High Gradient Plasma Wakefield Acceleration Using Ultra-Short Electron Bunches

Presented by
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for the
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OUTLINE

- Motivation and Goal
- PWFA: linear and non-linear predictions
- Plasma source and experimental set up
- Energy gain and loss measurements
- Hose instability and beam matching
- Proposed schedule
MOTIVATION/GOAL

E-157 and E-162 built a PWFA “laboratory”
built in the FFTB, and expertise to run it

+ 

Ultra-short electron bunches in the FFTB in 2002

= 

Unique and ultimate opportunity to perform PWFA experiments in the context of an actual high energy accelerator

+ 

Demonstrate ultra-high gradient acceleration of electrons
(1.75 GeV in 5.8 GeV/m) in a long plasma (30 cm)
SHORT BUNCHES IN THE FFTB

- Install four dipole chicane in Li10 during summer 2002 shutdown
  - Existing SLC bunch compressor (RTL) gives 1.2mm $\sigma_z$
  - After the 9 GeV point therefore compatible with PEP-II operation
  - Chicane ($R_{56} = -75\text{mm}$) compresses beam to $50\mu\text{m} \sigma_z$
  - Wakefields from 1.9 km add linear energy chirp to the beam
  - Chromatic correction bends in FFTB ($R_{56} = +2\text{mm}$) compress to $12\mu\text{m} \sigma_z$

- Rematch to FFTB with smaller $\beta$-functions and add sextupole(s) to control
  chromatic aberrations and second order dispersion
- We are planning for only $100\mu\text{m} \sigma_z$

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LINEAR PWFA SCALING

- $E_{z,\text{linear}} \propto \frac{N}{\sigma_z}$
  - Short bunch!

- $k_p \sigma_z \cong \sqrt{2}$
  - or $n_p \propto \frac{1}{\sigma_z^2}$

- However, when $n_b > n_p$, non-linear... or “blow-out” regime

- Scaling laws valid?

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## EXPERIMENTAL PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>E-157/162</th>
<th>E-164</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N ) ( (\text{mm}) )</td>
<td>2\times10^{10}</td>
<td>2\times10^{10}</td>
</tr>
<tr>
<td>( \sigma_z ) ( (\mu\text{m}) )</td>
<td>10-50</td>
<td>20-40</td>
</tr>
<tr>
<td>( \Delta \gamma \gamma ) (rms)</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>( I_{\text{peak}} ) (kA)</td>
<td>( \approx2 )</td>
<td>( \approx10 )</td>
</tr>
<tr>
<td>( \gamma \varepsilon_x ) (m-rad)</td>
<td>3\times10^{-5}</td>
<td>5\times10^{-5}</td>
</tr>
<tr>
<td>( \gamma \varepsilon_y ) (m-rad)</td>
<td>0.5\times10^{-5}</td>
<td>1\times10^{-5}</td>
</tr>
</tbody>
</table>

Linear theory gain: \( eE_{z,\text{linear}} = 240 \text{MeV/m} \left( \frac{N}{4 \times 10^{10}} \right) \left( \frac{0.6\text{mm}}{\sigma_z(\text{mm})} \right)^2 \)

**E-157/162**

120 MeV/m in \( 1.5\times10^{14} \text{ cm}^{-3} \)

\( N=2\times10^{10}, \sigma_z=0.6 \text{ mm} \)

**E-164**

4.3 GeV/m in \( 5.6\times10^{14} \text{ cm}^{-3} \)

\( N=2\times10^{10}, \sigma_z=0.1 \text{ mm} \)
PWFA scaling remains valid in the non-linear or “blow-out” regime.

\[ eE_z, \text{linear} < eE_z, \text{non linear} \]

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ACCELERATING FIELD (ON AXIS)

3-D PIC, \( n_p = 5.6 \times 10^{15} \text{ cm}^{-3} \), \( \sigma_z = 100 \mu \text{m} \), \( \sigma_{x,y} = 20 \mu \text{m} \) => \( n_b/n_p > 5 \)

In the non linear, blow-out regime \( (n_b > n_p) \):

