Injection and single stage acceleraton of 100 GeV positron beam in plasma wakefield

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October 26, 2023, Nanjing

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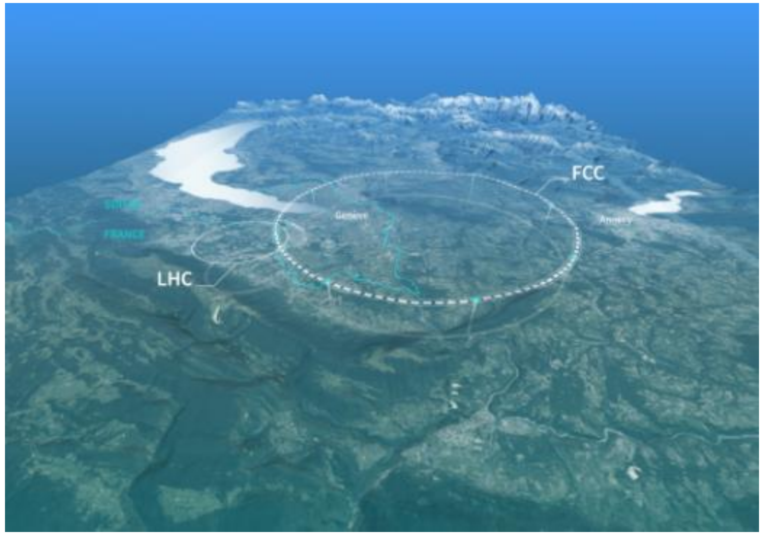
01 Introduction

Introduction



A schematic map showing a possible location for the Future Circular Collider (Image: CERN)

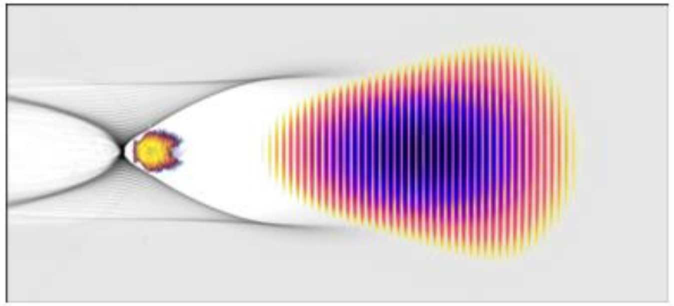
E_{max}~100 MeV/m

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

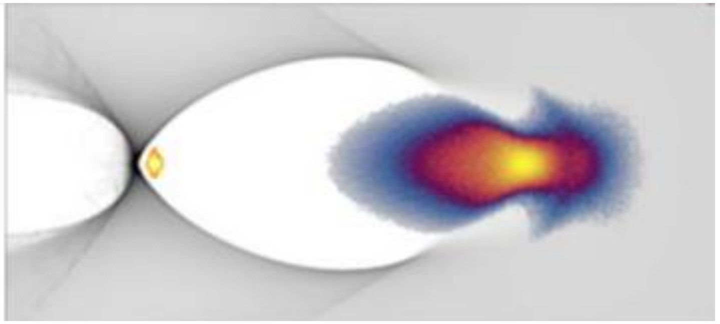
T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.



LWFA

E_{max}~100 GeV/m



PWFA

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen[a]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and
J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024
(Received 20 December 1984)

A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma_0^3 mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.

PACS numbers: 52.75.Di, 29.15.–n

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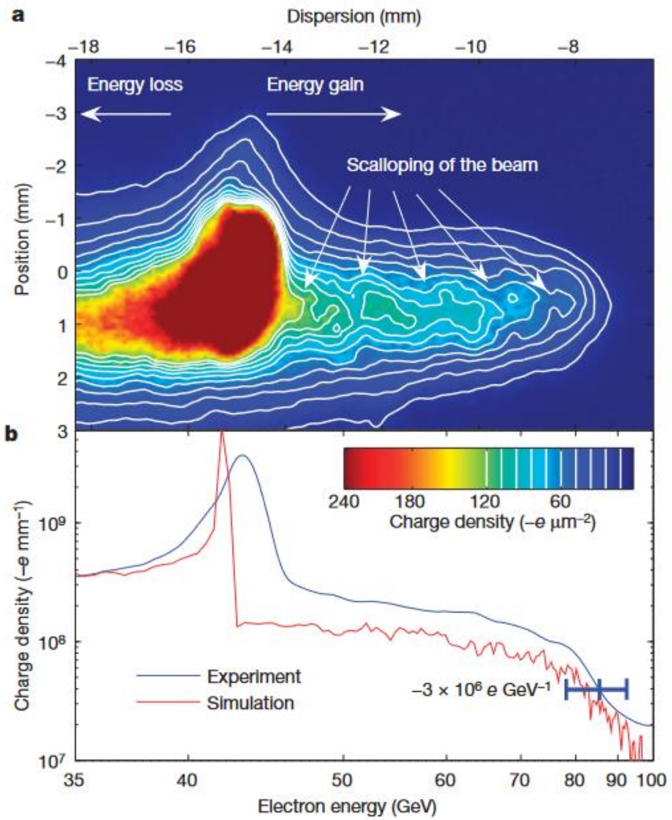
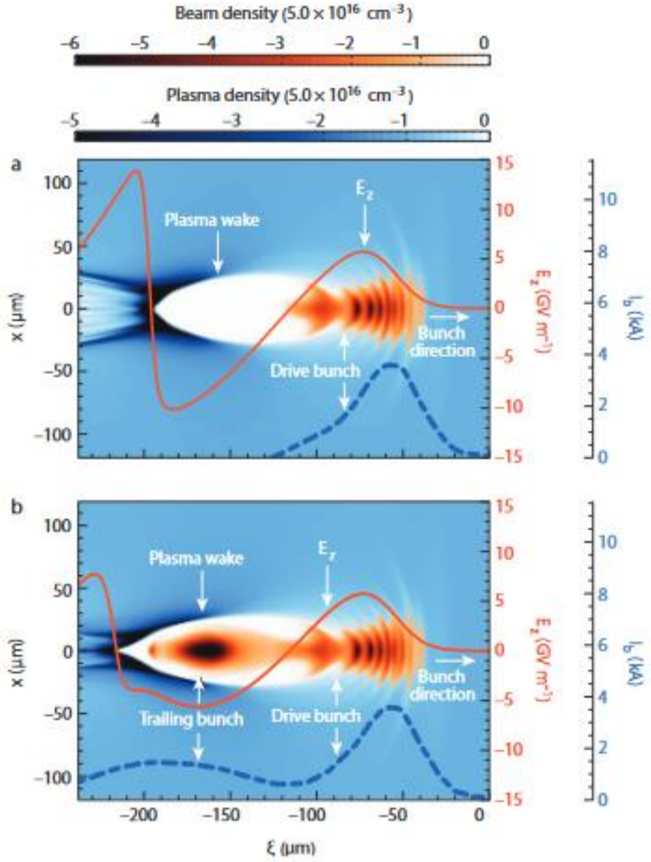
Energy doubling of 42 GeV electron



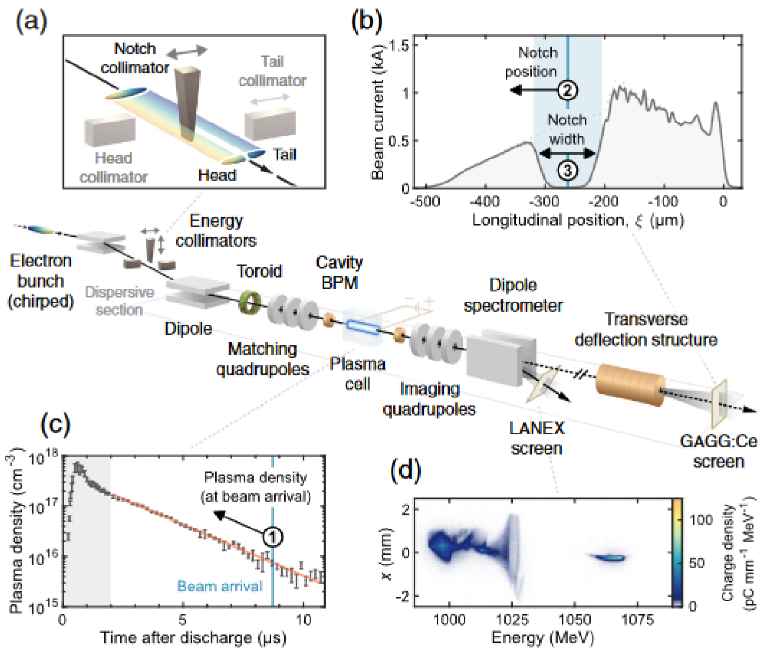
Ian Blumenfeld, Nature (2007)

High-efficiency acceleration of a self-injected bunch



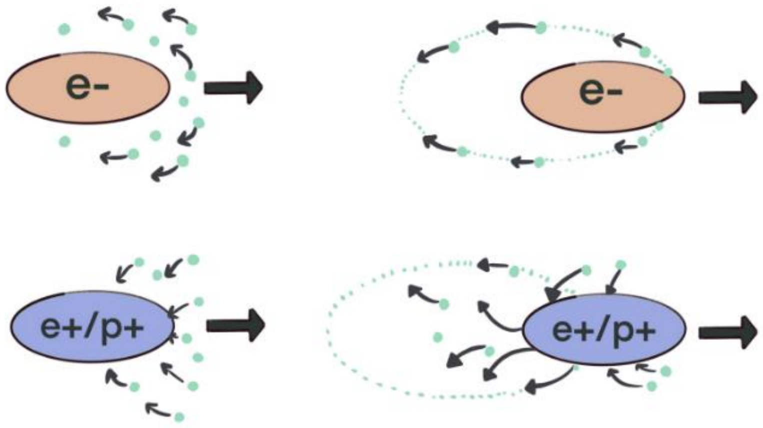
M. Litos, Nature (2014)

High-gradient and high-quality acceleration



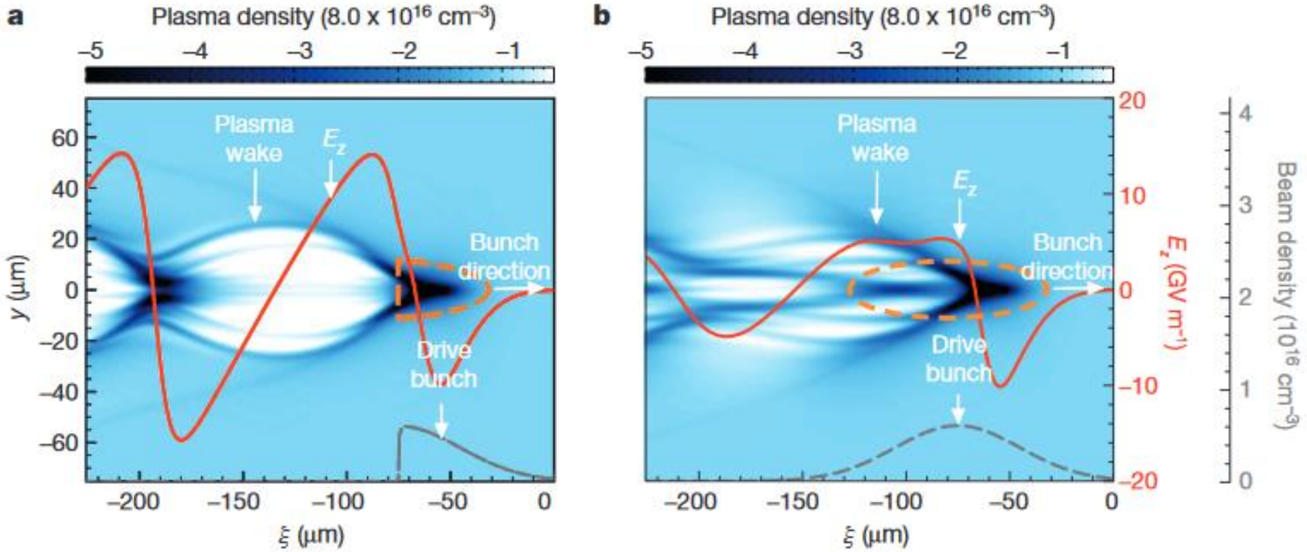
C. A. Lindstrøm, PRL (2021)

Introduction -- Positron driver

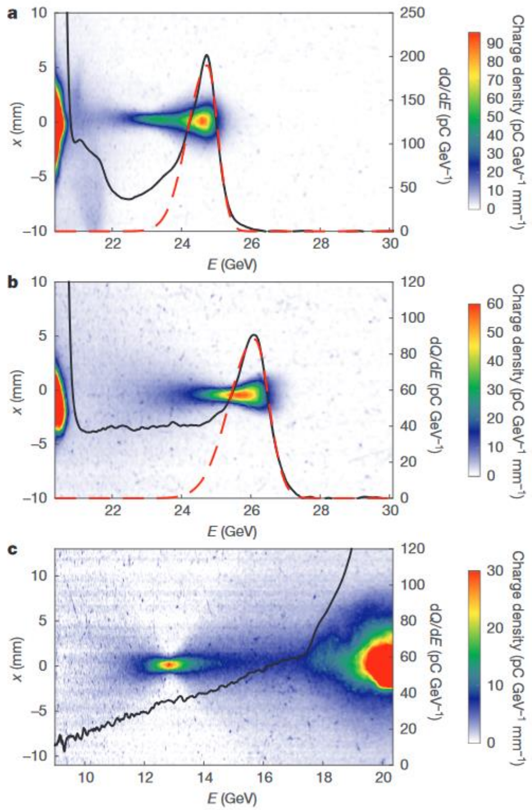


blow-out

suck-in



S.Corde, Nature (2015)

