Positron Acceleration in a Hollow Channel Plasma Wakefield Accelerator

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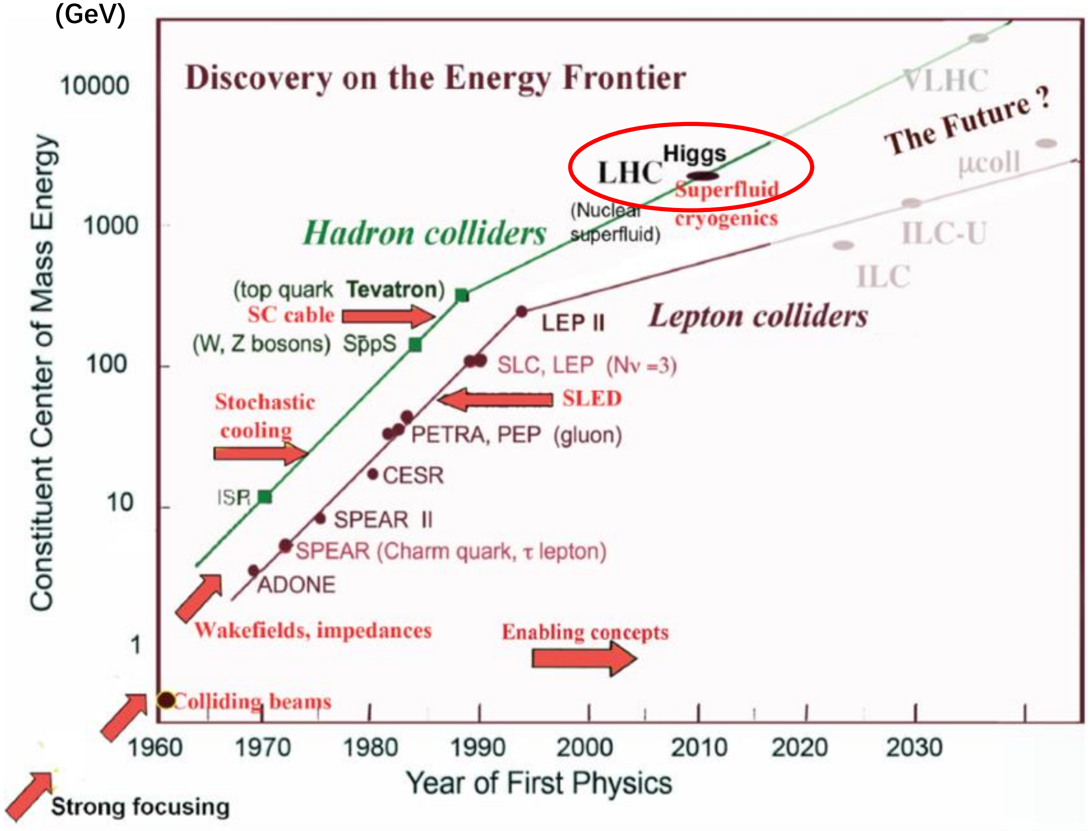
Toward Future Collider

- **Precision measurements of the Higgs Boson is of the most important issues for particle physics, and we need a high energy electron-positron collider.**

Livingston plot



- **The candidates for the future electron-positron collider**
  - The International Linear Collider
  - Future Circular Collider, Circular Electron Positron Collider
  - Circular Electron Positron Collider with plasma injector
  - Other advanced acceleration based collider

Plasma Based Acceleration : An Important Option

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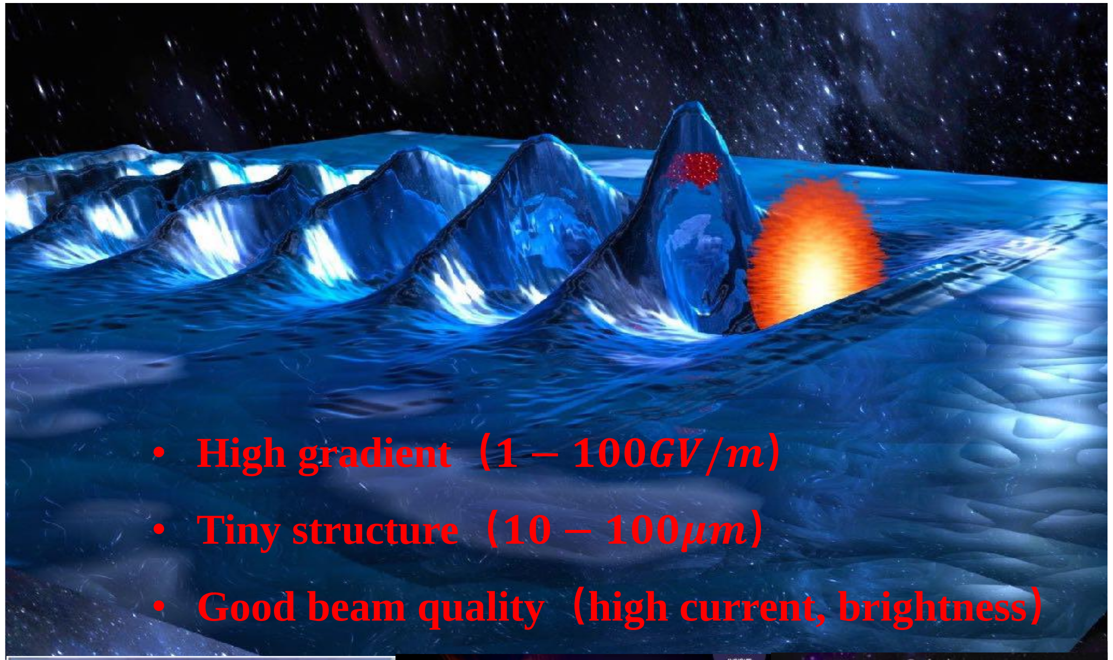


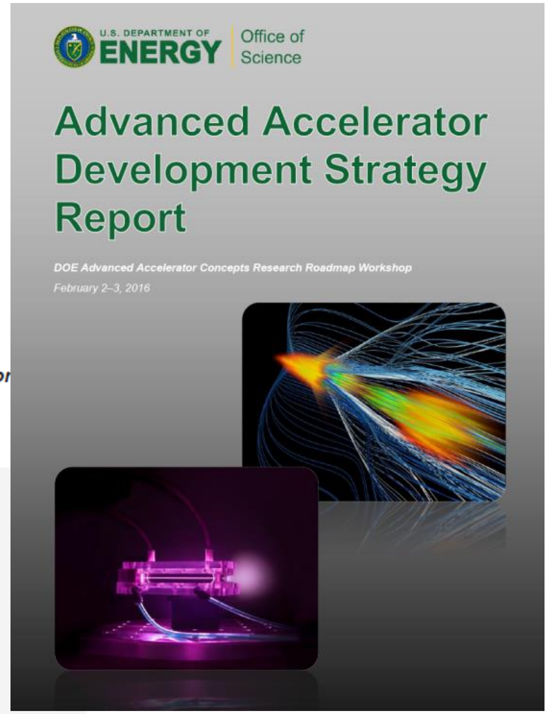
- High gradient（$1-100GV/m$）
- Tiny structure（$10-100\mu m$）
- Good beam quality（high current, brightness）

T.Tajima and J.M. Dawson PRL (1979) **LWFA**
P.Chen, J.M. Dawson et.al. PRL (1983) **PWFA**

Consensus on plasma based acceleration

High-priority future initiatives

B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs.
The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.



