Wakefield Acceleration in Dielectric Structures

J.B. Rosenzweig

UCLA Dept. of Physics and Astronomy

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Future colliders: ultra-high fields in the accelerator

- High fields in violent accelerating systems
  
  \[ \frac{eE_z}{mc\omega} \sim 1 \]

- High field implies short \( \lambda \)
  - Relativistic oscillations...
  - Limit peak power
  - Stored energy

- Challenges
  - Ultra-small beams
  - Structure breakdown
  - Pulsed heating
  - What sources < 1 cm?
Scaling the accelerator in size

- Lasers produce copious power (~J, >TW)
  - Scale in size by 4 orders of magnitude
  - $\lambda < 1\ \mu m$ gives challenges in beam dynamics
  - Reinvent resonant structure using dielectric (E163, UCLA)

- To jump to GV/m, only need mm-THz
  - Must have new source...
Promising paradigm for high field accelerators: wakefields

- Coherent radiation from bunched, $v \sim c$, e\textsuperscript{-} beam
  - *Any impedance* environment
  - Powers more exotic schemes: plasma, dielectrics
- Non-resonant, *short pulse* operation possible
- Intense beams needed by other fields
  - X-ray FEL
  - X-rays from Compton scattering
  - THz sources
High gradients, high frequency, EM power from wakefields: CLIC @ CERN

**CLIC wakefield-powered resonant scheme**

(concept borrowed from W. Gai...)

CLIC 30 GHz, 150 MV/m structures
The dielectric wakefield accelerator

- Higher accelerating gradients: GV/m level
  - Dielectric based, low loss, short pulse
  - Higher gradient than optical? Different breakdown mechanism
  - No charged particles in beam path...
- Use wakefield collider schemes
  - CLIC style modular system
  - Afterburner possibility for existing accelerators
- Spin-offs
  - High power THz radiation source
**Dielectric Wakefield Accelerator Overview**

- Electron bunch ($\beta \approx 1$) drives *Cerenkov wake* in cylindrical dielectric structure
- Variations on structure features
- Multimode excitation
- Wakefields accelerate trailing bunch
  - Mode wavelengths
    \[
    \lambda_n \approx \frac{4(b-a)}{n} \sqrt{\varepsilon - 1}
    \]
  - Peak decelerating field
    \[
    eE_{z,\text{dec}} \approx \frac{4N_b \gamma m_e c^2}{\sigma a} \sqrt{\frac{8\pi}{\varepsilon - 1}} \varepsilon \sigma + a
    \]
    Extremely good beam needed
  - Transformer ratio (unshaped beam)
    \[
    R = \frac{E_{z,\text{acc}}}{E_{z,\text{dec}}} \leq 2
    \]

**Design Parameters**
- $a, b, \sigma_z, \varepsilon$

Ez on-axis, OOPIC
Experimental History
Argonne / BNL experiments

- Proof-of-principle experiments
  (W. Gai, et al.)
  - ANL AATF
- Mode superposition
  - ANL AWA, BNL
- Transformer ratio improvement
  (J. Power, et al.)
  - Beam shaping
- Tunable permittivity structures
  - For external feeding
    (A. Kanareykin, et al.)

Gradients limited to <50 MV/m by available beam
T-481: Test-beam exploration of breakdown threshold

- Go beyond pioneering work at ANL
  - Much shorter pulses, small radial size
  - Higher gradients...
- Leverage off E167
- Goal: breakdown studies
  - Al-clad fused SiO$_2$ fibers
    - ID 100/200 µm, OD 325 µm, $L=1$ cm
  - Avalanche v. tunneling ionization
  - Beam parameters indicate $E_z \leq 11$GV/m can be excited
    - $3 \text{ nC, } \sigma_z \geq 20 \mu\text{m, } 28.5 \text{ GeV}$
- 48 hr FFTB run

T-481 “octopus” chamber
Breakdown Limits on Gigavolt-per-Meter Electron-Beam-Driven Wakefields in Dielectric Structures

M. C. Thompson,1,2,* H. Badakov,1 A. M. Cook,1 J. B. Rosenzweig,1 R. Tikhoplov,1 G. Travish,1 I. Blumenfeld,3
M. J. Hogan,3 R. Ischebeck,3 N. Kirby,3 R. Siemann,3 D. Walz,3 P. Muggli,4 A. Scott,5 and R. B. Yoder6

1Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA
2Lawrence Livermore National Laboratory, Livermore, California 94551, USA
3Stanford Linear Accelerator Center, Menlo Park, California 94025, USA
4University of Southern California, Los Angeles, California 90089, USA
5University of California, Santa Barbara, California 93106, USA
6Manhattan College, Riverdale, New York 10471, USA
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First measurements of the breakdown threshold in a dielectric subjected to GV/m wakefields produced by short (30–330 fs), 28.5 GeV electron bunches have been made. Fused silica tubes of 100 μm inner diameter were exposed to a range of bunch lengths, allowing surface dielectric fields up to 27 GV/m to be generated. The onset of breakdown, detected through light emission from the tube ends, is observed to occur when the peak electric field at the dielectric surface reaches 13.8 ± 0.7 GV/m. The correlation of structure damage to beam-induced breakdown is established using an array of postexposure inspection techniques.
T481: Beam Observations

View end of dielectric tube; frames sorted by increasing peak current
T-481: Inspection of Structure Damage

Damage consistent with beam-induced discharge

Aluminum vaporized from pulsed heating!

