Energy Recovery for Plasma-based Positron Acceleration

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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.

**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).
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)
Energy Efficiency Requirements

Input to Snowmass ITF
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.

Key Ingredients for Plasma Collider
- High gradient (multiple GV/m)
- High quality ($O(10^{-7})$ 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%

Efficiency: 42%

Emittance Preservation
Lindstrøm et al, Submitted (2022)
Previous FACET Experiments ⇒

Positron beams can self-load a nonlinear wake and create a focusing region for trailing positron particles.
Promising Positron PWFA Developments

**Plasma Column Regime**
- High quality/beam preserving
- Self-stabilizing
- Low efficiency (≤ 5%)

**Uniform Plasma Regime**
- High quality/beam preserving
- High efficiency (35%)


Zhou et al. arXiv 2211.07962 (2022)

Electron Filament (no e^+ beam present)

Focusing and Acc. for e^+

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SLAC
Energy Recovery for Positron PWFA

Energy Recovery in LWFA

Positron PWFA Scheme

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

Linear Regime: Near-100% Energy Recovery


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.

Net Increase in Efficiency for Plasma Column Regime

No energy recovery
Efficiency $\rightarrow$ 3.8%

Recovery beam behind
Efficiency $\rightarrow$ 12.0%

Recovery beam in front
Efficiency $\rightarrow$ 27.4%

Must be cautious about changing optimal positron beam loading

Comparable to electron PWFA efficiencies (shown earlier)

Convergence issues will be addressed in future research
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 ⇒ Future work: rerun with mesh refinement.
Uniform Plasma has high extraction efficiency

No energy recovery
Efficiency → 25.9%

Recovery beam behind
Efficiency → 45.0%

Recovery beam in front
Efficiency → 73.5%

All of these are sufficient!
Efficiency Comparisons

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<th>(c)</th>
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<td>$\eta$ [%]</td>
<td>25.9</td>
<td>45.0</td>
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Table 1: Trailing beam parameters for plasma column simulations. Subscripts $p$ and $r$ correspond to the positron and electron (recovery) beam, respectively.

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

**However:** These recovery schemes must be subjected to beam offsets to determine the holistic benefits in each regime.
Initial investigations of electron bunch energy recovery schemes seem promising!

**Question:** Are these scenarios stable to small beam offsets?

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

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)

(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))
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.
Drive electron beam energy loss is the experimental signature for the single bunch experiment.
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.
E333 First Step: Drive Beam Misalignments

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.
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?

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

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

Challenging beamlines and beam parameters.

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.
Thank you!
Plasma Column Simulation Parameters

- Helium Plasma \( (n_e = 10^{17} \text{ cm}^{-3}) \)
- 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: \(\epsilon_{x,y} = 0.45 \mu\text{m}, 1.25 \times 10^6\) 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 \( (n_e = 7.8 \times 10^{15} \text{ cm}^{-3}) \)
- 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, \(\sigma_{x,y} = 5 \mu\text{m} \text{ and } \sigma_z = 40 \mu\text{m}, \ 6 \mu\text{m rad}\)
- Trailing beams: Radially Gaussian
- Positron beam: \(\sigma_{x,y} = 2 \mu\text{m}, 2.5 \mu\text{m rad}\)
- Recovery beam: \(\sigma_{x,y} = 3 \mu\text{m}, 7.5 \mu\text{m rad}\)