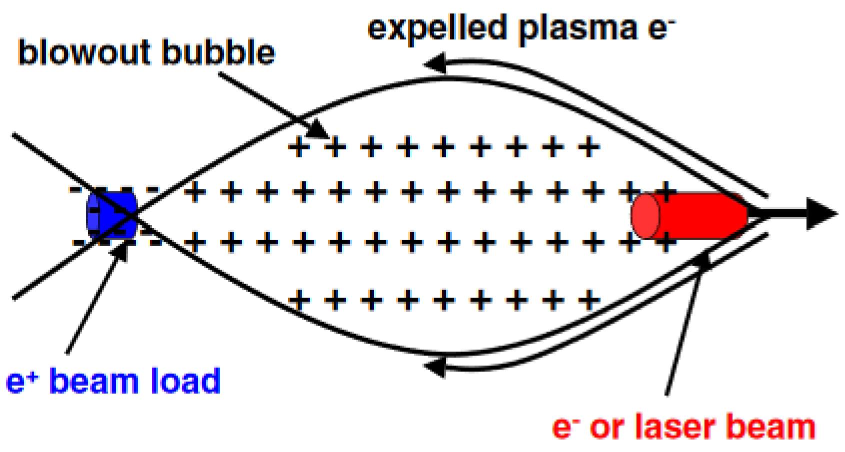


High-efficiency acceleration of a self-injected positron bunch

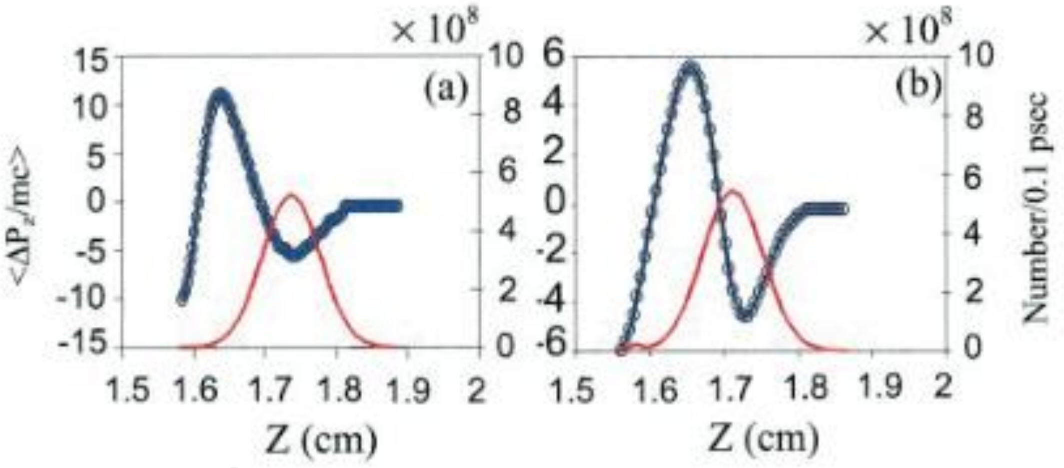
Introduction -- Electron driver

1. The accelerating field of a positron driver is found to be 2 to 5 times smaller than an electron driver with similar parameters.

2. Acceleration and focusing fields vary transversely, making it difficult to accelerate high quality positron beam.



X. Wang, PRL (2009)



electron positron

S. Lee, PRL (2001)

In nonlinear PWFA driven by electrons, the only region that both accelerates and focuses positrons is where the plasma electrons cross the axis.

Introduction -- Electron driver

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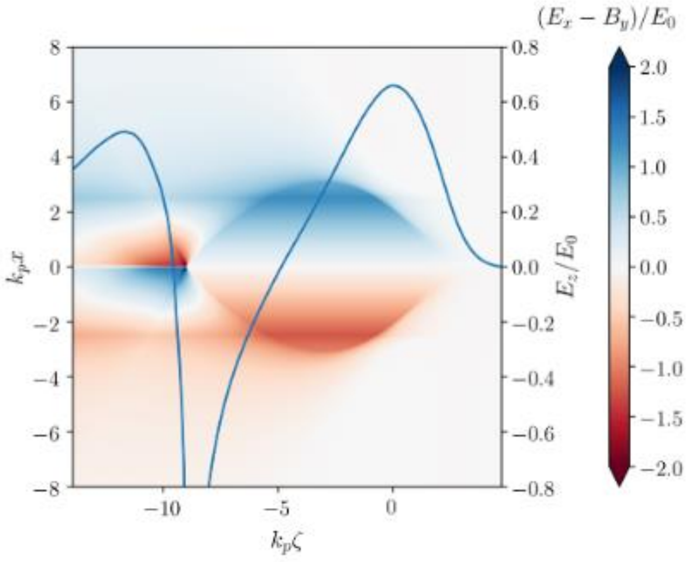
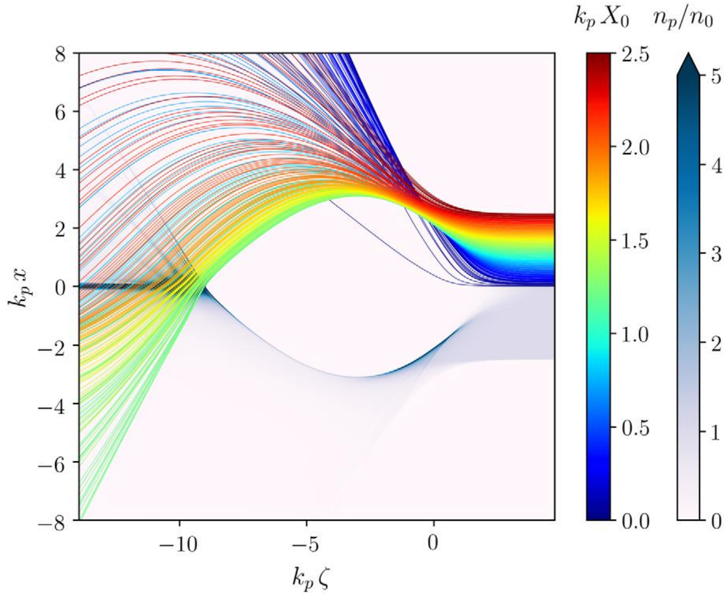
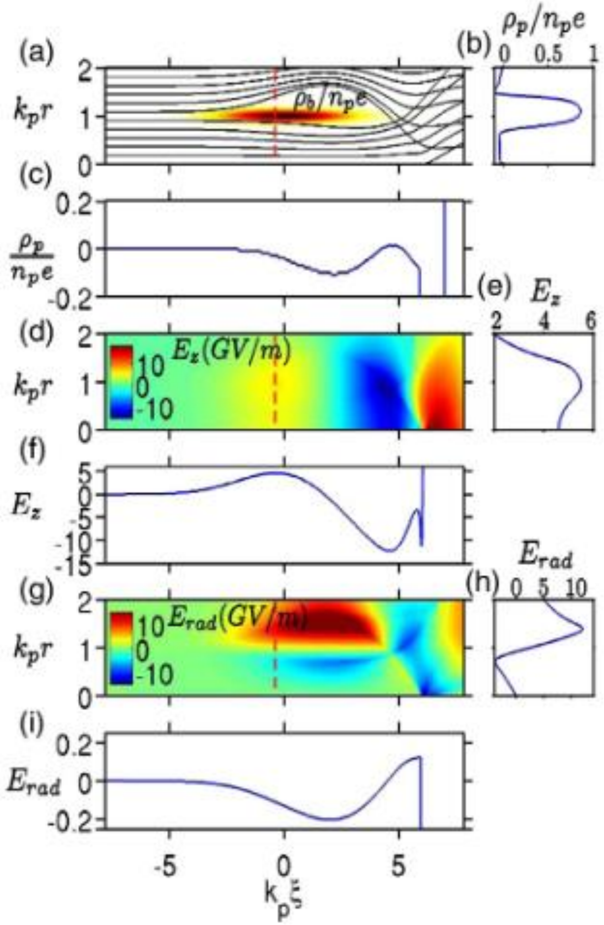
The common method to expand the focusing area of positrons is to use specially structured drive bunches or plasma. This allows the formation of an electron filament along the axis during the process of evolution, thereby focusing the positrons.







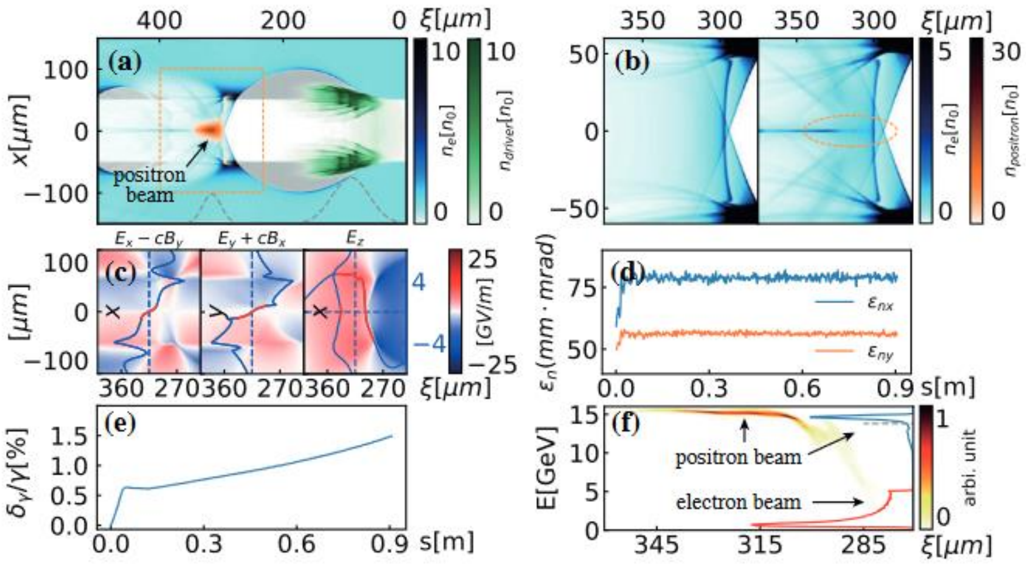
Finite-radius plasma channel: high beam quality and acceleration gradient but low efficiency

Hollow Electron Beam: low charge

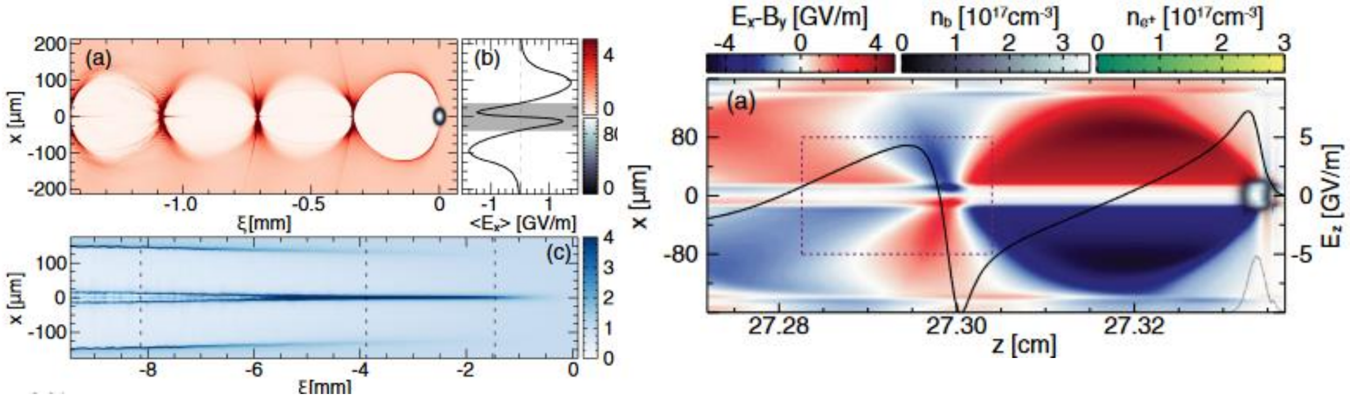
Diederichs, S. Phys. Rev. Accel. Beams,(2019)

T. M. Antonsen, Jr.PRL 115, 195001 (2015)

Introduction -- Electron driver



S. Y. Zhou, PRL,(2021)



T. Silva, PRL,(2021)

Hollow plasma channels with asymmetric driver: stable acceleration with high charge and high efficiency but low beam quality

Thin, warm, hollow plasma channel: a simple setup but suffers from low energy efficiency

These schemes can't keep the balance between efficiency and beam quality, and positrons can't be accelerated to high energy in a single stage due to the intense instabilities.

