E200: Plasma Wakefield Acceleration
Status and Plans

Chan Joshi
University of California Los Angeles
For the E200 Collaboration

SAREC Meeting, SLAC : Sept 15-17th 2014
Work Supported by DOE
Experimental Setup of E200

Now plasma pre-ionized by a 0.75-1.50 axicon over up to 2 meters using a 250 mJ, 100 fs Ti-sapphire laser

E200 Collaboration
Successful generation of drive and witness bunches

Peak beam current is marginal for ionizing Li, so need a pre-ionized plasma

Impose a positive chirp
Disperse the beam
Place appropriate masks
Recompress the beam

\[ N_{\text{drive}} = 6.0 \times 10^9 \sim (1 \text{nC}) \]
\[ N_{\text{trailing}} = 2.0 \times 10^9 \sim (0.3 \text{nC}) \]

Small \( O(0.1^0) \) changes in the phase ramp leads to beams spectrum and Therefore changes to trailing/drive charge
Acceleration of a Discrete Bunch of Electrons

- **Status at SAREC 2013**

- 80 pC in “core” of trailing bunch

- Same amount of charge accelerated outside core

- Core energy gain: 1.6 GeV

  Gradient of ~5 GeV/m
Detailed Analysis Now Completed

- Particle-In-Cell (PIC) simulation with QuickPIC (UCLA) for beam-plasma interaction
- PIC output then propagated through simulated beamline
- Shows very good qualitative agreement with observed final spectrum
- Gives insight into beam-plasma coupling: trailing bunch was too long and wide to fully couple into plasma wake
- Shows loading of wake → key to efficient energy extraction
- Energy loss of drive bunch = energy put into wake
- Energy transfer efficiency from wake to trailing bunch:
  \[ \eta = \frac{\text{energy gain by trailing bunch}}{\text{energy loss by drive bunch}} \]
- Mean wake-to-bunch energy transfer efficiency of 31% (18% core)
- Max efficiency of 50% (30% core)
- Approaching collider design!
Evidence for Beam Loading

Efficiency Variation is correlated to Trailing Bunch/ Drive Bunch charge ratio

For a given drive bunch charge

\[ T = \frac{E_+}{E_-} \] reduces as trailing charge increases
But \( E_+ \) flattens as the wake is strongly loaded
Therefore efficiency expected to increase
Median energy spread of 350 MeV or 1.7%
Initial Energy Spread on the beam 1%
The increase in energy spread expected from non-optimal beam loading of wake

Fig. Redacted
Smallest energy spread is on the order the initial energy spread. This implies wake flattening due to near optimum beam loading.
Text Redacted
New Results on PWFA in 2013/14

PWFA Experiments with Electrons

1) Increased the plasma length from 36 cm to 1.3 m by using a longer Li oven but reduced the plasma density to increase the accelerated witness bunch charge

Results- Energy gain increased from 1.6 GeV to 6 GeV consistent with gradient-length product. Energy spread however was also increased from nominally 2% to about 10% due to a combination of non optimized beam loading, jitter between the drive and the trailing bunch.

PWFA experiments with a compressed positron bunch

1) Used a compressed e+ bunch to excite high gradient wake in plasma

Results- We were able to transport the positron bunch over 1.3 m length of plasma. Positron acceleration up to 6 GeV seen. Simulations reveal a new regime for e+ acceleration.

2) First results on formation of a 10 cm scale hollow plasma channel (See Spencer’s Talk)
Increased Plasma Length $\rightarrow$ Increased Energy Gain

- 2014: increased plasma length from 30cm to 130cm
- $\rightarrow$ Increased energy gain
- Reduced plasma density to $3 \times 10^{16}$ cm$^{-3}$ for better coupling
- Early analysis:
  - $\sim$100pC accelerated
  - O(10%) energy spread
  - mean energy gain 6 GeV

100 Shots ordered by drive-witness bunch separation

- Single shot with 6 GeV Energy Gain

Fig. Redacted

Energy (GeV)

- 26
- 24
- 28

smaller separation $\rightarrow$
Electro-Optic Sampling (EOS)

- PWFA performance depends on longitudinal profile of beam
- EOS:
  - non-destructive
  - shot-by-shot
  - beam arrival time
  - beam temporal profile
- First steps taken in 2014 with spatially encoded EOS
- Arrival time jitter: 100 fs (rms) [Yunfeng Xi, UCLA]
- Two-bunch separation correlated with EOS signal
What about Positrons?

