Plasma dechirper for electron/positron beams in plasma based accelerator

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Motivation for a plasma dechirper: the physical picture

Theory and simulation verification

Experimental demonstration of a plasma dechirper
  - Experimental platform
  - Plasma source based on laser ionization
  - Preliminary experimental results
  - Future works
Electron/positron beams with low energy spread at ~ 0.1% level are typically needed for challenging applications like FELs and colliders.

Achievable energy spreads in typical plasma based accelerators (PBA) are currently at ~ 1% level.

Simple methods for reducing the energy spreads from ~ 1% to ~ 0.1% level is highly needed.

Can we do it, and How?
Energy chirp dominates energy spread in PBA

- In PBA, slice energy spreads are mainly determined by injection methods, typically at MeV level or even lower.
- Relatively large acceleration phase span in PBA leads to large energy chirp (approximately linear).

energy chirp reduction $\Rightarrow$ energy spread reduction
A two-steps strategy: divide and conquer

- **first step:** obtaining a stable positively-chirped beam with few percent energy spread
- **second step:** post-processing the beam using a passive dechirper

- a tenuous uniform plasma
- a hollow plasma channel
A sample 3D PIC simulation shows energy spread reduction from \(\sim 1\%\) level to \(\sim 0.1\%\) level or lower.

Energy spread: \(10\,\text{MeV} \rightarrow 0.97\,\text{MeV}\)

\(1\% \rightarrow 0.097\%\)
Two important quantities for a plasma dechirper

- The minimum energy spread achievable

\[ E_{rms\_min} = E_{rms\_init} G \]

- The plasma length for this minimum energy spread

\[ d = \frac{\Delta E}{|qE_{z\_tail}|} X \]

G and X are two geometrical factors determined by beam profile.
Theoretical formulas for G and d

- G and d can be calculated based on the linear wakefield theory \[1\]

\[
Z'(\xi) = -4\pi \int_{-\infty}^{\xi} d\xi' \rho_{\parallel}(\xi') \cos k_p (\xi - \xi') \\
R(r) = \frac{k_p^2}{2\pi} \int_{0}^{2\pi} d\theta \int_{0}^{\infty} r' dr' \rho_{\perp}(r') K_0(k_p |\vec{r} - \vec{r}'|)
\]

- Longitudinal flat-top, transverse flat-top profile \(\rho_{\parallel}(\xi) = qn_b \Theta(\xi) \Theta(L - \xi), \rho_{\perp}(r) = \Theta(a - r)\)

\[
G_{ff} = \frac{2C}{\sqrt{48 - 24C + 7C^2}} \\
d_{ff} = \frac{2\sqrt{3} \times E_{\text{rms} - \text{init}}}{m c \omega_p n_b k_p L \times R(0)} \times \frac{48 - 12C}{48 - 24C + 7C^2}
\]

- Longitudinal flat-top, transverse parabolic profile \(\rho_{\parallel}(\xi) = qn_b \Theta(\xi) \Theta(L - \xi), \rho_{\perp}(r) = 1 - \frac{r^2}{b^2}\)

\[
G_{fp} = \sqrt{\frac{640(k_p b)^4 D^2 - 1024(k_p b)^4 D + 412(k_p b)^4}{960(k_p b)^4 D^2 - 7680(k_p b)^2 D^2 + 46080D^2 - 1584(k_p b)^4 D + 6720(k_p b)^2 D + 657(k_p b)^4}} D = R(0)
\]

\[
d_{fp} = \frac{2\sqrt{3} \times E_{\text{rms} - \text{init}}}{m c \omega_p n_b k_p L \times R(0)} \times \frac{(640D^2 - 1056D + 438)(k_p b)^4 - 480(8D^2 - 7D)(k_p b)^2 + 15360D^2}{(320D^2 - 528D + 219)(k_p b)^4 - 320(8D^2 - 7D)(k_p b)^2 + 15360D^2}
\]

