Positron Acceleration in Plasma

regimes comparisons and critical parameters

Gevy Jiawei Cao
University of Oslo

NAPAC 2022, Albuquerque, New Mexico

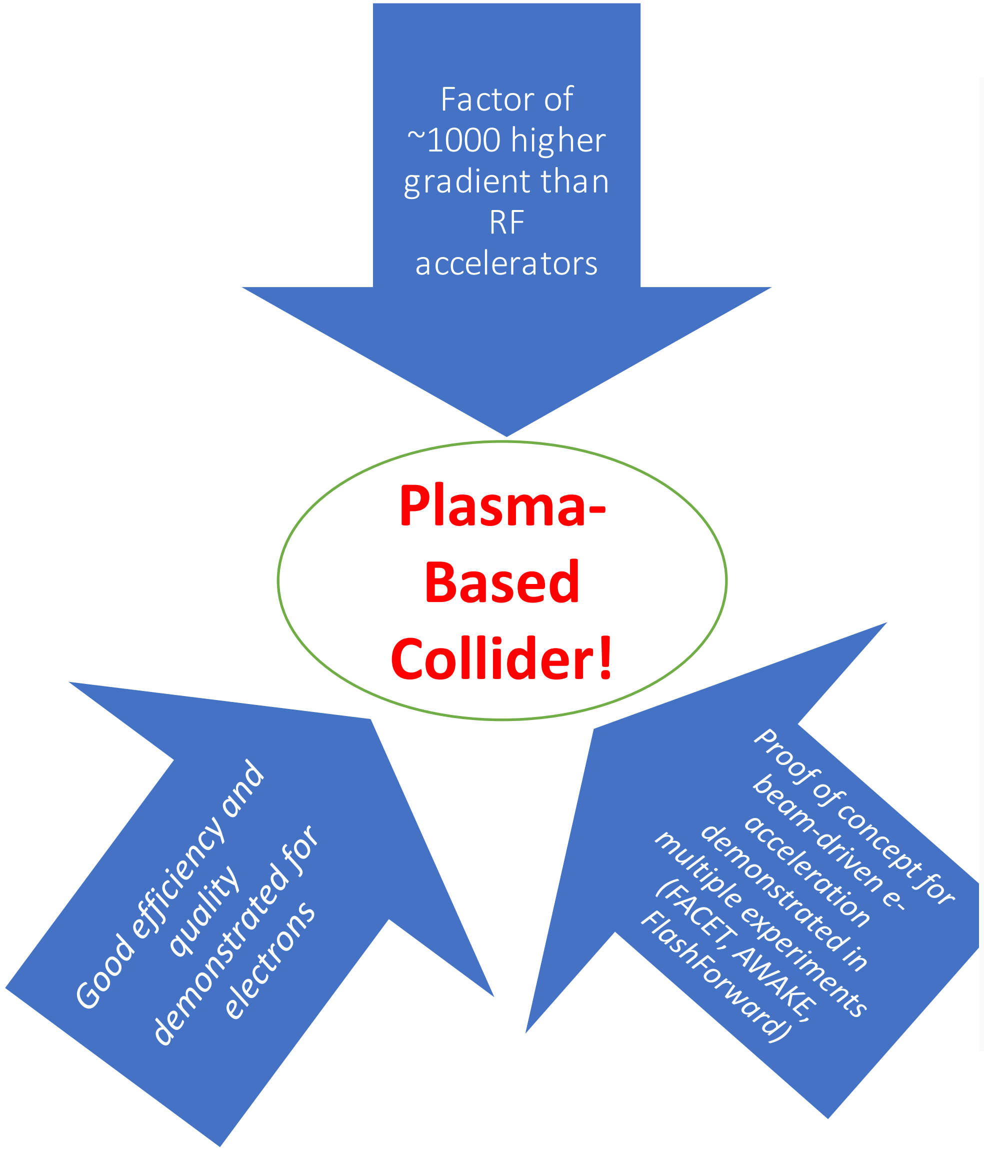
August 10th, 2022

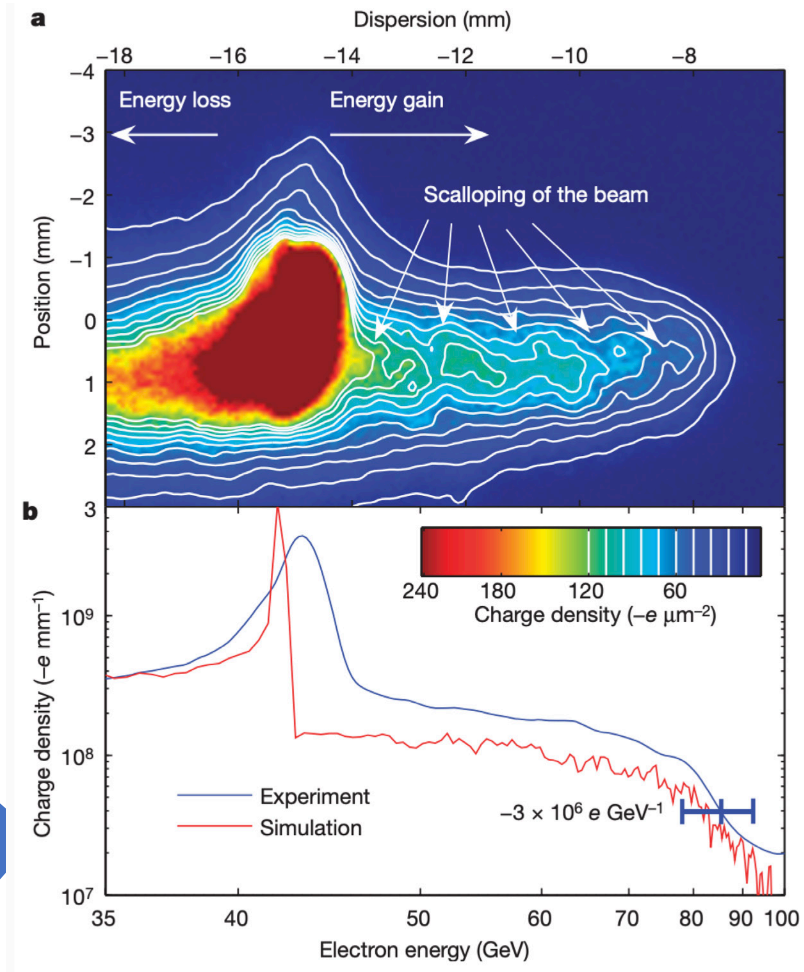
Outline

- Motivation for plasma acceleration in high-energy collider applications
- The positron problem in plasma
- Proposed positron acceleration regimes in plasma
- The trade-off between efficiency and beam quality
- Comparison on common grounds
- Summary

SLAC NATIONAL ACCELERATOR LABORATORY
UiO : University of Oslo
loa
ENSTA IP PARIS
l'X ÉCOLE POLYTECHNIQUE IP PARIS