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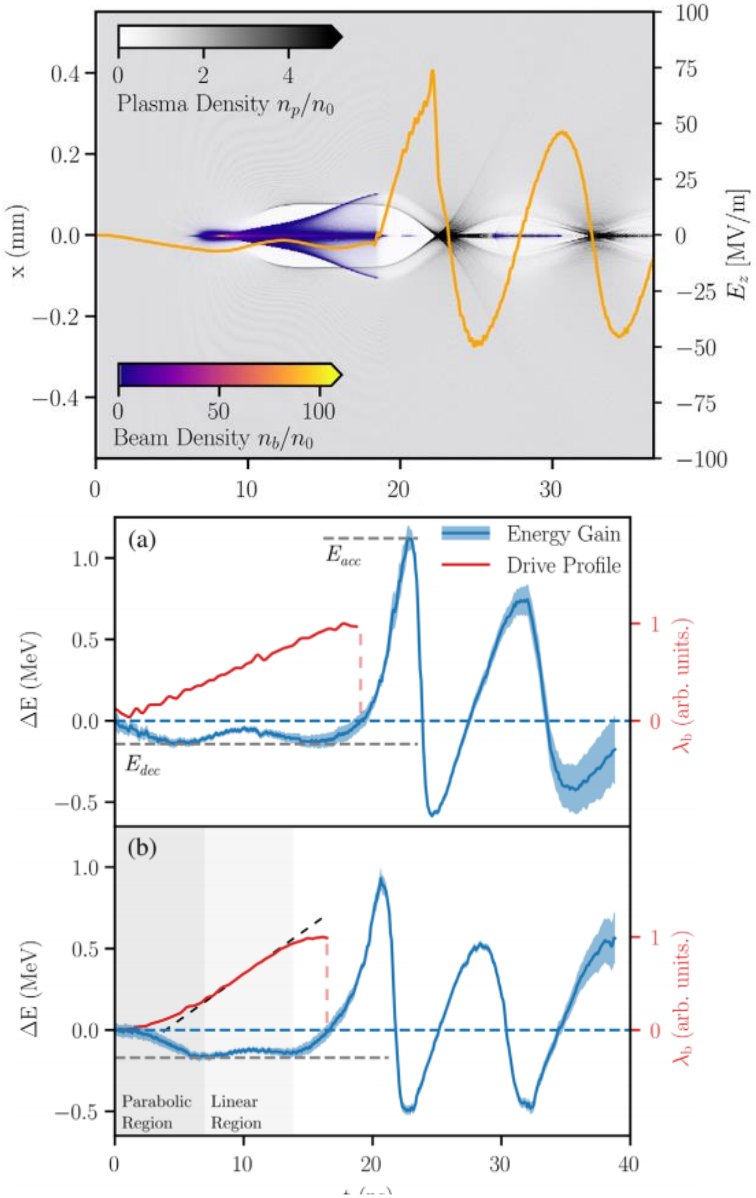
Transformer ratio for longitudinally symmetric drive bunch:

$$R=\frac{E_{\max}^{witness}}{E_{\max}^{driver}}=2-\frac{N_{witness}}{N_{driver}}\leq 2$$

To obtain a higher single stage energy gain:

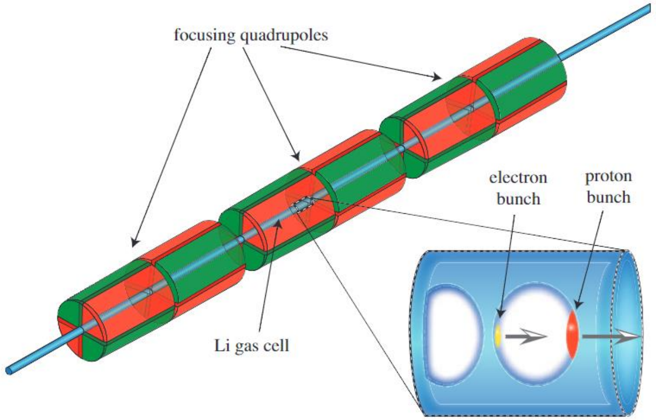
1. Use an asymmetric drive bunch to break the transformer ratio limit (bunch shaping)
2. Use a higher energy drive bunch.



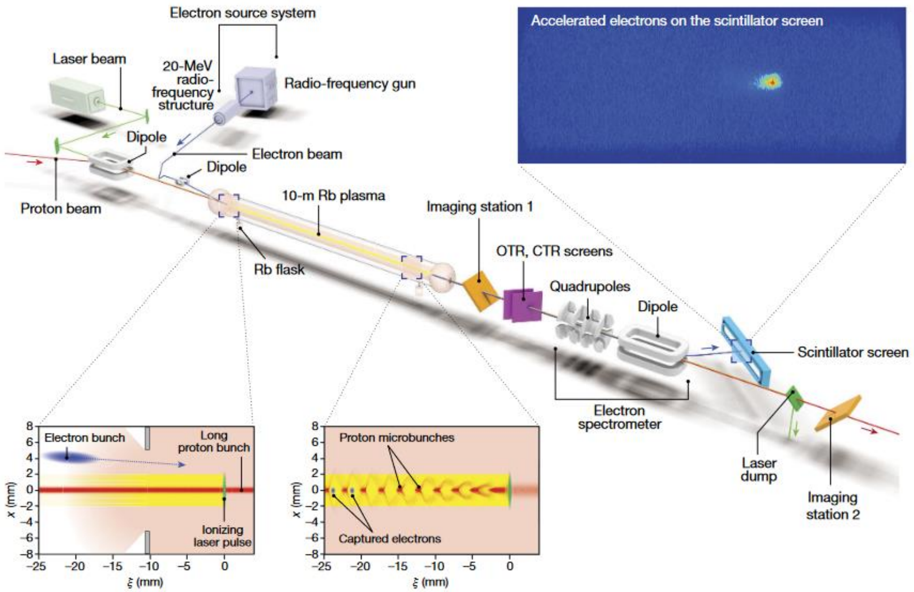
R. Roussel, PRL. (2022).

R = 7.8 ± 2.3

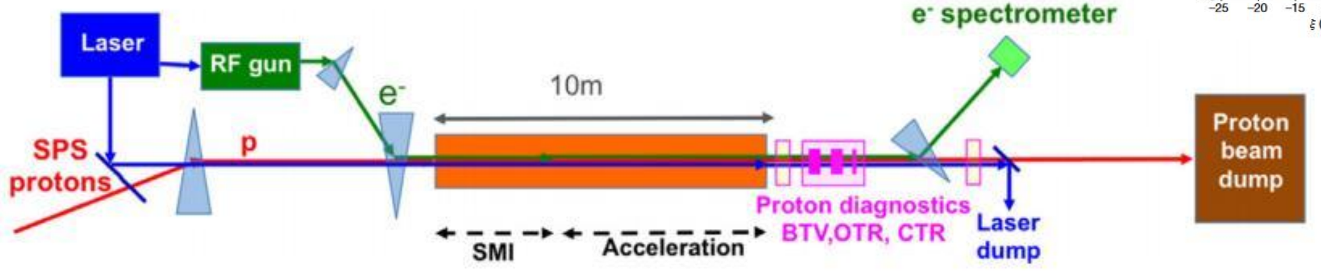
Introduction -- Proton driver



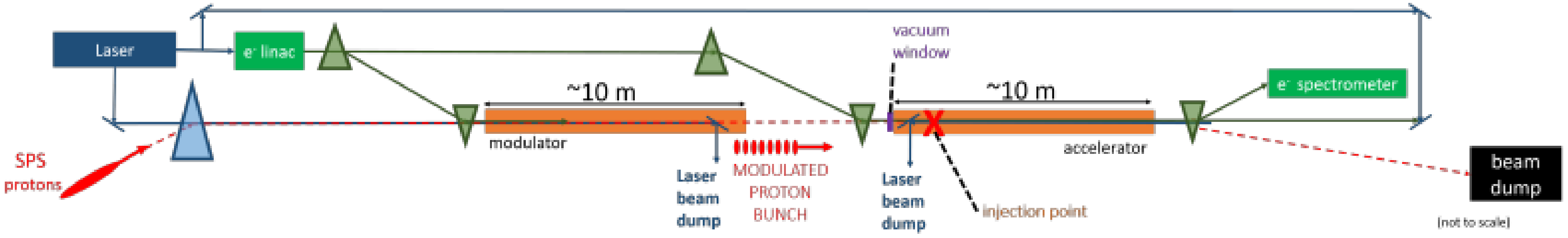
A. Caldwell, Nat Phys (2009)



E. Adli, Nature (2018)

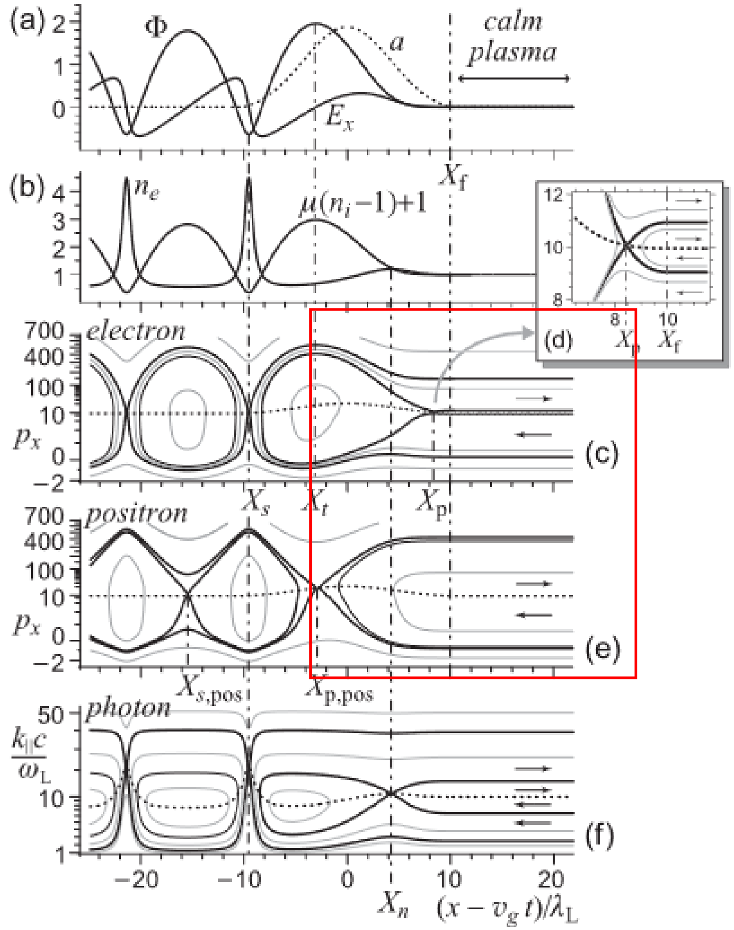


E. Gschwendtner, (AWAKE Collaboration), Nucl.Instrum. Meth. Phys. Res. Sect.(2016)



L. Verra, Journal of Physics (2020).

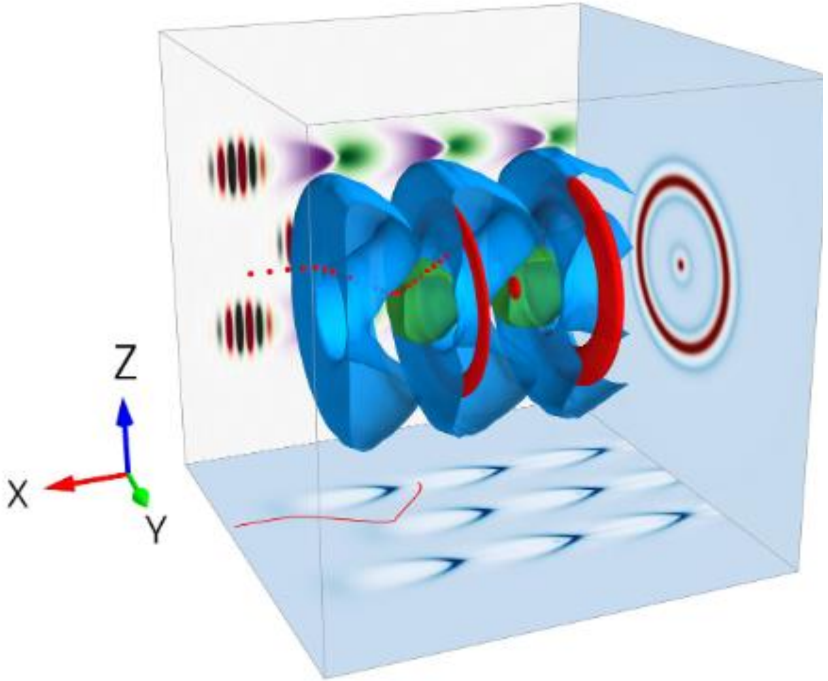
Introduction -- Injection

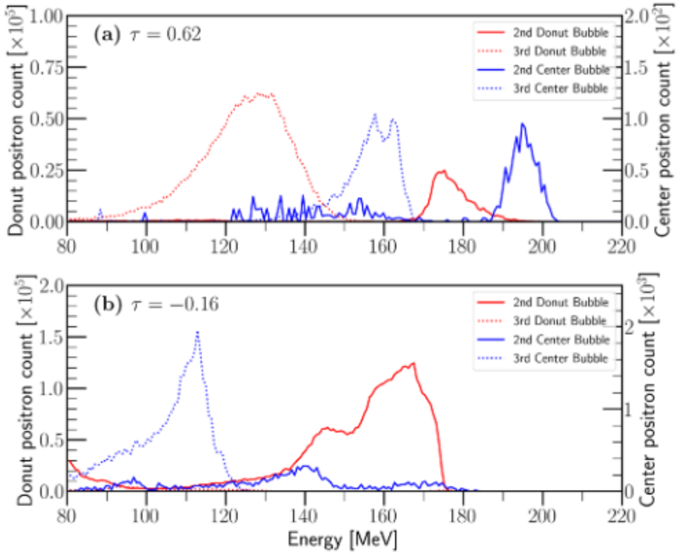


T. Esirkepov, PRL,(2006)

which regime is used, see e.g. [44]. Until new ideas for positron acceleration are conceived, we do not see a clear path towards a high-luminosity electron-positron collider based on PWFA.