Verification by PIC simulations

3D PIC simulation of a flat-top electron beam

<table>
<thead>
<tr>
<th>electron beam</th>
<th>energy</th>
<th>1 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy spread</td>
<td>10 MeV (RMS)</td>
<td></td>
</tr>
<tr>
<td>beam density</td>
<td>2.4×10^{18} cm^{-3}</td>
<td></td>
</tr>
<tr>
<td>peak current</td>
<td>2.5 kA</td>
<td></td>
</tr>
<tr>
<td>pulse duration</td>
<td>L = 5.0 um</td>
<td></td>
</tr>
<tr>
<td>transverse size</td>
<td>a = 2.85 um</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>plasma</th>
<th>density</th>
<th>3.0×10^{16} cm^{-3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>16.55 mm</td>
<td></td>
</tr>
</tbody>
</table>

energy spread:

10 MeV → 0.86 MeV
1% → 0.086%
G and d: theory vs simulation

\[ b = \sqrt{2a} \]

<table>
<thead>
<tr>
<th>beam current</th>
<th>beam density</th>
<th>transverse size</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 kA</td>
<td>$2.4 \times 10^{18} \text{cm}^{-3}$</td>
<td>$a = 2.85 \text{um}$</td>
</tr>
<tr>
<td>5.0 kA</td>
<td>$2.4 \times 10^{18} \text{cm}^{-3}$</td>
<td>$a = 3.80 \text{um}$</td>
</tr>
<tr>
<td>7.5 kA</td>
<td>$2.1 \times 10^{18} \text{cm}^{-3}$</td>
<td>$a = 5.07 \text{um}$</td>
</tr>
<tr>
<td>10.0 kA</td>
<td>$1.8 \times 10^{18} \text{cm}^{-3}$</td>
<td>$a = 6.33 \text{um}$</td>
</tr>
</tbody>
</table>

Agree very well!
Energy spread evolution for the beams with different density profiles

<table>
<thead>
<tr>
<th></th>
<th>longitudinal profile</th>
<th>transverse profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFTF</td>
<td>flat-top</td>
<td>flat-top</td>
</tr>
<tr>
<td>LFTP</td>
<td>flat-top</td>
<td>parabolic</td>
</tr>
<tr>
<td>LFTG</td>
<td>flat-top</td>
<td>gaussian</td>
</tr>
<tr>
<td>LGTG</td>
<td>gaussian</td>
<td>gaussian</td>
</tr>
</tbody>
</table>

10MeV $\rightarrow$ 2.6MeV
1% $\rightarrow$ below 0.3%
Emittance growth in a dechirper

Projected emittance growth caused by longitudinally varied transverse focusing field \( \rightarrow \) phase space mismatch

\[
-e(E_x - cB_y) \text{ [GeV/m]}
\]

\[
\begin{align*}
\xi & [\mu m] \\
x & [\mu m]
\end{align*}
\]

transverse focusing field

\[
\begin{align*}
\epsilon_n & [\mu m] \\
z & [\text{mm}]
\end{align*}
\]

normalized emittance

quasi-match \( \rightarrow \) 10~20\% normalized emittance growth for \( \sim \) um emittance
Solution for reducing emittance growth: A hollow channel plasma dechirper

- Transversely uniform $E_z \rightarrow$ zero slice energy spread increase
- Zero transverse focusing force within the channel $\rightarrow$ negligible emittance growth

Methods for hollow plasma channel creation have been actively explored and demonstrated [1]

Simulation verification

The linear energy chirp can be totally removed without slice energy spread increase for a flat-top current profile:

- **electron beam**
  - energy: 1 GeV
  - energy spread: 10 MeV (RMS)
  - beam density: $2.4 \times 10^{18} \text{cm}^{-3}$
  - peak current: 2.5 kA
  - pulse duration: $L = 5.0 \text{ um}$
  - transverse size: $a = 3.8 \text{ um}$

