Stable electron beams with low absolute energy spread from a laser wakefield accelerator with plasma density ramp controlled injection

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Improve present MeV class energy spread of LWFAs, stability, E

LBNL data

9 TW: 86 MeV/c
\( \Delta p = 4 \text{ MeV/c FWHM}^* \)

40 TW, 1 GeV/c,
\( \Delta p = 25 \text{ MeV/c rms}^{**} \)

Many groups report 100 MeV/c-class bunches, MeV/c \( \Delta p^{***} \).

Simulations, experiments** imply tradeoff \( p, \Delta p, \) stability

Initial optical injection\(^\dagger\) experiments\(^\Delta\) -- stable beams, MeV/c \( \Delta p^{\^} \)

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Plasma density ramp can control trapping for stability, $\Delta E$.

Trapping of plasma particles (1D) when -
$$(q/m)E\omega_p \sim v_{\text{wake}}$$

Decreasing plasma density (ramp) control:
plasma wavelength increases as the laser propagates

$$V_{\text{wake}} \sim V_{g,\text{driver}}(1 - \frac{d\lambda_p}{dz}) < V_{g,\text{driver}}$$

Decreased $V_{\text{wake}}$ and trapping threshold*

Allows operation far above trapping threshold:
- low energy
- High $\Delta p/p$ but low absolute $\Delta p$

NO requirement for laser modulation by plasma (unstable)
- stable beam for staging

* Bulanov PRE 1998
Experiments\(^\wedge\) select gradient using laser focal location in thin gasjet

Experimental Setup

Wake only large within \(Z_R \sim 200\mu m\) of focus:
Focus location determines gradient where wake excited

Plasma profile \(~ 0.7\text{mm FWHM}, n = 2.2 \times 10^{19}\text{cm}^{-3}\)

\(^\wedge\) Geddes sub. PRL, * Leemans, Plateau poster
Scanning jet with respect to focus: control of trapping and acceleration

Tuning with jet position

Sequential Bunch images
Day#1 run #1

Sequential Spectra
Day#2 run #1

Divergence (ea. image ±33mrad)

Unstable 10’s MeV/c (Geddes PoP 2005)

Self modulation & filamentation unstable

ICT(nC) +

Gamma

density fit, arb. units

Laser propagation

Down ramp:
Stable Q
Q±15%rms
Low $\gamma$ -> low E
3 nC

Similar to input
Transmit up to $\geq 70\%$ stable
Downramp: stable bunches with 20 keV/c transverse momentum

Electron beam image @ 72 cm

**FWHM Divergence** in X (Y)
28 (14) mrad
± 1.8 (2.5) mrad rms

**Pointing** stability in X (Y)
1.8 (1.2) mrad rms

Transverse momentum inferred ~ 20 keV/c FWHM
Downramp: Stable bunches with 170 keV/c $\Delta P$, 20 keV/c stability

Central momentum 0.76 MeV/c ±20 keV/c rms

Momentum spread 170 keV/c FWHM ± 20 keV/c rms

Divergence 20 mrad FWHM (Y), pointing 1.5 mrad rms

$Q_{\text{bunch}}$ from correlation of phosphor & ICT ~ 0.3-1 nC
**Sequential Bunch images**
Day#1 run #1

**Berkeley Lab**

**Downramp: stability over 7 days within 20 keV/c**

**October 19**

<table>
<thead>
<tr>
<th>Time</th>
<th>Central momentum</th>
<th>Momentum spread</th>
<th>Divergence</th>
<th>Charge fluctuation</th>
<th>Charge fluctuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0345a.m.</td>
<td>0.77 MeV/c</td>
<td>200 keV/c</td>
<td>23 mrad (Y)</td>
<td>23% rms</td>
<td>23% rms</td>
</tr>
<tr>
<td>0432a.m</td>
<td>0.78 MeV/c</td>
<td>190 keV/c</td>
<td>18 mrad (Y)</td>
<td>21% rms</td>
<td>21% rms</td>
</tr>
</tbody>
</table>

Mode pellicle removed

100 % injected beams w/in spec. window
Simulations show downramp trapping, nearly reproduce bunches in VORPAL particle in cell simulations, near experimental Parameters.

Plasma density downramp slows wake, inducing trapping.

Consistent with experimental data:
- bunches at MeV momenta, \( dp \sim 200 \text{ keV/c} \), \( Q \sim 0.2 \text{nC} \)
- stable over physical parameter scans
- 10’s of keV/c transverse momentum
- order 200 fs length at THz emission surface

- Bunches ~ 30fs long at formation
  - suitable for LWFA injector

Stage down ramp bunch to capillary for stability, quality, 10 GeV beams

- Couple injector to capillary channel
- Experimental setup

- Stage low energy injector and 1-10 GV accelerator modules
  - Staging ~ preserves energy spread: improve emittance, stability*
  - 10 GeV using ~ PW of laser energy and meter-scale plasma

* Shadwick, BAPS, 2005
Plasma density ramp control: stable low Δp beams for LWFA injectors

Used plasma density gradient in gas jet to control trapping, producing bunches at 0.76 MeV

Longitudinal & transverse momentum spread, stability one to two orders improved from conventional LWFA:
- momentum spread 170 keV/c
- central momentum ±20 keV/c
- pointing ± 2mrad
- divergence implies $p_\perp \sim 20$ keV/c
- stability over 7 days, similar over 1+ year

Next: experiments and detailed simulations to:
- stage bunches to accelerator channel
- optimize injection
- optimize emittance preservation