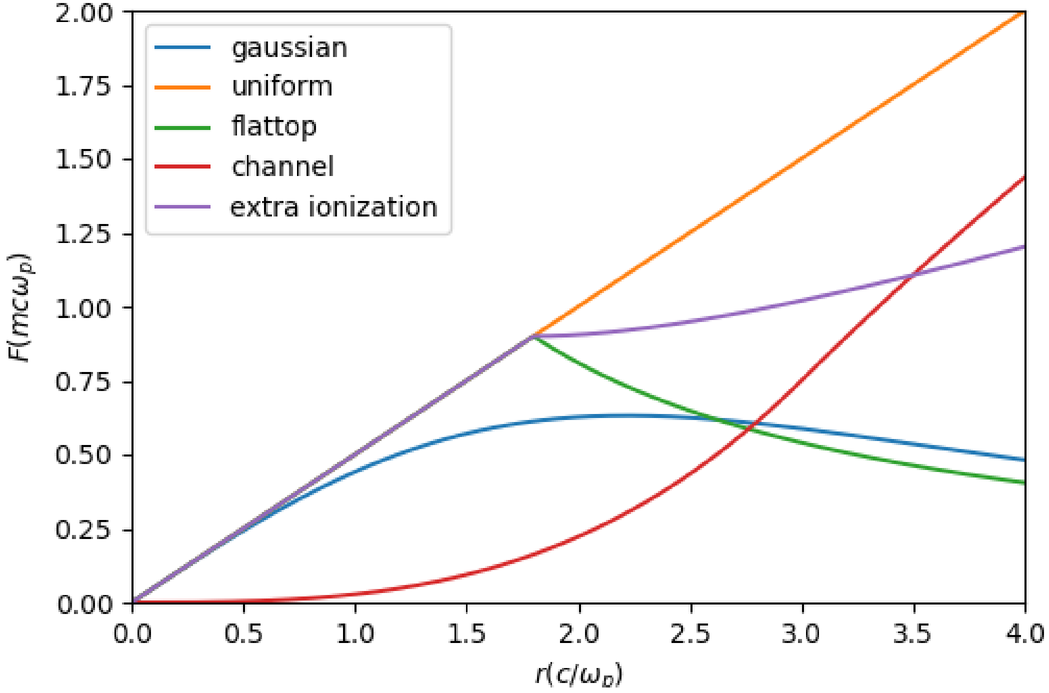
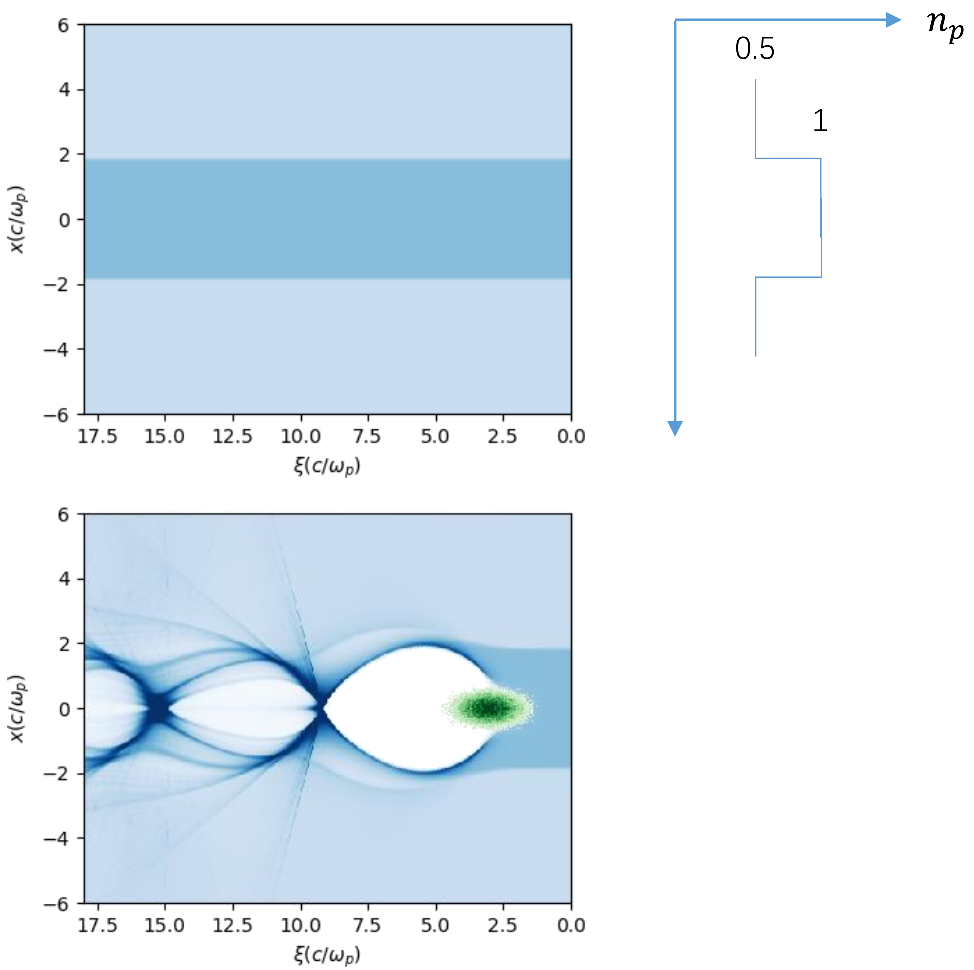