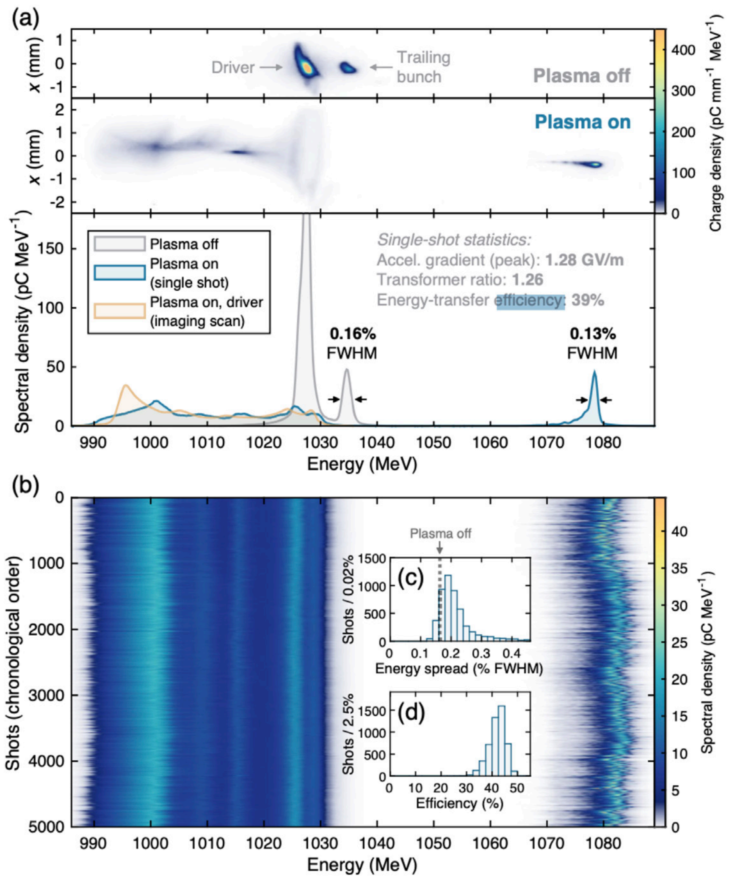
Motivation to use plasma accelerators





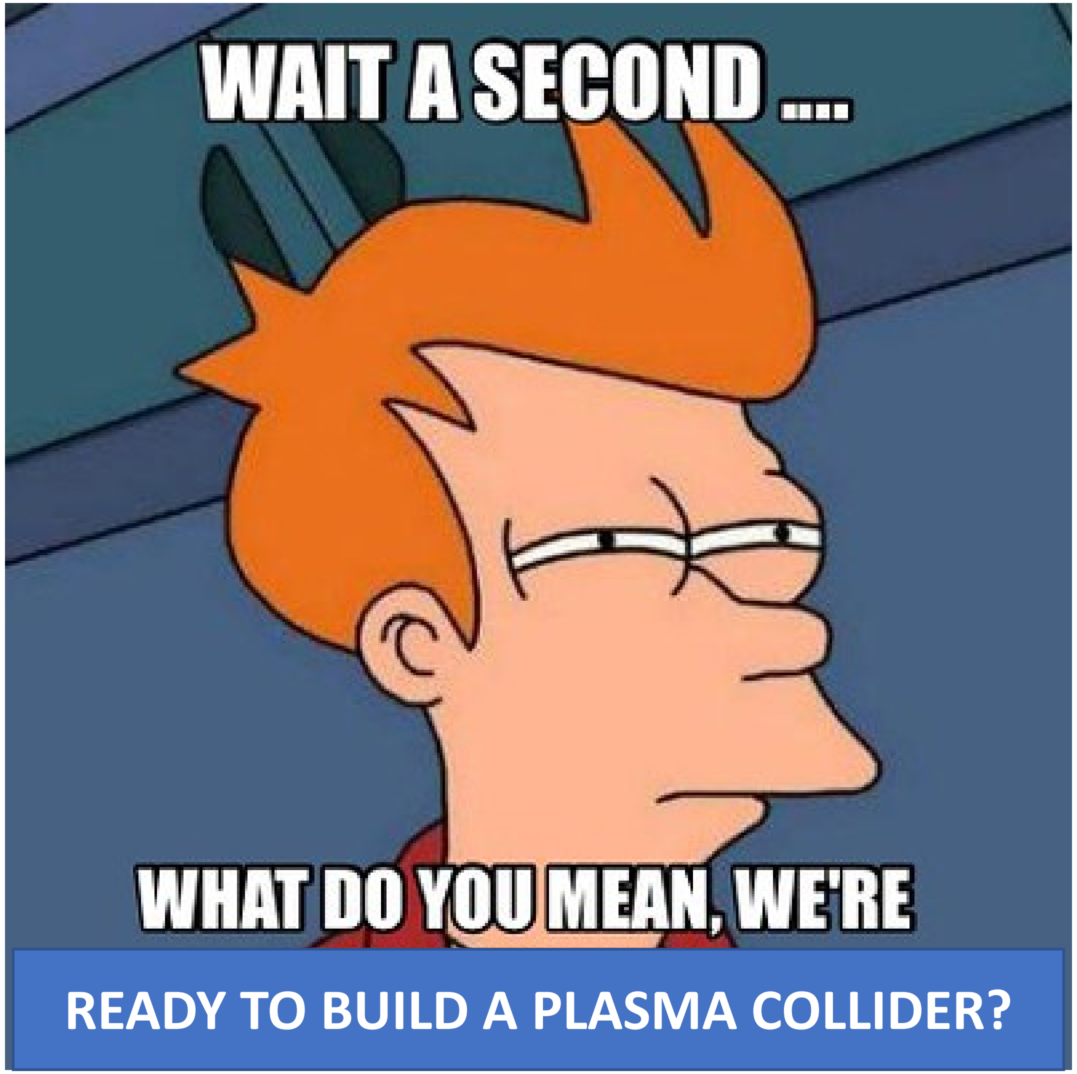
~50 GeV acceleration in 1m at SLAC

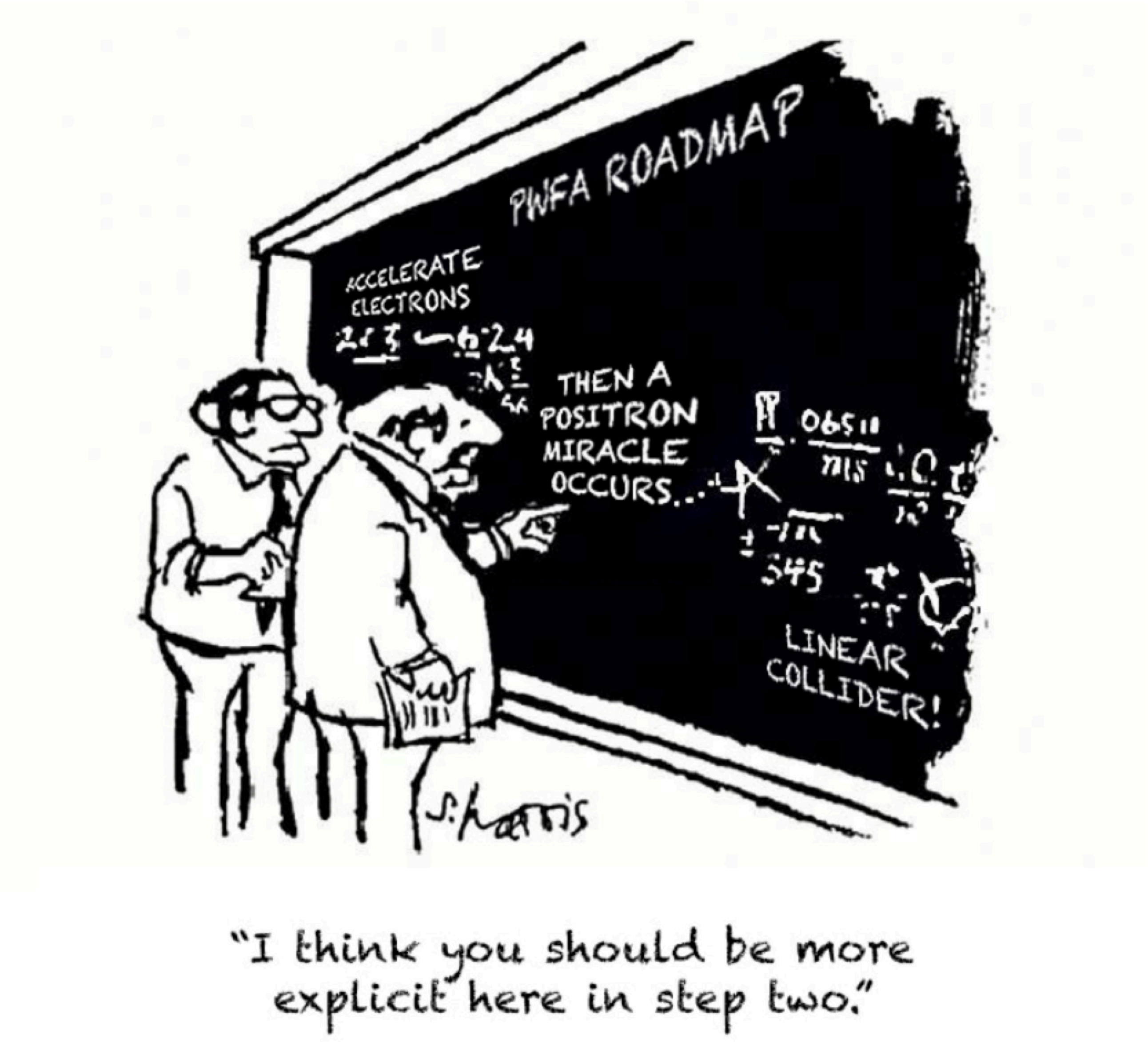
I.Blumenfeld *et al, Nature 445*, p.741-744, 2007.



Sub-% energy spread at ~40% efficiency at DESY

C. A. Lindstrøm *et al, Phys.Rev.Lett 126*, p.014801, 2021.





Taken from PhD thesis, C.A.Lindstrøm, 2019

adapted from © S. Harris

The Positron Problem

What we need:

$$\frac{\partial E_z}{\partial \xi} = 0 \quad (1)$$

$$\frac{\partial F_r}{\partial \xi} = 0 \quad (2)$$

$$\frac{\partial F_r}{\partial r} \text{ independent of } \xi \quad (3)$$

