Energy Recovery for Plasma-based Positron Acceleration

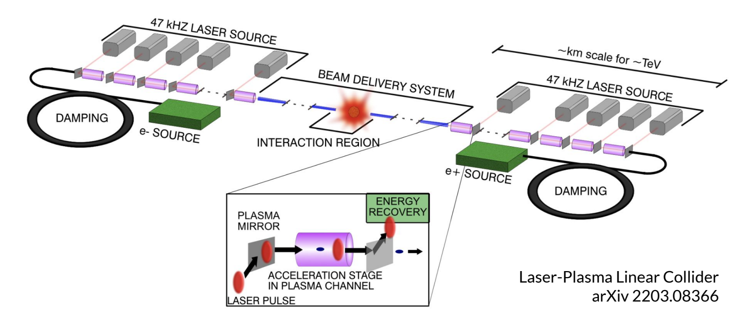
Max Varverakis, Robert Holtzapple, CalPoly
Carl Schroeder, LBNL
Severin Diederichs, DESY
Valentina Lee, CU Boulder
Spencer Gessner, SLAC

FACET-II Science Workshop

October 19, 2023

The HEP community aims for the 10 TeV Scale

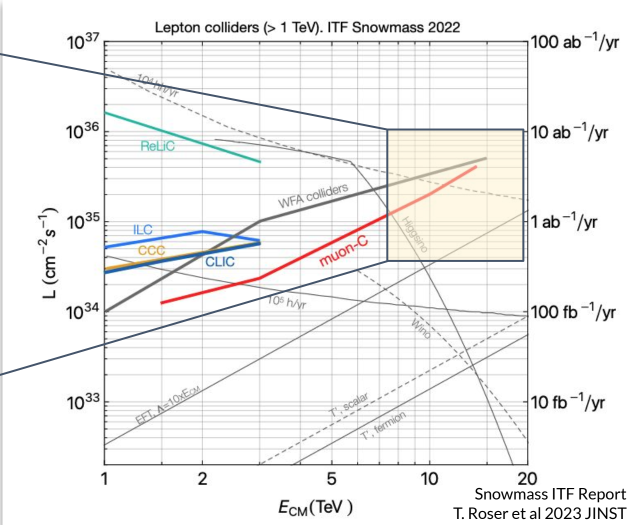
The AAC community is motivated to pursue concepts for an *ultra-high energy linear collider* to meet the needs of the HEP Energy Frontier.



Laser-Plasma Linear Collider
arXiv 2203.08366

Snowmass Energy Frontier Report:

While the naturalness principle suggests new physics to lie at mass scales close to the electroweak scale, in many cases direct searches for specific models have placed strong bounds around 1-2 TeV. Thus, the energy frontier has moved beyond the TeV scale and the exploration of the 10 TeV scale becomes crucial to shed light on physics beyond the Standard Model (SM).



Snowmass ITF Report
T. Roser et al 2023 JINST

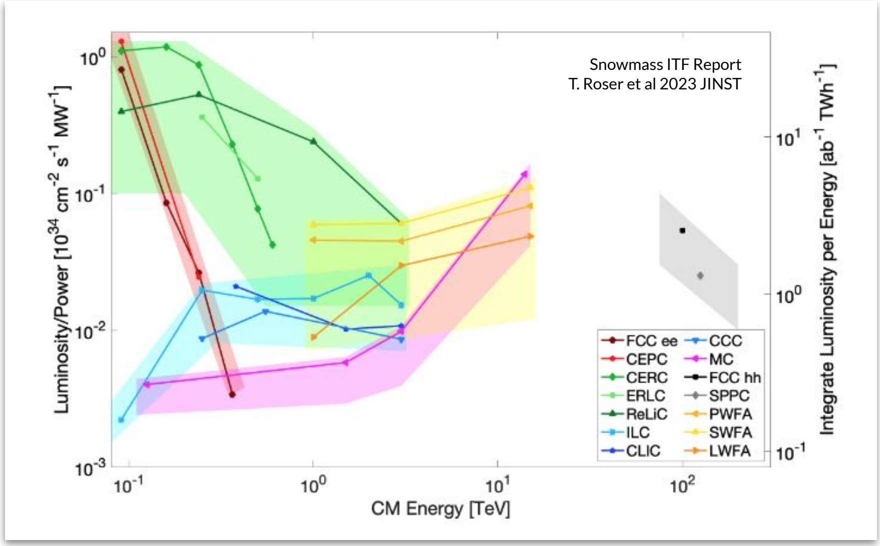
Efficiency is Key

Colliders don't just require high collision energies, they also require large luminosities.

Luminosity-per-beam power is a key figure of merit for collider concepts:

$$\frac{\mathcal{L}}{P_{\text{tot}}} = \frac{\eta N}{4\pi\sigma_x\sigma_y E_b}$$

Efficiency of accelerator



Plasma Acceleration for Linear Colliders

Plasma-based particle acceleration is a promising technology that may enable a compact future linear collider at the TeV scale.*

Progress in beam-driven plasma wakefield acceleration (PWFA) has addressed many challenges towards the realization of a future plasma collider.

However, the task of developing eco-friendly particle colliders has become progressively more challenging as the quest to probe physics at ever-increasing energy levels intensifies.

*Chen et al. arxiv 2009.13672 (2020)

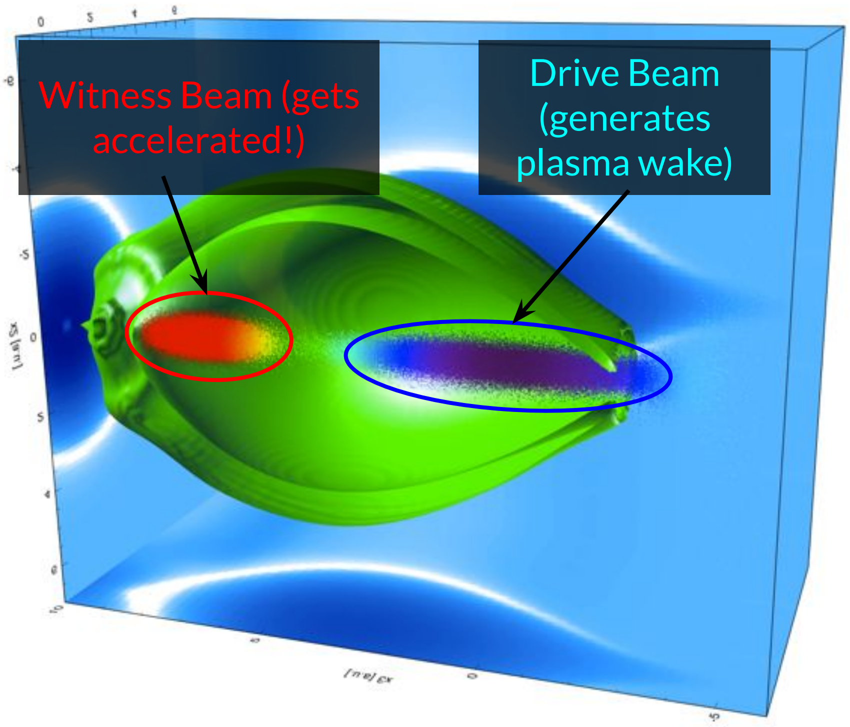


Figure by Frank Tsung (UCLA).

Energy Efficiency Requirements

<u>Input to Snowmass ITF</u>
PWFA efficiency: 37.5%

Chen et al. arxiv 2009.13672 (2020)

It is important to minimize environmental impact of current/future colliders.