Only place in the world to study this topic !!

\[ N = 2 \times 10^{10} \quad (1.6 \times 10^{10}) \]

Energy 20 GeV

Rep Rate 60 HZ

Energy/pulse 150 J

Focal Spot Size 30 micron (???)

Pulse Width 15 micron compressed (40 micron)
WAKEFIELD FIELDS for e⁻ & e⁺
very different in Nonlinear Regime

\[ n_e = 1.5 \times 10^{14} \text{ cm}^{-3} \]

homogeneous, QUICKPIC

- Transverse Field constant After Plasma electrons Blown-Out
- Longitudinal field Shows Accelerating “Spike”
- Fields vary along r, stronger
- Less Acceleration
FOCUSING OF $\text{e}^-/\text{e}^+$ at FFTB

- Beam images $\approx 1\text{m}$ from plasma exit ($\varepsilon_x \neq \varepsilon_y$)

$$n_e = 0 \quad n_e \approx 10^{14} \text{ cm}^{-3}$$

- Ideal Plasma Lens in Blow-Out Regime

- Plasma Lens with Aberrations (Halo Formation)

How to minimize emittance growth of positrons due to nonlinear focusing fields?
- Explore wakes in hollow channels.

Positron Acceleration @ FFTB

Time Resolved Spectrum

\[ N = 1.2 \times 10^{10} \text{ e}^+, \quad n_e = 1.8 \times 10^{14} \text{ cm}^{-3}, \quad L = 1.4 \text{ m} \]

Experimental Measurement:

Peak Energy Gain

78 MeV

79 ± 15 MeV

## Science Rationale for the Positron Acceleration Program

<table>
<thead>
<tr>
<th>Previous Work</th>
<th>Current Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration Gradient  50 MeV/m</td>
<td>Increase gradient to 1 GeV/m</td>
</tr>
<tr>
<td>Energy Gain    70 MeV</td>
<td>Increase Energy gain to &gt; GeV</td>
</tr>
<tr>
<td>Non linear focusing forces produced halo of charge around the beam</td>
<td>Is emittance growth avoidable? Is there a way to maintain good beam emittance for the trailing bunch?</td>
</tr>
<tr>
<td>Exploratory studies of hollow plasma channels.</td>
<td></td>
</tr>
</tbody>
</table>
High Gradient Acceleration of Positrons

- FACET commissioned positron delivery in 2014
- First demonstration of high gradient acceleration of positrons in PWFA: ~4 GeV/m
- Ionization injected electrons accelerated to several GeV

QuickPIC Sim:
Longitudinal Field

Figures redacted
Positron Beam Driven PWFA

Drive Beam: $\sigma_r = 70.0 \, \mu m$, $\sigma_z = 30.0 \, \mu m$, $N_2 = 2.0 \times 10^{10}$, $\varepsilon_N = 100.0 \, \text{mm}\cdot\text{mrad}$

**Plasma Density**: $8.0 \times 10^{16} \, \text{cm}^{-3}$ (1.3 meters long)

Figures redacted
Plan for next year

• 1) Clean up high gradient positron acceleration with a compressed bunch data for high-impact publication.
• 2) Perfect the electro-optic sampling technique to better determine the timing between the drive and the trailing bunch
• 3) Get more systematic data on the long Li oven with drive-trailing electron bunch configuration.
• 4) Characterize laser produced Hydrogen plasmas
• 5) Repeat the two bunch experiment in the hydrogen plasma. Higher energy gain, low energy spread, high energy transfer efficiency
The FACET E200 PWFA Collaboration


Work supported by DOE contracts DE-AC02-76SF00515, DE-AC02-7600515, DE-FG02-92-ER40727 and NSF contract PHY-0936266

M. Litos, AAC 2014 – San Jose, CA