Uniform, (immobile) negatively charged particles

The Positron Problem

What we need:

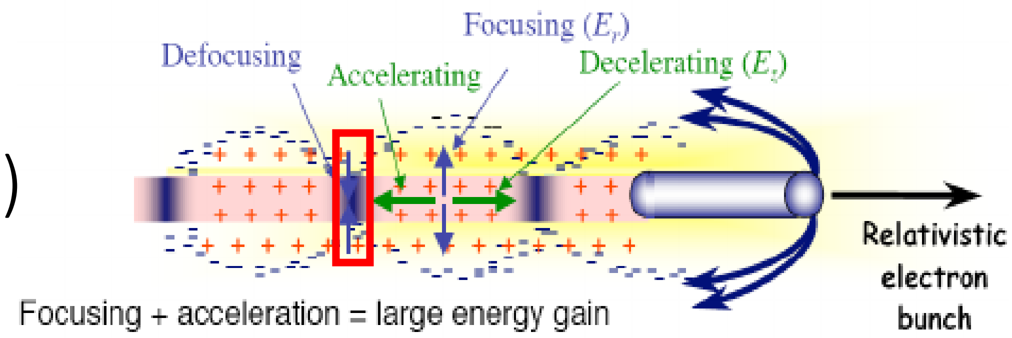
$$\frac{\partial E_z}{\partial \xi} = 0 \quad (1)$$

$$\frac{\partial F_r}{\partial \xi} = 0 \quad (2)$$

$$\frac{\partial F_r}{\partial r} \text{ independent of } \xi \; (3)$$

Uniform, (immobile) negatively charged particles

Non-linear (bubble, $\frac{n_b}{n_o} \gg 1$)



Challenges: high plasma e-density, short usable region.

The Positron Problem

What we need:

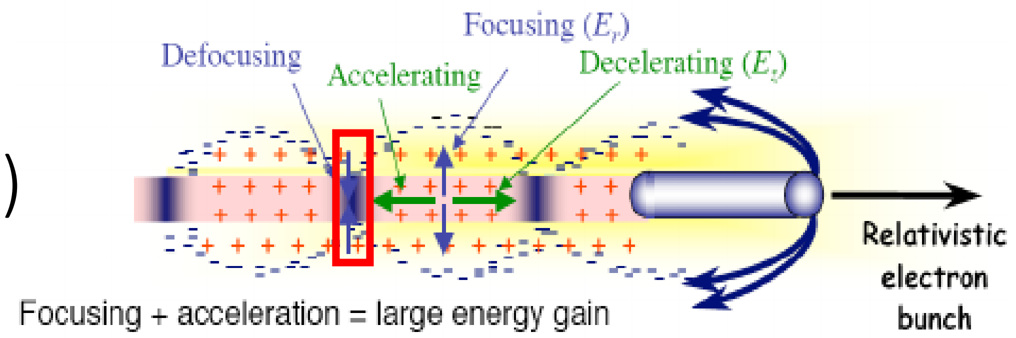
$$\frac{\partial E_z}{\partial \xi} = 0 \quad (1)$$