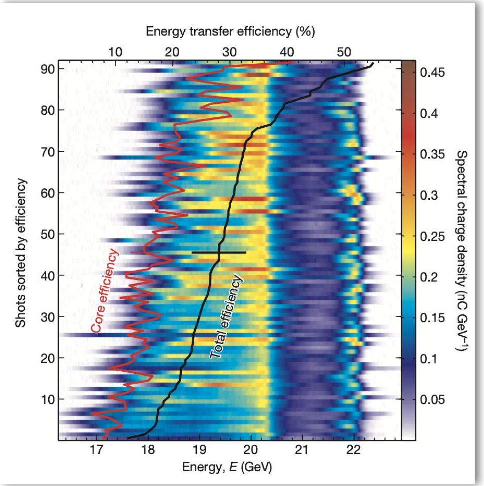
⇒ High efficiency wakefield acceleration is crucial for the realization of a future linear plasma collider.

<u>Key Ingredients for Plasma Collider</u>

- High gradient (multiple GV/m)
- High quality ($\mathcal{O}(10^{-7})$ nm emittance)
- Beam quality preserving (percent-level energy spread)
- Self-stable
- High wall-plug efficiency

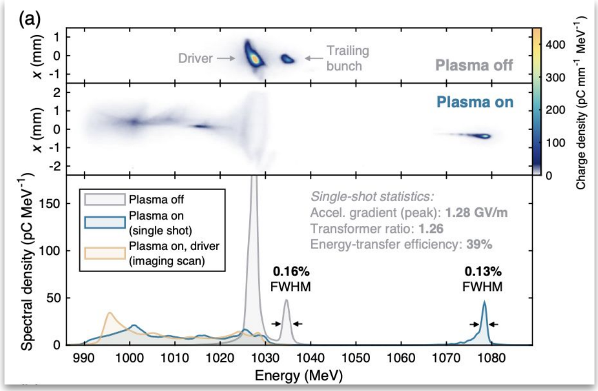
Plasma Acceleration for Electrons

High gradient, high quality, and high efficiency ***electron*** PWFA has been demonstrated experimentally:



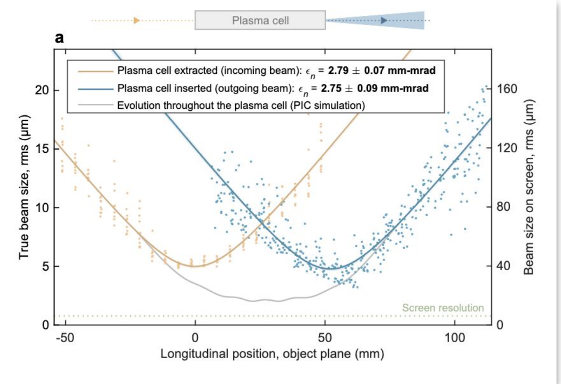
Core Efficiency: 30%

Litos et al, Nature, 515, 92–95 (2014)



Efficiency: 42%

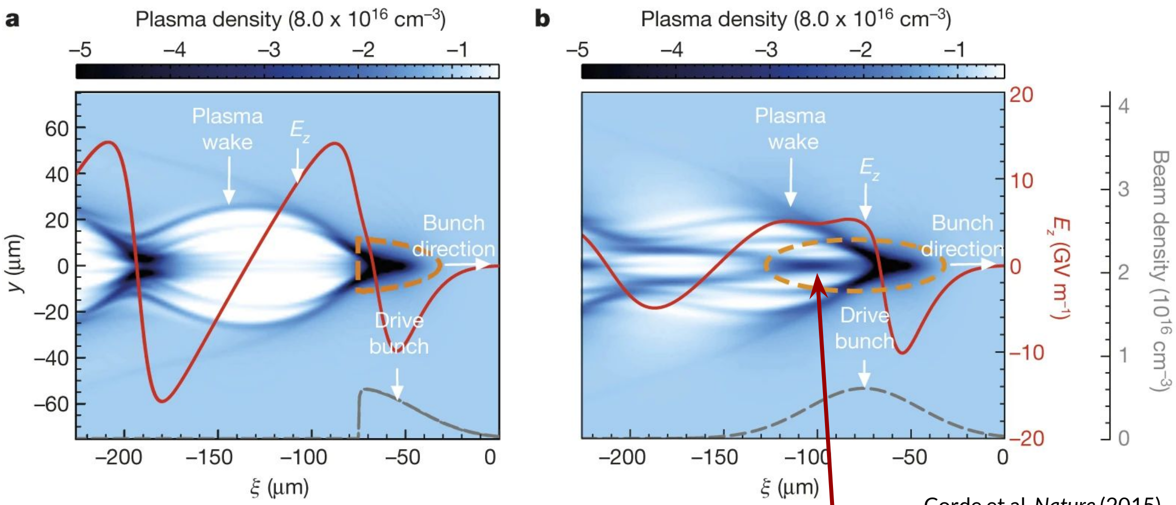
Lindstrøm et al, Phys. Rev. Lett. 126, 014801 (2021)



Emittance Preservation

Lindstrøm et al, Submitted (2022)

Self-Loading Positron Beams in the Non-linear Regime



Corde et al. *Nature* (2015)

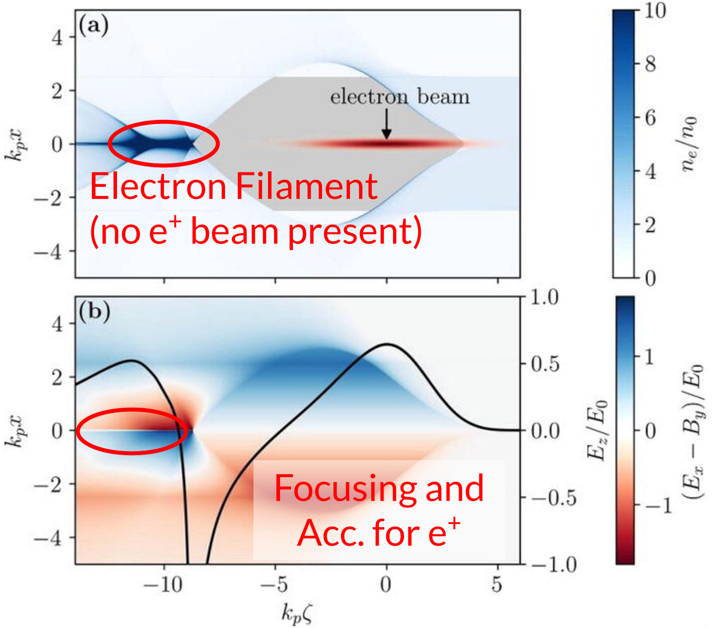
Previous FACET Experiments ⇒

Positron beams can <u>self-load a nonlinear wake</u> and create a focusing region for trailing positron particles.

SLAC

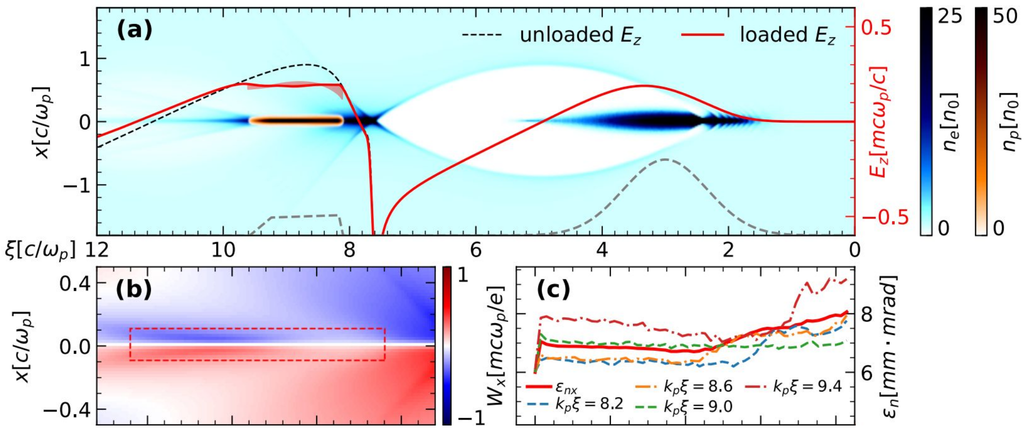
Promising Positron PWFA Developments

Plasma Column Regime



Diederichs et al, Phys. Plasmas. 2023; 30(7).

