Electron Beam Driven Wakefield Acceleration

M.J. Hogan, ICFA Workshop on Physics and Application of High Brightness Beams - Erice, Sicily 2005
Electron Beam Driven Wakefield Accelerators Have the potential to deliver accelerating gradients many orders of magnitude larger than conventional metallic structures.

Wakefield Accelerators Have Promising Potential.
Many Issues Being Addressed by **Experiments**:

<table>
<thead>
<tr>
<th>Material Issues</th>
<th>Dielectric</th>
<th>Plasma</th>
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<tr>
<td>• Breakdown of the dielectric</td>
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<td>• Breakdown of the dielectric-conducting boundary surface</td>
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<td>ANL AWA</td>
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<td>UCLA/SLAC T-481</td>
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<td>• Long, uniform high-density plasma sources can be difficult</td>
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<td>• Relativistic plasma-electrons, Ion motion</td>
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<td>BNL ATF PWFA</td>
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<td>UCLA/USC/SLAC E-164</td>
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<th>Optimum Drive Beam</th>
<th>Dielectric</th>
<th>Plasma</th>
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<tr>
<td>• High charge (100nC)</td>
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<td>BNL ATF Stella-LWFA</td>
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*Problems relating to the witness beam are still next generation (although near term) experiments*
Dielectric Wakefield Accelerator (DWA)

On Axis Accelerating Field & Dielectric Surface Field:

\[ E_{z,\text{vac}} = \frac{4Q}{a \left[ 2 \frac{\varepsilon}{\sqrt{\varepsilon - 1}} \Delta z + a \right]} \]

\[ \text{for } \Delta z \ll a \]

\[ E_{z,\text{vac}} = \frac{2Q}{a^2} \]

\[ E_{r,\text{surface}} = \frac{1}{\varepsilon_0 (2\pi)^{3/2} a \sigma_z} \frac{Q}{\varepsilon - 1} \frac{1}{\pi a^2} \left[ \frac{V}{m} \right] \]

Want:
- High Charge
- Short Bunches
- Narrow Tubes
Parameters of recent experiment:

- Cylindrical ceramic tube (cordierite)
- Inner radius: 5 mm, Outer radius: 7.5 mm
- Dielectric constant: 5
- Length: 102 mm
- Standing-wave structure
- Field probe to sample the field (-60 dB)
- RF mixer, down convert from 15 GHz to 5 GHz, analyze with high bandwidth scope
Argonne Wakefield Accelerator

Recent 15 GHz Wakefield Measurements

Output of mixer circuit

Excitation by single bunch and Two bunches separated by 1.5 ns:

~30 MV/m gradient. No signs of breakdown!
Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)

Existing bends compress to <100 fs

~1 Å

Damping Ring

50 ps

SLAC Linac

0.4 ps

20-50 GeV

FFTBB

<100 fs

Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)

1.5%

30 kA

80 fsec FWHM

28 GeV
Chamber @ FFTB Focal Point

Dielectric Tube Holder

End View of Fiber

Study Breakdown As a Function of Bunch Length and Fiber Diameter

200 μm ID

100 μm ID

\( E_z \) at the Dielectric Surface (V/m)

Beam Length \( \sigma_z \) (m)
Phase One of the Experiment

The first run of the experiment occurred in Aug 2005. The objective of the run was to examine breakdown thresholds. Direct Measurements of CCR will be attempted in the next run.

Major Observations:

- A sharp increase in visible emission from the capillaries near the mid-range of beam current, probably indicating breakdown.
- Principle form of damage to the dielectric wake structures appear to be vaporization of the aluminum cladding. The fused silica appeared substantially intact.

Aluminum Vaporized from the Fibers and Deposited on the Top Plate of the Holder

See Gil Travish Talk in WG4(?)
Plasma Wakefield Accelerator (PWFA)

- Space charge of **drive beam** displaces **plasma electrons**
- **Plasma ions** exert restoring force $\Rightarrow$ **Space charge oscillations**
- **Wake Phase Velocity** = Beam Velocity (like wake on a boat)

### Linear PWFA Theory:

- $E_{z,\text{linear}} \propto \frac{N}{\sigma_z^2}$ $\Rightarrow$ Short bunch!

- For $k_p\sigma_r \ll 1$ and $k_p\sigma_z \equiv \sqrt{2}$ or $n_p \propto \frac{1}{\sigma_z^2}$

- 2D/3D PIC Simulations have born out this dependence (snow plow etc...)

$E_z$: accelerating field
$N$: # e⁻/bunch
$\sigma_z$: gaussian bunch length
$k_p$: plasma wave number
$n_p$: plasma density
$n_b$: beam density
Multi-Bunch PWFA Experiment at Brookhaven ATF

**Goal**: Resonantly drive a plasma wakefield using a train of microbunches ~1μm wide separated at 10.6μm

- 10.6μm IFEL Bunches the Electron Beam (STELLA)
- The Bunched Electron Beam Resonantly Drives a Plasma Wake in the 10^{19} cm^{-3} Capillary Discharge Plasma (not in blow-out regime)
The electron beam density $\times 100$ (1), the theoretical wakefield (2) and the OSIRIS simulated wakefield (3) after 1mm of propagation in the plasma. Results for resonant plasma density ($n_0 = 1.0 \times 10^{19} \text{cm}^{-1}$) for 10.6$\mu$m bunch spacing. 