$$\frac{\partial F_r}{\partial \xi} = 0 \quad (2)$$

$$\frac{\partial F_r}{\partial r} \text{ independent of } \xi \ (3)$$

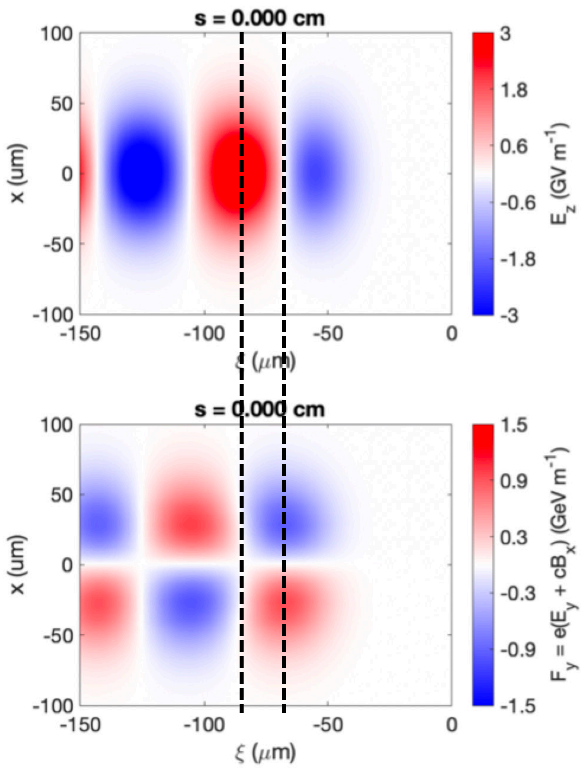
Uniform, (immobile) negatively charged particles

Non-linear (bubble, $\frac{n_b}{n_o} \gg 1$)



Challenges: high plasma e-density, short usable region.

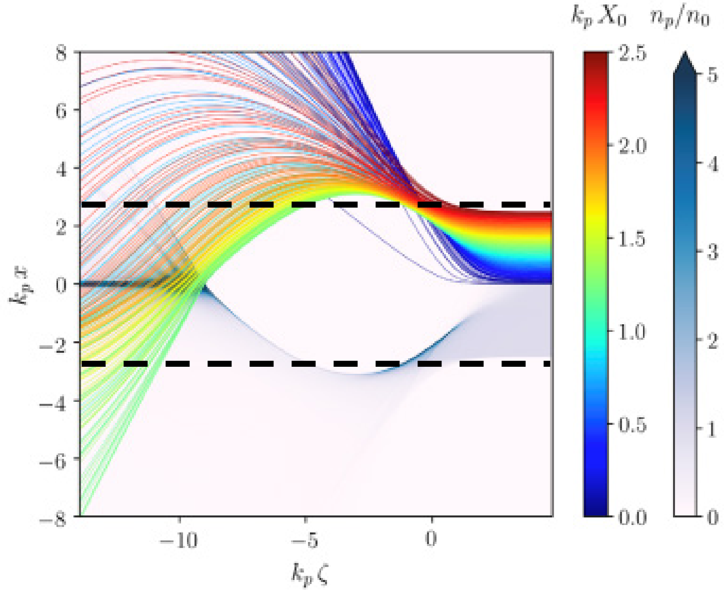
Linear/quasi-linear ($\frac{n_b}{n_o} \ll 1$)