E. Adli, Philosophical Transactions of the Royal Society A, (2019)





Z. Y. Xu, PRAB, (2021)

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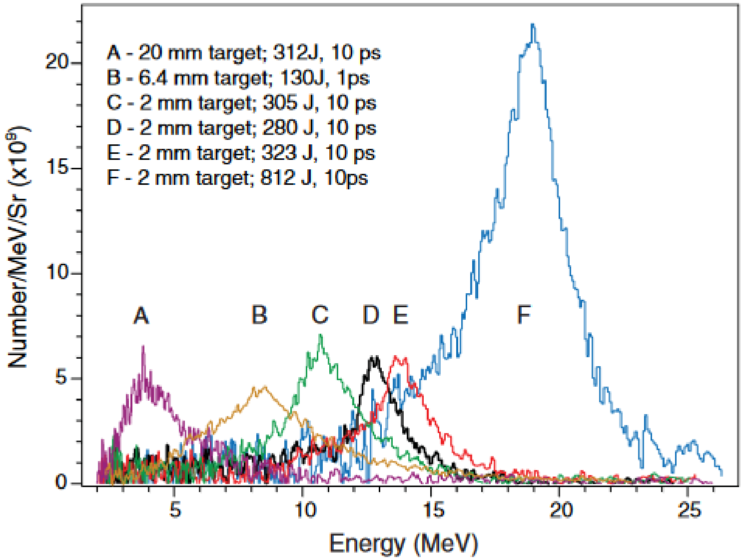
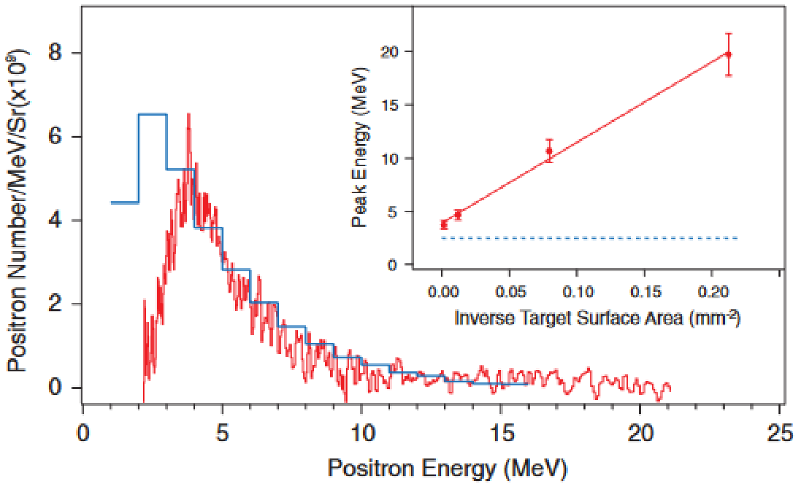
broad-spectrum positrons directly produced by the BH process





	Laser parameters		Positron jet parameters						Derived quantities	
Shots	E_{Laser} (J)	Φ (mm)	$N_{\mathrm{total}\ e^+}$	E_{peak} (MeV)	E_{FWHM} (MeV)	Spread (%)	θ^b (Degree)	η_{energy} (%)	$T_{\parallel}$ (MeV)	$T_{\perp}$ (MeV)
A	312	20	1.8e10	4.0 (0.1)	2.3 (0.3)	57 (6)	25	0.01	2.9 (0.2)	0.4
B	130	6.4	2.0e10	8.5 (0.2)	3.3 (0.3)	39 (6)	20 (5)	0.03	6.5 (0.6)	1.6
C[a]	305	2	3.0e10	10.8 (0.1)	3.1 (0.1)	29 (2)	18	0.02	4.2 (0.2)	0.8
D	280	2	2.3e10	12.8 (0.1)	1.9 (0.2)	15 (4)	17	0.02	2.5 (0.3)	1.0
E	323	2	2.6e10	13.7 (0.1)	2.8 (0.2)	21 (3)	20	0.04	4.1 (0.2)	1.2
F	812	2	1.8e11	18.7 (0.1)	3.6 (0.2)	19 (2)	17	0.04	4.2 (0.2)	2.0

H. Chen, PRL,(2010)

Acceleration:

(1) The region for simultaneous focusing and acceleration is very small, thus requiring special drive beams or plasma structures.

(2) It is challenging to balance efficiency and beam quality.

(3) Due to intense instabilities, high-energy acceleration cannot be achieved in a single stage.

(4) High efficiency multistage acceleration is needed toward the energy for collider.

Injection: (1) All the plasma positron acceleration schemes directly place the positron bunch in the acceleration region.

(2) No scheme can achieve the injection of common positron sources.

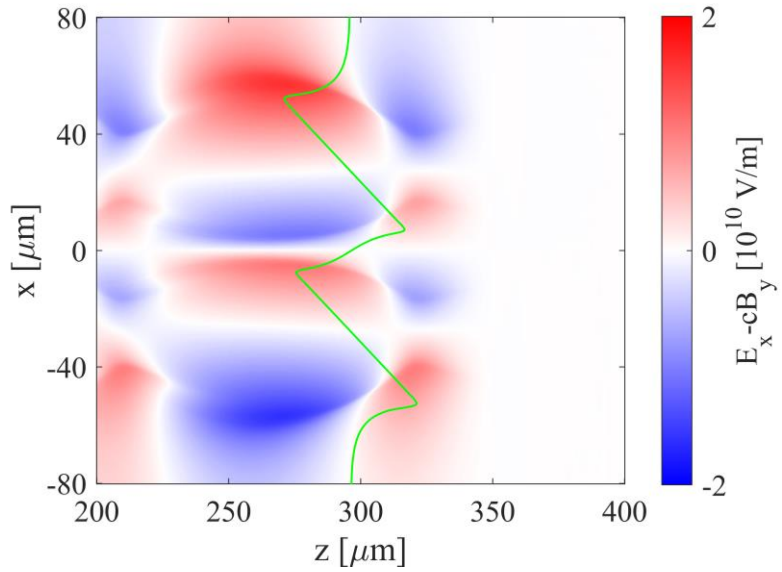
Thus, a scheme is urgently needed that can **inject** both cold positrons and common positron sources into the acceleration region and simultaneously achieve **high-efficiency**, **high-quality**, and **high-energy** acceleration aimed at colliders.

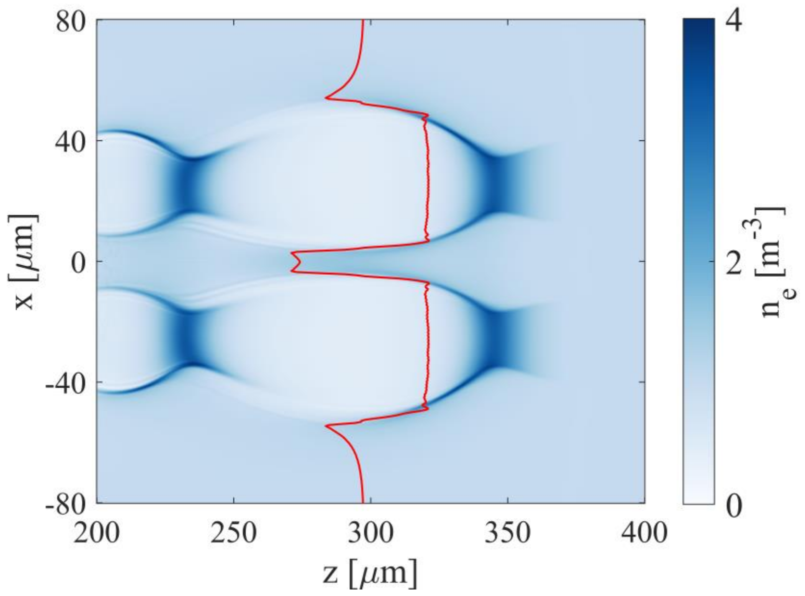
02 Positron Injection

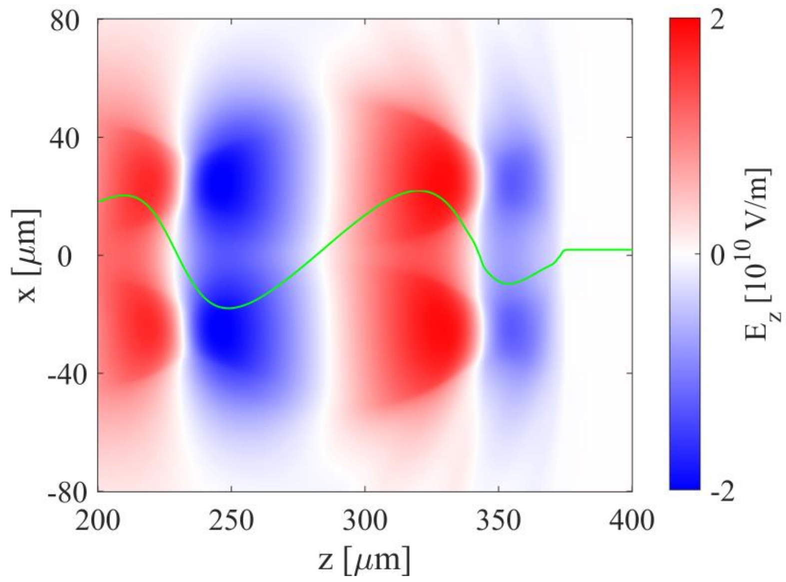
Positron Injection -- Field structure

Driver: a hollow proton beam

3D PIC simulation software: WarpX







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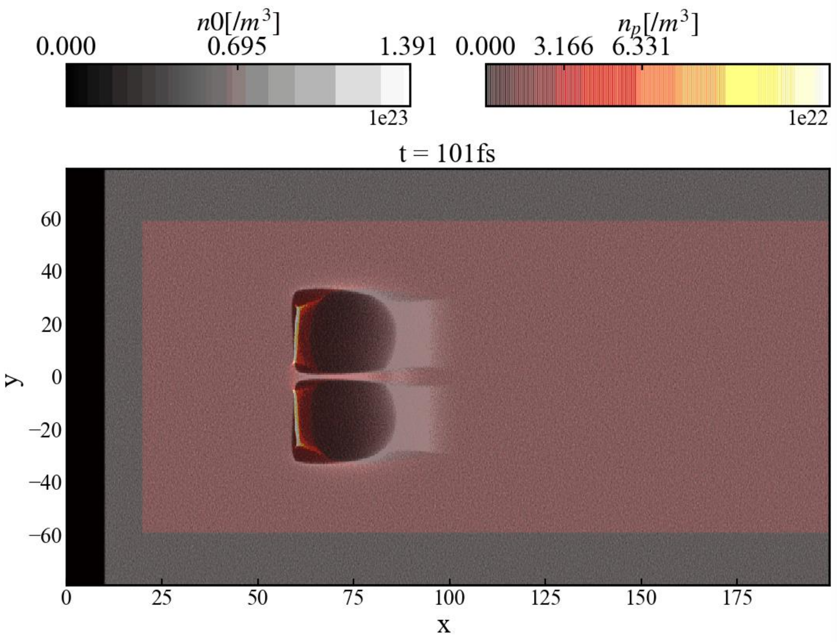
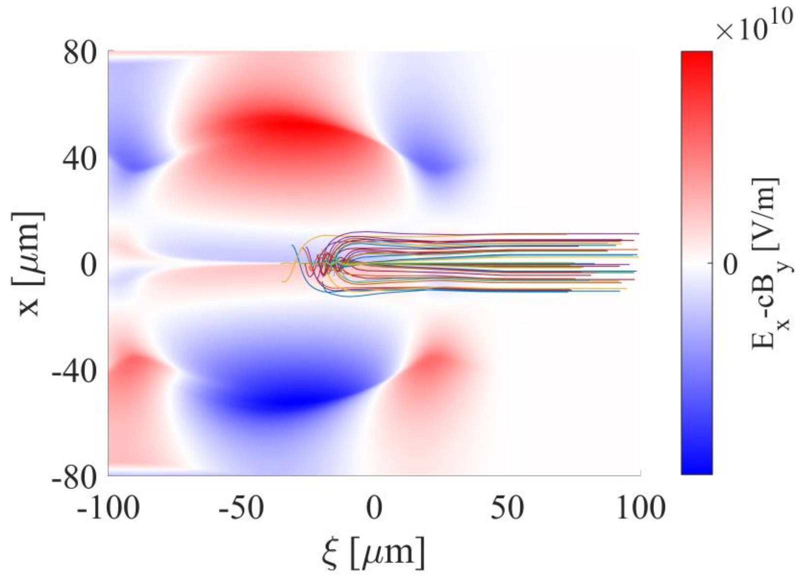
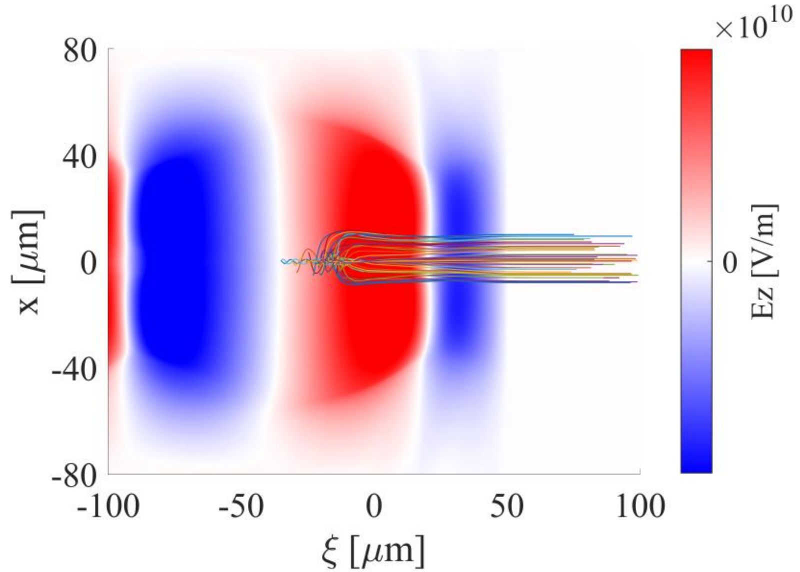
Positron Injection -- Injection of the cold positrons

$r_i = 3\ \mu m$







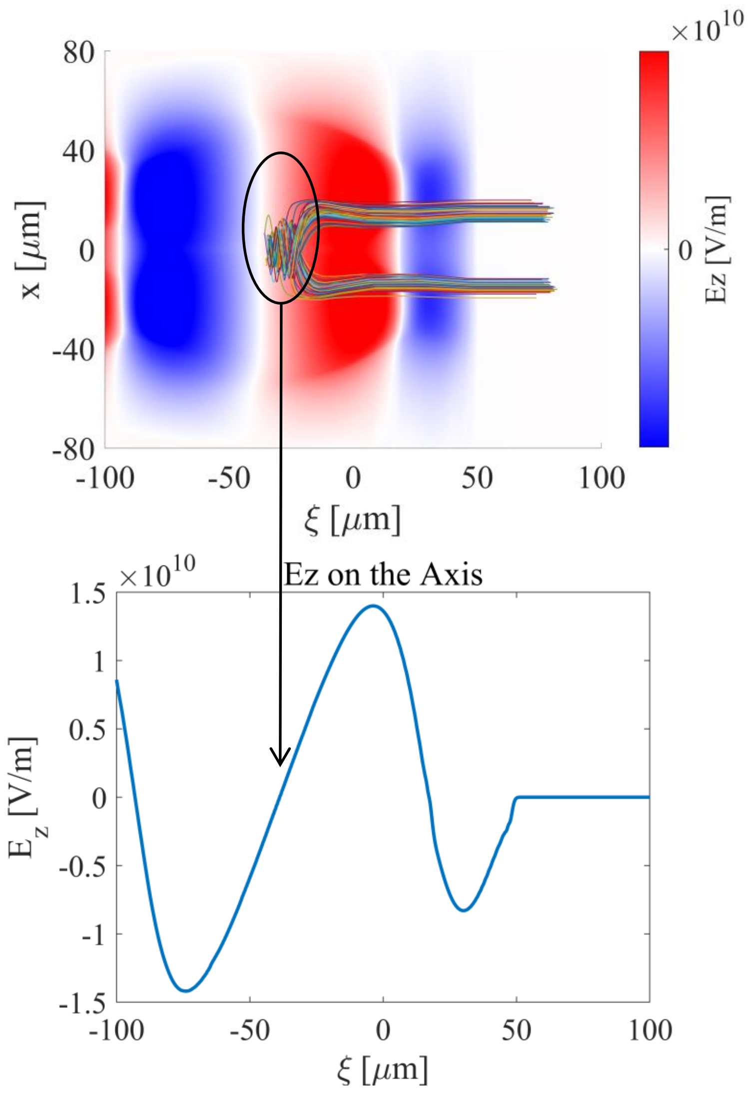
Injection conditions:

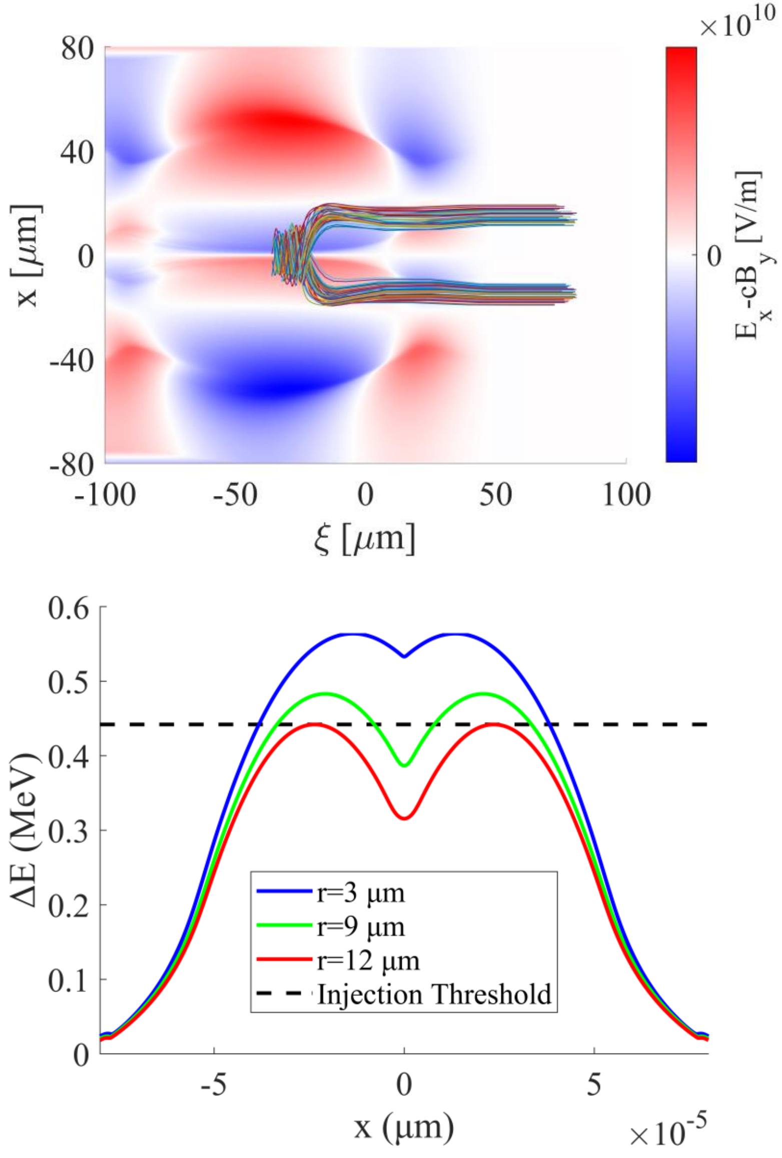
1. Longitudinal condition: Positrons are in the acceleration field and can keep up with the phase velocity of the plasma.
2. Transverse condition: Positrons overcome the transverse force to enter the wakefield region and can be focused.

to be submitted

Positron Injection -- Longitudinal injection threshold

$r_i = 9\ \mu m$





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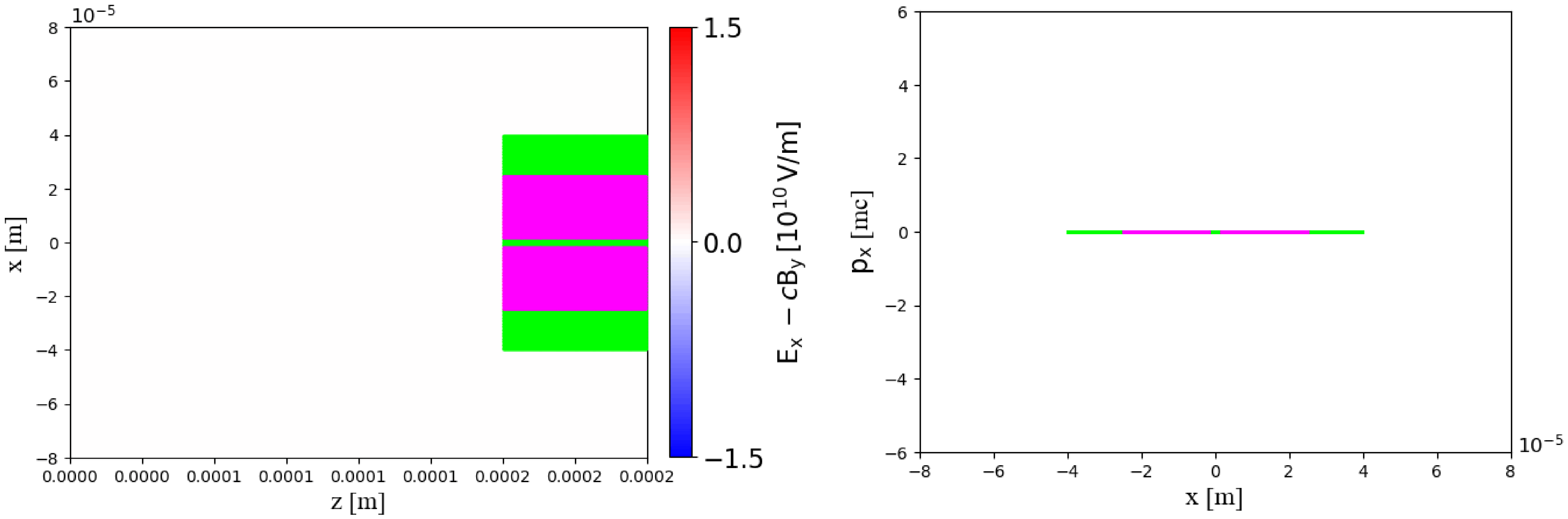
Positron Injection -- **Injection of the positrons from BH positron source**



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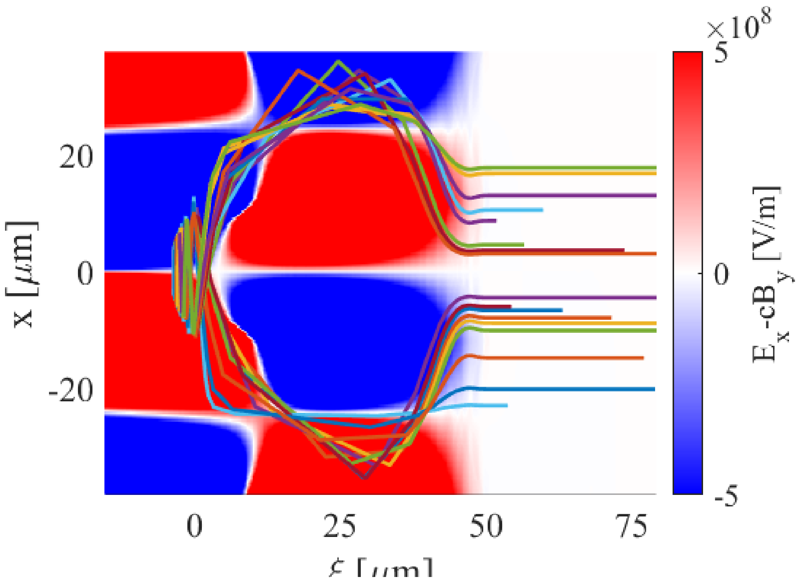
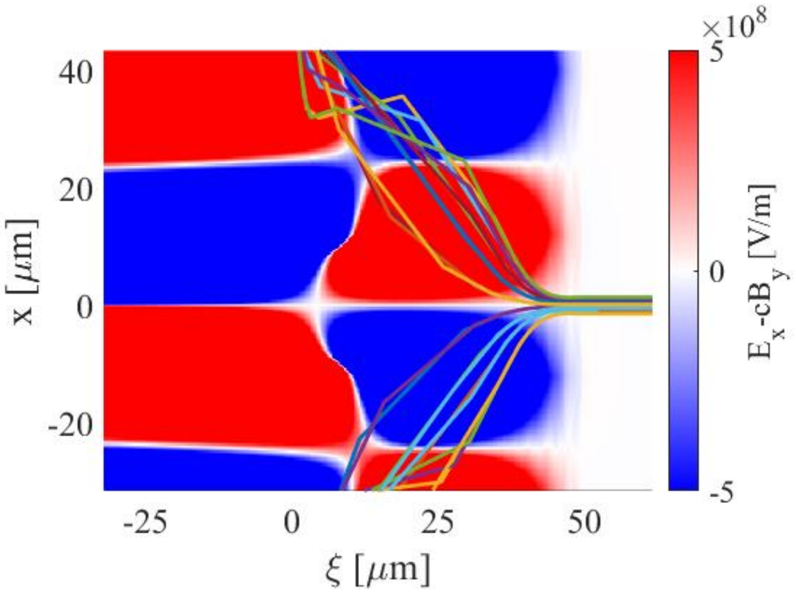
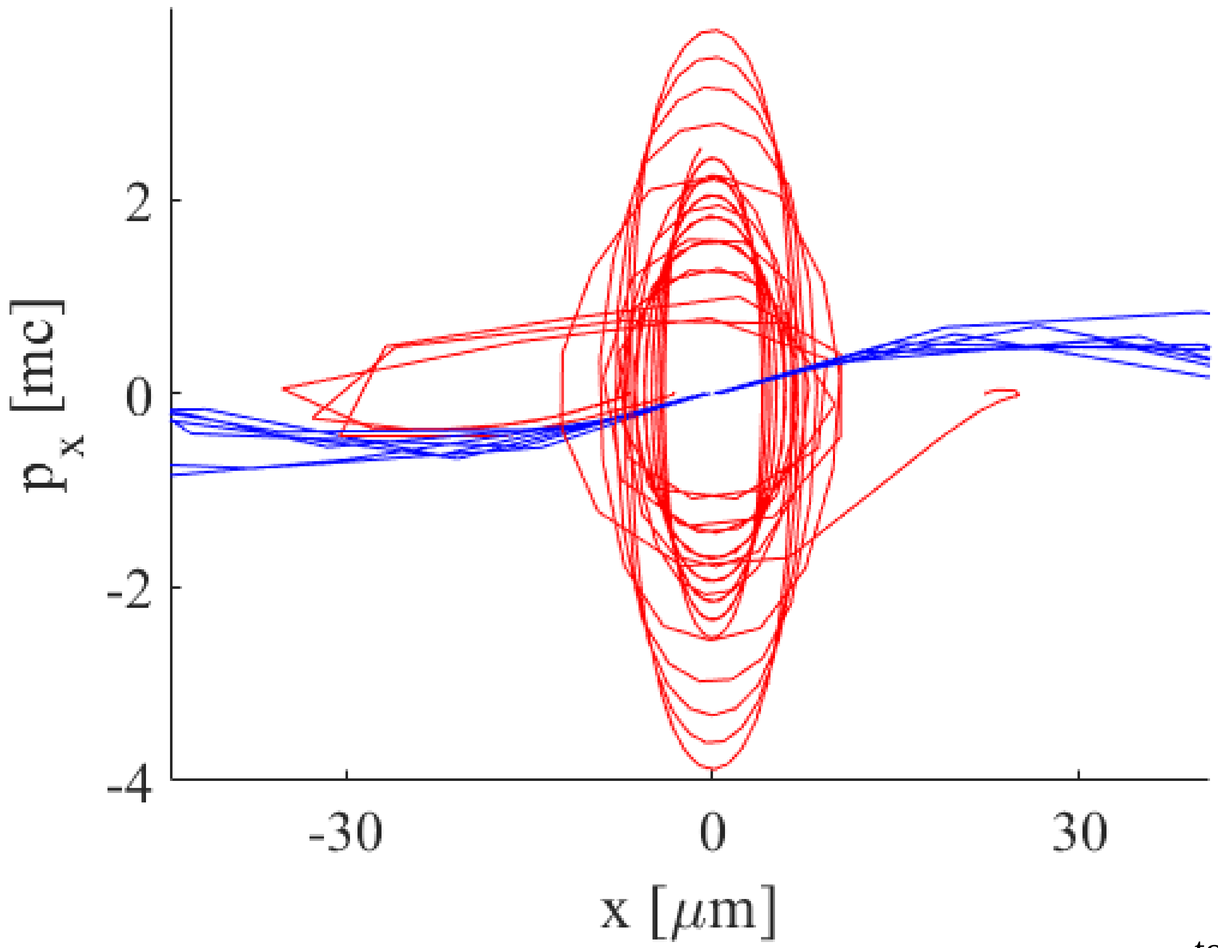
Positron Injection -- Injection of the thermal positrons