EuPRAXIA

NOVEL FUNDAMENTAL RESEARCH
COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

2020 update of the European strategy for particle physics

Major Challenge for Plasma Based Collider : Positron Acceleration

High Energy

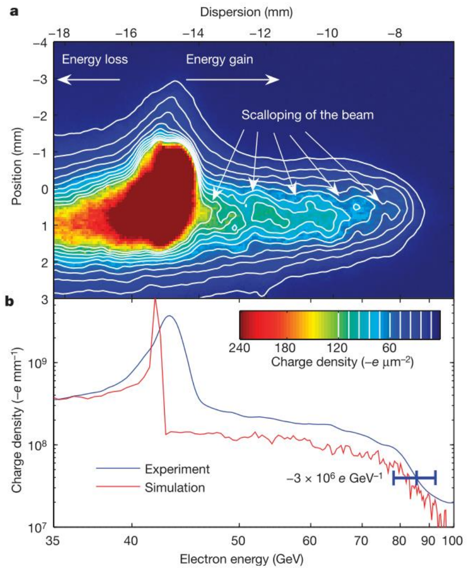
Over 42GeV acceleration in 85cm plasma

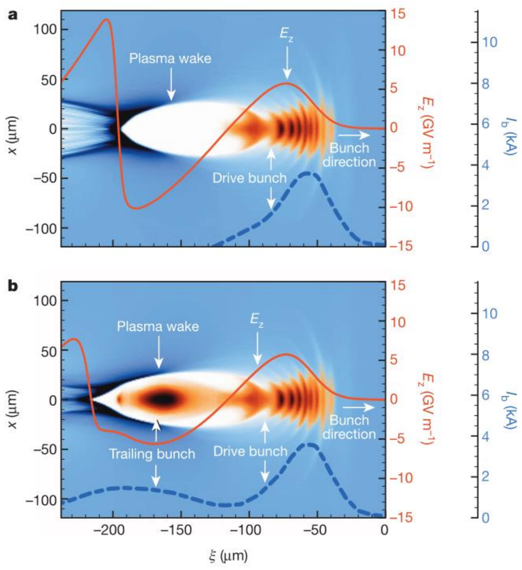
High Efficiency

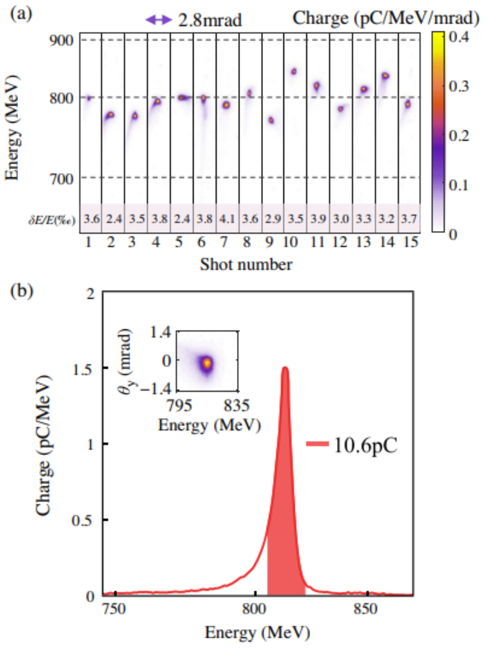
>30% energy transfer efficiency

Narrow Energy Spread

<1% rms energy spread





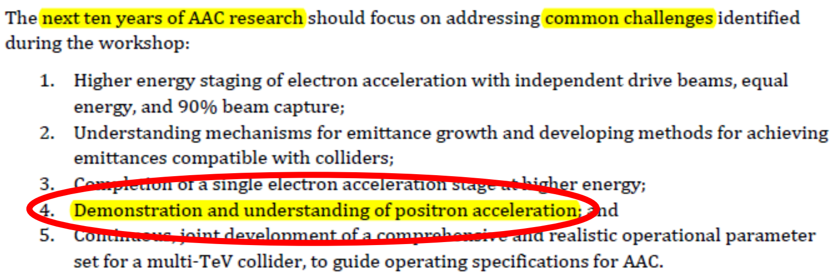


Is there a **stable**, **efficient** and **uniform** positron acceleration regime?

M. Litos et al., Nature 515 (2014)

Ian Blumenfeld et al., Nature 445 (2007)

L. T. Ke et al. PRL 126, 214801 (2021)

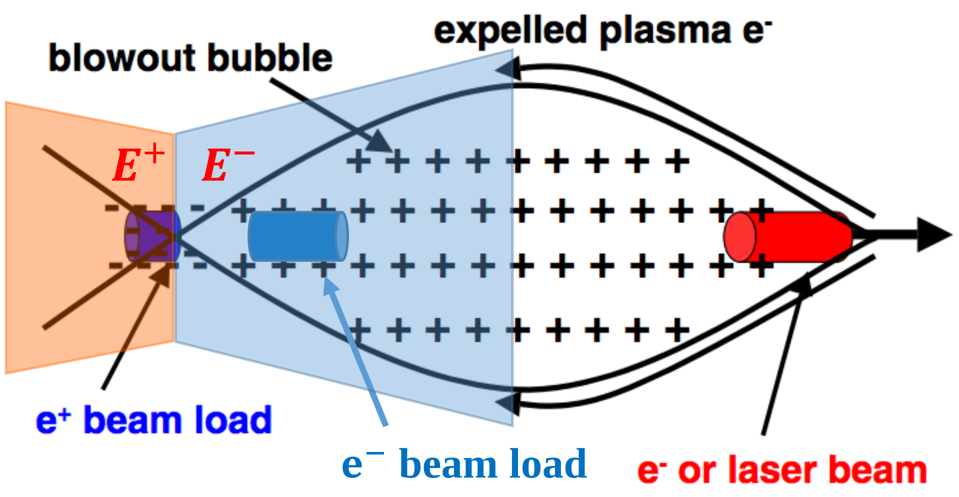

The next ten years of AAC research should focus on addressing common challenges identified during the workshop:

1. Higher energy staging of electron acceleration with independent drive beams, equal energy, and 90% beam capture;
2. Understanding mechanisms for emittance growth and developing methods for achieving emittances compatible with colliders;
3. Completion of a single electron acceleration stage at higher energy;
4. Demonstration and understanding of positron acceleration; and
5. Continuous, joint development of a comprehensive and realistic operational parameter set for a multi-TeV collider, to guide operating specifications for AAC.