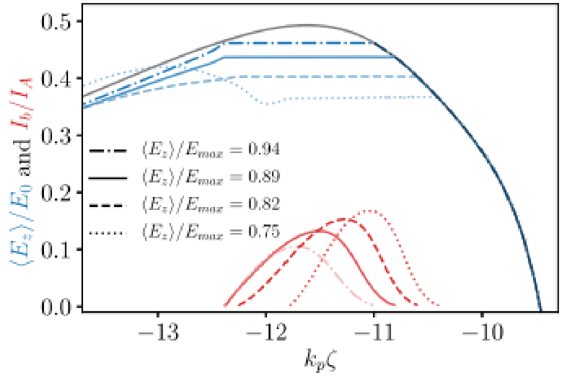


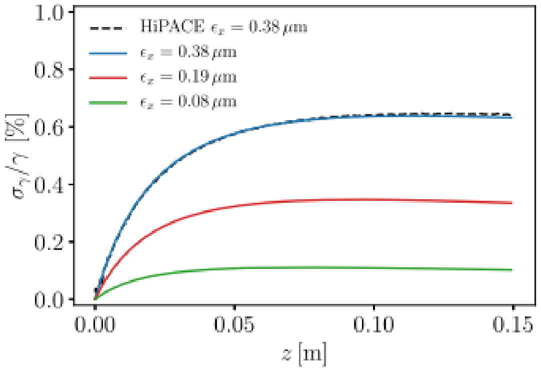
Challenges: low Q, low E_z, low η

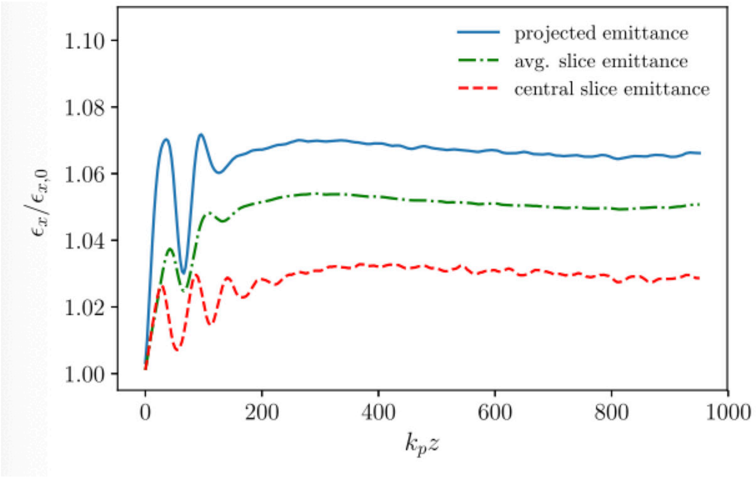
Proposed e+ acceleration regimes

Finite Radius Plasma Column

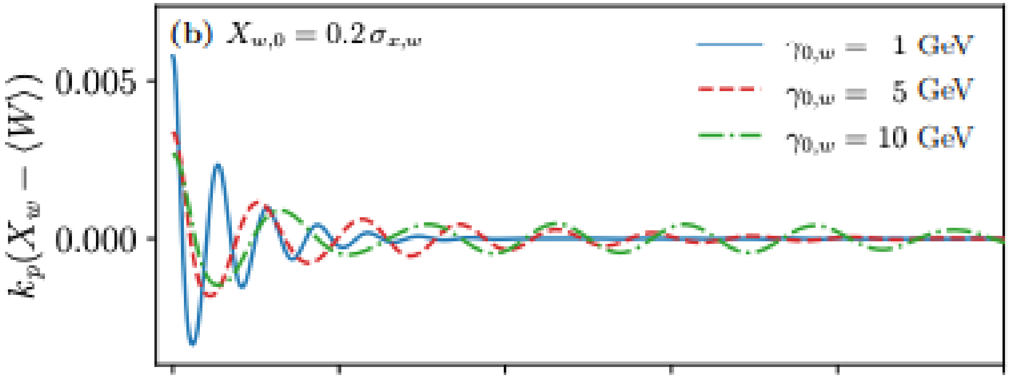








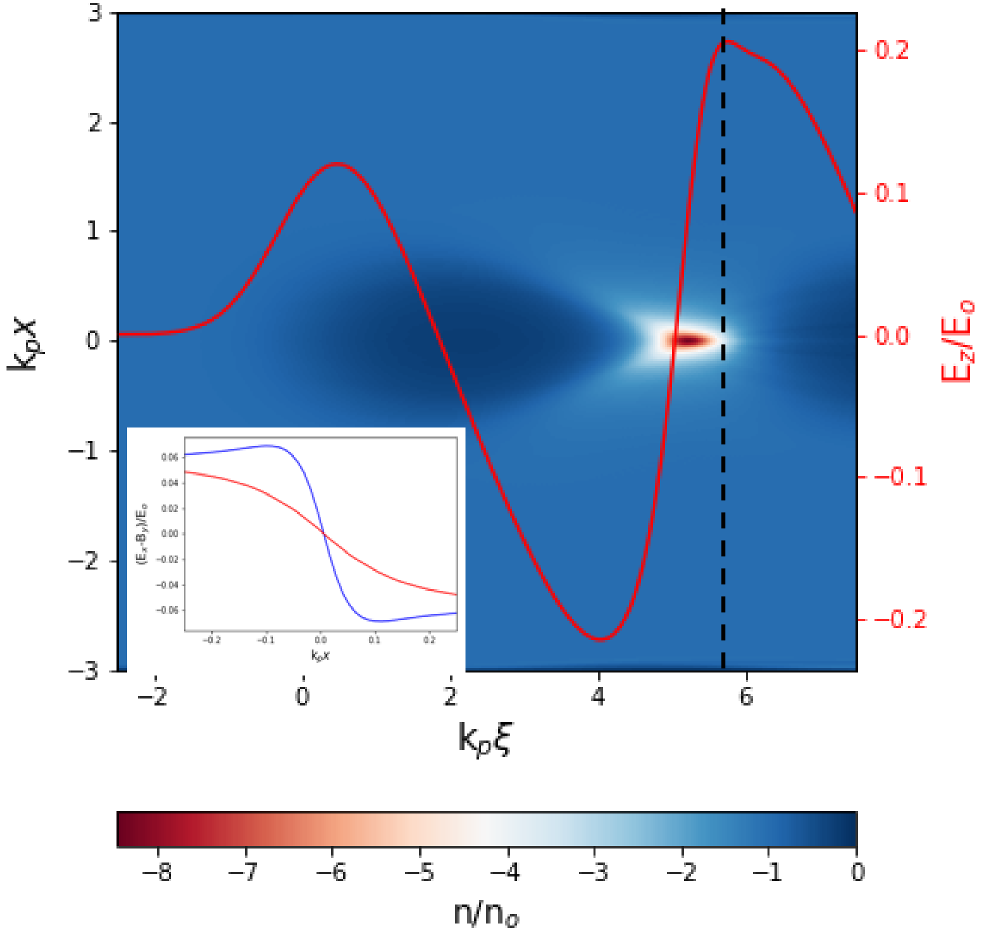
- Based on the trajectories of the plasma e- coming back to axis due to non-linear ion fields, creating an elongated filement on-axis
- Has shown low energy spread, low emittance growth and stability in simulations
- Approved FACET-II experiment



S. Diederichs *et al*, PRAB 22, 081301 (2019)
S. Diederichs *et al*, PRAB 23, 121301 (2020)
S. Diederichs *et al*, doi: 10.48550/arXiv.2206.11967 (2022)