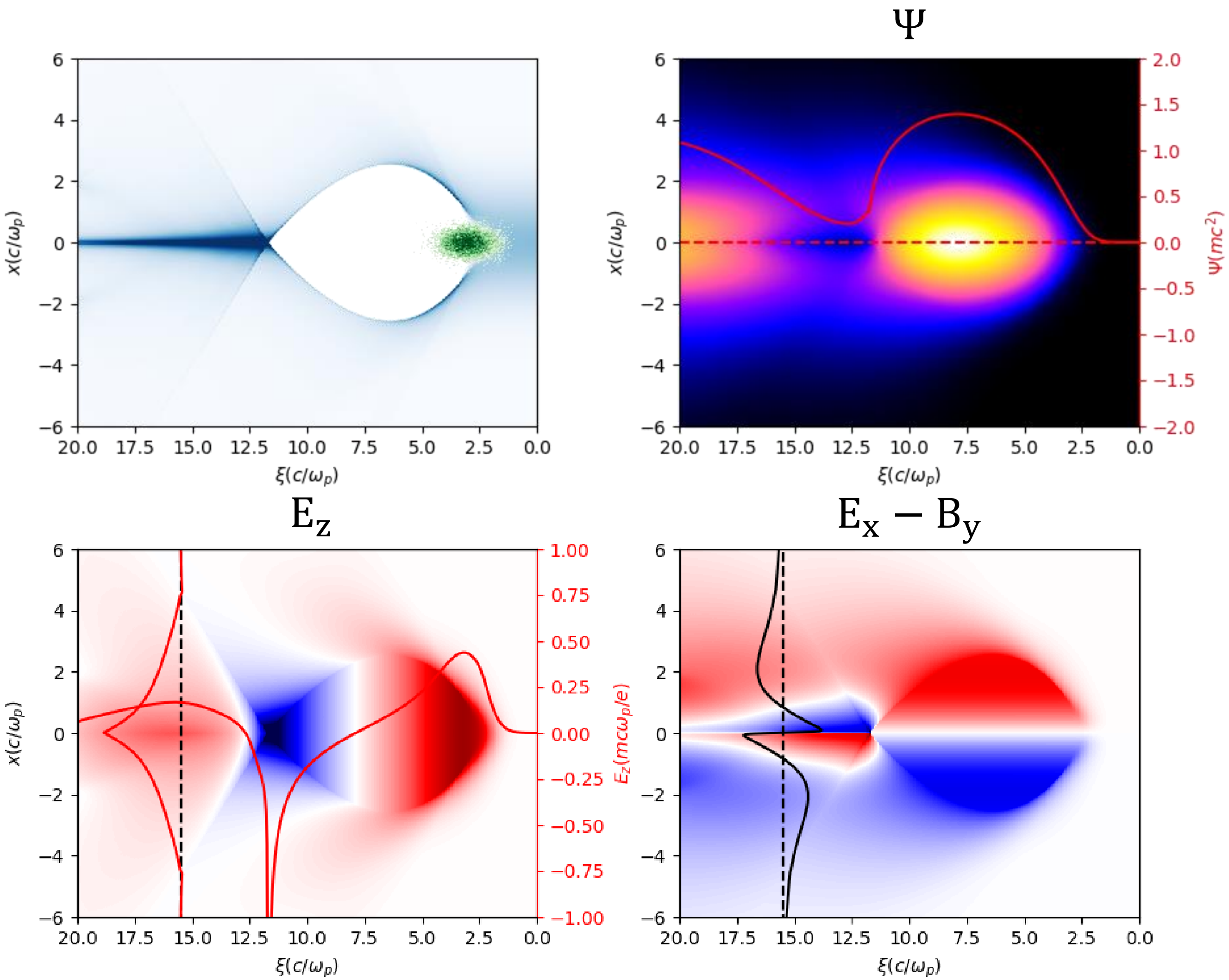


