Energy-chirp compensation in plasma

ATF proposal

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Main goal: generate beams from a plasma wakefield accelerator of sufficient quality to show FEL gain at few nm.
a 1 GeV beam-driven plasma wakefield accelerator facility
Plasma accelerators operate off-crest, produce chirped beams
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- Negative chirps are characteristic for unloaded beam-driven wakefield accelerators

> Beam loading may be difficult to control + influence other beam properties, e.g. slice energy spread, transverse emittance

> Independent way of beam dechirping would be desirable

Wakefield-based beam dechirper techniques have been proposed and demonstrated


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- Beam wakefields in the pipe are dechirping

- Compensate energy chirps at a few 10 MeV/mm within meters
- Beams from plasmas feature chirps of 10 GeV/mm

Simulations by P. Emma
Chirp complicates beam transport and applications

Beams at plasma exit:
- ~% level energy spread
- small beta function, mrad divergence

Leads to transverse emittance growth in free drift
\[ \varepsilon_n^2 \approx \langle \gamma \rangle^2 \cdot (\sigma_E^2 \sigma_\chi^4 s^2 + \varepsilon^2) \]

Chirp may degrade performance in applications, e.g. FELs

In-plasma energy chirp compensation is desirable
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Transverse emittance growth

![Graph showing transverse emittance growth with in-plasma and typical chirp compensation.](image)

- $E = 1.5 \text{ GeV}$, $\sigma_E = 1\%$, $\epsilon_{n,0} = 0.5 \mu\text{m rad}$
Proposal: a plasma-based dechirper

- utilize wakefield slope and focusing properties generated by beam itself driving a plasma wake

- for energy chirp compensation: $6 \cdot \sigma_z \lesssim \frac{\lambda_p}{4}$
Step 1: demonstrate the basic idea of plasma dechirping

Proposed experiment at the ATF: utilise chirped electron beam to self-dechirp in a plasma wakefield

Electron beam requirements
- monotonically changing, increasing energy from head to tail
- an energy bandwidth of $\geq 1\%$ rms
- sufficient current density to drive a wakefield

> measure energy spread as a function of bunch charge and plasma density
PIC simulations show feasibility - Case A

Beam parameters

- $E = 70 \text{ MeV}$
- $\Delta E = 2.35\% \text{ FWHM}$
- $\sigma_x,\sigma_y = 50 \mu\text{m}$
- $\sigma_z = 150 \mu\text{m}$
- $I = 122 \text{ A}$
- $\varepsilon_{x,y} = 1 \mu\text{m}$
- $Q = 150 \text{ pC}$

Plasma parameters

- $n_0 = 1 \times 10^{14} \text{ cm}^{-3}$
- $d = 99 \text{ mm}$
- box-profile

- conservative ATF parameters
- projected FWHM energy spread reduced from 2.35\% to 0.38\%, reduced by factor of $\sim 6$
- length of plasma exceeds current capabilities of ATF plasma cell ($\sim 20 \text{ mm}$)
PIC simulations show feasibility - Case B

T. Mehrling et al., Plasma Phys Control Fusion 56, 084012 (2014)

Beam parameters

\( E = 70 \text{ MeV} \)
\( \Delta E = 2.35\% \text{ FWHM} \)
\( \sigma_{x,y} = 50 \mu m \)
\( \sigma_z = 34 \mu m \)
\( I = 517 \text{ A} \)
\( \varepsilon_{x,y} = 1 \mu m \)
\( Q = 150 \text{ pC} \)

Plasma parameters

\( n_0 = 2 \times 10^{15} \text{ cm}^{-3} \)
\( d = 5 \text{ mm} \)
box-profile

- optimistic (realistic?) ATF parameters
- projected FWHM energy spread reduced from 2.35% to 0.35%, reduced by factor of ~6
- length of plasma compatible with current ATF plasma cell
PIC simulations show feasibility - Case B

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Outlook and step 2: integrate dechirper into plasma accelerator
(at future facilities ATF II, FACET II, FLASHForward, …)
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Generated wakefields at $3.0 \times 10^{19}$ cm$^{-3}$

- Witness beam drives resonant wake
- Driver far out of resonance

1.2 $\times 10^{18}$ cm$^{-3}$

14.6 mm
Outlook and step 2: integrate dechirper into plasma accelerator (at future facilities ATF II, FACET II, FLASHForward, …)

Generated wakefields at $3.0 \times 10^{19} \text{ cm}^{-3}$

- Witness beam drives resonant wake
- Driver far out of resonance

Witness beam after 0.95 mm:
$\sigma_z = 7 \mu\text{m}, \varepsilon_{x,y} = 1 \mu\text{m}, I_B = 10 \text{kA}, Q = 574 \text{ pC}, E = 1 \text{ GeV}$

- Drive beam:
  $\sigma_z = 0.23 \mu\text{m}, \varepsilon_{x,y} = 10.3 \mu\text{m}, I_B = 5 \text{kA}, Q = 32 \text{ pC}, E = 2.5 \text{ GeV}$

Witness beam:
FWHM energy spread 129.6 MeV, 5.1%
Summary

- Large energy spread complicates emittance preservation of beams from plasma wakefield accelerators during transport
- Chirp needs to be minimized before beam leaves plasma, classical dechirping schemes do not help
- Proposal: utilize self-generated wakefields in plasma for beam dechirping
  - Step 1: demonstrate proof-of-principle in existing ATF setup
  - Step 2: integrate dechirper section into plasma-wakefield accelerator at ATF II, FACET II, FLASHForward

- Experiment at ATF
  - Generate and characterize linearly chirped beams, X-band TDS would be of great benefit
  - Make beams drive wakes in plasma, scan charge and plasma density, measure beam spectrum after plasma
  - Should work with existing ATF equipment, asked for 100 hours of beam time

- Minimizing the energy spread is a key challenge for applications