Laser transmission test

Bisected fiber
OOPIC Simulation Studies

- Parametric scans for design
- Heuristic model benchmarking
- Show pulse duration in multimode excitation... hint at mechanism
- **Determine field levels in experiment: breakdown**
  - Gives breakdown limit of 5.5 GV/m deceleration field

Example scan, comparison to heuristic model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric inner diameter ((2a))</td>
<td>100 (\mu)m</td>
</tr>
<tr>
<td>Dielectric outer diameter ((2b))</td>
<td>324 (\mu)m</td>
</tr>
<tr>
<td>Dielectric relative permittivity ((\varepsilon))</td>
<td>(~3)</td>
</tr>
<tr>
<td>Number of (e^-) per bunch ((N_b))</td>
<td>(1.4 \times 10^{10})</td>
</tr>
<tr>
<td>RMS bunch length ((\sigma_z))</td>
<td>100 – 10 (\mu)m</td>
</tr>
<tr>
<td>RMS bunch radius ((\sigma_r))</td>
<td>10 (\mu)m</td>
</tr>
<tr>
<td>Beam energy</td>
<td>28.5 GeV</td>
</tr>
<tr>
<td>Maximum radial field at dielectric surface</td>
<td>27 GV/m</td>
</tr>
<tr>
<td>Maximum decelerating field (vacuum)</td>
<td>11 GV/m</td>
</tr>
<tr>
<td>Maximum accelerating field (vacuum)</td>
<td>16 GV/m</td>
</tr>
</tbody>
</table>
E169 Collaboration

H. Badakov$^\alpha$, M. Berry$^\beta$, I. Blumenfeld$^\beta$, A. Cook$^\alpha$, F.-J. Decker$^\beta$, M. Hogan$^\beta$, R. Ischebeck$^\beta$, R. Iverson$^\beta$, A. Kanareykin$^\epsilon$, N. Kirby$^\beta$, P. Muggli$^\gamma$, J.B. Rosenzweig$^\alpha$, R. Siemann$^\beta$, M.C. Thompson$^\delta$, R. Tikhoplav$^\alpha$, G. Travish$^\alpha$, R. Yoder$^\zeta$, D. Walz$^\beta$

$^\alpha$Department of Physics and Astronomy, University of California, Los Angeles
$^\beta$Stanford Linear Accelerator Center
$^\gamma$University of Southern California
$^\delta$Lawrence Livermore National Laboratory
$^\zeta$Manhattanville College
$^\epsilon$Euclid TechLabs, LLC
Collaboration spokespersons
E-169 Motivation

- Take advantage of unique experimental opportunity at SLAC
  - FACET: ultra-short intense beams
  - Advanced accelerators for high energy frontier
  - Very promising path: dielectric wakefields
- Extend successful T-481 investigations
  - Multi-GV/m dielectric wakes
  - Complete studies of transformational technique
E169 at FACET: overview

- Research GV/m acceleration scheme in DWA
- Goals
  - Explore breakdown issues in detail
  - Determine usable field envelope
  - Coherent Cerenkov radiation measurements
  - Explore alternate materials
  - Explore alternate designs and cladding
    - Radial and longitudinal periodicity...
  - Varying tube dimensions
    - Impedance change
    - Breakdown dependence on wake pulse length

- Approved experiment (EPAC, Jan. 2007)
- Awaits FACET construction

Already explored at UCLA Neptune
Observation of THz Coherent Cerenkov Wakefields @ Neptune

- Chicane-compressed (200 μm) 0.3 nC beam
  - Focused with PMQ array to $\sigma_r \sim 100 \text{ μm} (a=250 \text{ μm})$
- Single mode operation
  - Two tubes, different $b$, THz frequencies
- Horn-launched quasi-optical transport
- Autocorrelation in Michelson interferometer

![Measured Power Spectrum](image_url)
E-169: High-gradient Acceleration

Goals in 3 Phases

• **Phase 1: Complete breakdown study (when does E169->E168!)**
  - ✓ explore \((a, b, \sigma_z)\) parameter space
  - ✓ Alternate cladding
  - ✓ Alternate materials (e.g. CVD diamond)
  - ✓ Explore group velocity effect \(T = L_d/(c - v_g) \leq eL_d/c(\varepsilon - 1)\)