- Non sinusoidal wake
- Wake spike in the first acceleration region
- Large gradients where the beam charge is finite

\[ \approx 6 \text{ GeV/m} \quad \text{“linear”} \]

\[ \approx 14 \text{ GeV/m} \quad \text{non linear spike} \]
NUMERICAL SIMULATIONS RESULTS E-164

- Expected energy gain (slice average): **1.75 GeV** or **6%** (over 30 cm)
- Expected energy loss (slice average): **600 MeV** or **2%** (over 30 cm)
- Beam initial energy spread (rms): **1.5%**

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Expected energy gain (slice average): 275 MeV or <1% (over 1.4 m)

Expected energy loss (slice average): 100 MeV or <0.5% (over 1.4 m)

Beam initial energy spread: 1.5%
PLASMA SOURCE

\[ n_p = 0-6 \times 10^{15} \text{ cm}^{-3}, \quad L = 30-50 \text{ cm} \]

- Metal vapor in a heat-pipe oven

![Diagram of a metal vapor in a heat-pipe oven]

- Photo-ionization

\[ E(z) = E_0 e^{-n_0 \sigma_i z} \]

\[ n_{p \text{ entrance}} = n_0 \sigma_{i \text{ entrance}} E \]

\[ n_{p \text{ entrance}} A_{\text{exit}}^{-n_0 \sigma_i L} \approx 1 \]

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PLASMA PARAMETERS

Rubidium vapor in a heat-pipe oven:

- $\phi=4.17$ eV, ionize with $h\nu_{YAG\times4}=4.68$ eV (UV, $\lambda=266$ nm)
- $\sigma_{\text{ionization}}(4.68$ eV$)=2\times10^{-20}$ cm$^2$
- $n_0=4\times10^{16}$ cm$^{-3}$, $T_{Rb}\approx320^\circ$C, $P_{\text{He buffer}}=2.5$ Torr
- Required uv fluence for $n_p=10\times10^{15}$ cm$^{-3}$: $\approx10$ J/cm$^2$
- Small $\sigma_{\text{ionization}} \Rightarrow$ cst fluence over $L$
  $\Rightarrow$ Raleigh length: $2Z_R=2m\geq L$, $w_0\approx300$ µm
  $\Rightarrow$ very uniform plasma: $1-\exp(-n_0\sigma_iL)<3\%$
- Ionization refraction negligible for $n_{\text{critical}} Z_R L$
  $\Rightarrow n_p \text{ max }=14\times10^{15}$ cm$^{-3}$$>6\times10^{15}$ cm$^{-3}$

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EXPERIMENTAL SET-UP

- No pellicles in the beams
- $e^-$ beam scattering through $\approx 25$ m of He at 2.5 Torr
  $$\theta = \frac{13.6}{E(\text{MeV}) \sqrt{L_R}}, \text{ for } P=2.5 \text{ Torr, } L_R=1.7 \times 10^6 \text{ m}, \Rightarrow \theta = 1.8 \mu \text{rad}$$
  $$\varepsilon \approx \theta^2 L = 0.8 \times 10^{-10} \text{ m-rad} < \varepsilon_x \approx 10^{-9}, \varepsilon_y \approx 10^{-10} \text{ m-rad}$$
- $e^-$ beam impact ionization: $n_e = n_b \sigma_z n_g \sigma_{ii} \approx 10^9 - 10^{11} \text{ cm}^{-3}$

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**IMPACT IONIZATION** (E-162, preliminary)

\[ E = 28.5 \text{ GeV}, \quad \varepsilon_N = 5 \times 10^{-5} \text{ m-rad}, \quad \beta_x \approx 30 \text{ cm}, \quad d \approx 2.9 \text{ m} \]

Helium \((Z=2, Z_{\text{Li}}=3)\)

- In He: no significant effect on the beam for \(20 \text{ Torr} \times 2.9 \text{ m} \ldots\)

- Ionization cross section for ultra-relativistic \(e^-\): (M. Reiser, 1994)

\[
\sigma_{ii}[cm^2] = 1.87 \times 10^{-20} A_1 [ln(7.52 \times 10^4 A_2 \gamma^2)] - 1
\]