Advanced Accelerator Development Strategy Report, 2016

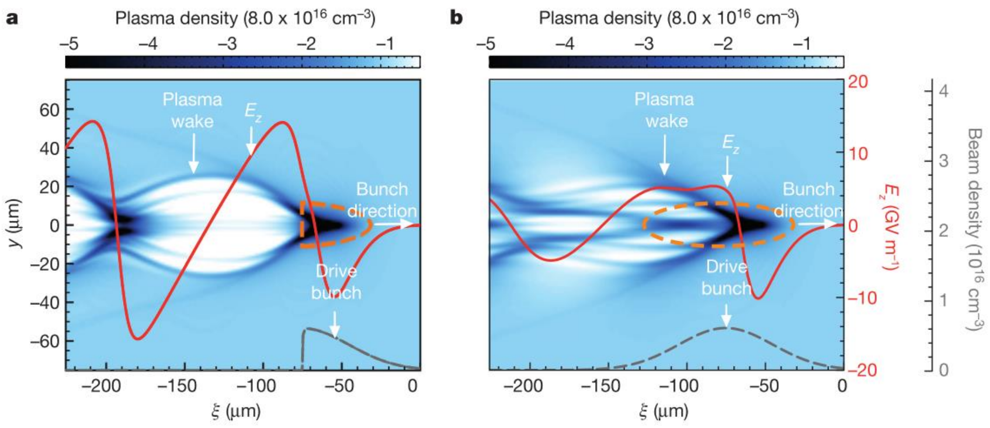
Plasma Wakefield Positron Acceleration

- **Blowout regime**

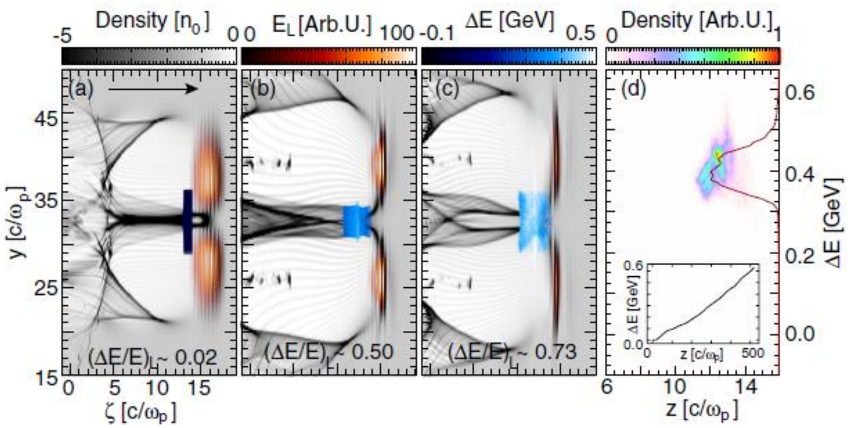


- Blowout regime is the most successful regime for electron acceleration.
- But it is recognized as not suitable for positron acceleration.

- **Positron self-loaded acceleration**



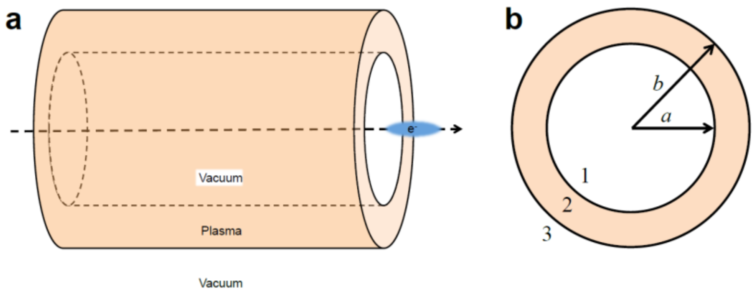
- **Hollow laser/electron driver**



S. Corde et al. Nature(2015)
J. Vieira and J. T. Mendonca, Phys. Rev. Lett. 112, 215001 (2014)
Neeraj Jain, *et al.*, Phys. Rev. Lett. 115, 195001 (2015)

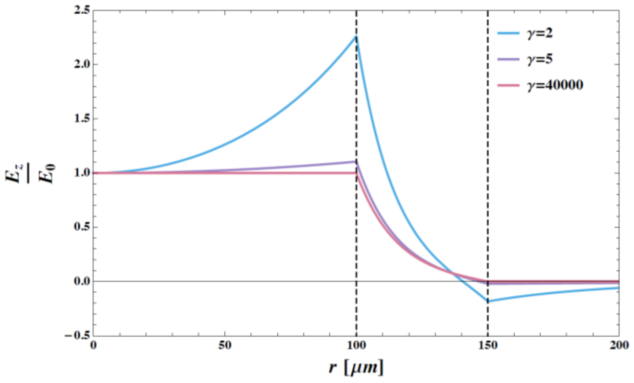
Hollow Channel Plasma Wakefield Accelerator

