Plasma Wakefield Energy Doubler for Cornell’s ERL

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Goal: $\sigma_z \sim \lambda_p$ as short as possible; $\sigma_r \ll \sigma_z$
Conventional RF acceleration: limited by material breakdown

Plasma acceleration: unlimited by material breakdown

$E_{\text{breakdown}} \sim 10^7 V/m$
$30 \text{ GeV} \Rightarrow 3 \text{ km (SLAC)}$

$E_{\text{accel}} \sim 10^{11} V/m$
$30 \text{ GeV} \Rightarrow 0.3 \text{ m}$
Quasi-monoenergetic \( (E_{\text{max}} = 160 \text{ MeV}^*) \)...


recent results: \( E_{\text{max}} = 300 \text{ MeV} \) (Michigan)
1 GeV (UC-Berkeley)

\[ Q \sim 1 \text{ nC} \]

\[ \pm 15 \text{ MeV} \]

\[ E > 70 \text{ MeV} \]

... & highly collimated \( (\sigma_\perp = 0.1 \pi \text{ mm-mrad}) \)
beam can be produced

\[ \sim 10 \text{ fs bunch duration} \]

convertible to 10 fs x-ray pulse
Emerging small-scale applications of LASER-plasma accelerators (0.1 - 1 GeV)

- Particle-beam-driven plasma accelerators fill a unique niche
- **HIGH ENERGY PHYSICS**
  - Plasma "afterburner", or energy doubler
- **Electrons & Protons from Laser-Plasma Accelerators**
- **Chemistry & Nutrition**
  - Radiolysis;
  - Food sterilization
- **Chemistry & Nutrition**
  - Radiolysis;
  - Food sterilization
- **Nuclear Engineering**
  - Rare, short-lived isotopes;
  - Transmutation of nuclear waste
- **Materials Science**
  - Flash γ-ray radiography of stressed materials
- **Nuclear Medicine**
  - Proton Cancer therapy;
  - \(^{11}\)C production for PET (U. Pittsburgh)
- **Structural Biology & Chemistry**
  - Fs-time resolved x-ray & electron diffraction
“Plasma Afterburner”: Booster for conventional accelerators

Chandrasekhar Joshi, *Scientific American* (Feb 2006)


**Goal:** double beam energy of conventional collider

**Demonstrated to date (E-157,162,164, 164x):**

- 27 GeV electron, 1 GeV positron energy gain in 0.1 m plasma
- > 2-fold improved focus

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**Main linear accelerator**

**Positron beam**

**Electron beam**

**Positron source**

**Positron return line**

**3 kilometers**

**200-MeV injector**

**Electron gun**

**50-GeV positrons**

**PLASMA AFTERBURNERS**

**50-GeV electrons**

**20 meters**

**Particle detector**

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SLAC / UCLA / USC collaboration
The largest accelerating gradients are realized in the densest plasmas, using the shortest drive bunches.

For optimized $k_p \sigma_z \equiv \sqrt{2}$:

$$(eE)_{linear} = 240 \frac{MeV}{m} \left( \frac{N}{4 \times 10^{10}} \right) \left( \frac{0.6}{\sigma_z [mm]} \right)^2$$


3D PIC simulations show the $\sigma_z^{-2}$ dependence predicted by linear theory ($n_b < n_0$) persists into nonlinear regime ($n_b > n_0$).
For optimized bunch length $k_p\sigma_z = \sqrt{2}$, best PWFA is realized in the nonlinear “blowout” regime: $n_b >> n_0$ AND $k_p\sigma_r < 1$


Desirable properties:
- uniform accelerating field profile
- linear focusing force, independent of z

$\Rightarrow$ drive pulse & trailing accelerating bunch propagate stably, w/ low emittance growth
Cornell ERL can pick up where SLAC left off