<table>
<thead>
<tr>
<th>Gas</th>
<th>(Z)</th>
<th>(A_1)</th>
<th>(A_2)</th>
<th>(\sigma_{ii}[cm^2])</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>2</td>
<td>0.75</td>
<td>0.62</td>
<td>(4.4 \times 10^{-19})</td>
</tr>
<tr>
<td>Ar</td>
<td>18</td>
<td>2.05</td>
<td>0.11</td>
<td>(2.4 \times 10^{-18})</td>
</tr>
</tbody>
</table>

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ENERGY GAIN/LOSS MEASUREMENT

- $\sigma_z = 100 \ \mu m$, $\tau_b = 1/3 \ ps \Rightarrow$ no time resolution of the Cherenkov light
- time integrated images with high S/N ratio (16-bit CCD)
- Relative energy gain/loss $>$ initial energy spectrum

From simulations (reminder):
- Expected energy gain (slice average): 1.75 GeV or 6% (over 30 cm)
- Expected energy loss (slice average): 600 MeV or 2% (over 30 cm)
- Beam initial energy spread (rms): 1.5%

- Imaging spectrometer $\sigma_y = \sqrt{\beta_y \varepsilon_y + \left(\frac{\Delta E}{E}\right)^2}$, keep $\beta_y \varepsilon_y << \left(\eta \frac{\Delta E}{E}\right)^2$
- $\beta_y = \beta_y \text{ plasma exit} \ast (\text{Magnification})^2$

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Hose Instability/ Beam Matching

- No significant instability observed with in E-162 with
  \( n_p \) up to \( 2 \times 10^{14} \text{ cm}^{-3} \), and \( L=1.4 \text{ m} \)
  - Hose instability grows as* \( \exp((k_\beta L)^{2/3}) \), where \( k_\beta = \omega_p/(2\gamma^{1/2}c) = (n_p e^2/e_0 m_e 2\gamma)^{1/2} \)
    - E-162: \( n_p=2 \times 10^{14} \text{ cm}^{-3}, L=1.4 \text{ m} \Rightarrow e^{4.5}=92 \)
    - E-164: \( n_p=6 \times 10^{15} \text{ cm}^{-3}, L=0.3 \text{ m} \Rightarrow e^{5.4}=227 \)
    \Rightarrow no significant growth expected(?)

- Beam matching to the plasma: \( \beta_{beam} = \frac{\sigma^2}{\epsilon} = \frac{\omega_p}{\sqrt{2\gamma}} = \beta_{plasma} \)

  \[ \sigma_{matched}(\epsilon_N=5 \times 10^{-5} \text{ m-rad,} n_p=6 \times 10^{15} \text{ cm}^{-3})=4.6 \text{ \mu m} \]
  - Minimize spot size variations
  - Stabilize hose instability

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* Whittum et al., PRL 1991
Assuming short bunches in the FFTB in October 2002:

- Access to the FFTB after Summer 2002 shutdown for installation (new laser, plasma source, ...)

- Request 3 runs of 3-4 weeks of access to the FFTB and 4 weeks of beam time, separated by 4-6 weeks for recovery, data analysis, and iteration on the experimental set-up

- Flexible!
PWFA “laboratory” built in the FFTB, and expertise acquired during E-157 and E-162

Ultra-short electron bunches available in the FFTB in 2002!

Demonstrate the acceleration of electrons in a long plasma (30 cm) with an accelerating gradient >1 GeV/m

From numerical simulations: gain of 1.75 GeV over 30 cm in a 5.8 GeV/m! (with $\sigma_z=100$ µm bunches)
ACCELERATING FIELD (ON AXIS)

3-D PIC, \( n_p = 5.6 \times 10^{15} \) cm\(^{-3} \), \( \sigma_z = 100 \) µm, \( \sigma_{x,y} = 20 \) µm

- Non sinusoidal wake
- Wake spike in the first acceleration region
- Large gradients where the beam charge is finite

In the non linear, blow-out regime \((n_b > n_p)\):

- Non sinusoidal wake
- Wake spike in the first acceleration region
- Large gradients where the beam charge is finite

\( eE_z(r=0) \) (GeV/m)

\( z \) (cm)

\( \approx 6 \) GeV/m “linear”

\( \approx 14 \) GeV/m non linear spike