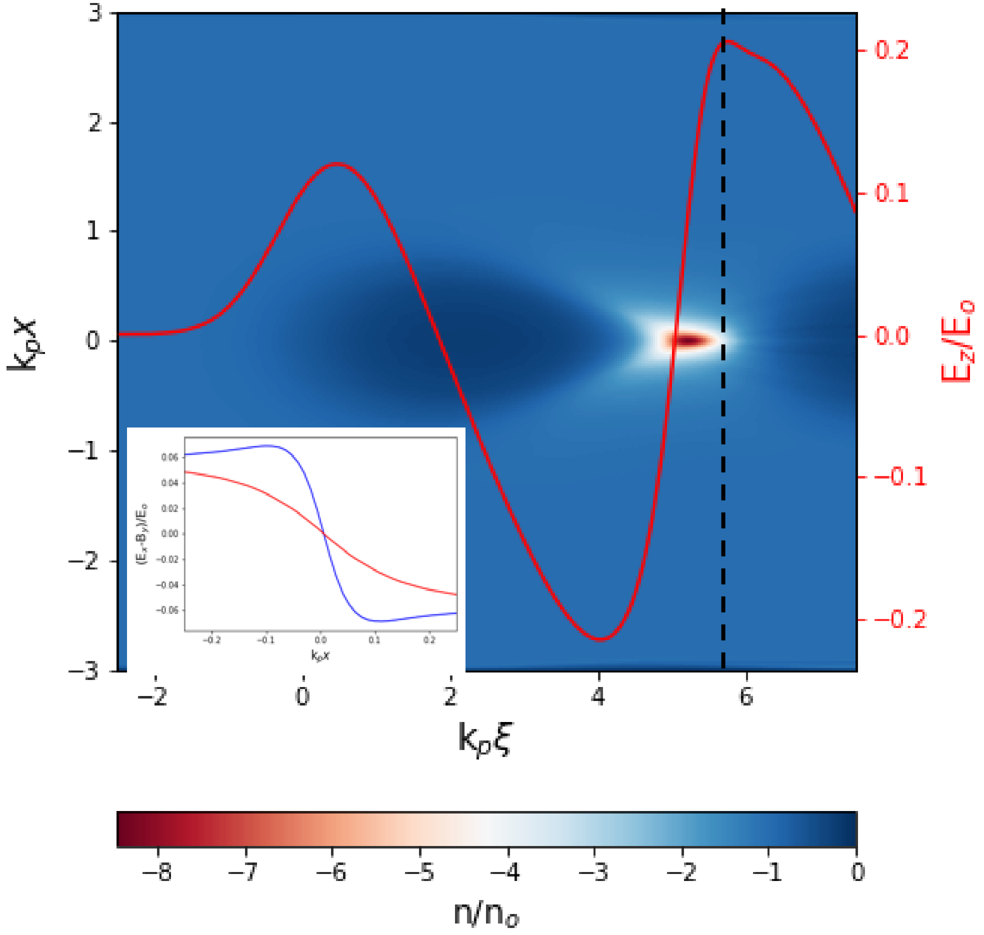
Proposed e+ acceleration regimes

Moderately non-linear regime



Proposed e+ acceleration regimes

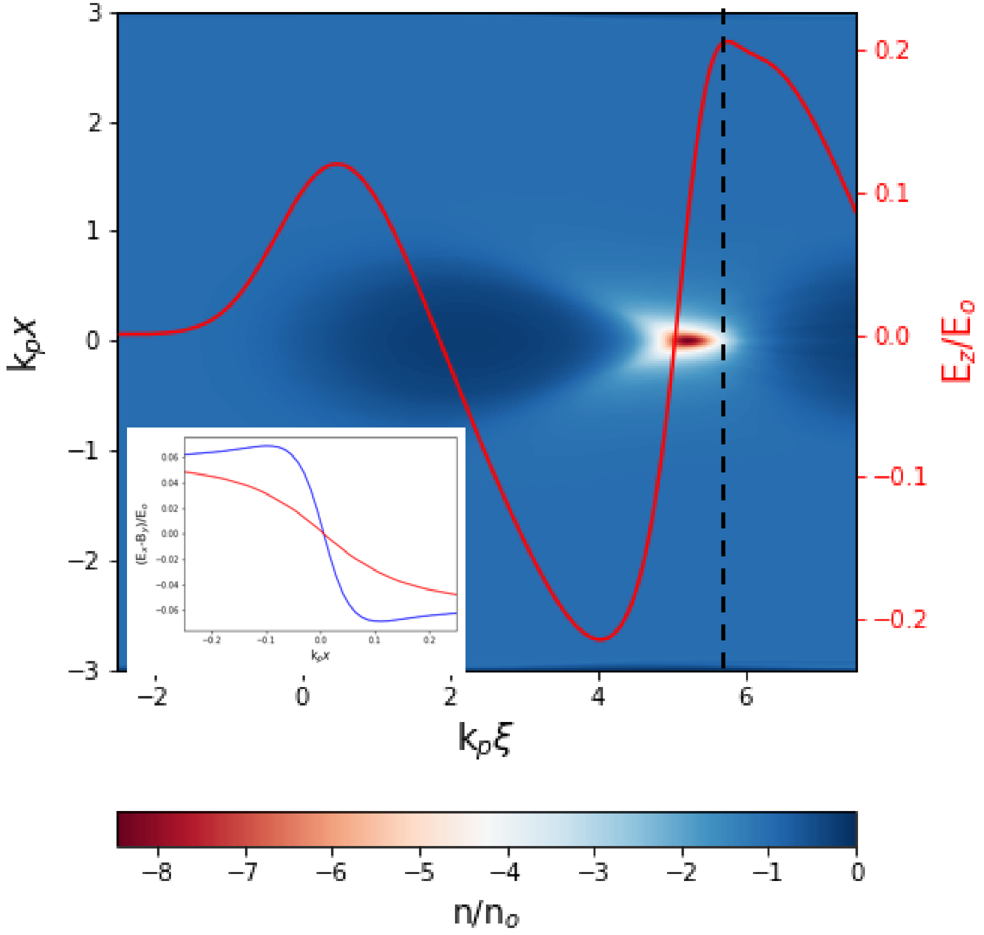
Moderately non-linear regime



$\frac{n_b}{n_o} \cong 1$ for the drive, good efficiency (~15%) and quality for 1 micron level emittance.

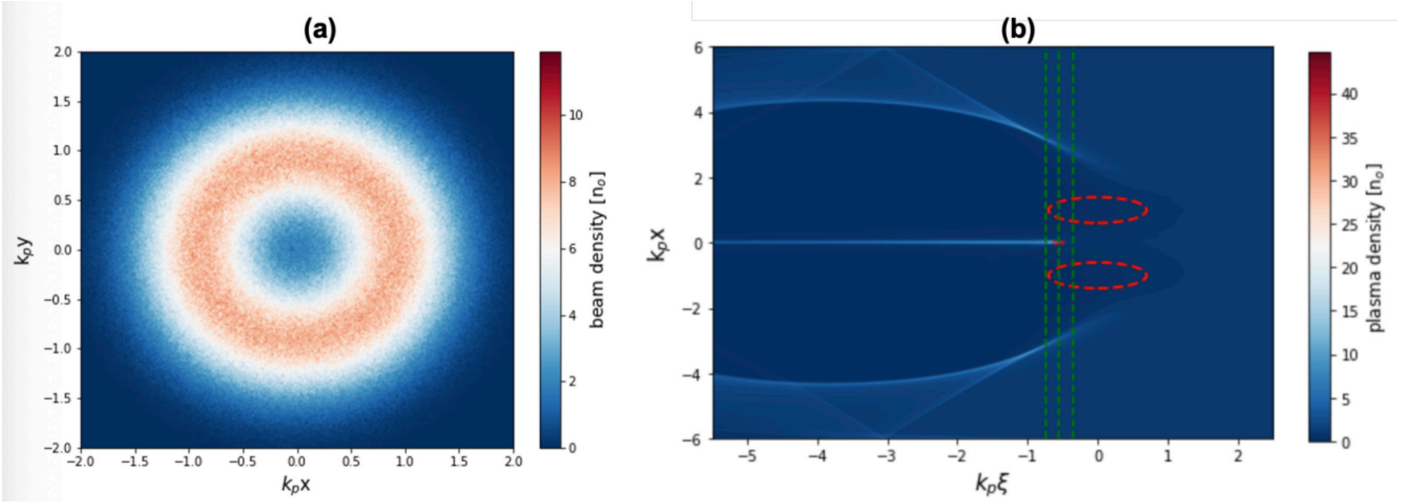
Proposed e+ acceleration regimes

Moderately non-linear regime



$\frac{n_b}{n_o} \cong 1$ for the drive, good efficiency (~15%) and quality for 1 micron level emittance.

Donut Driver



High gradient, high charge acceleration, but low efficiency and beam quality

Positron regime comparison chart

	Efficiency	Charge	Energy Spread	Emittance	Fields
Finite Radius	LOW	MID	LOW	100 nm	HIGH
Donut Driver	LOW-MID	HIGH	MID-HIGH	?	HIGH
MNL	MID	LOW	LOW-MID	1 um	MID
Linear	LOW	LOW	LOW	> 1 um	LOW
Warm Hollow Channel	LOW?	MID	LOW-MID	5-10 um	MID
Elongated Bubble	HIGH	LOW-MID	LOW-MID	1 um	HIGH
Asymmetric Hollow Channel	MID	HIGH	LOW	50 um	MID
Laser augumented blowout and e+ ring	LOW?	LOW-MID	LOW	~30 um	HIGH
	LOW: <10% MID: 10-40% HIGH: > 50%	LOW: <10 pC MID: O (100pC) HIGH: O (nC)	LOW: O (1%) MID: O (10%) HIGH: > 10%		LOW: O (1 GV/m) MID: <10 GV/m HIGH: > 10 GV/m

