Mapping plasma lenses

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Motivation

> Plasma accelerators create sub-μm emittance beams

> Intrinsic energy spread $\sigma_E$ of percent level

> Divergence $\sigma_{x'}$ typically mrad

> Emittance growth during drift $\Rightarrow \epsilon_n \sim \sigma_E \cdot \sigma_{x'}^2 \cdot s$

> Compact and strong capturing needed

> APLs provide short focal length

> Radially symmetric focusing

Active plasma lens principle

> Beam passes high current region
> Radially symmetric magnetic field
> Gradients of ~3kT/m achieved\(^1\)
> High voltage discharge ignites plasma
> Gas volume required
> Wakefields should be avoided

\[ B_\phi(r) = \frac{\mu_0 I_0}{2\pi} \cdot \frac{r}{R^2} \]

\[ \frac{\partial B_\phi}{\partial r} = 0.2 \cdot \frac{I[A]}{R[mm]^2} \cdot \frac{T}{m} \]

Probing the quality of plasma lenses

> Measure shot-to-shot stability
  - Assess gradient stability
  - Assess discharge stability
  - Stable electron beam needed

> Probe for inhomogeneity
  - Gradient depends on current distribution
  - Inhomogeneity leads to nonlinear focusing
  - Emittance degradation in the plasma lens

\[ B_\varphi(r) = \frac{\mu_0}{2} (a_1 + a_4 \cdot r^3) r \]

Magnetohydrodynamics simulation

To be published

Courtesy of J. van Tilborg and S. Bulanov
The Mainz Microtron

> Racetrack Microtron
  - $E = 855 \text{ MeV with } \sigma_E = 4 \cdot 10^{-5}$
  - Special operation mode with 10 ns bunch train
  - Current 100 $\mu$A – no wakefields
  - Norm. Emittance 1.5 mm mrad
  - Transverse jitter ~20% of beam size

> Beamline allowing for $H_2$ flow
Discharge characteristics

Current profile @20kV

- Amplitude stability of 1.5 A rms
- Plateau region of ~250 ns
- Current plateau tunable up to 1.5 kA
- Stable in timing: ~1 ns rms breakdown jitter
- Electron beam arrival monitored
- Single shot analysis possible
Lens position scan – gradient via dipole kick

> Lens position varied transversally
> Dipole kick introduced
> Beam position on screen changes
> Kick yields field – kicks yield gradient
> Position stability → gradient stability
Lens position scan – gradient via dipole kick

- Lens position varied transversally
- Dipole kick introduced
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- Kick yields field – kicks yield gradient
- Position stability → gradient stability
Gradient measurement results

> Scans using 7 mm long APL

> Very low transverse jitter

> Stable discharge and APL
  ▶ 100 shots per scan point
  ▶ No faulty discharges

> Higher gradients than expected
  ▶ 40% - 60% bigger than uniform density

<table>
<thead>
<tr>
<th>Current [A]</th>
<th>Uniform [T/m]</th>
<th>Linear [T/m]</th>
<th>Polynomial [T/m]</th>
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<tbody>
<tr>
<td>188</td>
<td>150</td>
<td>246 ± 10</td>
<td>265 ± 35</td>
</tr>
<tr>
<td>368</td>
<td>294</td>
<td>437 ± 8</td>
<td>475 ± 30</td>
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<tr>
<td>740</td>
<td>592</td>
<td>823 ± 8</td>
<td>886 ± 38</td>
</tr>
</tbody>
</table>

\[ I_0 = 2 \pi \int_0^R j(r) \cdot r dr \quad \rightarrow \quad B_{\varphi}(R) = \frac{\mu_0 I_0}{2\pi R} \]

To be published
Emittance measurement - MaMi-B beamline

> Two chambers
  ▶ First for plasma lens and screen
  ▶ Second for screen

> Large dipole
  ▶ Introduces dispersion
  ▶ Strong edge focusing

> Quadrupole triplet for scan
  ▶ Two independent power supplies
  ▶ Low maximum gradient quads
Emittance scan results

> Scans using 7 mm long APL
> rms beam size calculated for 100 shots
> Resolution of ~0.1 mm mrad
> MaMi-B emittance measured – 1.5 mm mrad
> Emittance increases in APL

<table>
<thead>
<tr>
<th>Current [A]</th>
<th>Normalized emittance [mm mrad]</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Simulated</td>
</tr>
<tr>
<td>188</td>
<td>2.6 ± 0.2</td>
<td>3.1 ± 1.3</td>
</tr>
<tr>
<td>368</td>
<td>3.6 ± 0.2</td>
<td>4.7 ± 1.1</td>
</tr>
<tr>
<td>740</td>
<td>9.5 ± 0.1</td>
<td>7.5 ± 1.1</td>
</tr>
</tbody>
</table>

To be published
Particle tracking simulations

- Results from offset scans fed into simulation
- MaMi-like beam sent through field
- Emittance for different currents and beam sizes
- Core emittance can be preserved
- Small beam size favorable

To be published
Particle tracking simulations

- Results from offset scans fed into simulation
- Low emittance beam sent through field
- Emittance for different currents and beam sizes
- Core emittance can be preserved in small emittance beams

To be published
FACET II considerations

> High current beams may drive wake

> Transversally large beam in APL needed

> Large beam needs large APL for emittance preservation

> Drive beam final focus

> Witness beam capturing

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Driver</th>
<th>Witness</th>
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<tbody>
<tr>
<td>$I_{\text{peak}}$ [kA]</td>
<td>200</td>
<td>15</td>
</tr>
<tr>
<td>$\sigma_{x,y}$ [μm]</td>
<td>200</td>
<td>150</td>
</tr>
<tr>
<td>$n_b$ [cm$^{-3}$]</td>
<td>$10^{16}$</td>
<td>$10^{15}$</td>
</tr>
<tr>
<td>$R$ [mm]</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$I_0$ [kA]</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>$g$ [T/m]</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>$n_0$ [cm$^{-3}$]</td>
<td>$5\cdot10^{16}$</td>
<td>$5\cdot10^{16}$</td>
</tr>
<tr>
<td>$K_{\text{APL}}/K_{\text{wake}}$</td>
<td>$10^5$</td>
<td>$10^6$</td>
</tr>
</tbody>
</table>
Summary

- First experiment with a plasma lens in a conventional electron accelerator
- Direct magnetic field measurement of a capillary plasma lens – 823 T/m over 350 μm
- Stability of discharge and APL assessed in gradient scans – very stable
- Study of emittance preservation shows degradation – explained by simulations
- Emittance preservation possible for relatively small beams
- Might be a technique worth considering for FACET II program
Thank you for your attention, please ask away!
APLs – a hot topic

> Recent publication shows heating effects
> Heating causes pinching of current
> Higher focusing field for core part of APL

J. vanTilborg et al., PRAB 20, 032803 (2017)