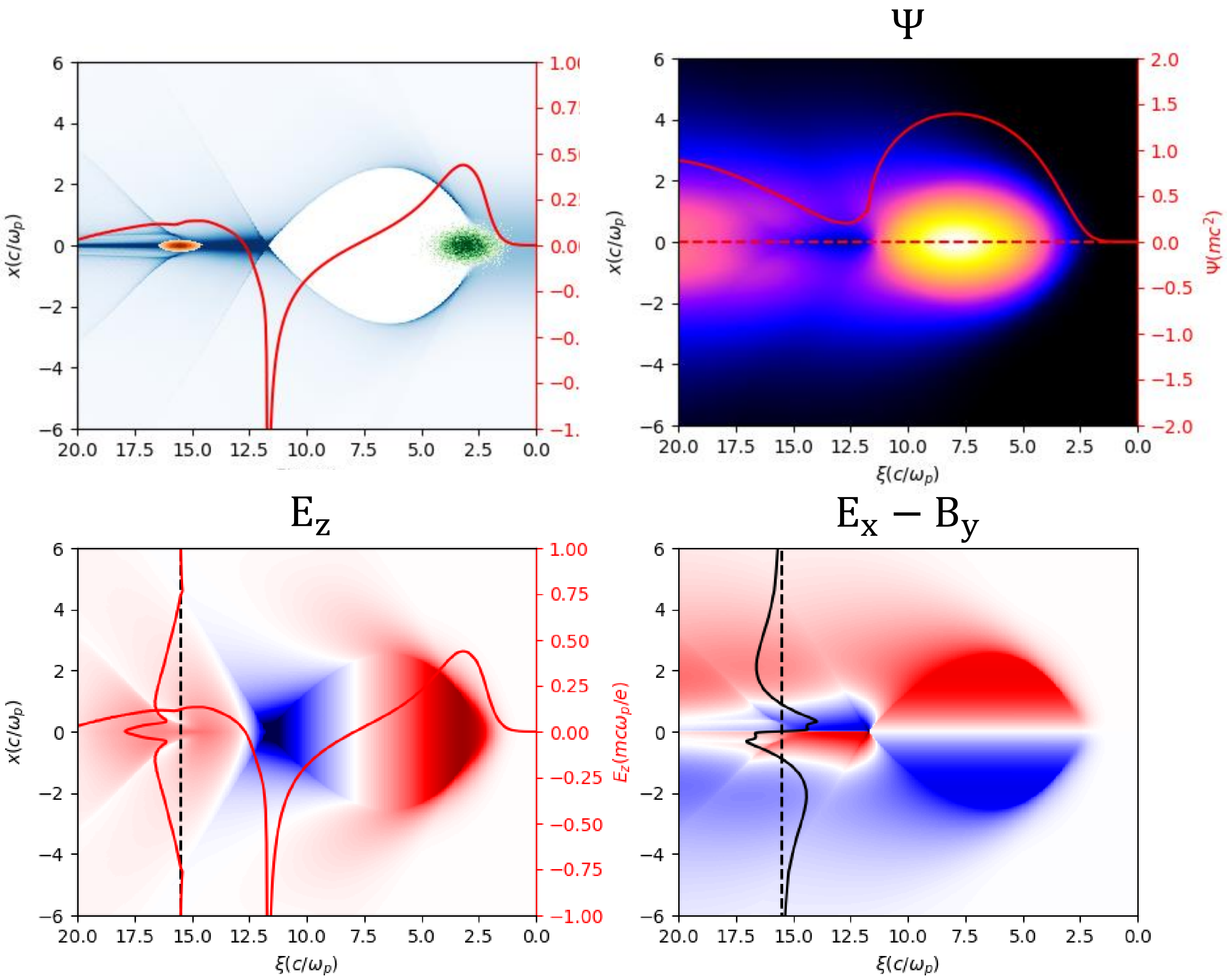


Wakefields



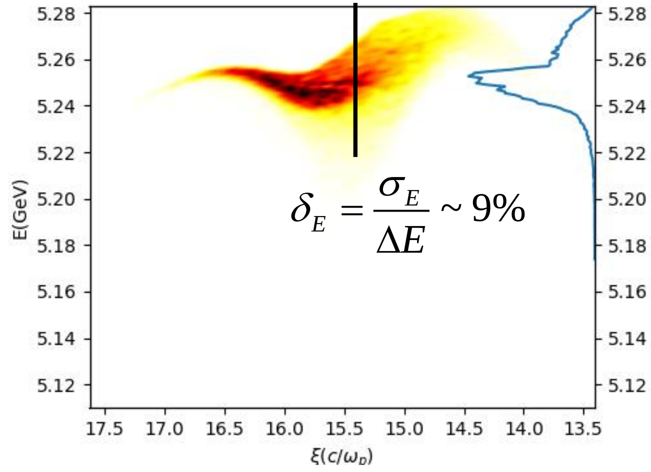
- Unlike the blowout regime, there is no cavity-like structure for positron acceleration.
- Nonuniform Ez field in the transverse plane, thus may lead to relatively large slice energy spread.
- Transverse focusing force is not linear (emittance preservation can be achieved by careful beam matching), and the focusing region is limited.