Uniform Plasma Regime



Zhou et al. arXiv 2211.07962 (2022)

Energy Recovery for Positron PWFA

Energy Recovery in LWFA

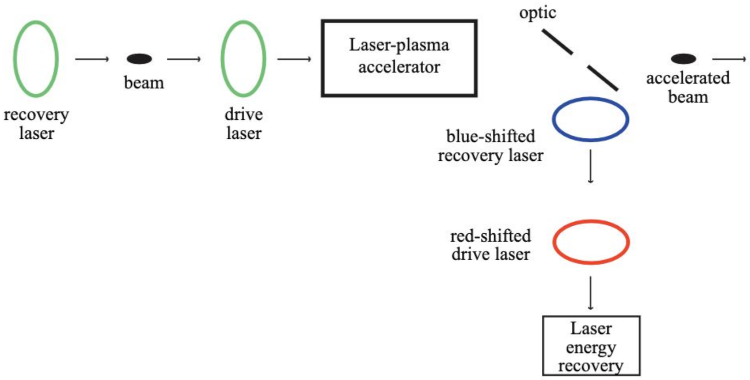
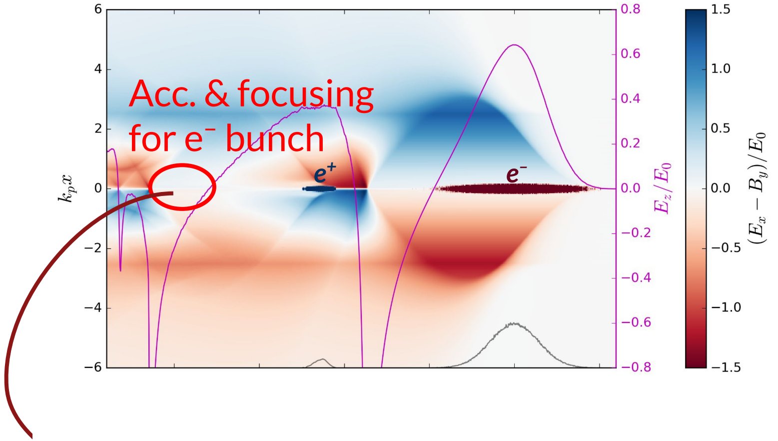


FIGURE 1. Schematic of an LPA stage using laser energy recovery.

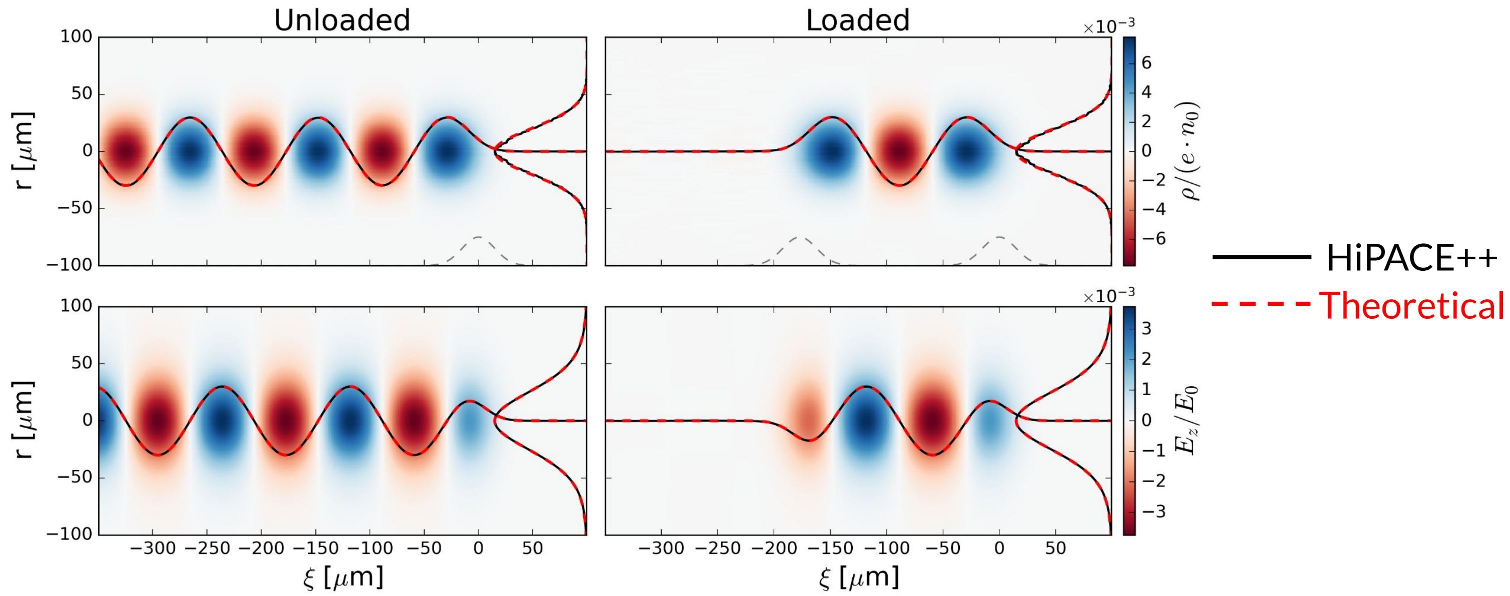
C. B. Schroeder et. al. "Efficiency considerations for high-energy physics applications of laser-plasma accelerators." AIP Conf. Proc. 1777, 020001 (2016)

Positron PWFA Scheme



Linear Regime: Near-100% Energy Recovery

Katsouleas et al. "Beam Loading in Plasma Accelerators", Part. Accel. 22 (1987) → Theoretical approach to beam loading in the linear regime



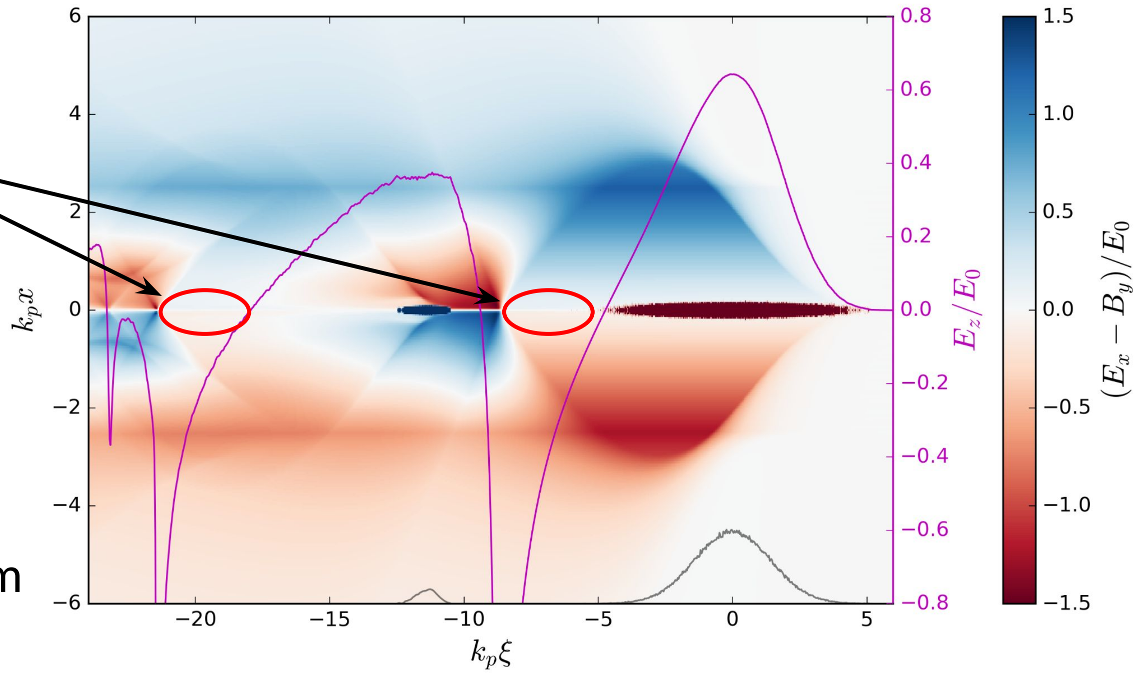
Question: *How well can we do this in the blowout regime for positrons?*