- **plasma**
  - density: $3.0 \times 10^{16} \text{cm}^{-3}$
  - length: 10.6 mm
  - inner radius: $r_c = 20 \text{ um}$
  - outer radius: $r_w = 50 \text{ um}$

**energy spread:**

$10 \text{MeV} \rightarrow 0.075 \text{MeV}$

$1\% \rightarrow \text{below } 0.01\%$
Advanced Acceleration platform at THU

30 TW laser + 45 MeV Linac
Experimental layout for plasma dechirper

Beam diagnostics

energy spectrometer resolution: 2.3 keV @ 41.5 MeV
Plasma source based on laser ionization

Laser ionization ($\text{H}_2+\text{He}$, ionizes the first electron of H)

Mixture gas: He + H2 (1%, 0.1%, 0.01%)

Ionization laser: 800nm, ~3.5mJ (on target), ~30fs, 110um (FWHM)

<table>
<thead>
<tr>
<th>Plasma parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma density</td>
</tr>
<tr>
<td>Plasma length</td>
</tr>
<tr>
<td>Plasma diameter</td>
</tr>
</tbody>
</table>

Gas jet

Ionization laser focal spot
A positive linear energy chirp is imposed on the electron beam by off crest acceleration (25 deg) in the Linac.

The electron beam is weakly compressed by an Chicane from ~ 1 ps to ~ 300 fs (RMS).

<table>
<thead>
<tr>
<th>electron beam parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>transverse size</td>
</tr>
<tr>
<td>bunch length</td>
</tr>
<tr>
<td>charge</td>
</tr>
<tr>
<td>peak current</td>
</tr>
<tr>
<td>mean energy</td>
</tr>
</tbody>
</table>

Longitudinal phasespaces before and after Chicane (simulated by ASTRA)

Beam waist profile
Beam energy spectrum without plasma

Beam energy profiles of 10 shots without plasma

standard deviation
Beam energy spectrum with plasma

Experimental results

3D simulation results via OSIRIS

0.5 MeV $\rightarrow$ 0.4 MeV (FWHM)

1.20% $\rightarrow$ 0.96%

without plasma

with plasma
Current limitation of the preliminary experiment

low current

large beam size → low beam density → low decelerating gradient
two possible methods to optimize further experiments

- with a longer plasma

<table>
<thead>
<tr>
<th>Plasma density</th>
<th>~5.0e14 cm⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma length</td>
<td>50mm</td>
</tr>
</tbody>
</table>

beam energy spectrum with/without plasma

0.5MeV  ➔  0.4MeV (FWHM)
1.20%  ➔  0.24%

3D simulation results via OSIRIS
two possible methods to optimize further experiments

- with a higher beam current and smaller beam size $\Rightarrow$ increase beam density

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>transverse size</td>
<td>$\sigma_r=\sim40\text{um}$</td>
</tr>
<tr>
<td>bunch length</td>
<td>$\sigma_z=\sim300\text{fs}$</td>
</tr>
<tr>
<td>charge</td>
<td>$\sim60\text{pC}$</td>
</tr>
<tr>
<td>peak current</td>
<td>$\sim80\text{A}$</td>
</tr>
<tr>
<td>mean energy</td>
<td>41.5MeV</td>
</tr>
</tbody>
</table>

3D simulation results via OSIRIS

Beam energy spectrum with/without plasma

- 0.5MeV $\Rightarrow$ 0.4MeV (FWHM)
- 1.20% $\Rightarrow$ 0.24%
We propose to use a plasma dechirper to reduce the linear energy chirp of electron/positron beam from PBA.

A theoretical model is developed to obtain the minimum energy spread achievable and the plasma dechirper length for different bunch profiles, and verified using full 3D PIC simulations.

Experimental result of energy-chirp reduction at THU is presented, which is a preliminary proof of this method.
THANK YOU!