Beam loading case



$n_p = 10^{16} cm^{-3}$ $Q_d = 2.83nC$ $Q_w = 0.57nC$

Spectrum of witness beam



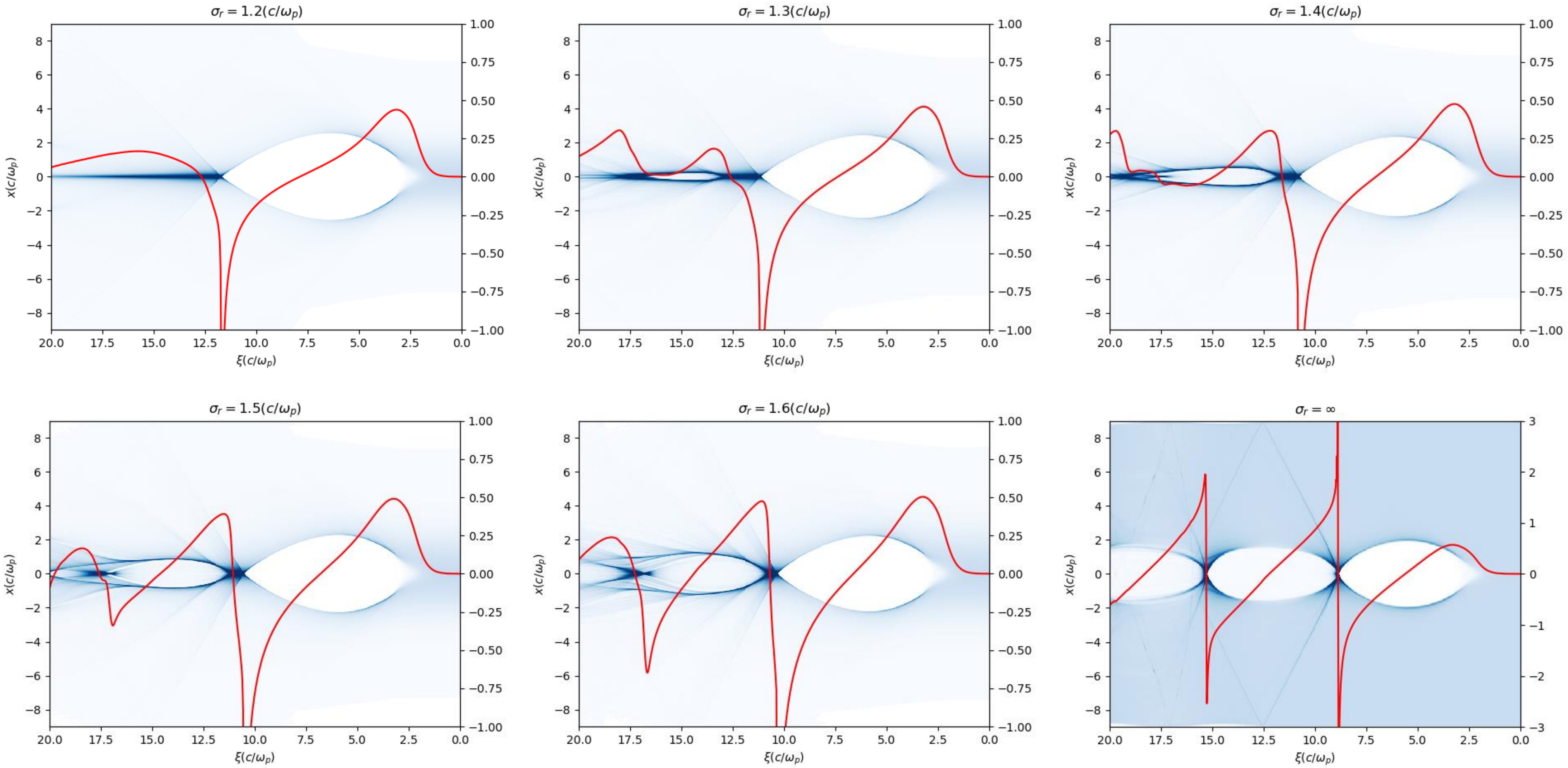
$$\delta_E = \frac{\sigma_E}{\Delta E} \sim 9\%$$

$$\eta = \frac{\Delta E_w}{\Delta E_d} = 6.5\%$$

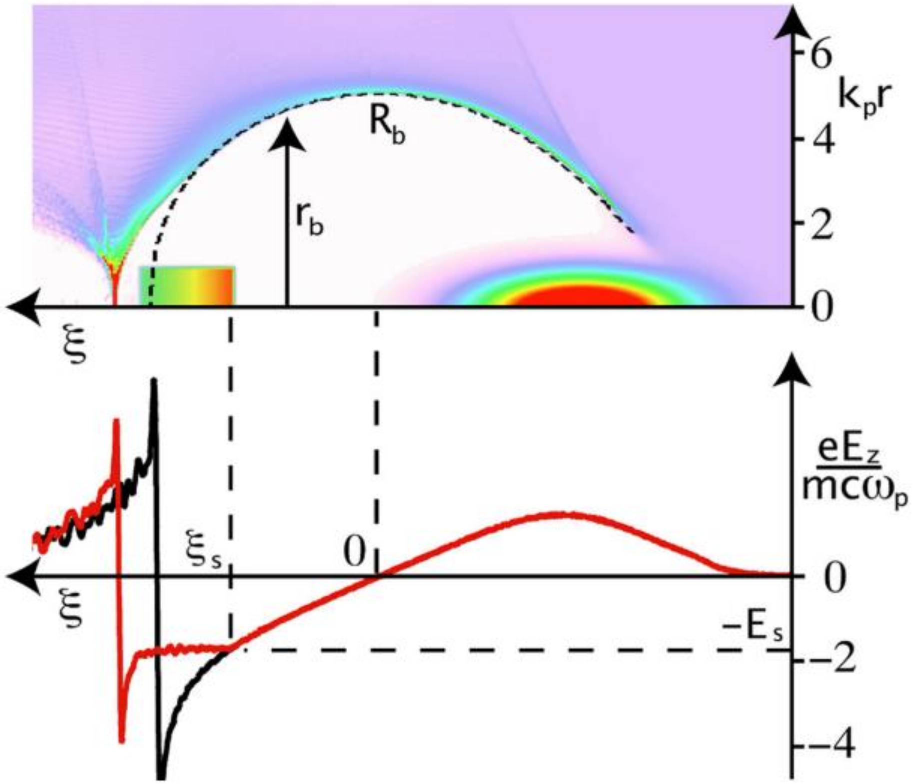
Electron and positrons are strongly coupled.