Efficiency Enhancements in the Plasma Column Regime

Two immediate opportunities to attempt energy recovery with a secondary electron bunch

Analyzed three scenarios in **HiPACE++**:

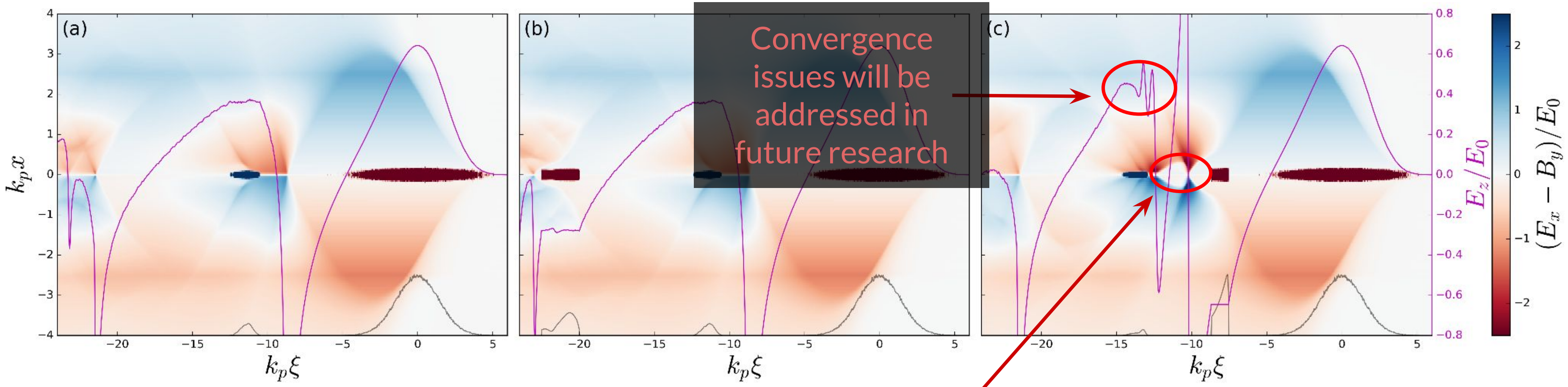
1. No energy recovery
2. Recovery in front of positron witness beam
3. Recovery behind positron beam



We used SALAME algorithm to flatten E_Z field for trailing bunches.

Diederichs et al, Phys. Rev. Acc. Beams 23, 121301 (2020)

Net Increase in Efficiency for Plasma Column Regime



<u>No energy recovery</u>
Efficiency → 3.8%

<u>Recovery beam **behind**</u>
Efficiency → 12.0%

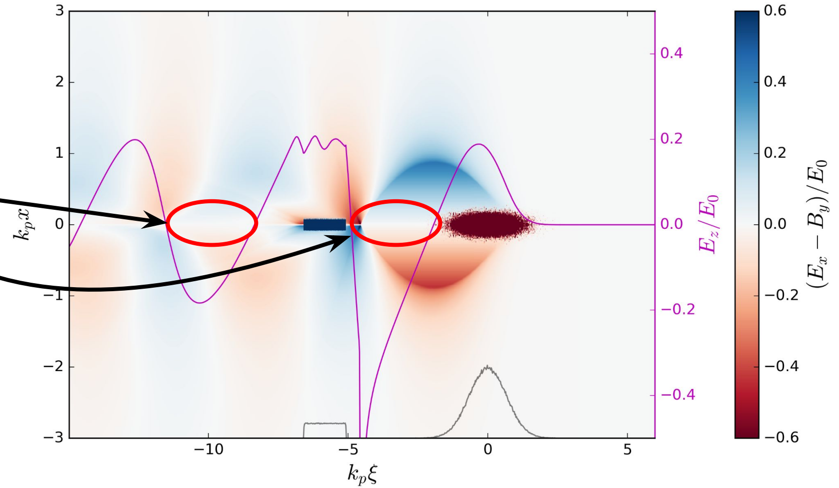
<u>Recovery beam in **front**</u>
Efficiency → 27.4%

Must be cautious about changing optimal positron beam loading

Comparable to **electron** PWFA efficiencies (shown earlier)

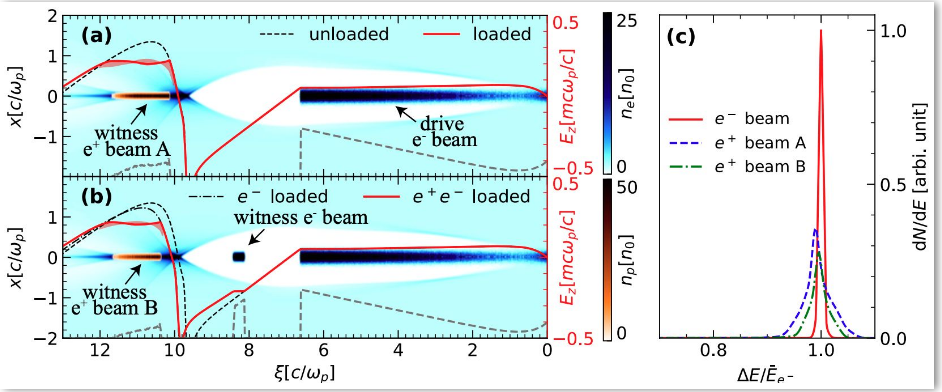
Efficiency Enhancements in Uniform Plasma Regime

Similar approach as in plasma column regime (two spots for electron energy recovery beam)



Analyzed three scenarios in **HiPACE++**:

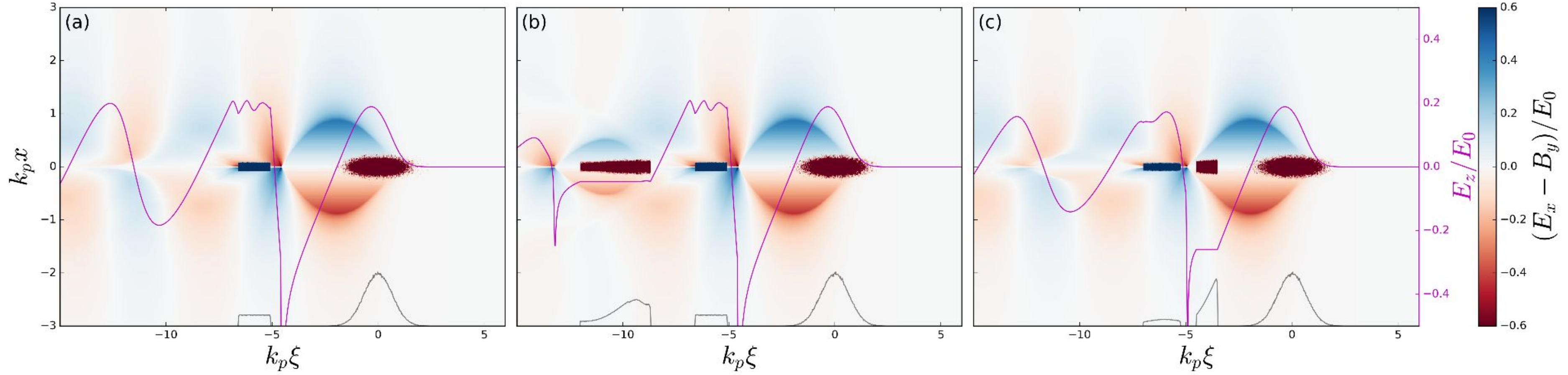
1. No energy recovery
2. Recovery in front of positron witness beam
3. Recovery behind positron beam



*For some bunches, we **did not** use the SALAME algorithm due to convergence issues at low resolutions ⇒ <u>Future work:</u> rerun with *mesh refinement*

Zhou et al. arXiv 2211.07962 (2022)

Uniform Plasma has high extraction efficiency



<u>No energy recovery</u>
Efficiency → 25.9%

<u>Recovery beam **behind**</u>
Efficiency → 45.0%

<u>Recovery beam in **front**</u>
Efficiency → 73.5%

All of these are sufficient!