- Hollow plasma channel

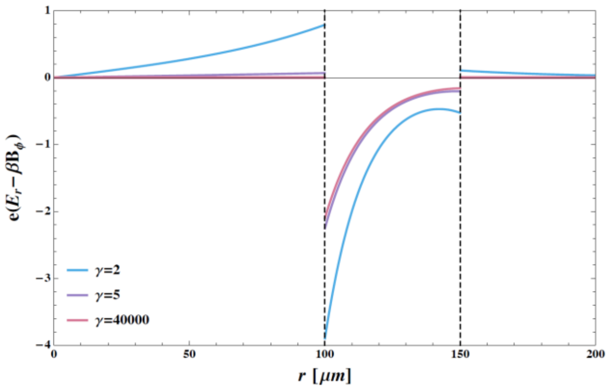


- Wakefield properties

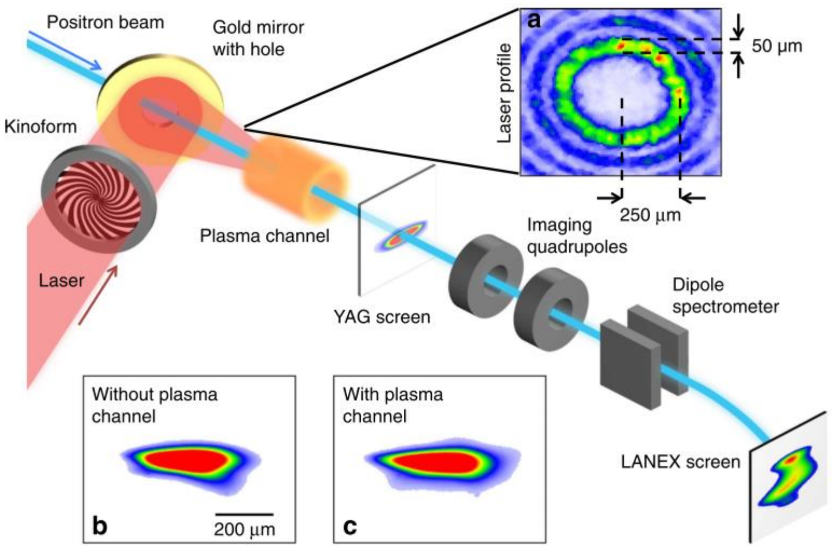
transversely uniform Ez



No transverse force



- Experimental demonstration

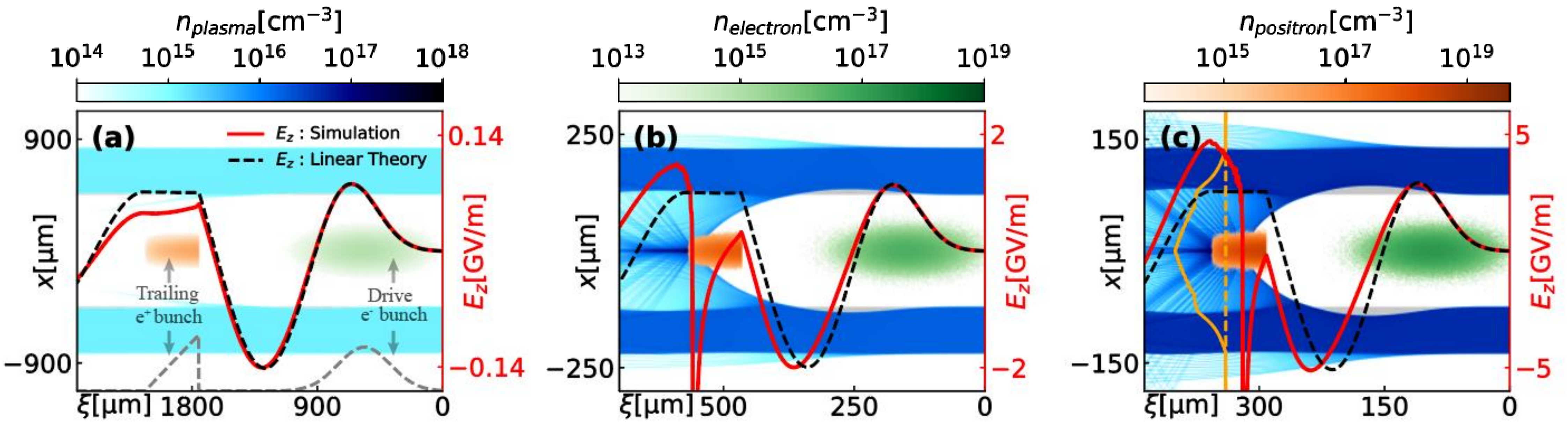


1. Positron beam loading via e^+, e^- beams overlapping with each other
2. Stable positron acceleration scheme using an asymmetric mode

Spencer Gessner, *et al.*, Nature Comms.(2015)

Positron Beam Loading in Hollow Plasma Channel

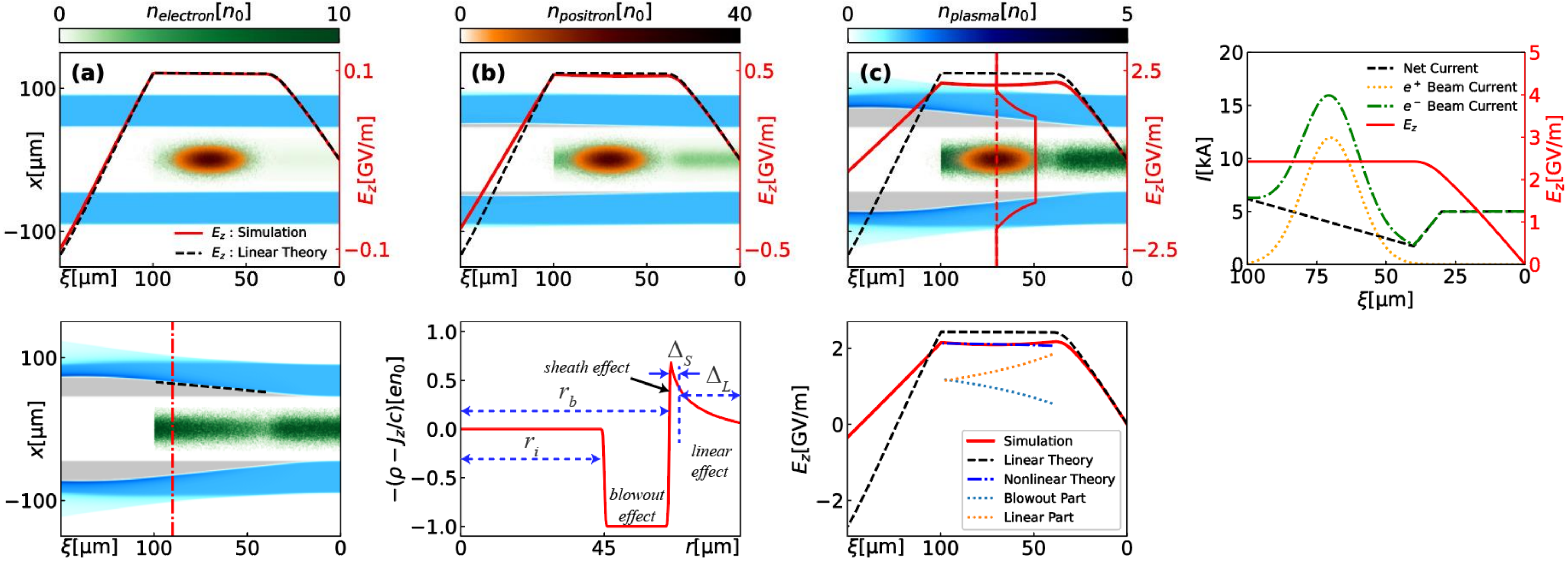
- How to achieve uniform, high efficiency, high gradient, high charge positron beam acceleration?
- Consider to accelerate 1nC positron bunch, using the drive-trailing bunch configuration in hollow plasma channel.



