Injection for Laser Plasma Acceleration using a Gas Jet Embedded into a Discharge Waveguide

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PAC 2009

http://loasis.lbl.gov/
High Acceleration Gradient $\Rightarrow$ TeV LPA Collider in <1km?

See PAC09 proceedings:
WE6RFP075 Geddes et al.
WE6RFP078 Schroeder et al.

Leemans & Esarey, Physics Today, March 2009
Challenges in Next 10 Years

Lasers: high average power

High-quality stable beams

Multi-GeV beams

TREX (50TW laser)

BELLA (1PW laser)

Staging, optimized structures

Modeling
Quasi-Monoenergetic Beams with Laser-produced Waveguide

- Pre-2004 electron beams had Boltzmann-like energy distribution with few particles at high energy.
- LOASIS group produced low energy spread beams by employing a laser-produced waveguide (overcame diffraction) to accelerate to $L_{\text{deph}}$.

To obtain higher energy:

$$\text{Energy Gain} = E_0 L_{\text{acc}} \propto \frac{I}{n_e}$$

Lower density + longer guiding structure

But laser-produced waveguide:
1) Linear scaling of laser energy required with accelerator length
2) Efficient only for high $n_e$

$n_e \sim 10^{19}\text{cm}^{-3}$

$Z_R = \frac{\pi w_0^2}{\lambda}$

- Mono-energetic $\sim 100\text{ MeV}$ in $<2\text{ mm}$
- Charge 0.3 $nC$
- Bunch length $<50\text{ fs}$
- Few % energy spread

Gas-injected Capillary Discharge Waveguide

- Gas injected near each end of channel
- \( n_e \sim 10^{17} - 10^{19} \text{ cm}^{-3} \)
- Gas ionized and heated by pulsed discharge
- Guiding channel formed by heat conduction to capillary wall

\[ \frac{1}{r} \frac{d}{dr} \left( r \kappa_{\perp} \frac{dT}{dr} \right) + \sigma_{\perp} E^2 = 0 \]
GeV Beams in 3cm

- 40TW laser
- Capillary discharge
- 1 Tesla magnetic spectrometer
- Optical diagnostics (not shown)

Divergence (rms): 1.6 mrad
Energy spread (rms): 2.5%
Resolution: 2.4%

Lee mans et al., Nature Physics 2006
GeV Beams Repeatable but not Stable – Available Controls not Sufficient

Laser energy, pulse width, plasma density, discharge delay, plasma channel density, depth, and length, degree of ionization

But optimizing injection does not optimize guiding (accelerating structure)
Need to separate injection and acceleration
Lowering the Plasma Density has Increased the Energy of Laser Wakefield Accelerators

- 2004 and previous experiments
  - Density $\sim$ few $10^{19}$ cm$^{-3}$, 10TW

- 2006 Experiments
  - Density $\sim$ few $10^{18}$ cm$^{-3}$, 40TW

- 2008/2009 Experiments
  - Optimize controlled dark current free accelerating structure
  - Employ injector

\[ \text{Energy Gain} \propto \frac{I}{n_e} \]

Geddes et al., *Nature*, 2004; Leemans et al., *Nature Physics* 2006; Gonsalves et al., in prep
Down-ramp Injector Demonstrated: Simulations Show Injector Coupled to Low Density Accelerator Produces Low Energy Spread Beams

Inject low $\Delta E$: $\Delta E$ conserved during acceleration so as $E \uparrow$, $\Delta E/E \downarrow$

<table>
<thead>
<tr>
<th>n</th>
<th>Laser focused on down-ramp of gas jet density profile</th>
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<tr>
<td>n</td>
<td>Laser 10TW</td>
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<td>n</td>
<td>Laser focused on down-ramp of gas jet density profile</td>
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<td>MEV beam produced with</td>
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<tr>
<td>n</td>
<td>▪ Low divergence (20 mrad)</td>
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<td>n</td>
<td>▪ Good stability</td>
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<tr>
<td>n</td>
<td>▪ Central energy (760 keV/c ± 20 keV/c rms)</td>
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<tr>
<td>n</td>
<td>▪ Momentum spread (170 keV/c ± 20 keV/c rms)</td>
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<tr>
<td>n</td>
<td>▪ Beam pointing (1.5 mrad rms)</td>
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<tr>
<td>n</td>
<td>Laser transmission 70% and mode still good for driving wakefield</td>
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<tr>
<td>n</td>
<td>Energy Spectrum at Ramp Exit</td>
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<tr>
<td>n</td>
<td>#/P$_z$ (MeV/c)</td>
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<td>n</td>
<td>P 1.5 MeV/c</td>
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<td>$\Delta P$ 200 keV/c</td>
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<td>P 20 MeV/c</td>
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<tr>
<td>n</td>
<td>$\Delta P$ 200 keV/c</td>
</tr>
</tbody>
</table>

Geddes et al., PRL V 100, 215004 (2008)

*Nieter et al., JCP 2004
Gas Jet Nozzle Machined Into Capillary Can Provide Local Density Perturbation

Laser-machined gas jet

Measured surface profile

Axis of the capillary

Density profile in jet region
Jet Improves Beam Stability

Stability with jet

Input Parameters: $P_{\text{jet}} \approx 145$ psi, $N_e \approx 2 \times 10^{18} \text{ cm}^{-3}$, $a_0 \approx 1$ (25TW), Laser pulse length $\approx 45$ fs

- Pointing $\pm 0.8$ mrad
- Divergence 1 mrad
- Energy $300 \text{ MeV} \pm 7 \text{ MeV}$
- $\Delta E/E$ 6% $\pm$ 0.7%
- $Q$ 7.3pC $\pm$ 1.7pC

Best stability without jet

Input Parameters: no jet in cap, $N_e \approx 2 \times 10^{18} \text{ cm}^{-3}$, $a_0 \approx 1$ (25TW), Laser pulse length $\approx 45$ fs

- Pointing $\pm 1.8$ mrad
- Divergence 1 mrad
- Energy $440 \text{ MeV} \pm 95 \text{ MeV}$
- $\Delta E/E$ 4% $\pm$ 2%
- $Q$ 2.6pC $\pm$ 2.0pC

NB: Both data sets show subsequent shots
Energy Control by Varying Jet Pressure

- Energy of the beam tuned without significant increase in energy spread
  - BUT Beam parameters not independent yet
  - Increased jet pressure $\Rightarrow$ pump depletion, reduced energy
  - Increase further, sharper reduction in energy – beam loading?

![Graph showing the relationship between gas jet pressure and energy control parameters.](image-url)
Staging: solving the issue of laser depletion

- Not only vital for achieving higher beam energy but separate stages allows for fully tunable second stage to explore the physics of LPA’s from the linear regime to the bubble regime.

- Plasma mirror reduces distance between stages and accelerator length.

See proceedings Panasenko et al., WE6RFP077
Summary and *Near Future* Experiments

**Highest energy beams from LPA with capillary technology**

Near Future:
- Down-ramp injection
- Demonstrate staging (↑E and more)

Tailoring density profile increases beam stability

- 500 MeV -density below usual injection threshold
- Enhancement of stability in charge and energy
- Increase in control over beam parameters
- 1 mrad divergence and pointing stability

![Graph showing charge density vs. energy with energy levels ranging from 0 to 750 MeV and density levels from 0 to 0.14 pC/MeV]