Efficiency Comparisons

Simulation	(a)	(b)	(c)
$k_p\xi_{p,\mathrm{head}}$	−10.5	−10.5	−12.9
$k_p\xi_{r,\mathrm{head}}$	–	−20.0	−7.6
Q_p [pC]	182	181	64
Q_r [pC]	–	−517	−707
η [%]	3.8	12.0	27.4

Table 1: Trailing beam parameters for plasma column simulations. Subscripts p and r correspond to the positron and electron (recovery) beam, respectively.

Simulation	(a)	(b)	(c)
$k_p\xi_{p,\mathrm{head}}$	−5.1	−5.1	−5.3
$k_p\xi_{r,\mathrm{head}}$	–	−8.7	−3.5
Q_p [pC]	102	102	63
Q_r [pC]	–	−310	−177
η [%]	25.9	45.0	73.5

Table 2: Trailing beam parameters for uniform plasma simulations. Subscripts p and r correspond to the positron and electron (recovery) beam, respectively.

*Highest efficiency for plasma column regime is comparable with baseline efficiency in uniform regime

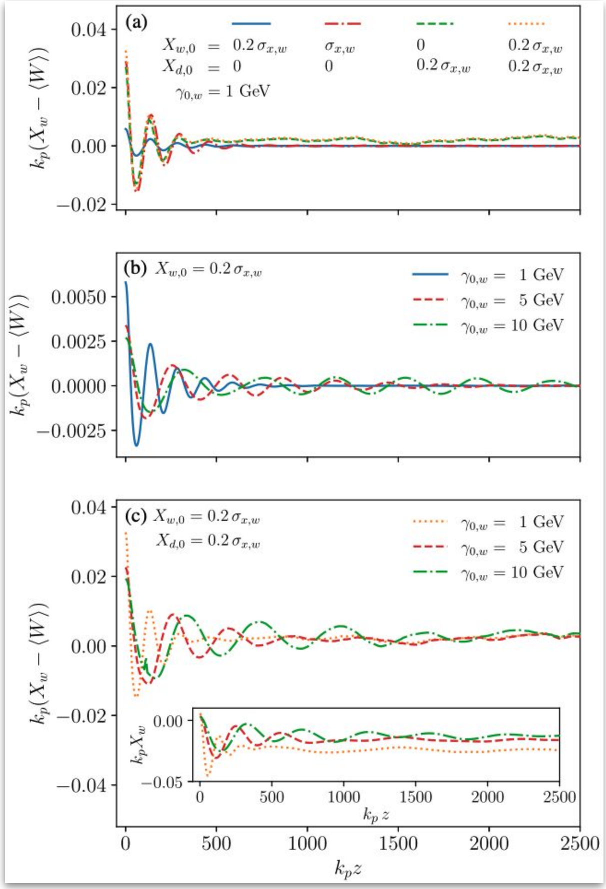
<u>**However:**</u> These recovery schemes must be subjected to beam offsets to determine the holistic benefits in each regime.

Beam Offsets in Plasma Column Recovery Schemes

Initial investigations of electron bunch energy recovery schemes seem promising!

<u>Question:</u> Are these scenarios stable to small beam offsets?

Previous work indicates that the <u>plasma column regime</u> (without energy recovery) is stable under beam misalignments.



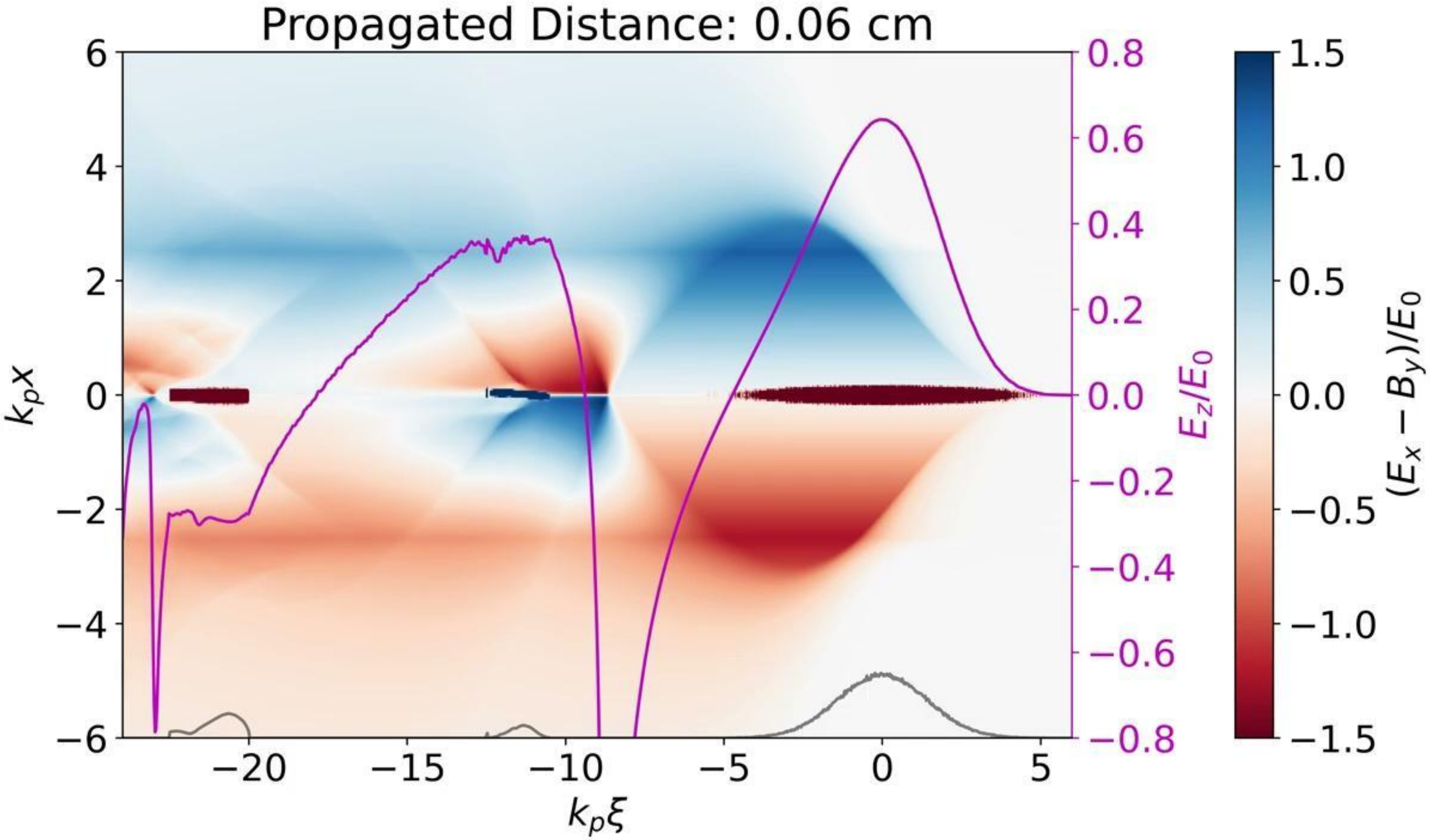
Diederichs et al, Phys. Rev. Acc. Beams 25, 091304 (2022).