The wakefields are coupled with the profile of electrons.

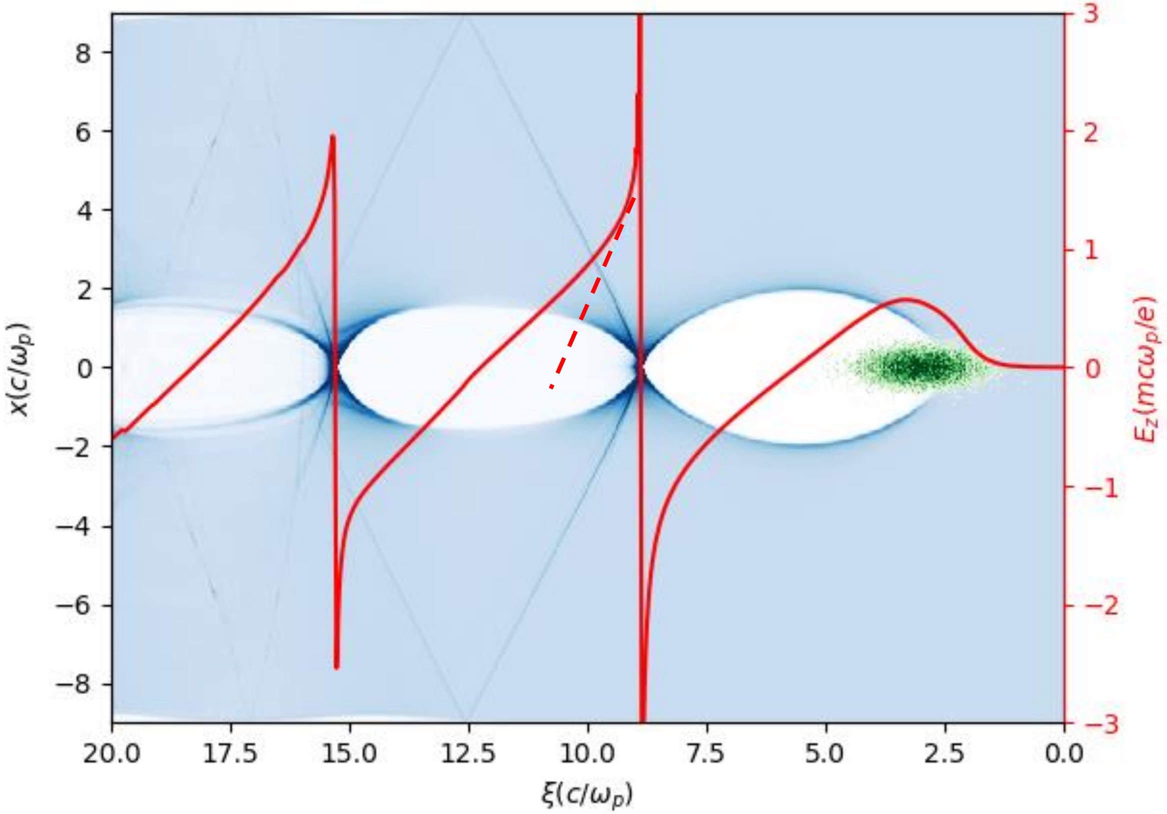
Search for other options



Beam loading problem



Electron beam loading



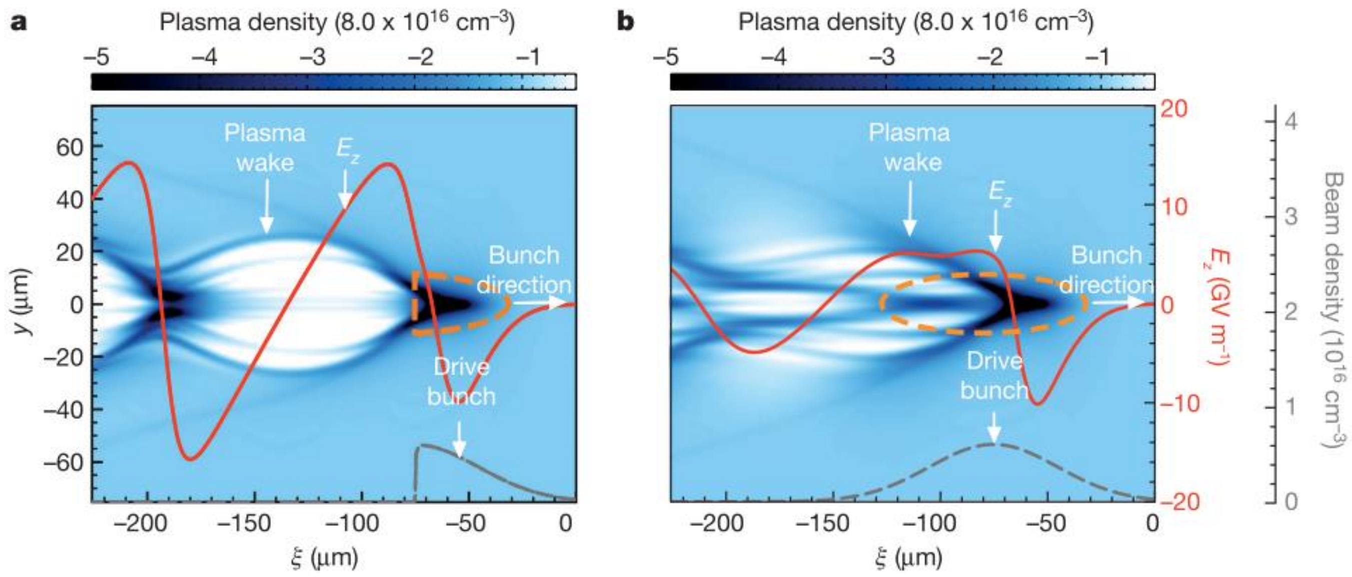
Positron beam loading

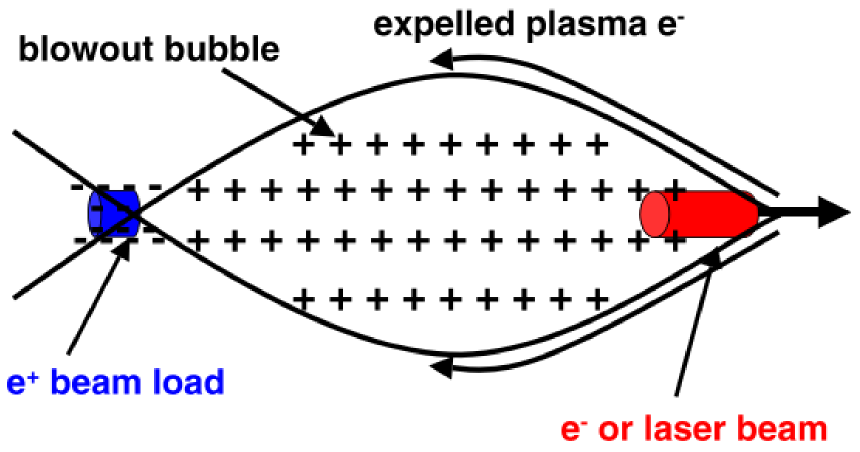
M. Tzoufras et al. PRL 101, 145002 (2008)

Some hints

What will happen when positron beam is loaded at the front of a bubble?

Will the E_z be flattened?