Positron regime comparison chart

	Efficiency	Charge	Energy Spread	Emittance	Fields
Finite Radius	LOW	MID	LOW	100 nm	HIGH
Donut Driver	LOW-MID	HIGH	MID-HIGH	?	HIGH
MNL	MID	LOW	LOW-MID	1 um	MID
Linear	LOW	LOW	LOW	> 1 um	LOW
Warm Hollow Channel	LOW?	MID	LOW-MID	5-10 um	MID
Elongated Bubble	HIGH	LOW-MID	LOW-MID	1 um	HIGH
Asymmetric Hollow Channel	MID	HIGH	LOW	50 um	MID
Laser augumented blowout and e+ ring	LOW?	LOW-MID	LOW	~30 um	HIGH

	Efficiency	Charge	Energy Spread	Fields
	LOW: <10%	LOW: <10 pC	LOW: O (1%)	LOW: O (1 GV/m)
	MID: 10-40%	MID: O (100pC)	MID: O (10%)	MID: <10 GV/m
	HIGH: > 50%	HIGH: O (nC)	HIGH: > 10%	HIGH: > 10 GV/m

PHYSICAL REVIEW RESEARCH **3**, 043063 (2021)

Efficiency and beam quality for positron acceleration in loaded plasma wakefields

C. S. Hue,[1,*] G. J. Cao,[1,2,*] I. A. Andriyash,[1] A. Knetsch,[1] M. J. Hogan,[3] E. Adli,[2] S. Gessner,[3] and S. Corde[1,†]

[1]*LOA, ENSTA Paris, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 91762 Palaiseau, France*

[2]*Department of Physics, University of Oslo, NO-0316 Oslo, Norway*

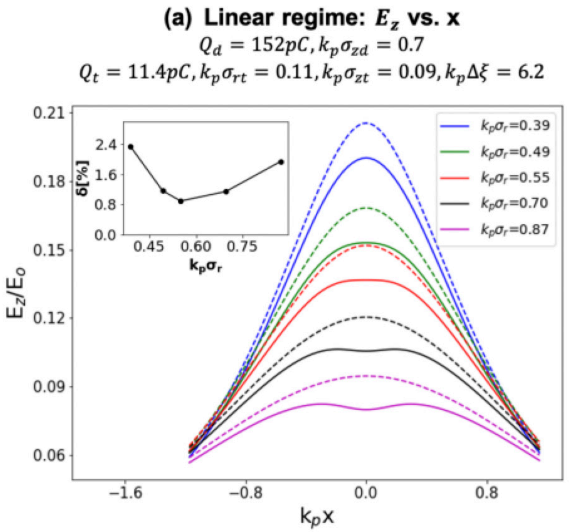
[3]*SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*

(Received 2 July 2021; accepted 1 October 2021; published 22 October 2021)

Accelerating particles to high energies in plasma wakefields is considered to be a promising technique with good energy efficiency and high gradient. While important progress has been made in plasma-based electron acceleration, positron acceleration in plasma has been scarcely studied and a fully self-consistent and optimal scenario has not yet been identified. For high energy physics applications where an electron-positron collider would be desired, the ability to accelerate positrons in plasma wakefields is, however, paramount. Here we show that the preservation of beam quality can be compromised in a plasma wakefield loaded with a positron beam, and a tradeoff between energy efficiency and beam quality needs to be found. For electron beams driving linear plasma wakefields, we have found that despite the transversely nonlinear focusing force induced by positron beam loading, the bunch quickly evolves toward an equilibrium distribution with limited emittance growth. Particle-in-cell simulations show that for μm-scale normalized emittance, the growth of uncorrelated energy spread sets an important limit. Our results demonstrate that the linear or moderately nonlinear regimes with Gaussian drivers provide a good tradeoff, achieving simultaneously energy-transfer efficiencies exceeding 30% and uncorrelated energy spread below 1%, while donut-shaped drivers in the nonlinear regime are more appropriate to accelerate high-charge bunches at higher gradients, at the cost of a degraded tradeoff between efficiency and beam quality.

DOI: 10.1103/PhysRevResearch.3.043063

Critical parameters in e+ acceleration



- The uncorrelated energy spread (slice energy spread)

$$\delta = \frac{\int [\delta(\xi) \int (n_t dxdy)] d\xi}{N_t}$$

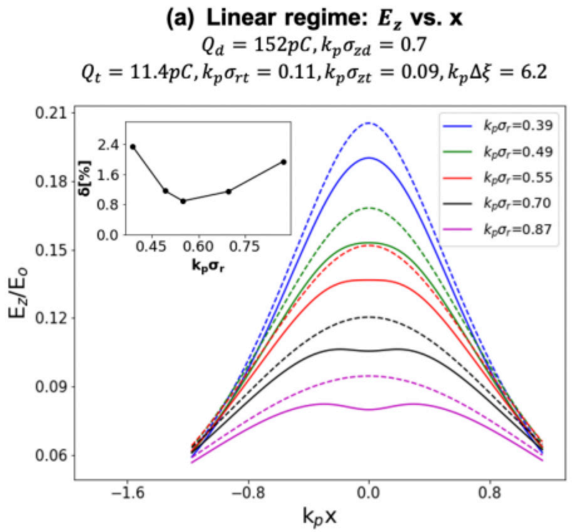
Becomes a problem with a larger trailing load

- "Loading severity"

$$k_b\sigma_z = \sqrt{n_b e^2/(m_e\epsilon_o)}/c$$

$k_b\sigma_z > 1$ → severe loading that results in irregular plasma e- oscillations in the e+ beam → emittance growth

Critical parameters in e+ acceleration



- The uncorrelated energy spread (slice energy spread)