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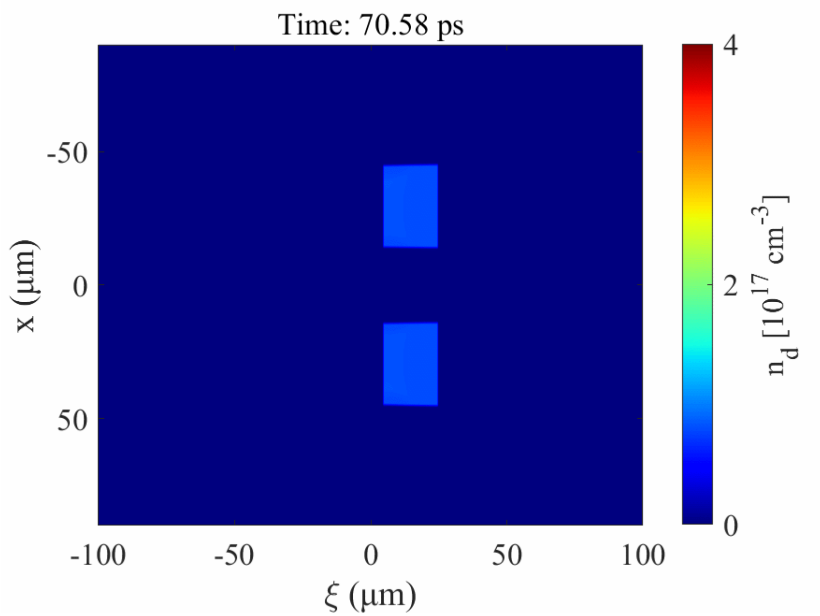
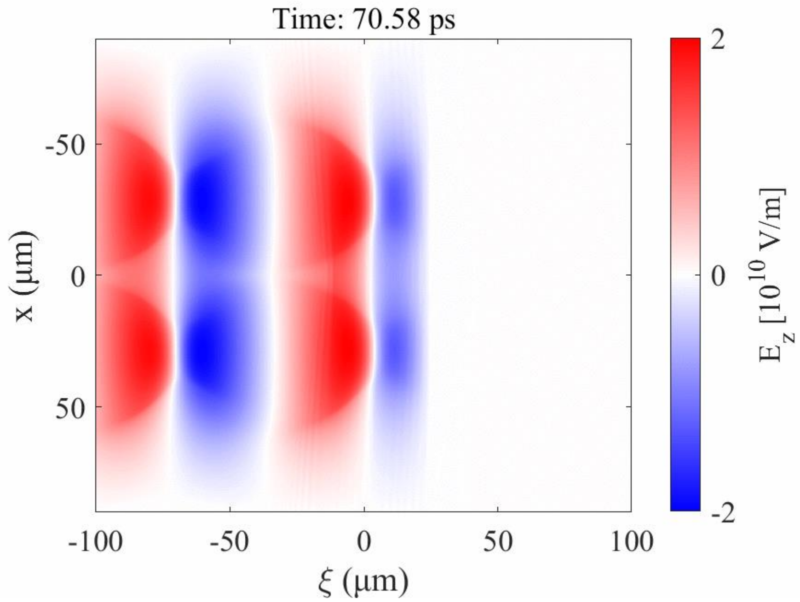
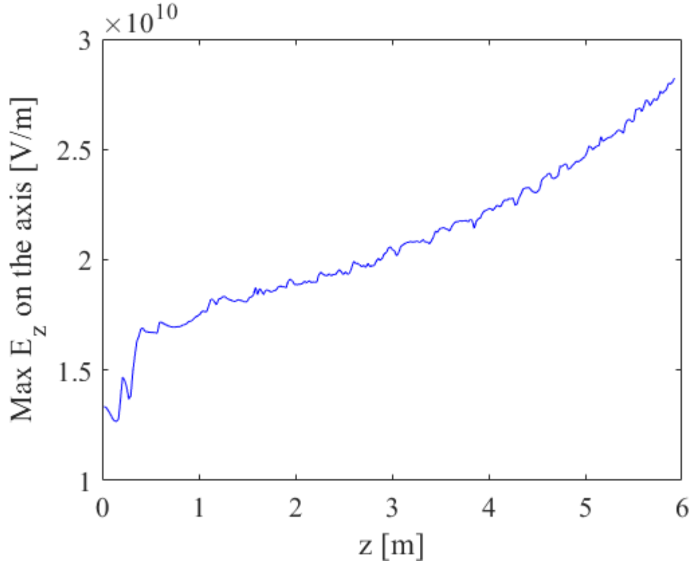
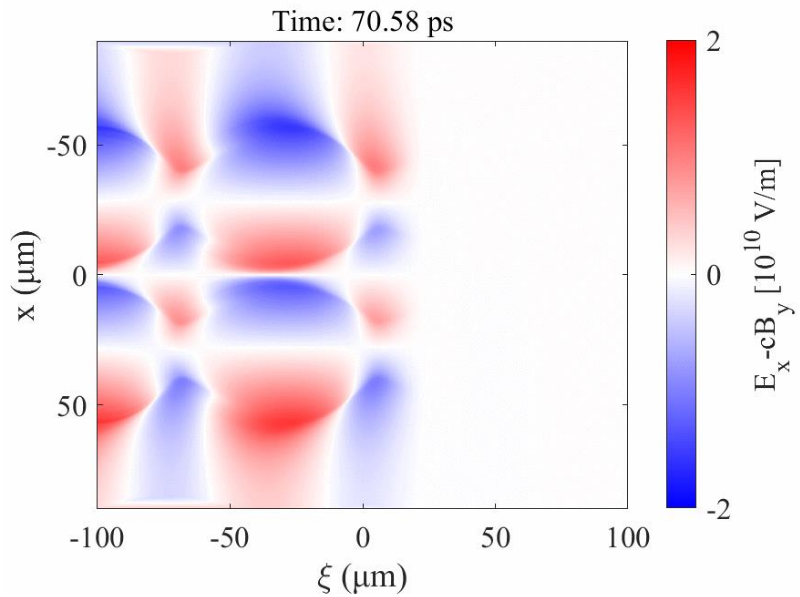
03 Acceleration and Evolution

Acceleration and Evolution -- 2D results









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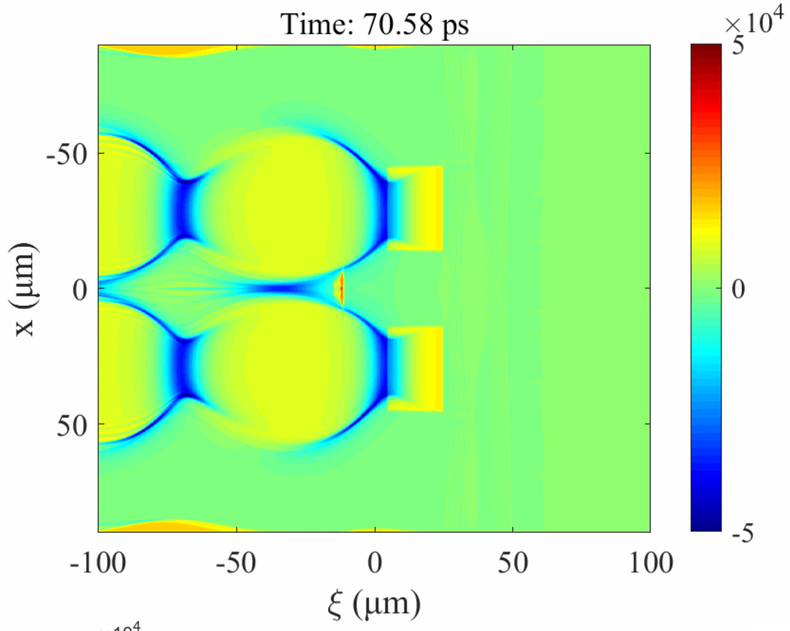
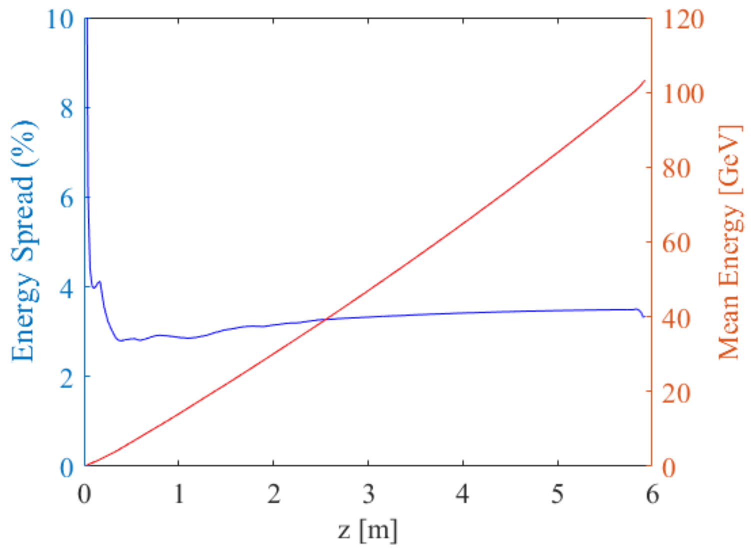
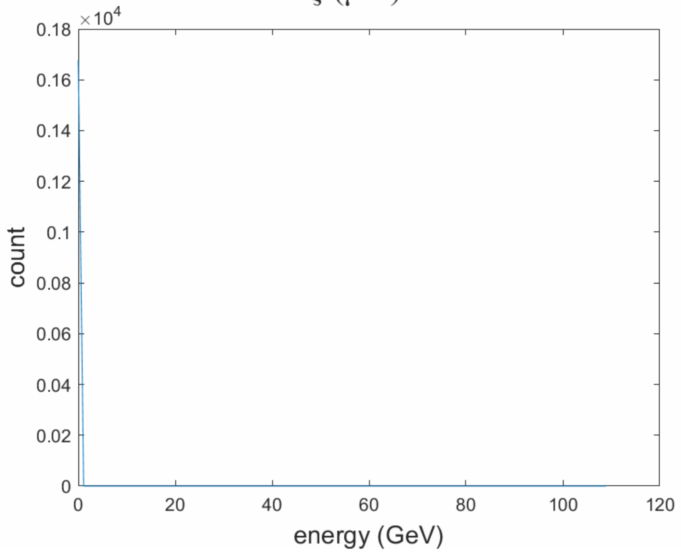
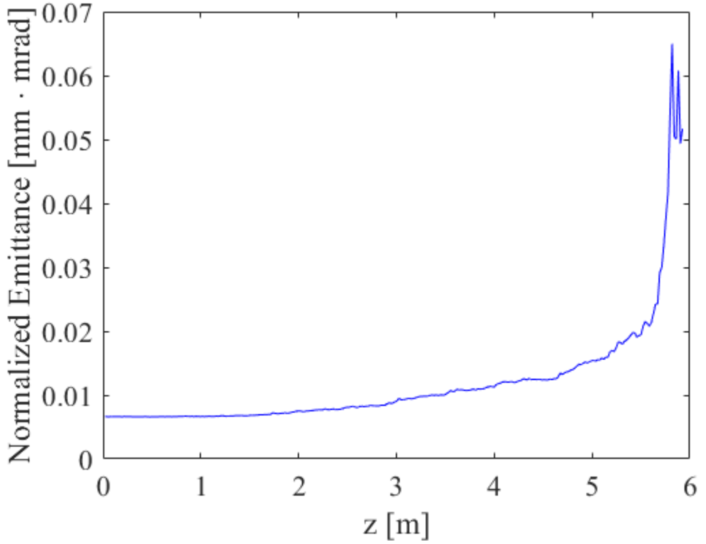
Acceleration and Evolution -- 2D results









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Acceleration and Evolution -- parameter scanning

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$r_i = 12\ \mu m$

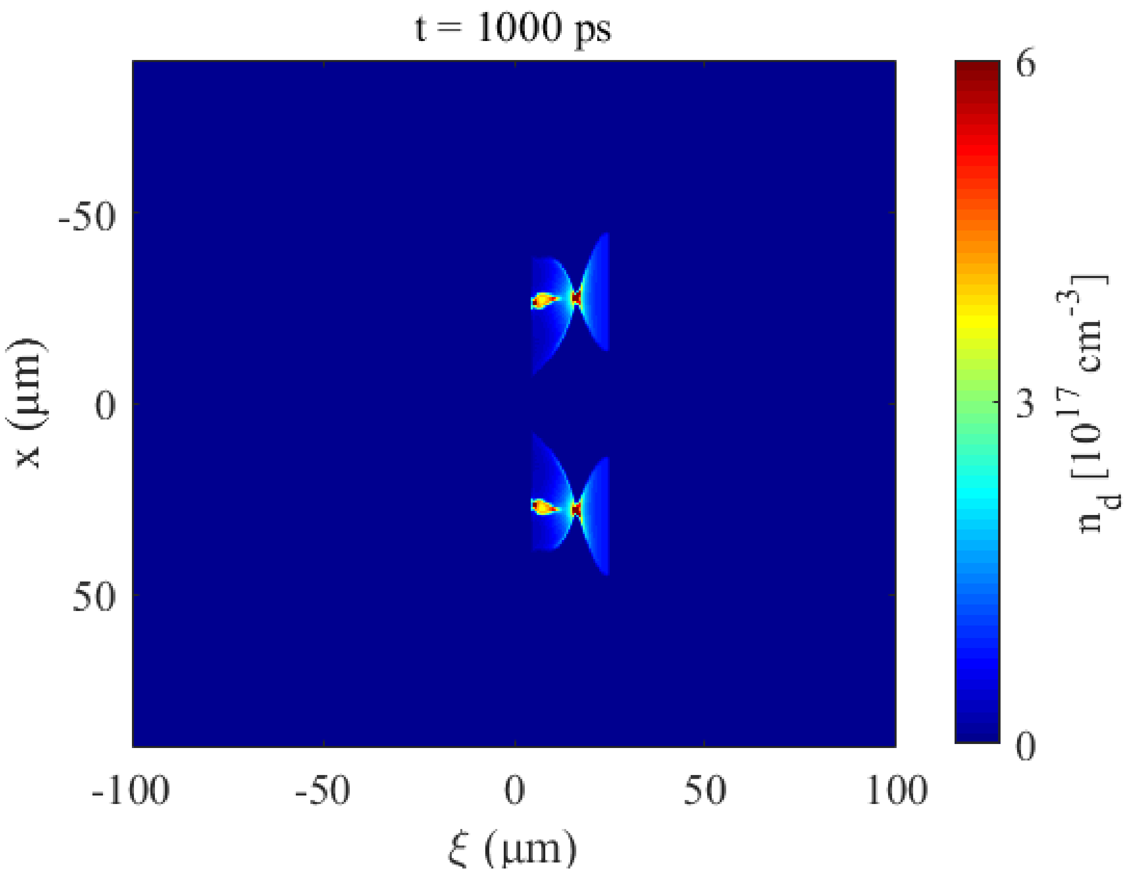
E_{driver} (TeV)	Average gradient (GV/m)	distance	energy (GeV)
0.5	16.0	0.63	10
1	17.5	2.10	37
2	17.6	2.71	48
3	17.2	3.32	57
4	17.2	4.08	70
5	17.3	4.65	81
6	18.0	5.33	96
7	17.5	5.88	105