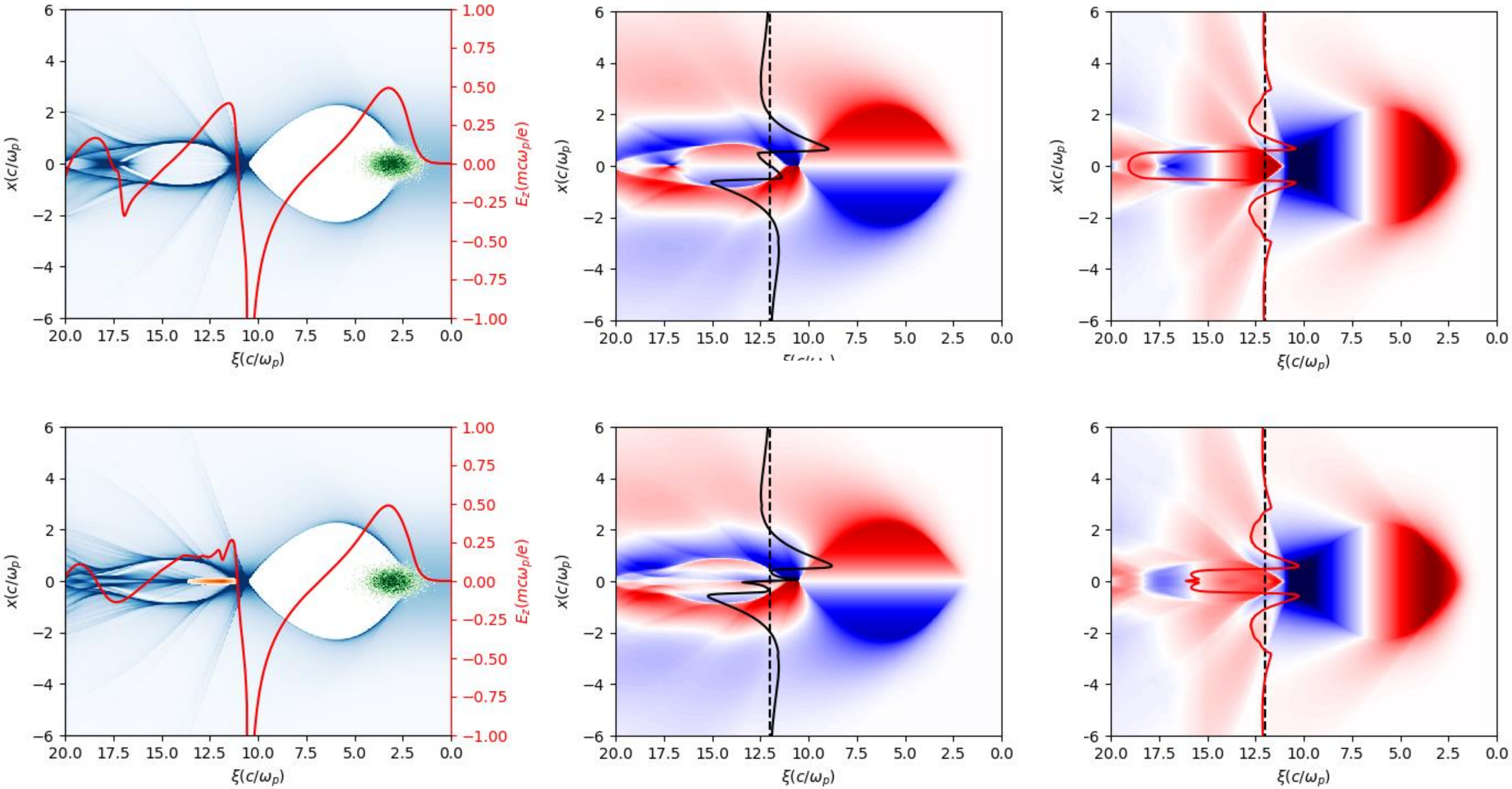


S. Corde et al. Nature 524, 442-445 (2015).

X. Wang et al. PRL 101, 124801 (2008).

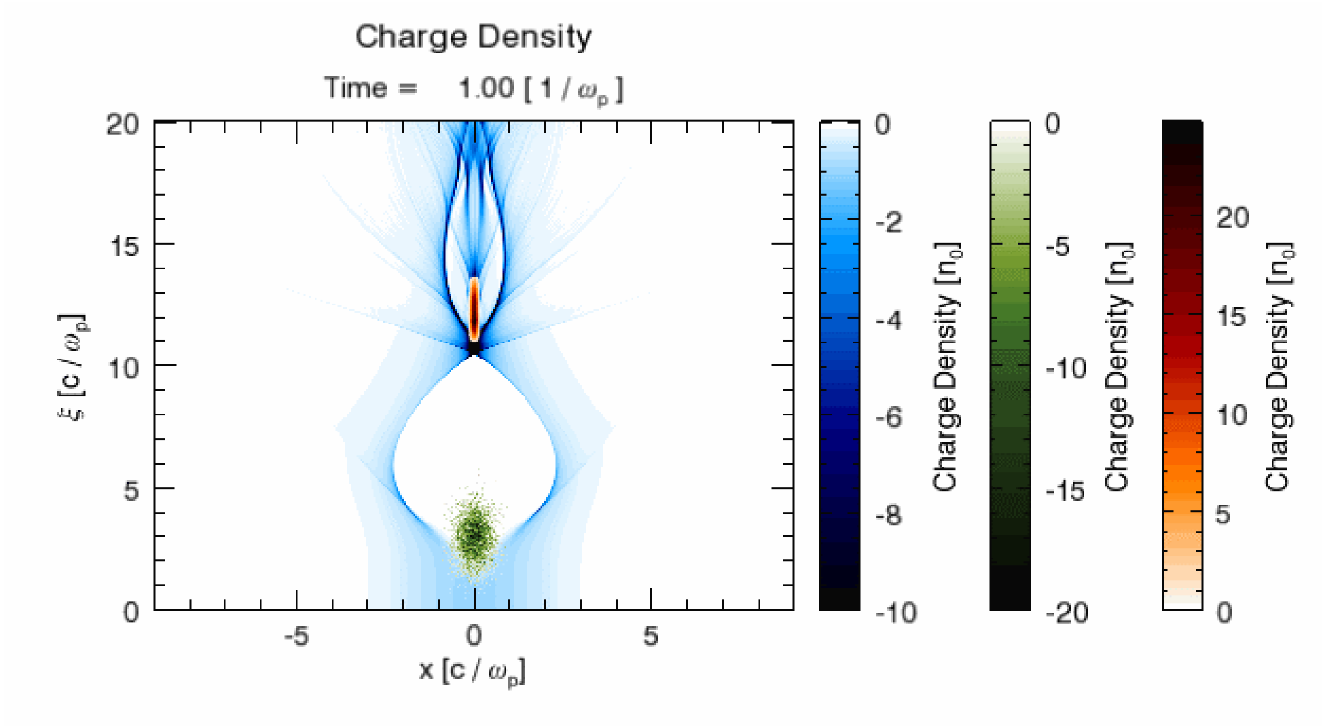
Beam loading example

$\sigma_r = 1.5(c/\omega_p)$ $n_p = 10^{16} cm^{-3}$ $Q_d = 2.83nC$ $Q_w = 0.42nC$

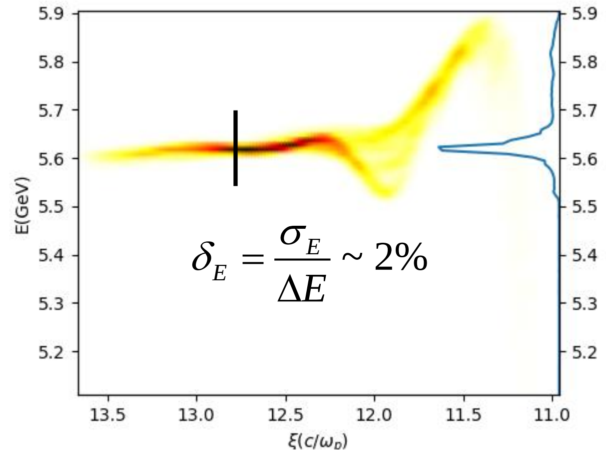


In the bubble center, there's an electron column. The focusing force and acceleration field are from different sources.