- Due to the nonlinear plasma response, it is hard to achieve this goal.

Positron Beam Loading in Hollow Plasma Channel

- What about putting the positron bunch at the same location with the drive electron bunch?



- Accelerate 1nC positron bunch with ~GV/m gradient, < 0.5% induced energy spread and ~50% energy transfer efficiency. arXiv:2111.04319

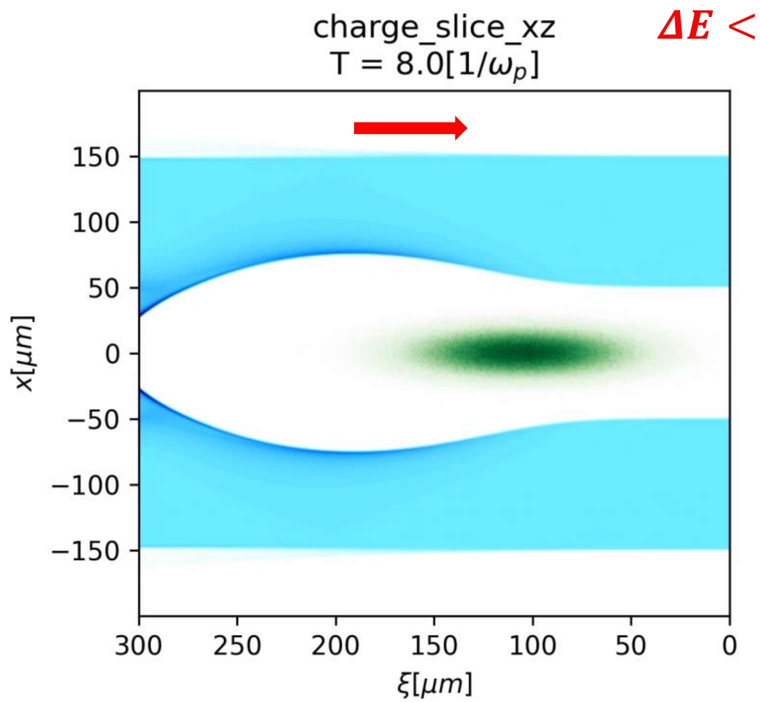
Stability Of Hollow Plasma Channel

- Another major challenge for applying hollow plasma channel to high energy acceleration : transverse instability.

$n_p = 3.11\times10^{16} cm^{-3}$ $r_{in} = 50\mu m$ $Q = 2nC$

$E = 10GeV$ $E_{max} \sim 8GV/m$ $x_{offset} = 0.1\mu m$

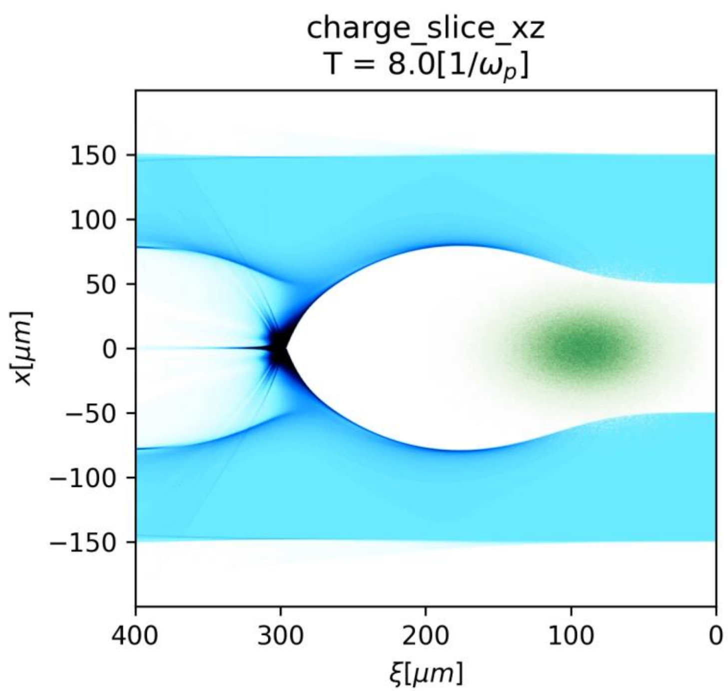
$\Delta E < 1GeV$



- Transversely asymmetric beam can suppress the BBU-like instability.