$E_{driver} = 7\ TeV$

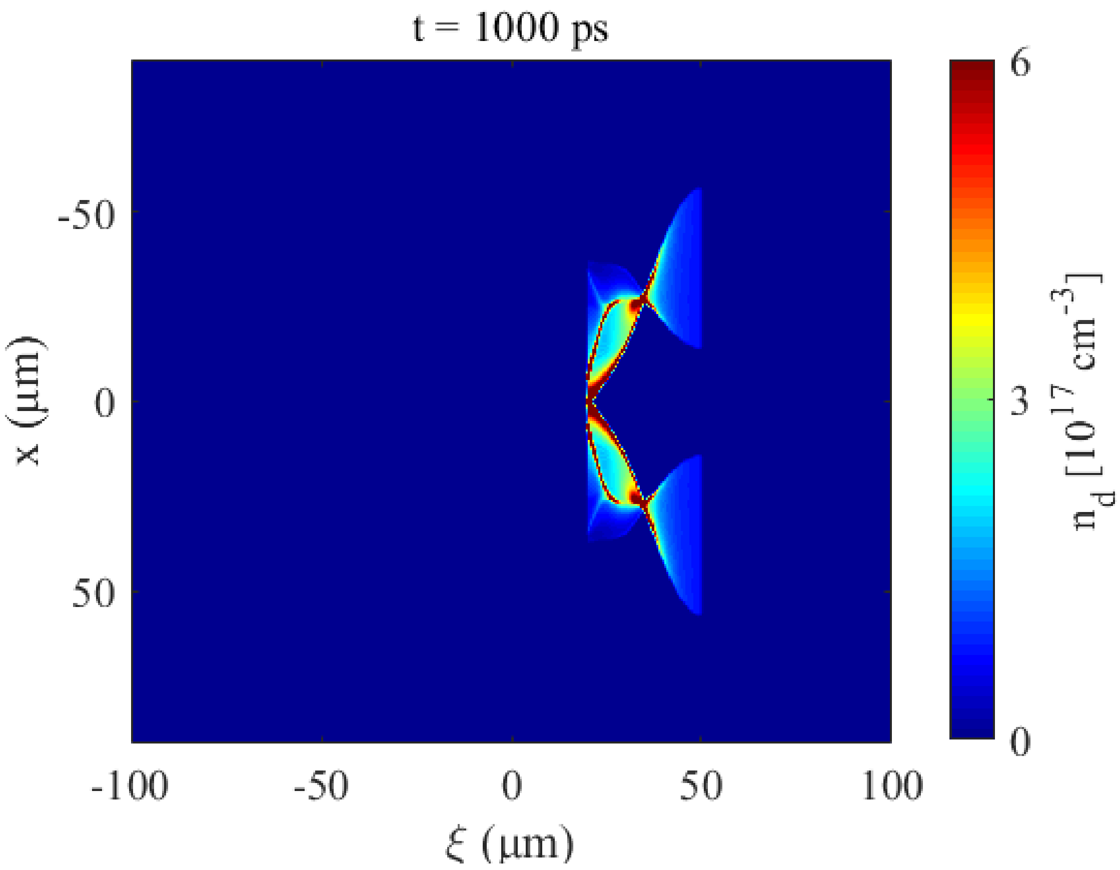
r_i (μm)	Average gradient (GV/m)	distance (m)	energy (GeV)
2	26.9	0.22	6
4	26.0	0.42	11
6	22.4	1.88	25
8	20.2	2.58	38
10	18.9	4.02	76
12	17.5	5.88	105
15	15.7	8.22	129
20	14.5	11.10	160

to be submitted

Acceleration and Evolution -- Comparison between 2D and 3D



n_d at 1000 ps in 2D simulation

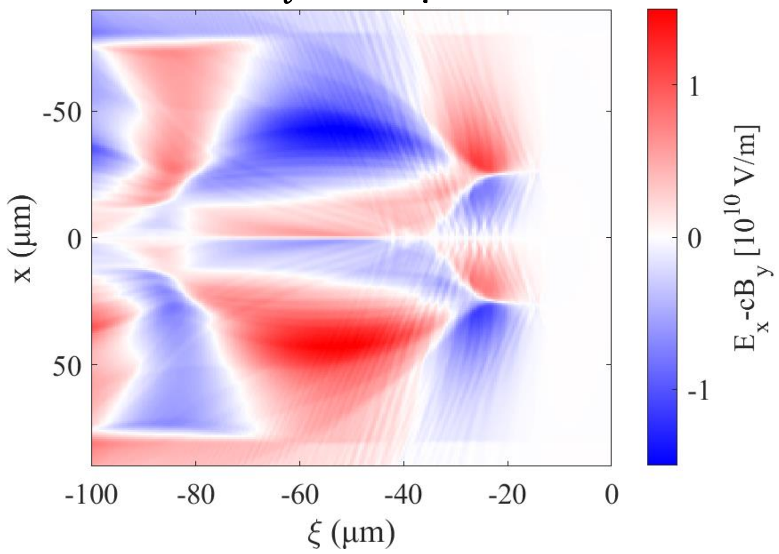


n_d at 1000 ps in 3D simulation

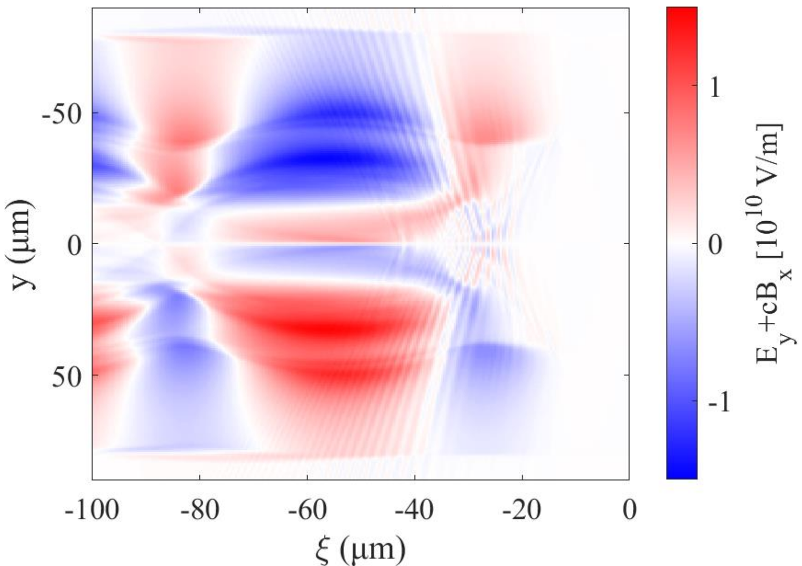
to be submitted

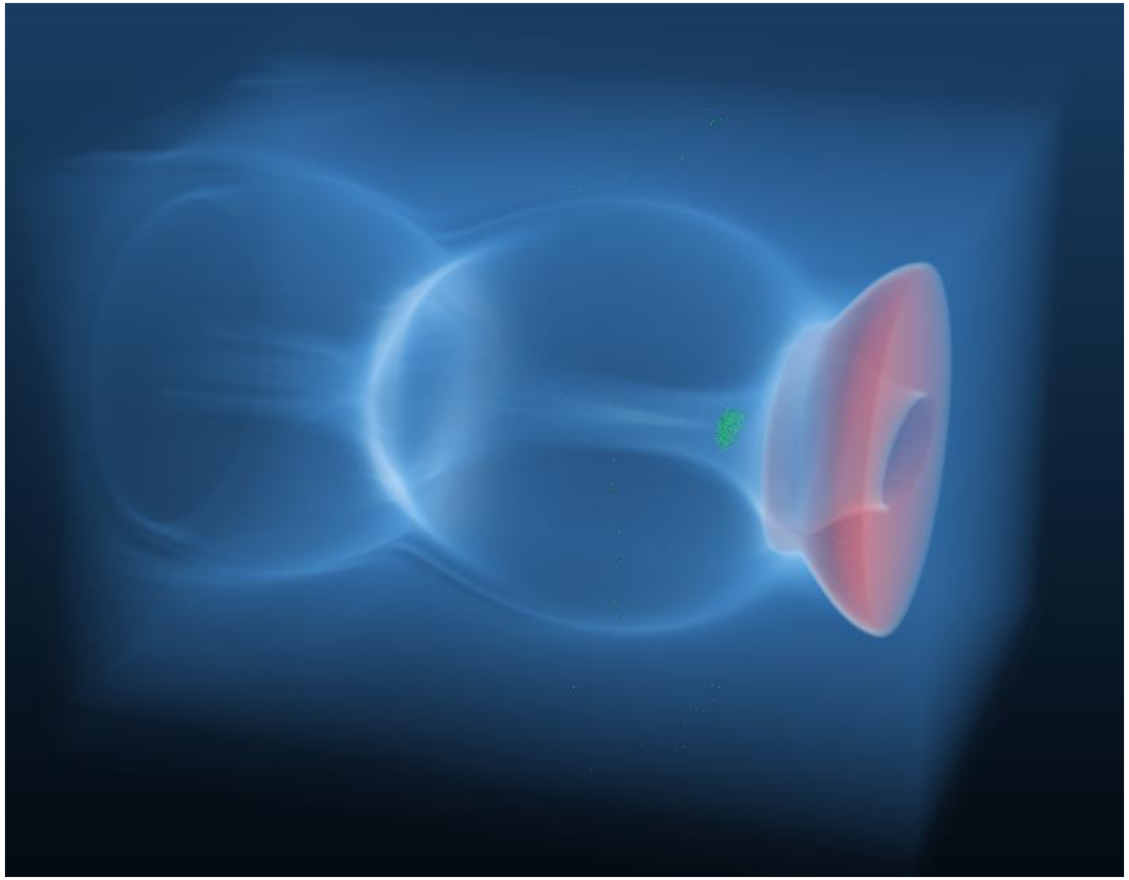
Acceleration and Evolution -- Asymmetric driver

$r_i = 15\ \mu m$



$r_i = 30\ \mu m$





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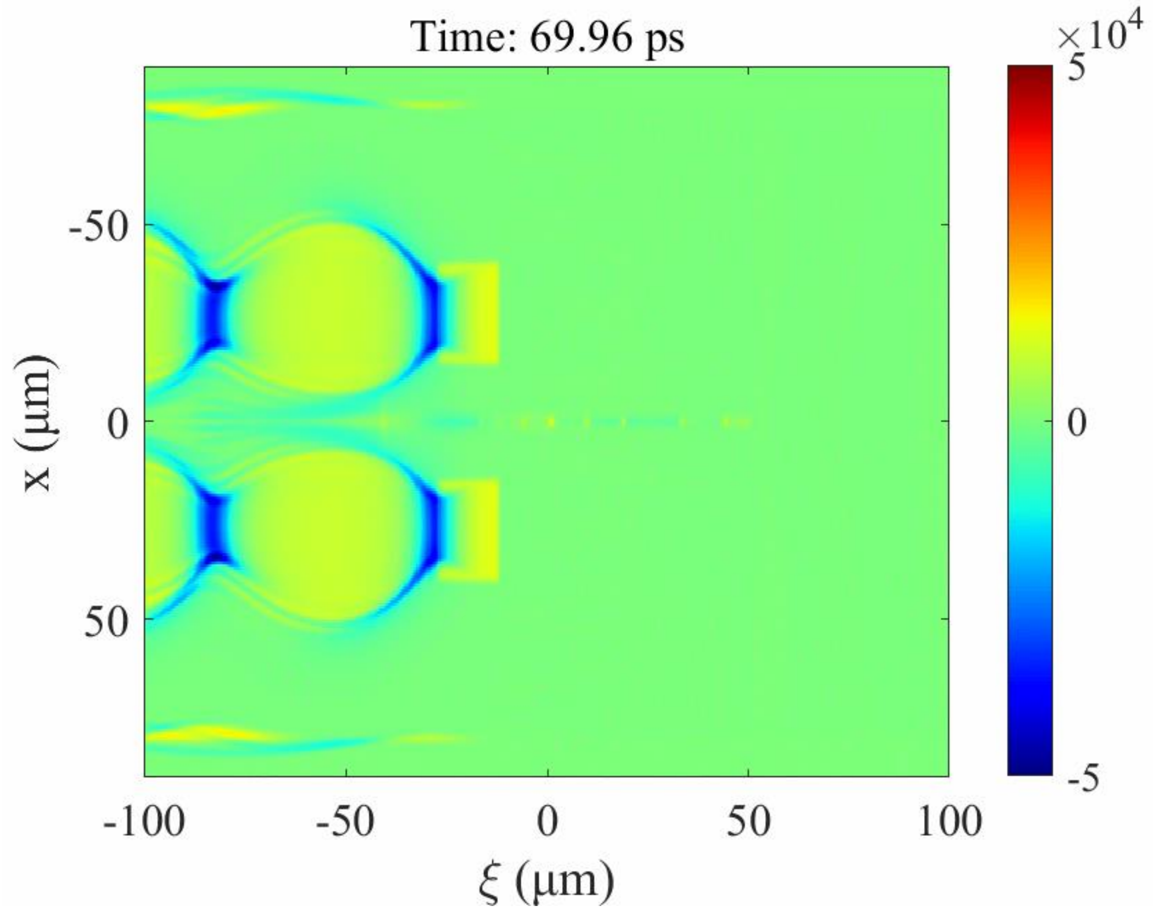
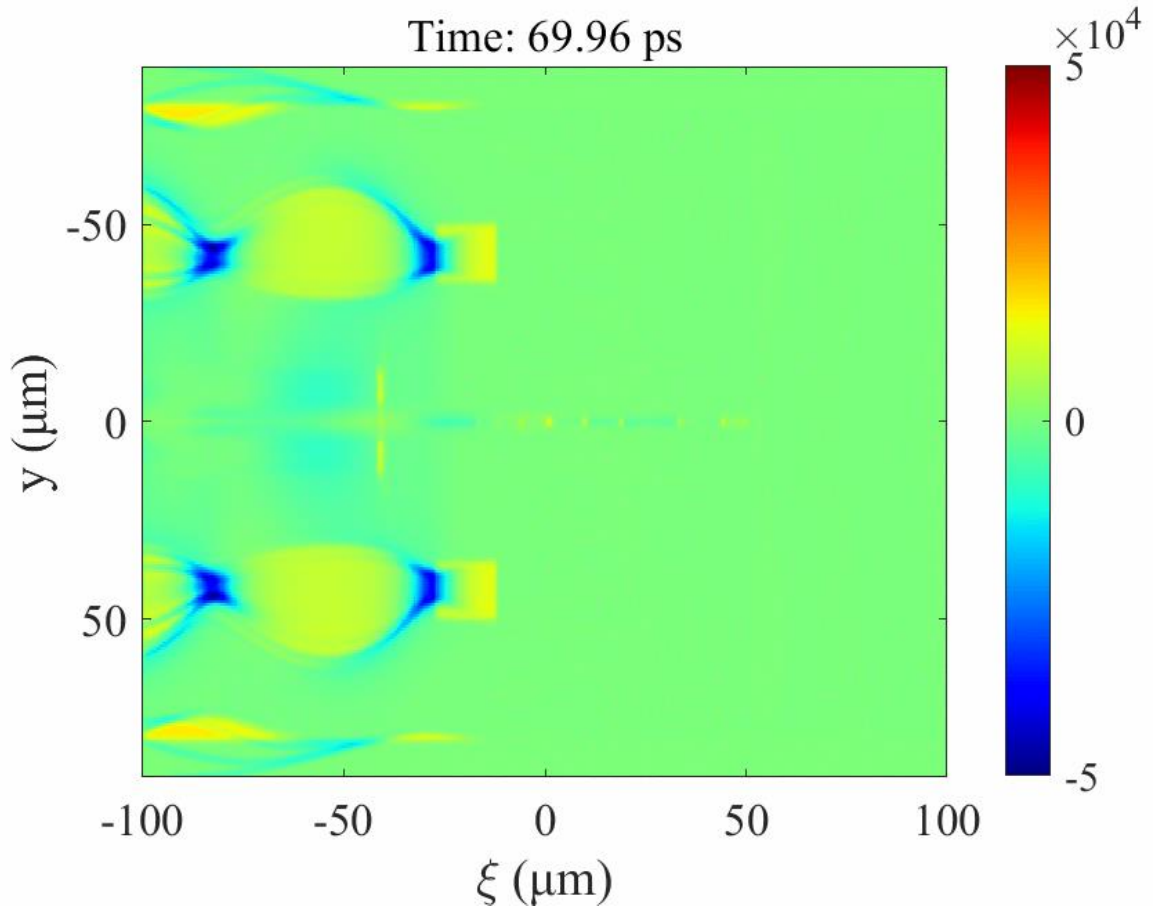
Acceleration and Evolution -- 3D test