The results



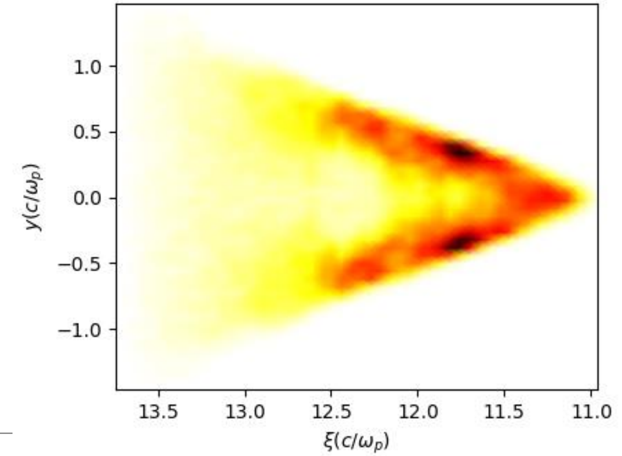
Spectrum of witness beam



$$\delta_E = \frac{\sigma_E}{\Delta E} \sim 2\%$$

$$\eta = \frac{\Delta E_w}{\Delta E_d} = 6.7\%$$

Final transverse profile

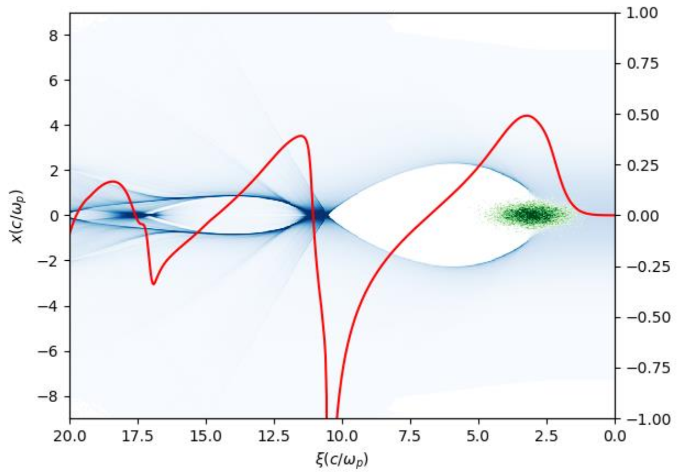


Beam loading effect – an explanation

- In the nonlinear theory of blowout regime.

$$\psi(r=0,\xi)=\frac{r_b^2(\xi)}{4}(1+\beta(\xi)) \qquad \beta(\xi)=\frac{(1+\alpha)^2\ln(1+\alpha)^2}{(1+\alpha)^2-1}-1 \qquad \alpha\equiv\frac{\Delta}{r_b}$$

$$E_z(r=0)=\frac{\partial\psi(r=0,\xi)}{\partial\xi}\approx\frac{1}{2}r_b\frac{\partial r_b}{\partial\xi}$$

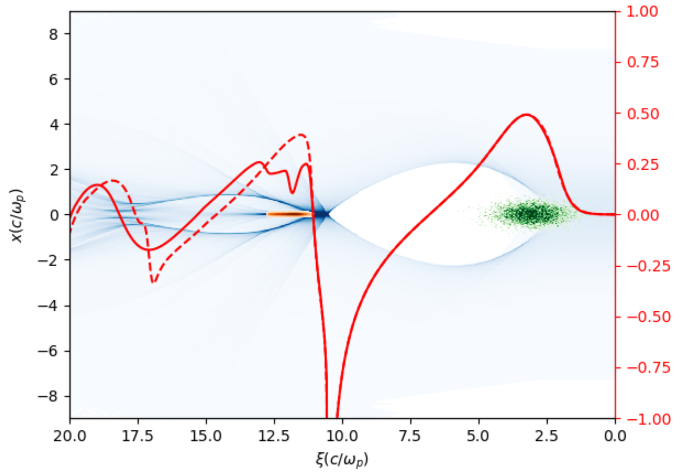


- If there is an electron column in the center of the bubble.

$$\psi(r=0,\xi)=\frac{r_b^2(\xi)}{4}(1+\beta(\xi))-\frac{1}{4}(1+n_t)r_t^2(2\ln\frac{r_b(\xi)}{r_t}+1+\beta(\xi))$$

$$E_z(r=0)\approx\frac{1}{2}r_b\frac{\partial r_b}{\partial\xi}-\frac{1}{2}(1+n_t)r_t^2\frac{1}{r_b}\frac{\partial r_b}{\partial\xi}$$

  - r_t is the radius of the electron column, and $n_t=-(\rho-J_z/c)/(en_p)$ in the column.



W. Lu et al. Physics of Plasmas **13**, 056709 (2006)

Summary

- We can tailor the transverse shape of plasma to change the structure of wakefield.
- Positron beam loading can have good properties in a bubble-like structure.

- Further research
  - Investigate the electron and positron coupling
  - Explore the beam loading effect in the uniform plasma (higher efficiency)

Thank you for your attention!