$\sigma_x = 20\mu m$ $\sigma_y = 10\mu m$

$\sigma_z = 30\mu m$



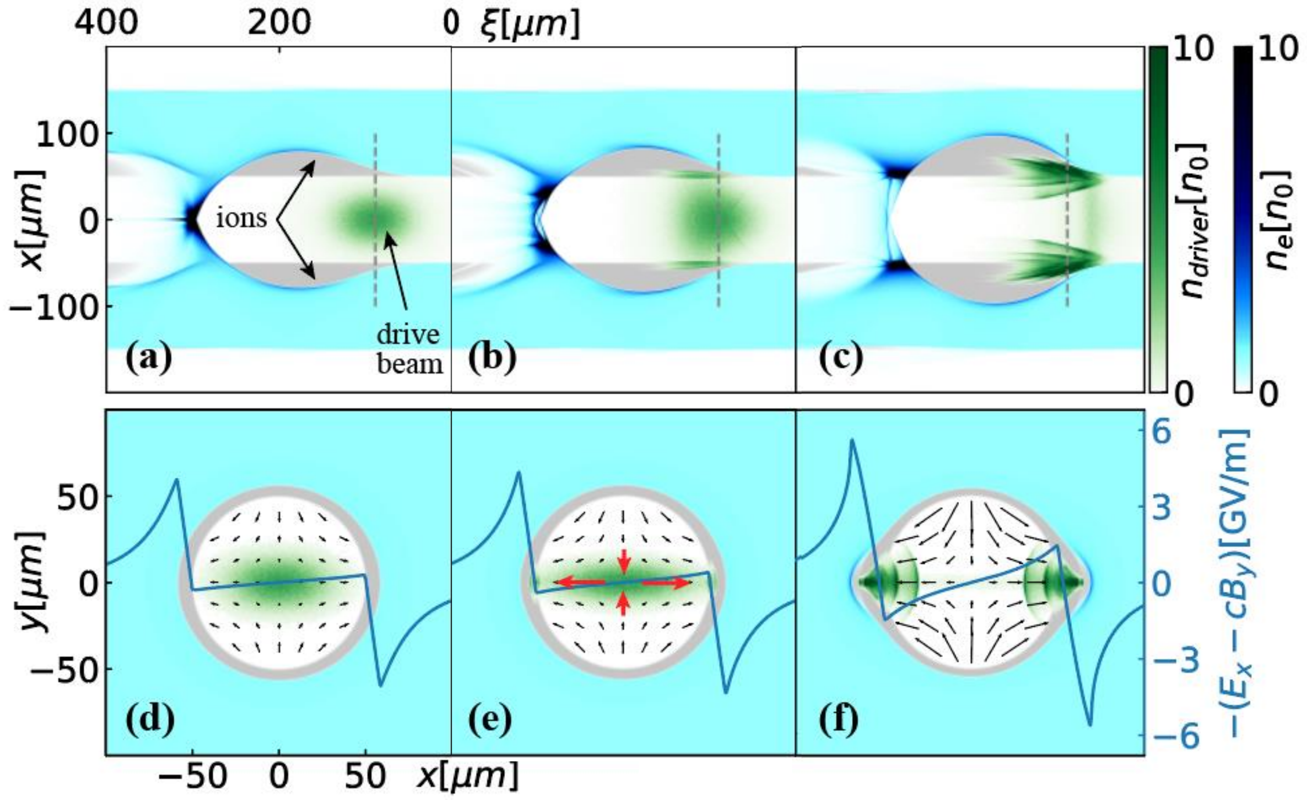
Stability Of Hollow Plasma Channel

- **Evolution and wakefields**

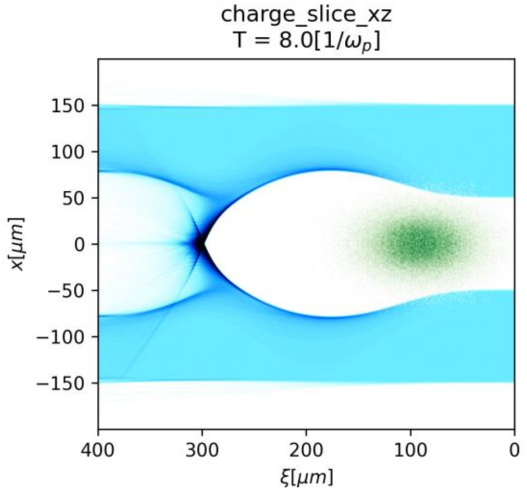
$$\vec{W}_{\perp 1}(x,y,\xi)=0$$

$$\vec{W}_{\perp 2}(x,y,\xi)=\lambda\widehat{W}_{\perp 2}(\xi)[(\sigma_x^2-\sigma_y^2)(x\hat{x}-y\hat{y})$$

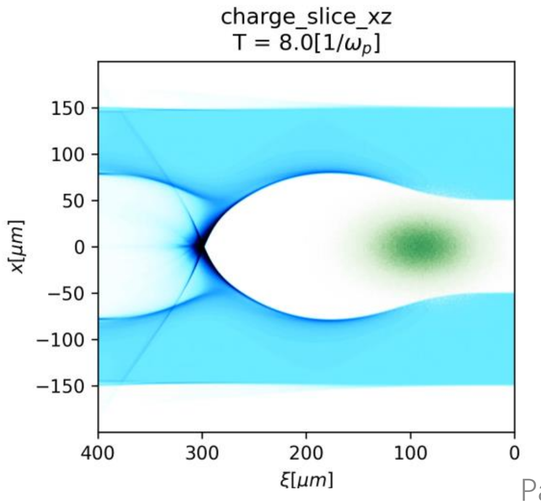
$$\langle x\rangle=\langle y\rangle=\langle xy\rangle=0 \qquad \langle x^2-y^2\rangle\neq 0$$



$x_{off}=0.1\mu m$



$y_{off}=0.1\mu m$



Unloaded Plasma Wakefield

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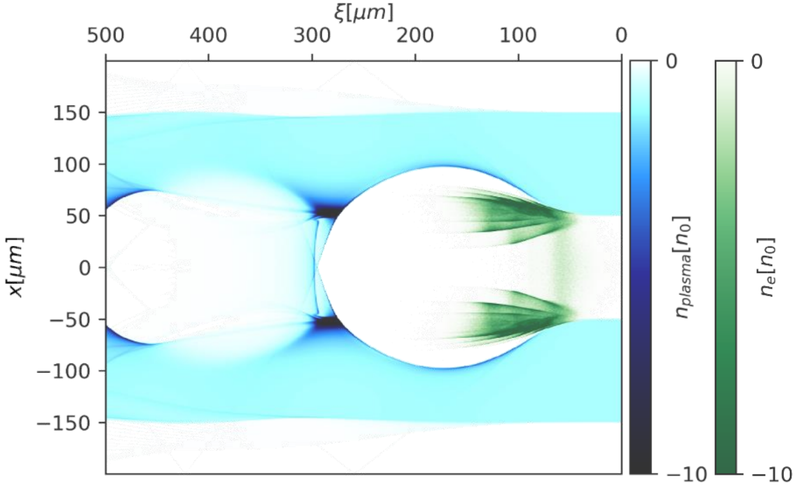
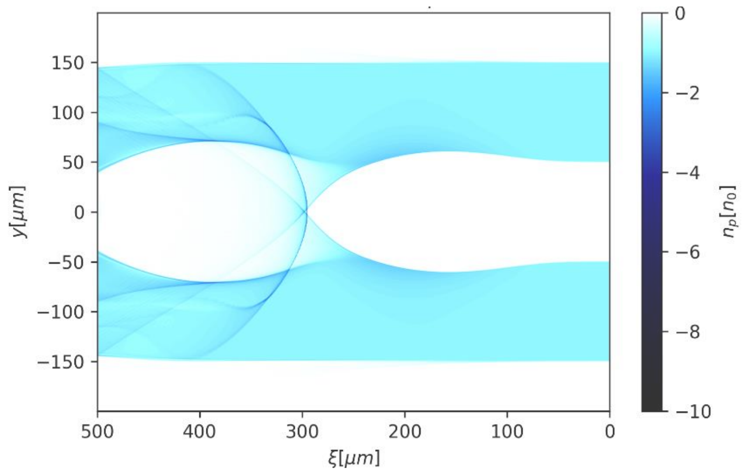
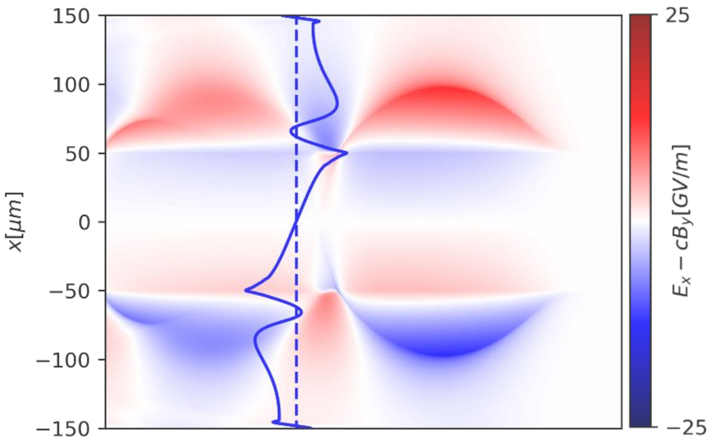
Plasma profile at x-z plane	Plasma profile at y-z plane