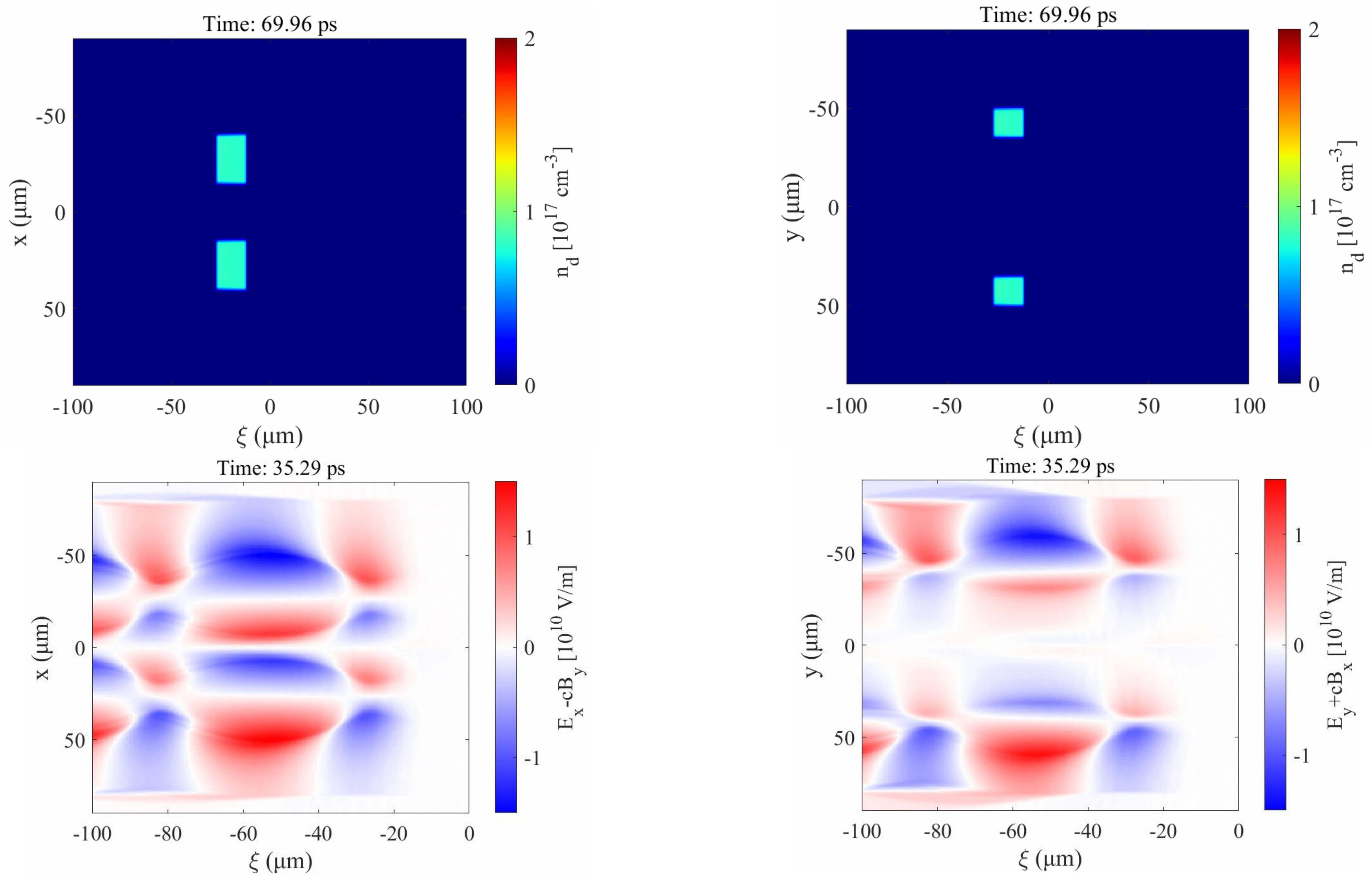
charge density in z-x slice plane



charge density in z-y slice plane

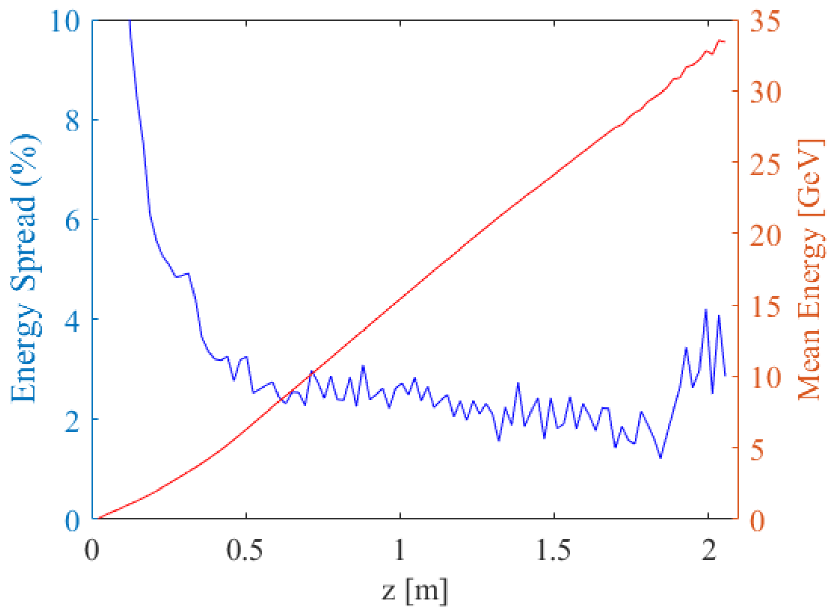
to be submitted

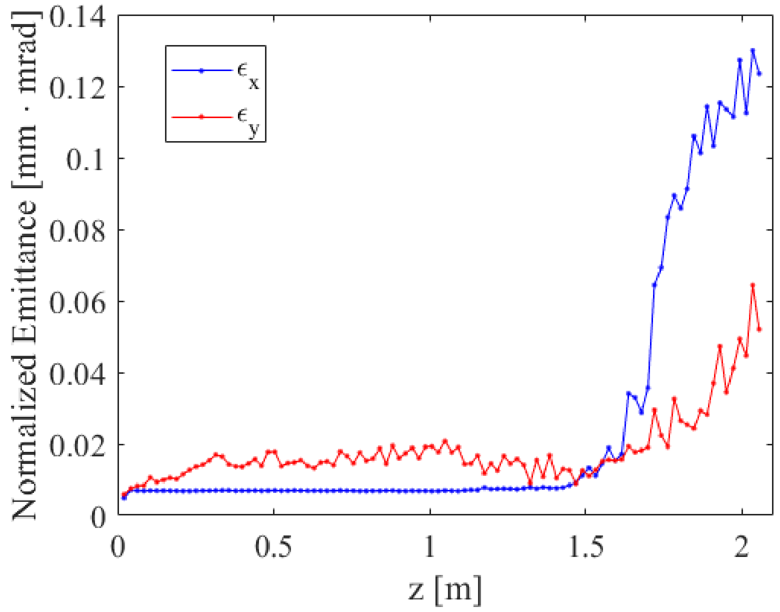
Acceleration and Evolution -- 3D test

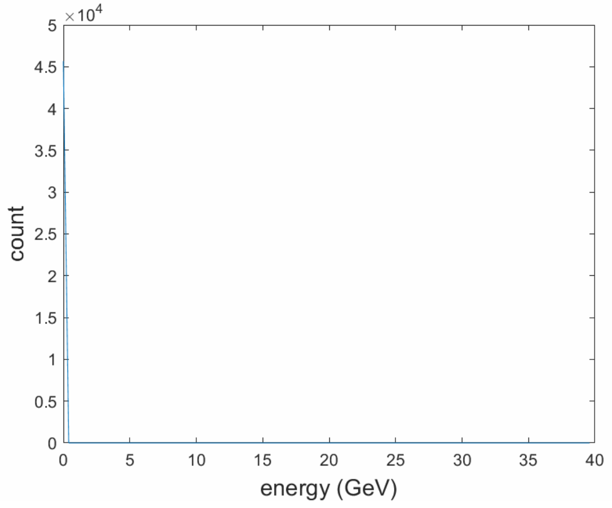


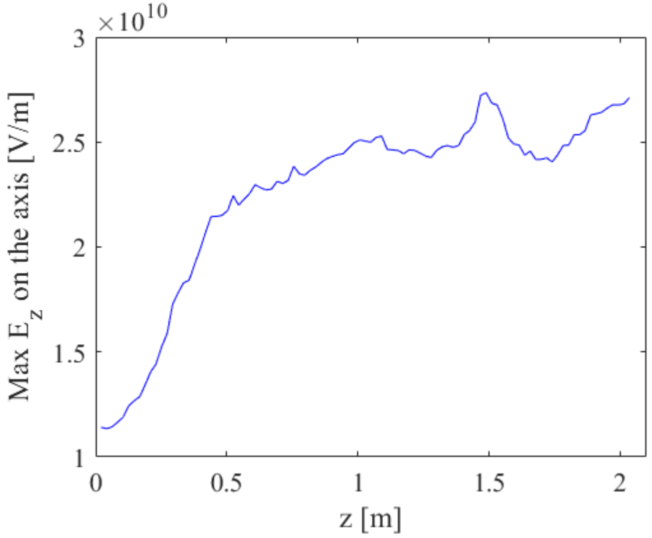
to be submitted

Acceleration and Evolution -- 3D test









to be submitted

04 Conclusion

Conclusion

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	Gradient (GV/m)	Charge(pC)	efficiency (%)	intial energy(GeV)	final energy(GeV)	enery gain (GeV)	spread (%)	emmitance(mm mrad)
N. Jain,PRL(2015)	8.9	13.6	0.17	23	35.4	12.4	0.3	0.036
S. Diederichs, PRAB(2020)	30	52	3	1	5.5	4.5	0.86	0.38
L. Reichwein, PRE(2022)	20	15	5.5	~	10	~10	3.4	31
T. Silva,PRL(2021)	3.5	100	4.7	0.5	1.45	0.95	6	7.4
S. Zhou,PRL(2021)	4.9	490	33	10.2	14.6	4.4	5.3	67
Our work	20	10	15.2	0-25 MeV	105	105	3	0.05

Conclusion

- We use a hollow proton bunch to generate the wakefield, completing the injection of positrons in a uniform plasma.
  - For low-energy positrons, the injection position is closely related to the initial energy and inner radius, with an energy threshold.
  - For positrons with a broad energy spectrum, the transverse field deflects the positrons, and the injection position is independent of intital energy.
- In a single stage, the positrons energy gain exceed 100 GeV with high effiency and high beam quality.
- Parameter scannings show that the main parameters affecting the acceleration results are the energy of the drive bunch and density distribution.
- The use of asymmetric hollow proton bunch can effectively suppress its evolution.

Thanks!