<table>
<thead>
<tr>
<th>Expt.</th>
<th>$\tau_{\text{bunch}}$ [fs]</th>
<th>$\sigma_z$ [µm]</th>
<th>$\sigma_r$ [µm]</th>
<th>$n_{\text{optimum}}$ [10$^{18}$ cm$^{-3}$]</th>
<th>$E_{z}^{\text{max}}$ [GeV/cm]</th>
<th>$L_{\text{plasma}}$ [cm]</th>
<th>$\Delta E$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC E-157</td>
<td>2000</td>
<td>600</td>
<td>$\sim$50</td>
<td>0.000016</td>
<td>0.0024</td>
<td>100</td>
<td>0.24</td>
</tr>
<tr>
<td>SLAC E-164X</td>
<td>70</td>
<td>20</td>
<td>$\sim$20</td>
<td>0.14</td>
<td>0.5</td>
<td>3-30</td>
<td>1-15</td>
</tr>
<tr>
<td>Cornell Short-Pulse</td>
<td>50</td>
<td>15</td>
<td>$&lt;5$</td>
<td>0.25</td>
<td>1.0</td>
<td>1-5</td>
<td>1-5</td>
</tr>
<tr>
<td>Cornell Ultra-Short Pulse</td>
<td>20</td>
<td>6</td>
<td>$&lt;2$</td>
<td>1.56</td>
<td>5</td>
<td>$\sim$1</td>
<td>5</td>
</tr>
</tbody>
</table>

- **E-157**: long bunch, $\sigma_r/\sigma_z << 1$, low density, low gradient
- **E-164X**: short bunch, $\sigma_r/\sigma_z \approx 1$, medium density, high gradient
- **Cornell**: ultrashort bunch, $\sigma_r/\sigma_z << 1$, high density, ultrahigh gradient

**THEORY SPARSE $\Rightarrow$ EXPERIMENTS NEEDED**
First Generation Experiment:
to perfect plasma wakes, we must SEE them

• Generate wakefields in dense plasma (~ $10^{18}$ cm$^{-3}$) using ultrashort, low emittance ERL bunches

• Measure wake structure by Frequency Domain Holography, using ~ mJ probe laser pulses synchronized w/ photocathode laser

• Compare FDH measurements with (PIC) simulations
Copper RF accelerator cavities must be precision-engineered.

Simulations show widely varying plasma wake structures...

...AND we can't even see them!

Driving Pulse

Electron density

Sinusoidal

Distorted sinusoid

Spherical “bubble”
Single-Shot “Frequency Domain Holography”

Chirped Probe is temporally long and records effect of multiple oscillations simultaneously, meaning technique is single-shot.

Ultra-intense Pump Pulse, 1 Joule, 30 fs, 800 nm
or Electron Bunch, 1 nC, 20-50 fs

Wakefield $n_e = n_0 + \delta n_e(t)$

Ionization Front

Fixed Delay, $\Delta t$

Chirped Reference Pulse (400 nm)

Chirped Probe Pulse (400 nm)

Signal HOLOGRAM

Null HOLOGRAM

Nicholas Matlis
Ph.D.’06
“Reading” the Hologram
(Full Electric Field Reconstruction)

**BASIC SCHEME**

1. Reconstruct spectral E-field of probe pulse from holographic spectrum

\[ E_{\text{probe}}(\omega) = |E(\omega)| \, e^{-i\phi(\omega)} \]

2. Fourier Transform to the time-domain to recover temporal phase

\[ E_{\text{probe}}(t) = |E(t)| \, e^{-i\delta\phi(t)} \]

3. Calculate electron density from extracted temporal phase

\[ \delta n_e(t) \]
Holographic snapshot of an ionization front


- $I_{pump} = 10^{16}$ W/cm$^2$
- single shot measurement

He$^2^+$

He$^+$

r (µm)

t (fs)

-500
500
Holographic snapshots of laser wakefields

\[ P \sim 10 \text{ TW}, \ I \sim 10^{18} \text{ W/cm}^2 \]

\[ d) \]

- Electron Density [cm\(^{-3}\)]
- Plasma Period [fs]

- \[ 6e18 \] to \[ 6e18 \]
- \[ 0e18 \] to \[ 6e18 \]