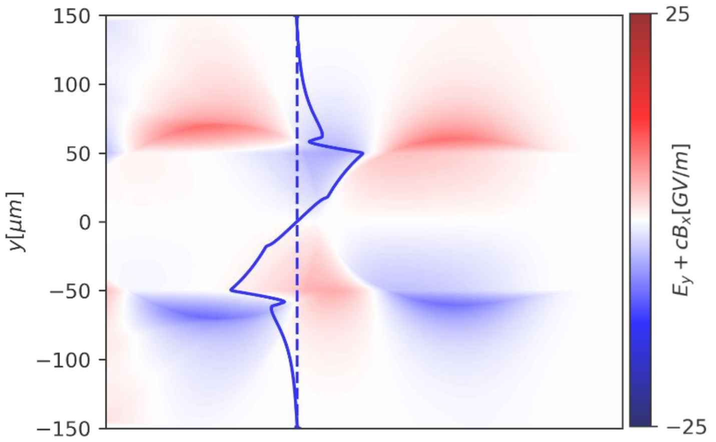


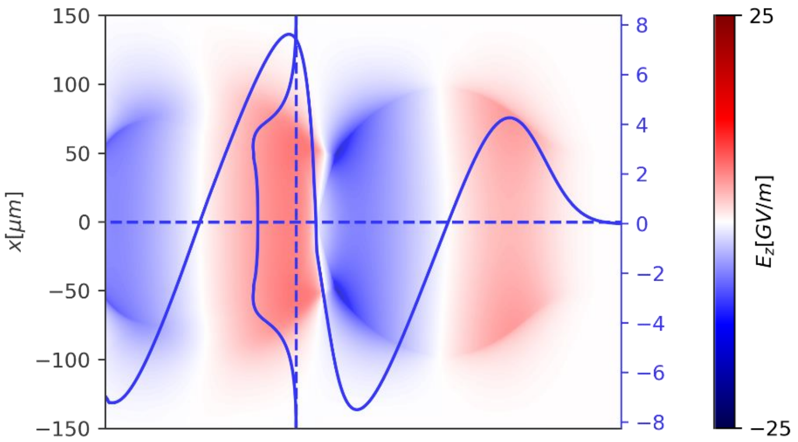


- **Properties of plasma wakefields**
  - **Ez is almost uniform in transverse direction.**
  - **At positron acceleration phase, focusing force is quasi-linear.**

Transverse wakefield at x-z plane	Transverse wakefield at y-z plane	Longitudinal wakefield at x-z plane







Positron Beam Loading Effects $Q_p = 0.64nC\ \sigma_x = 5\mu m\ \sigma_y = 4\mu m\ \sigma_z = 15\mu m$

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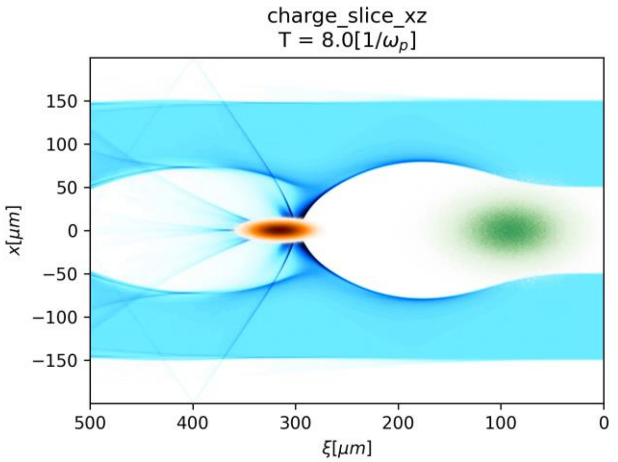
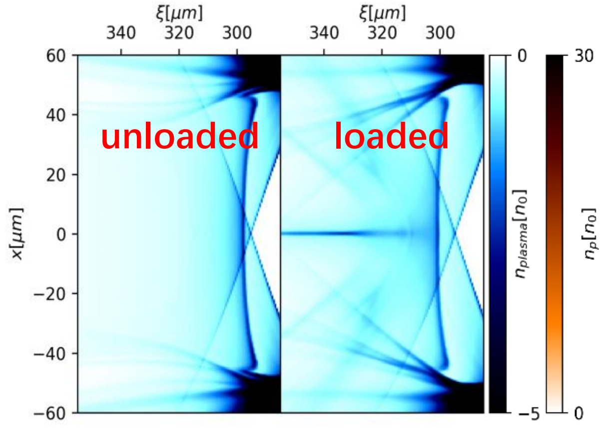
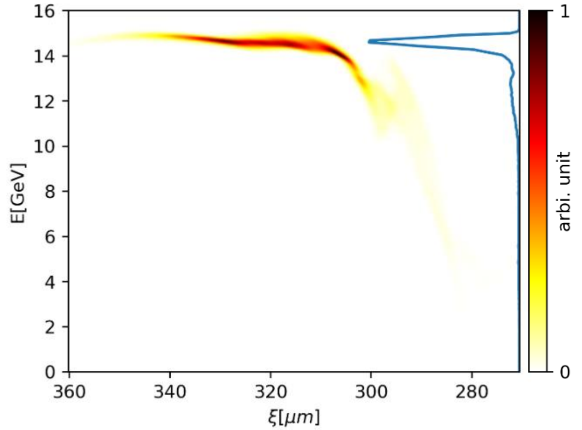
Movie	Plasma profiles	Positron beam spectrum

