Adiabatic Plasma Lens Experiments at SPARC

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Abstract

• Plasma lenses in the underdense regime have been shown to give extremely strong linear focusing, with strength proportional to the local plasma ion density. This technique has been proposed as the basis of an scheme for future linear colliders that mitigates the Oide effect through adiabatic focusing. In this scenario the plasma density in the lens is ramped slowly on the scale of betatron motion, to funnel the beam to its final focus while forgiving chromatic aberrations.

• We present the physics design of an adiabatic plasma lens experiment to be performed at SPARC_LAB.
  – We illustrate the self-consistent plasma response and associated beam optics for both symmetric and asymmetric beams in plasma, simulated by QuickPIC using density profiles obtained from experiment.
  – We discuss experimental plans including plasma source development and betatron-radiation-based beam diagnostics.
Adiabatic Plasma Lens for Linear Collider Final Focus

- Plasma collider accelerator at 10 GeV/m is 100’s of m long
- Advanced linear final focus design ~ 2km long for chromatic aberration correction
- Limited also by Oide effect – radiation in final quads
- Need two things:
  - Stronger focusing
  - *Adiabatic* focusing
- Use plasmas!

Raimondi and Seryi, PRL 86 3779 (2001)
The PWFA Underdense “Blowout” Regime


- Beam much denser than plasma \( n_b >> n_0 \)
- Very nonlinear plasma waves
  - Plasma electrons exit beam channel
- “Linear” wakefields, stable beam propagation
- \( E_z \) (accel) constant in \( r \) (EM wave)
  - Focusing linear in \( r \) (ES ion field)

Plasma wake \( (E_z) \) w: radial dependence of fields in beam region. Linear in \( r \)!
Guiding in a Blowout Regime PWFA

• Match beam to focusing
  – Exploit finite ramp
• Measurements challenging
• 1st streak camera -> now RF deflector

The underdense lens case

• Would like to focus *without* longitudinal wakes; transverse effects dominant
• The conditions of interest are
  \[ n_b >> n_0 \quad k_{p_r} < 1 \quad k_{p_z} > 2 \]
• Similar to PWFA but with longer beam, higher charge
  – Ex: Q=600 pC, \( \tau = 600 \) fsec (400 A). “Full beam”
  – Plasma densities controls equilibrium beta...
Blowout regime focusing: underdense thin plasma lens

- Use as thin lens (non-equilibrium case)
- “Mismatch” beam size to focusing in plasma
- Remove most aberrations of linear focusing regime if

\[ n_b > n_0 / 2 \]

The beam area is reduced by a factor of 22. Equivalent to *luminosity enhancement*

Also demonstrated:
- \( t \)-dependent focusing
- focusing w/*asymmetric beam* for LC

*M.C. Thompson, et al., Phys. Plasmas, 17, 073105 (2010)*
Adiabatic plasma lens

• Use adiabatically increasing focusing strength through ramping density slowly

\[ k^2(z) = 2 \frac{r_e n_0(z)}{e} = \frac{K_p(z)}{2} \]

• This define a quasi-equilibrium $\beta\varepsilon\tau\alpha$-function

\[ q_{eq}(z) \quad k^1(z) \]

when the change is slow enough...

\[ L_s \quad n_0(z) / n_0(z) \gg q_{eq}(z) \]

• Mitigates synchrotron energy loss aberrations

Ramped focusing with strong aberrations, a bit like a Winston-cone in optics
Adiabatic plasma lens at SPARC

• Path to compact linear collider final focus
  – Mitigate Oide effect
  – Open the door to plasma compensation of beam-beam interaction?

• Collaboration on plasma source
  – Filippi, LNF; Zigler, Hebrew Univ.

• Experimental team/infrastructure at SPARC
<table>
<thead>
<tr>
<th>Beam parameters for simulation</th>
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<tbody>
<tr>
<td>Energy</td>
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<tr>
<td>RMS bunch length ($\sigma_z$)</td>
</tr>
<tr>
<td>Normalized emittance</td>
</tr>
<tr>
<td>Bunch charge</td>
</tr>
<tr>
<td>Initial plasma density, $n_p$</td>
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<tr>
<td>Matched beta_eq</td>
</tr>
<tr>
<td>Ramp scale $L_s$</td>
</tr>
<tr>
<td>Sigma $x,y$</td>
</tr>
<tr>
<td>Ramp length, $L$</td>
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</tbody>
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Exponential rise over 400x
Beam density and spot evolution

QEB
Time = 100.00 [1/\omega_p]

Time = 15400.00 [1/\omega_p]
Plasma source development

- Use tapered plastic capillary to control expansion of plasma at entrance
- Tapered edge density (spectroscopic measure)

More details: Wednesday poster session 19:30 “Tapering of plasma density ramp profiles for adiabatic lens experiments”
Beam measurements

- Too small to measure optically
- Use betatron radiation instead, in flat density region after ramp
- Method already utilized at LWFA facilities
- Short wavelength radiation (nm)

\[
K_u = k_\beta \gamma x_0 = 1.33 \times 10^{-2} \gamma^{-0.5} n_0 \left(10^{16} / \text{cc}\right) x_0 \left(\mu\text{m}\right)
\]

\[
\lambda_r(\theta) = \frac{\lambda_\beta}{2\gamma^2} \cdot \left[1 + \frac{1}{2} K_u^2 + (\gamma \theta)^2\right]
\]

- In 2 cm, lots of it! \( N = L_f / N \ (/ 4) N a^2 \ 10^7 \)
- Spectroscopic determination of emittance

\[
\Delta \lambda_{\text{rms}} = 2 \varepsilon_{\text{rms},n} / \gamma
\]
Spectral structure of betatron radiation

From SPECTRA simulations
Single shot X-ray spectrometer

- UCLA-BNL inverse Compton scattering

Full results in Sakai, et al., PRAB 20 060701 (2017)
Future work

• Examine asymmetric beams
  – Highly relevant to LC final focus
• Optimize plasma source
• Upgrade crystal spectrometer
• Layout completion for SPARC
• Experiments!