SLAC

Positron Beam Offset (Recovery Trailing Positrons)

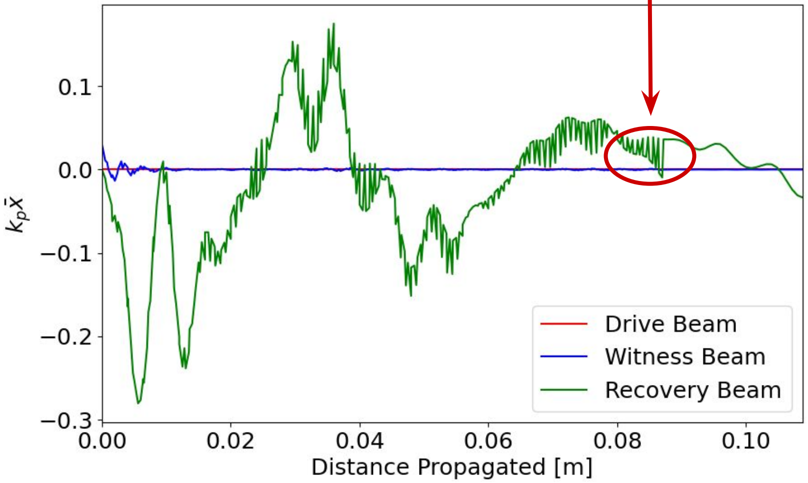
Positron bunch transverse offset by $1\sigma_x$

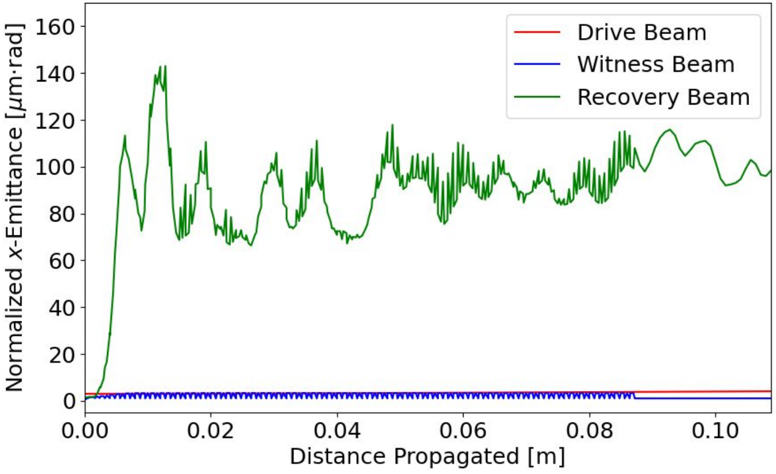
No recovery beam offset



Beam Evolution due to Positron Beam Offset

Unphysical jumps in avg. x-position
(due to simulation boundary)





Next steps for energy recovery simulations

(1) Ensure convergence by:

a. Rerunning with *mesh refinement** to better resolve and flatten the avg. wake around trailing bunches.
b. Increasing the number of macroparticles.
c. Increasing plasma temperature to 50 eV (Talk by S. Diederichs @ 9:45 AM)

* M. Thevenet, EAAC 2023

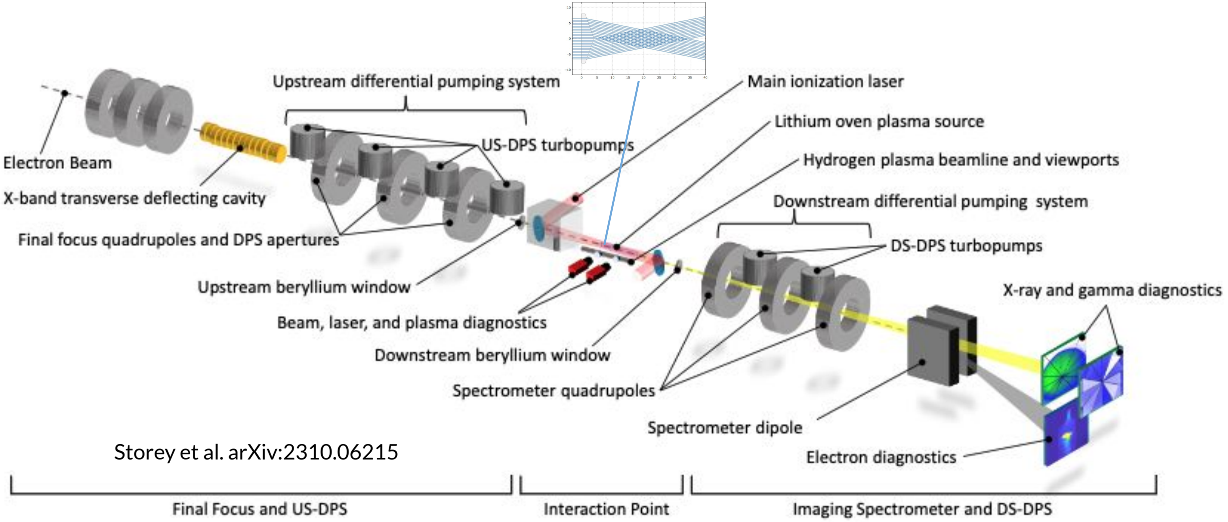
(2) Simulate beam offsets for the remaining energy recovery schemes.

(3) Use tailored drive beam current profiles to further increase efficiencies

(See Fig. 4 in Zhou et al. arXiv 2211.07962 (2022))

The E333 Experiment at FACET-II

Narrow plasma column created by axicon or tandem lens.