$$\delta = \frac{\int [\delta(\xi) \int (n_t dx dy)] d\xi}{N_t}$$

Becomes a problem with a larger trailing load

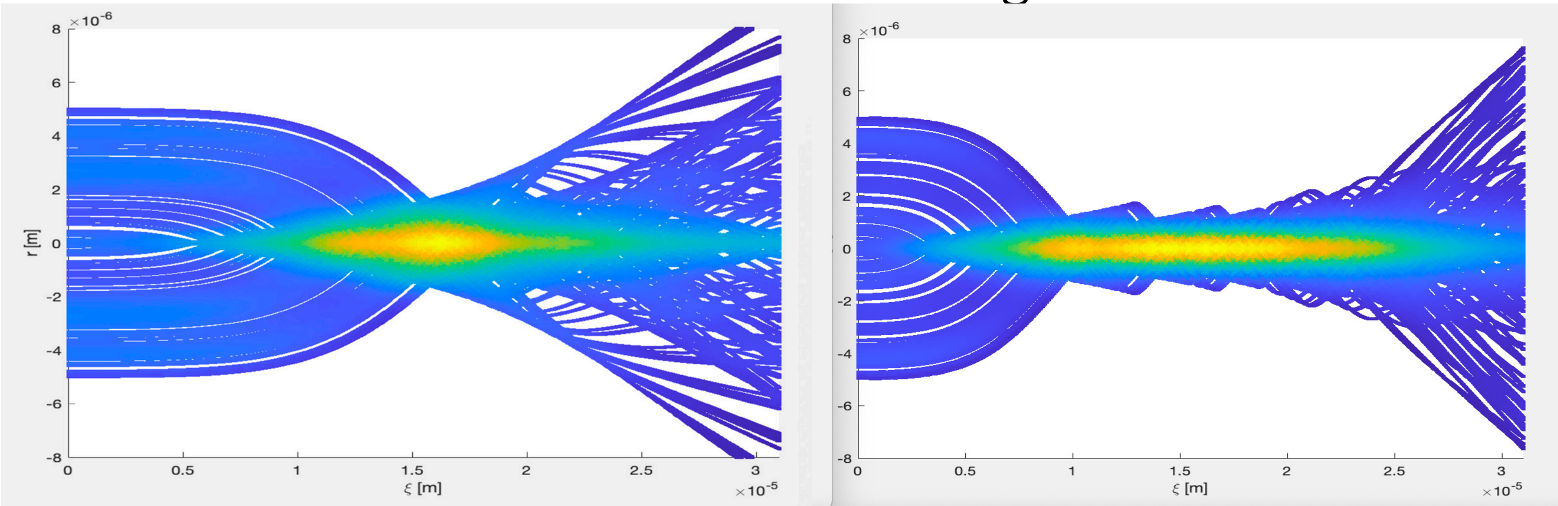
- “Loading severity”

$$k_b \sigma_z = \sqrt{n_b e^2/(m_e \epsilon_o)}/c$$

$k_b\sigma_z > 1$ → severe loading that results in irregular plasma e- oscillations in the e+ beam

→ emittance growth

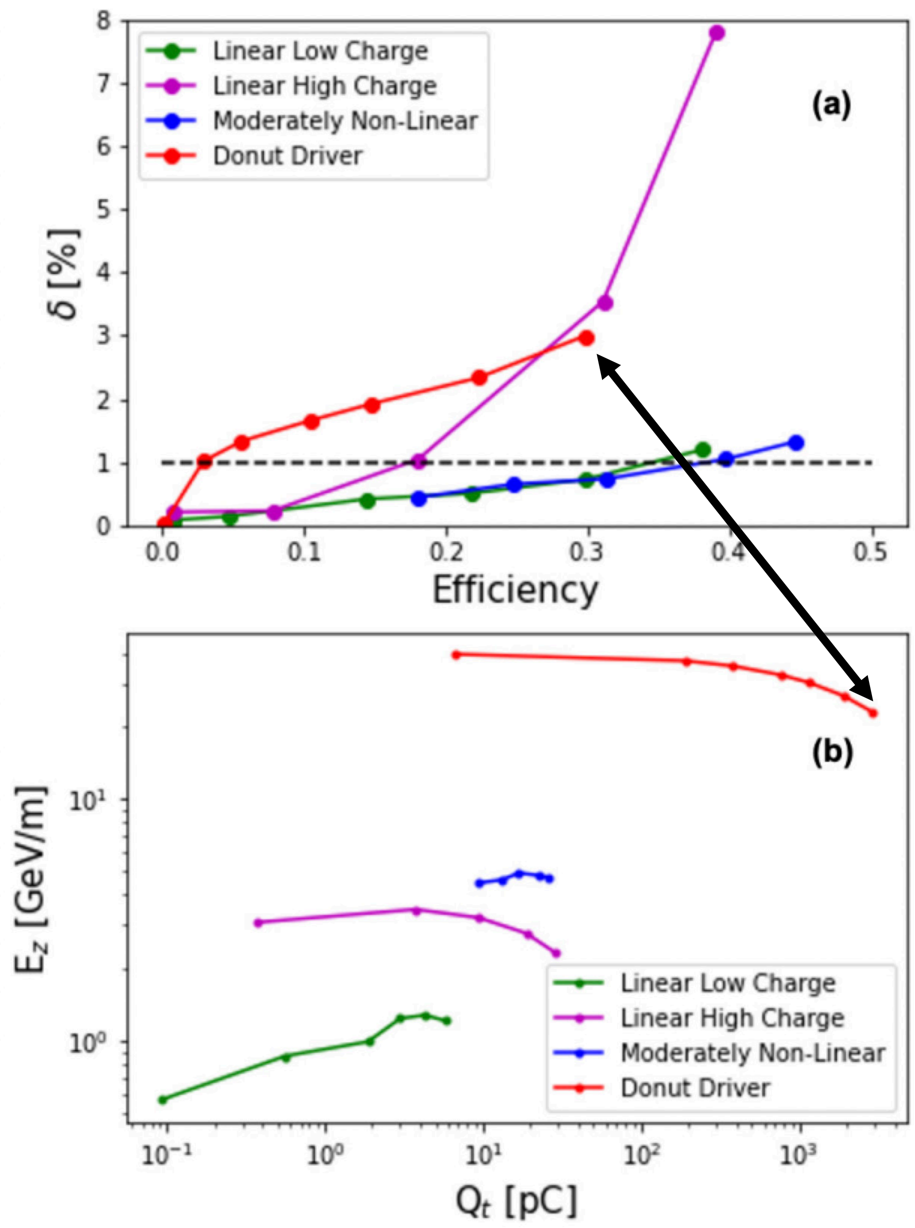
$k_b\sigma_z \cong 0.08$



$k_b\sigma_z \cong 0.8$

Positron regime comparison on common grounds

- Similar trailing e+ parameters with $\sigma_r \cong 1\ \mu$m, $\sigma_z = 2.14\ \mu$m, $\epsilon_N \cong 1$ mm mrad. Drive e- beam $\sigma_z = 16.7\ \mu$m, plasma density = 5E16 cm^{-3} in all regimes.
- 4 parameters scanned over a similar range compared at the same time.
- Planning to add the finite radius plasma column into the comparison (Viktoriia Zakharova)



Summary

- Accelerating positrons in plasma with good efficiency and quality is essential for a linear e+e- collider using plasma acceleration.
- There have been many ideas on e+ acceleration regimes in plasma.
- Comparing these regimes on common grounds will help us understand better and identify the most feasible/favorable regime going forward.
- At the same time, it is necessary to keep working on low efficiency, high energy spread and severe loading mitigation techniques in existing regimes and/or proposing new regimes, as well as testing them in experimental facilities.

THANKS TO MY CO-AUTHORS AND COLLABORATORS

Celine S. Hue
Sébastien Corde
Erik Adli
Spencer Gessner
Igor A. Andriyash
Alex Knetsch
Mark Hogan

SLAC NATIONAL ACCELERATOR LABORATORY

loa

ENSTA IP PARIS

l'X ÉCOLE POLYTECHNIQUE IP PARIS

UiO : University of Oslo