- \[ E_z^{\text{max}} \sim 3 \times 10^{10} \text{ V/m} \]
**Strong wakes have curved wavefronts**

\[ P \sim 30 \text{ TW}, \quad I \sim 3 \times 10^{18} \text{ W/cm}^2 \]

\[ n_e = 2.17 \times 10^{18} \text{ cm}^{-3} \]

\[ \gamma \approx 1 \]

\[ \omega_p = \left[ \frac{n_e e^2}{\varepsilon_0 m_e} \right]^{1/2} \]

\[ \gamma \approx 1.5 \]

**Importance of wavefront curvature:**

- collimates e⁻ beam
- threshold of wave-breaking & electron injection
- \( E_{z, max} \approx 1.5 \times 10^{11} \text{ V/m} \)

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Plasma wake physics to observe by FDH

- PWF microstructure vs. drive parameters ($\sigma_z/\sigma_r$, N) in the high density blowout regime, where theory is sparse and simulations problematic.
- Effect of beam loading & drive bunch depletion on wake structure
- Onset of wave breaking & electron injection from background plasma
- Onset of hosing instability

PWF-accelerated beam properties to measure

- energy
- energy spread
- transverse emittance
- bunch charge
- bunch length

Characterize x-rays emitted by...

- Re-injection into ERL undulators
- Betatron oscillations in ion column [e.g. $10^7$ photons @ 6.4 keV in .01° cone]$^1$
- Thomson scatter by counter-propagating intense laser pulse[$10^8$ photons@ 1keV]$^2$

$^1$ SLAC E-157  $^2$ T Phuoc, PRL 90, 075002 (2003), laser wakefield
Summary

• Plasma wakefield boosters can potentially add flexibility to the Cornell ERL at low cost
  - optional increased energy
  - auxiliary ultrashort hard x-ray source

• R&D using visualization methods such as Frequency Domain Holography, is needed to perfect them

• They may also provide low-cost upgrades for HEP accelerators
The Cornell ERL is well qualified for 2nd generation plasma afterburner accelerator experiments

- basic physics
- accelerator development

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>SLAC E-164X</th>
<th>Cornell ERL</th>
<th>Importance</th>
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</thead>
<tbody>
<tr>
<td>( \tau_{\text{bunch}} )</td>
<td>~70 fs</td>
<td>20-50 fs</td>
<td>resonantly drive WF in dense ( n_e &gt; 10^{17} \text{ cm}^{-3} ) plasma ( \Rightarrow ) high accelerating gradient ( E_z &gt; 100 \text{ GeV/m} )</td>
</tr>
<tr>
<td>transverse emittance</td>
<td>60 ( \times ) 15 mm-mrad</td>
<td>5 mm-mrad</td>
<td>tight focus ( \sigma_r &lt; \lambda_p \approx 10 \mu \text{m} ) { &quot;blowout&quot; regime: ( n_{\text{bunch}} &gt; n_e ) \bullet ( \sigma_r ), ( \lambda_p ), ( \sigma_r &lt; \lambda_p ) } \bullet ( n_{\text{bunch}} &gt; n_e ) \bullet ( \sigma_r ), ( \lambda_p ), ( \sigma_r &lt; \lambda_p ) \bullet ( n_{\text{bunch}} &gt; n_e ) \bullet ( \sigma_r ), ( \lambda_p ), ( \sigma_r &lt; \lambda_p )</td>
</tr>
<tr>
<td>bunch charge</td>
<td>~ 5 nC</td>
<td>~ 1 nC</td>
<td>\bullet \text{high S/N in physics experiments} \bullet \text{high average current from plasma WF accelerator}</td>
</tr>
<tr>
<td>repetition rate</td>
<td>10 Hz</td>
<td>~ MHz</td>
<td></td>
</tr>
</tbody>
</table>
Counter-propagating Thomson scatter: tunable, fs X-ray pulses on a table-top

Ta Phuoc et al., PRL 90, 075002 (2003)

Counter-propagating Laser

LWFA e⁻ beam
(≈ tens MeV)

μm

Undulator

X-ray beam: \( \lambda = \frac{\lambda_{\text{L}}}{4\gamma^2} \)

X-ray beam: \( \lambda = \frac{\lambda_{\text{und}}}{2\gamma^2} \)