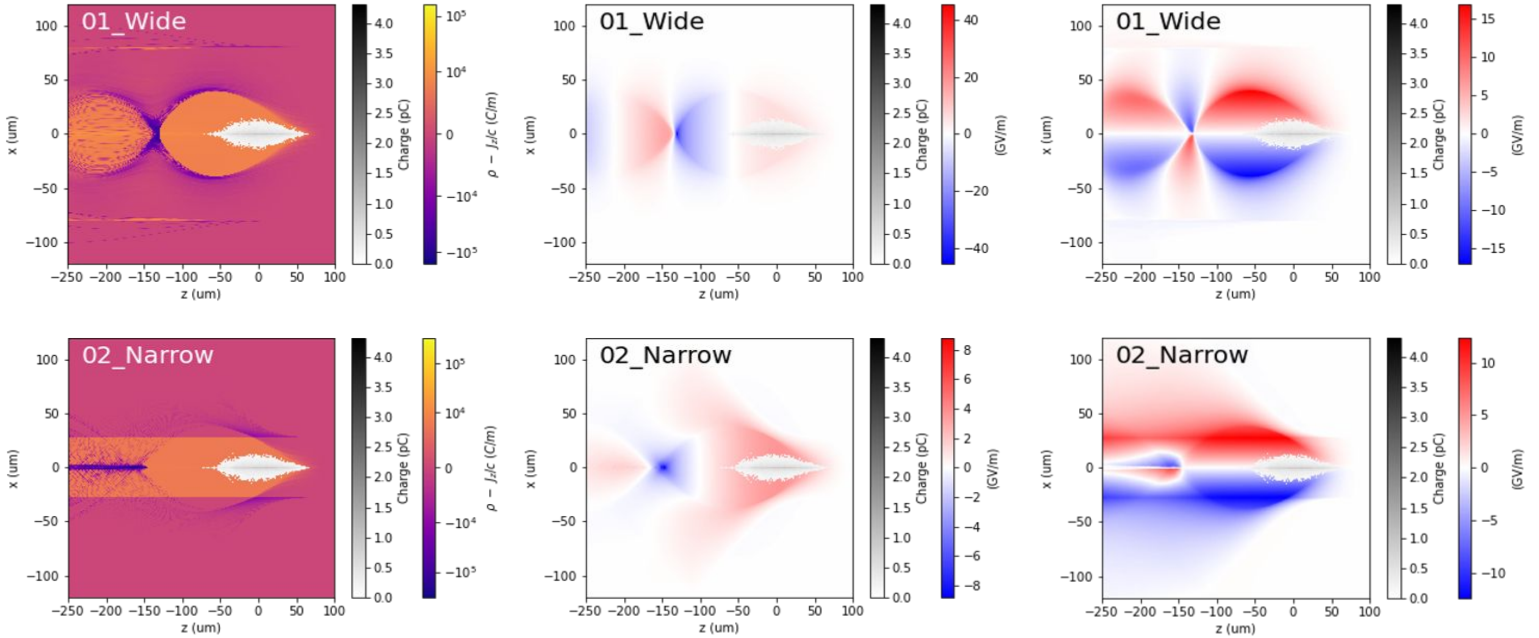


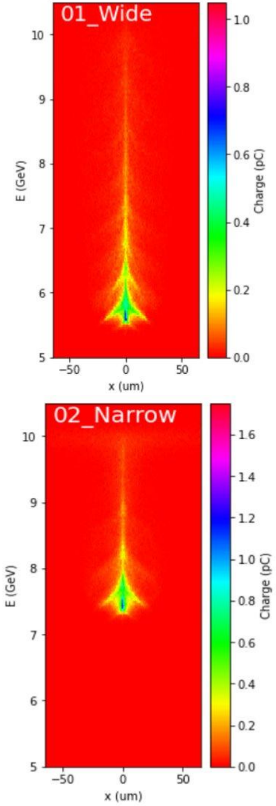
Storey et al. arXiv:2310.06215

E333 Scientific goal: Accelerate a positron beam in an electron beam-driven wake in the plasma column regime.

First Step: **Study the dynamics of the electron beam driver**. The experimental setup is similar to the E301 experiment.

E333 First Step: Single Bunch Experimental Signatures

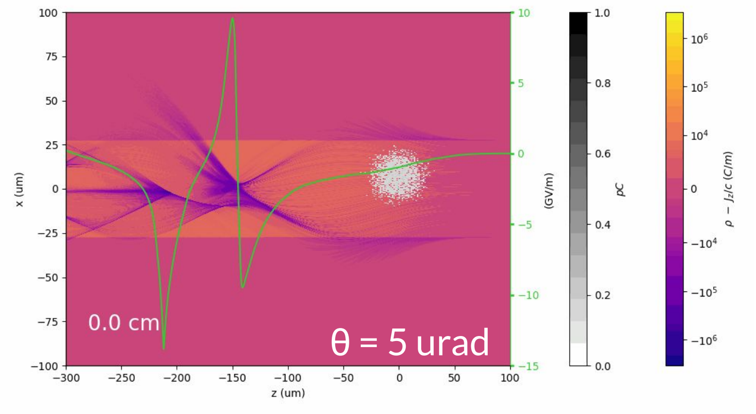


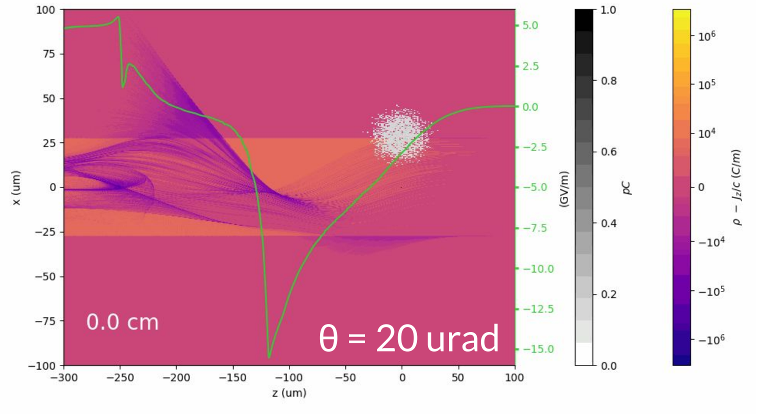


Drive electron beam energy loss is the experimental signature for the single bunch experiment.

V. Lee

E333 First Step: Single Bunch Experimental Signatures





The relative alignment of the drive beam and plasma column is an additional degree of freedom in the experiment. The plasma column provides a guiding force, but the energy and position of the drive beam are affected by the offset and tilt, which can be observed in the experiment.

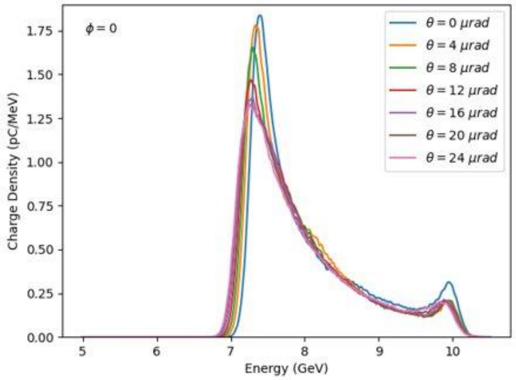
V. Lee

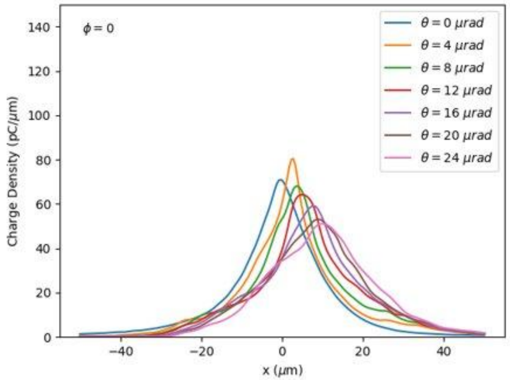
E333 First Step: Drive Beam Misalignments

Energy Spectrum

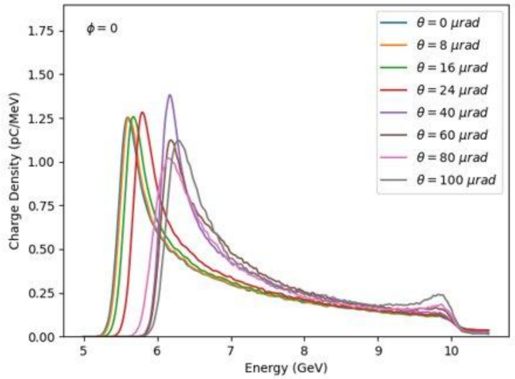
Position

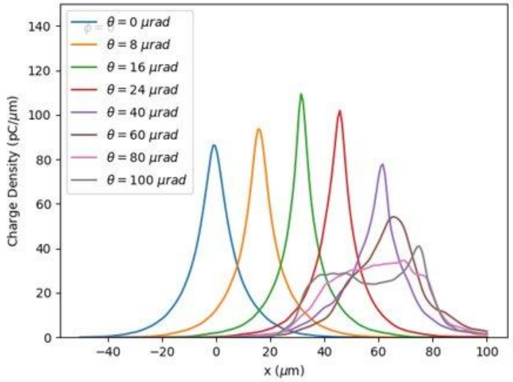
Narrow Plasma PWFA
Plasma Column Regime
Plasma FWHM = 55um





Wide (nominal) plasma
Uniform Regime
Plasma FWHM= 160um





Electron beam guiding by the narrow plasma column is an experimental observable.