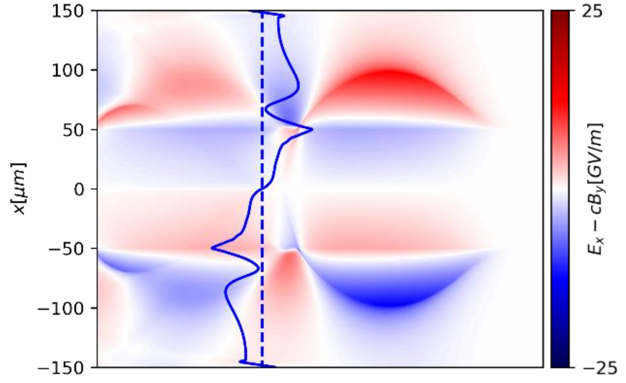


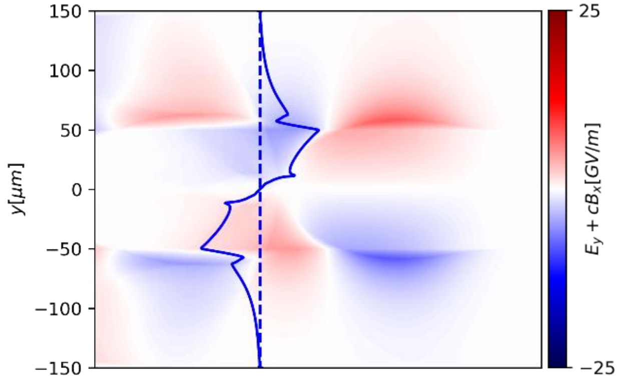


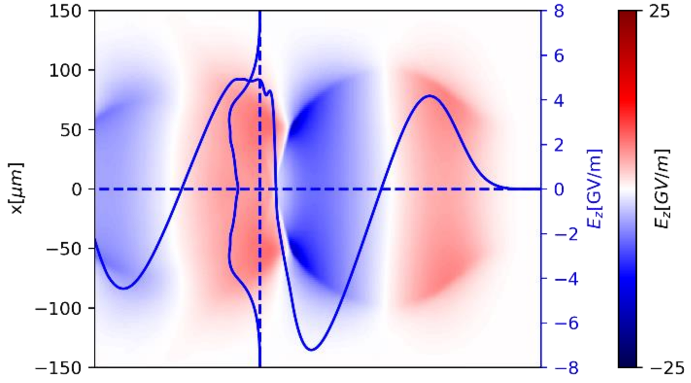


- **Results**
  - **~5GV/m gradient**
  - **>30% beam loading efficiency**
  - **~1.5% energy spread**

Transverse wakefield at x-z plane	Transverse wakefield at y-z plane	Longitudinal wakefield at x-z plane







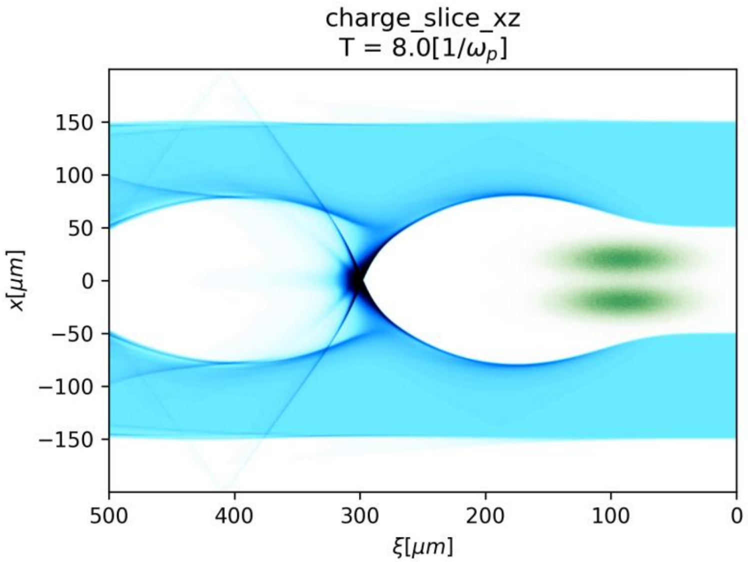
- **Beam loading effects**
  - **Focusing region extends**
  - **E_z is flattened**

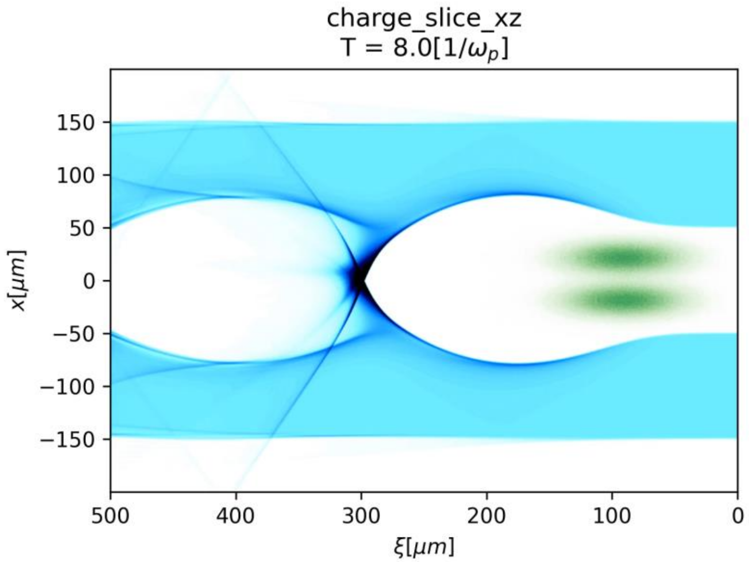
PRL 127, 174801 (2021)(Editors' Suggestion)

Summary

- **Stable, uniform, efficient** positron acceleration is the key challenge for applying plasma wakefield accelerators to high energy physics.
- By making the **electron and positron beam spatially overlapped**, positron beam can obtain excellent beam quality.
- **A transversely asymmetric electron beam** can drive a stable wake in hollow plasma channel, which can accelerate positron beam with high efficiency and narrow energy spread.
- There are still a lot to be explored in hollow plasma channel, such as the two-bunch driver ……

Two-bunch drive beam $Q_t = 2nC$	$x_{off} = 1\mu m$





Thanks for your attention!