$[0.01 \, e/(m c \omega_p) = 30 \text{MV/cm}]$
Expected Energy Gain is 21MeV Over 3mm of Plasma (70MeV/cm)

Weak Focusing of the Electron Beam

Characterizing the plasma density using Stark broadening and CO2 transmission

Characterizing the electron bunching using CTR

Ensure the plasma density resonance and observe the energy gain
Seeded Self-Modulated Laser Wakefield Acceleration (Seeded SM-LWFA)

- New hybrid plasma-based acceleration scheme combining both plasma wakefield acceleration (PWFA) and laser wakefield acceleration (LWFA) [1]
  - Use ultrashort (<1 ps) seed e-beam pulse to generate wakefields in plasma
  - CO₂ laser pulse immediately follows and amplifies wakefields via SM-LWFA
  - Second e-beam pulse follows as witness and experiences energy exchange
- Experiment being performed at Brookhaven National Laboratory Accelerator Test Facility (ATF) using 0.5 - 1 TW CO₂ laser as part of STELLA-LW program
  - Use capillary discharge as plasma source (either polypropylene or gas-filled)
  - ATF has already demonstrated dual e-beam generation (i.e., seed & witness)
  - Can use chicane to compress seed to ~100 fs while not compressing witness
- Motivation: Provides means to use existing CO₂ laser beam and, at same time, may permit greater control of wakefield phase because wakefield does not start from noise as it typically does during SM-LWFA

Model Results for Seeded SM-LWFA

• Assumes: Seed pulse length = 118 fs, focus size = 50 \( \mu \text{m} \) (1\(\sigma\)), 199 pC
  Witness pulse length = 1.23 ps, focus size = 20 \( \mu \text{m} \) (1\(\sigma\))
  Plasma density = 0.89 \( \times \) \(10^{17}\) \( \text{cm}^{-3}\); Laser power = 0.5 TW
Energy Spectrum Prediction

• Assumes:
  - Seed pulse length = 118 fs, focus size = 50 µm (1σ), 199 pC
  - Witness pulse length = 1.23 ps, focus size = 20 µm (1σ)
  - Plasma density = 0.89 \times 10^{17} \text{ cm}^{-3}; \text{Laser power} = 0.5 \text{ TW}
  - Plasma acceleration length = 2 mm; e-beam energy = 64 \text{ MeV}

\( \tau_d \) is delay time between seed and witness pulses
UCLA/USC/SLAC PWFA Experiments at the FFTB

Focusing e⁻

\[ \sigma_0 \text{ Plasma Entrance } = 50 \, \mu \text{m} \]
\[ \epsilon_x = 12 \times 10^{-5} \, \text{m rad} \]
\[ \beta_0 = 1.16 \, \text{m} \]

Phase Advance \( \Psi \propto n_e^{1/2}L \)


X-ray Generation


Wakefield Acceleration e⁺

Relative Energy (MeV)

![Graph](graph.png)

Wakefield Acceleration e⁺


Matching e⁻

\[ \sigma_x = n_e L \]
\[ \epsilon_x = 18 \times 10^{-5} \, \text{m-rad} \]
\[ \beta_0 = 6.1 \, \text{cm} \]
\[ \alpha_0 = -0.6 \]

Phase Advance \( \Psi \propto n_e^{1/2}L \)


Electron Beam Refraction at the Gas–Plasma Boundary

\[ \theta \propto 1/\sin \phi \]

θ≈ϕ

BPM Data

Model

![Graph](graph.png)

Electron Beam Refraction at the Gas–Plasma Boundary

*Nature* 411, 43 (3 May 2001)
Accelerating Gradient > 27 GeV/m! (Sustained Over 10cm)

- Large energy spread after the plasma is an artifact of doing single bunch experiments
- Future experiments will accelerate a second “witness” bunch
- Electrons have gained > 2.7 GeV over maximum incoming energy in 10cm
- Confirmation of predicted dramatic increase in gradient with move to short bunches
- First time a PWFA has gained more than 1 GeV
- Two orders of magnitude larger than previous beam-driven results

Energy Gain >10 GeV in 30cm Plasma

• Spectrometer Re-design Necessary to Transport Low Energy Electrons
Always New Things to Look at!

Narrow Energy Spread

Trapped Particles
Future Experiments (~ 6 months)

- Redesign Spectrometer for Larger Energy Acceptance
- Try to Double Energy of Some Electrons in 1 Meter Plasma
- Two bunches via notch collimator in FFTB:
Conclusions:

• Exciting Time for Beam Driven Wakefield Experiments
• Dielectric Wakefield Accelerators show promise with good dielectric tolerance to large surface fields
• Plasma Wakefield Accelerators have demonstrated very large gradients and multi-GeV energy gain
• Much more work to be done:
  • Accelerate a second bunch (not just particles) with narrow energy spread and good emittance
  • Positrons??
  • Care needs to be taken when extrapolating to future scenarios and experiments designed accordingly
Argonne Wakefield Accelerator Group

UCLA/SLAC Ultra-High Gradient Cerenkov Wakefield Accelerator Experiment
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