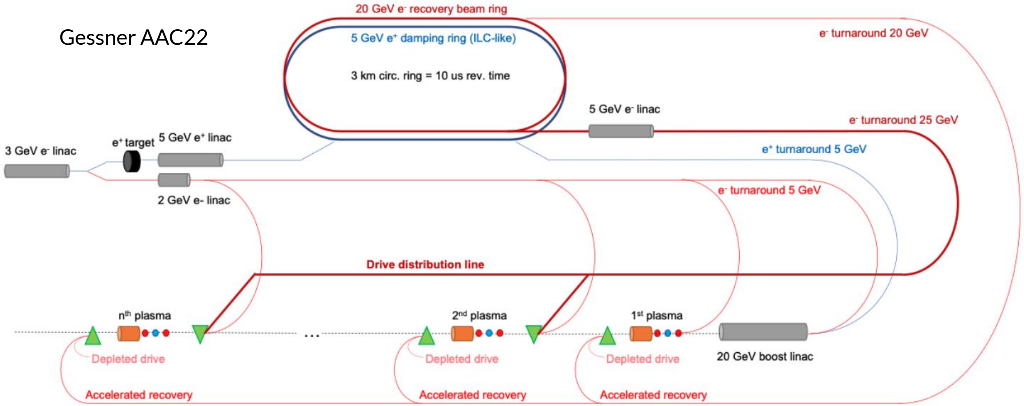
SLAC

V. Lee

Electron Recovery Beams

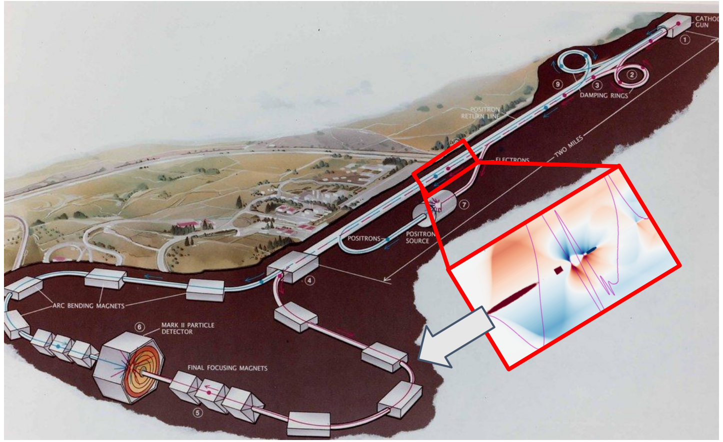
If the acceleration of the electron and positron bunches in the plasma wakefield is successful, what should we do with the electron recovery bunch?

Gessner AAC22



Electron recovery scheme where recovery bunches become drive bunches for subsequent stages.

Challenging beamlines and beam parameters.



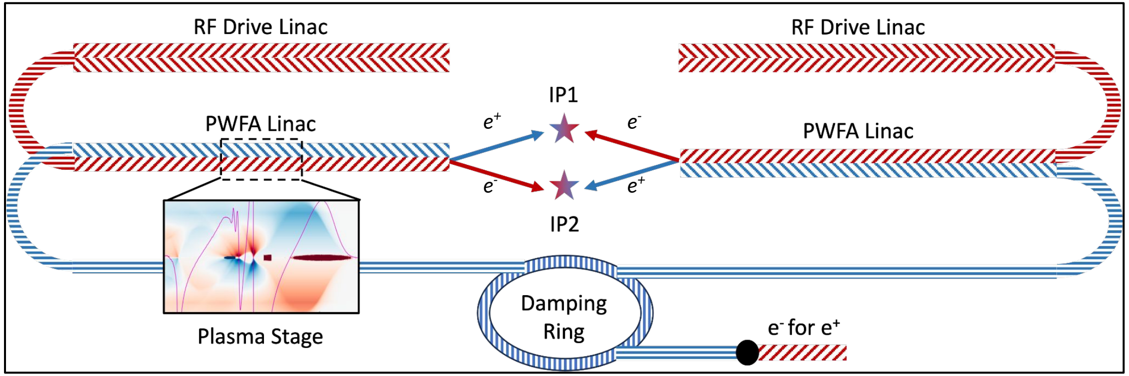
SLC-type collider with a single linac is compact and cost effective.

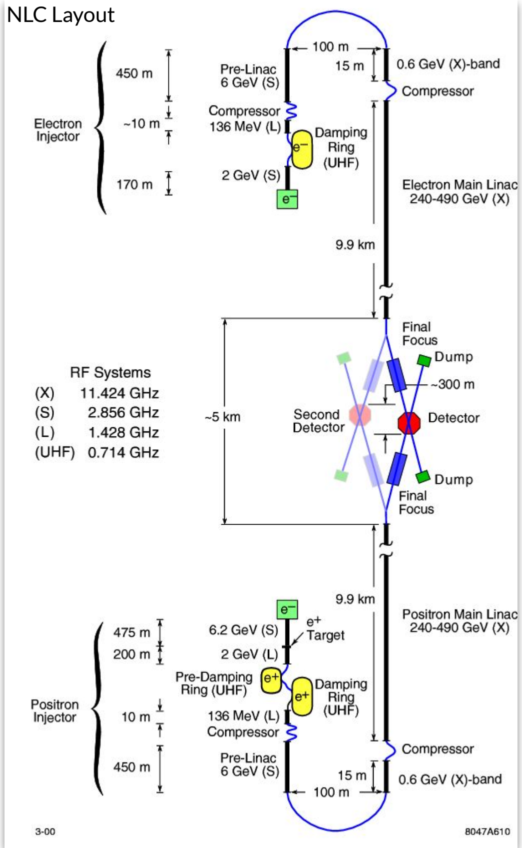
Final arcs do not scale favorably with energy.

A Dual-IP Collider Concept

The NLC collider concept featured two IPs to support two general purpose detectors.

The forked collider concept naturally supports a double IP configuration with positrons from one linac colliding with electrons from the other.





Conclusion and Next Steps

- Initial investigations of electron-driven positron PWFA with energy recovery modifications look promising!
  - Plasma column regime: $\eta = 4\% \rightarrow \eta = 28\%$
  - Uniform plasma regime: $\eta = 26\% \rightarrow \eta = 74\%$

- More simulations are needed.
  - First, repeat baseline simulations with mesh refinement and higher plasma temperature.
  - Second, continue studies of transverse stability with recovery bunches.

- Development of the forked collider concept.
  - Self-consistent beam parameters.
  - Alignment tolerances.
  - Estimates of inter-stage designs.
  - GUINEA-PIG and WarpX simulations of collisions.

SLAC

Thank you!

Plasma Column Simulation Parameters

- Helium Plasma ($n_e = 10^{17}$ cm^{-3})
- Plasma PPC: 400 e^- and 16 ion
- Plasma column radius: 2.5 k_p^{-1}
- Plasma temp: 15 eV
- Drive beam: 10^6 macroparticles, -3.38 nC, bi-Gaussian, 5.11 GeV $\epsilon_{x,y} = 2.96\ \mu\text{m rad}$, $\sigma_{x,y} = 0.05\ k_p^{-1}$ and $\sigma_z = 1.41\ k_p^{-1}$
- Trailing beams: 1 GeV, radially Gaussian,
- Positron beam: $\epsilon_{x,y} = 0.45\ \mu\text{m}$, 1.25 x 10^6 macroparticles, $\sigma_{x,y} = 0.029\ k_p^{-1}$
- Recovery beam: $\sigma_{x,y} = 0.05\ k_p^{-1}$ and $\epsilon_{x,y} = 1.33\ \mu\text{m rad}$, 10^6 macroparticles

Uniform Non-linear Plasma Simulation Parameters

- Helium Plasma (n_e = 7.8x10^{15} cm^{-3})
- Plasma PPC: 25 e^- and 25 ion
- Plasma temp: 0 eV
- All beams: 10^6 macroparticles, 2.5 GeV
- Drive beam: –534 pC, bi-Gaussian, $\sigma_{x,y} = 5\ \mu m$ and $\sigma_z = 40\ \mu m$, $6\ \mu m$ rad
- Trailing beams: Radially Gaussian
- Positron beam: $\sigma_{x,y} = 2\ \mu m$, 2.5 μm rad,
- Recovery beam: $\sigma_{x,y} = 3\ \mu m$, 7.5 μm rad