• **Coherent Cerenkov (CCR) measurement**
  - ✓ Total energy gives field measure
  - ✓ Harmonics are sensitive \(\sigma_z\) diagnostic

\[
\begin{align*}
U_C & \approx \frac{eN_b E_{z,dec} L_d}{2} \\
U_n & \approx \frac{\pi^2 n N_b^2 r_c m e^2 \sigma_z^2 L_d}{2a(b-a)^2 \sqrt{8\pi(\varepsilon - 1)\varepsilon \sigma_z + (\varepsilon - 1)a}} \exp \left[ \frac{n \pi \sigma_z}{2(b - a)\sqrt{\varepsilon - 1}} \right]^2
\end{align*}
\]

| \(\sigma_z\) | \(\geq 20 \mu\text{m}\) |
| \(\sigma_r\) | \(< 10 \mu\text{m}\) |
| \(U\) | 25 GeV |
| \(Q\) | 3 - 5 nC |

FACET beam parameters for E169: high gradient case
E-169 at FACET: Phase 2 & 3

- **Phase 2:** Observe acceleration
  - ✔ 10-33 cm tube length
  - ✔ longer bunch, acceleration of tail
  - ✔ “moderate” gradient, 1-3 GV/m
  - ✔ single mode operation

- **Phase 3:** Scale to 1 m length
  - ✔ Alignment, transverse wakes, BBU
  - ✔ Group velocity & EM exposure

<table>
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<tr>
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<th>Value</th>
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<tbody>
<tr>
<td>$\sigma_z$</td>
<td>50-150 $\mu$m</td>
</tr>
<tr>
<td>$\sigma_r$</td>
<td>&lt; 10 $\mu$m</td>
</tr>
<tr>
<td>$E_b$</td>
<td>25 GeV</td>
</tr>
<tr>
<td>$Q$</td>
<td>3 - 5 nC</td>
</tr>
</tbody>
</table>

FACET beam parameters for E169: acceleration case
Experimental Issues: Alternate DWA design, cladding, materials

- Aluminum cladding in T-481
  - Vaporized at moderate wake amplitudes
  - Low vaporization threshold; low pressure and thermal conductivity of environment

- Dielectric cladding
  - Lower refractive index provides internal reflection
  - Low power loss, damage resistant

- Bragg fiber?
  - Low HOM

- Alternate dielectric: CVD diamond
  - Ultra-high breakdown threshold
  - Doping gives low SEC
  - First structures from Euclid Tech.
Control of group velocity with periodic structure

- For multiple pulse beam loaded operation in LC, may need $low \nu_g$
- Use periodic DWA structure in $\sim \pi$-mode
- Example: simple SiO$_2$-diamond structure
Alternate geometry: slab

- Slab geometry suppresses transverse wakes*
  - Also connects to optical case
- Price: reduced wakefield
- Interesting tests at FACET
  - Slab example, >600 MV/m

Towards a linear collider...

- **What have we learned?**
  - One might use gradients of 2-3 GV/m
    - Near to plasma w/o attendant challenges
  - Frequencies of interest are ~ few THz (?)
  - Need nC level drive bunch, <50 μm rms

- **What do we need to learn?**
  - Usable gradients, materials, aging
  - Structure design features (e.g. slab, $v_g$ control)
  - Transverse wakes, beam loading
  - Full system considerations
Parameter list: a departure point

<table>
<thead>
<tr>
<th></th>
<th>ILC Nominal</th>
<th>DWA LC</th>
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<tbody>
<tr>
<td>E&lt;sub&gt;cms&lt;/sub&gt;</td>
<td>GeV</td>
<td>1000</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>e</td>
<td>2.0E+10</td>
</tr>
<tr>
<td># bunches/train</td>
<td>#</td>
<td>2820</td>
</tr>
<tr>
<td>train repetition rate</td>
<td>kHz</td>
<td>5.0E-02</td>
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<tr>
<td>final bunch length</td>
<td>psec</td>
<td>1.00</td>
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<tr>
<td>design wavelength</td>
<td>micron</td>
<td>230609.58</td>
</tr>
<tr>
<td>Normalized emittances</td>
<td>micron</td>
<td>10/0.04</td>
</tr>
<tr>
<td>I. P. Spot Size</td>
<td>nm</td>
<td>554/3.5</td>
</tr>
<tr>
<td><strong>Enh. Luminosity</strong></td>
<td>/cm&lt;sup&gt;2&lt;/sup&gt;/s</td>
<td><strong>4.34E+34</strong></td>
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<tr>
<td>Beam Power</td>
<td>MW</td>
<td>22.6</td>
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<tr>
<td>Wall-Plug Power</td>
<td>MW</td>
<td>104.0</td>
</tr>
<tr>
<td>Gradient</td>
<td>MeV/m</td>
<td>30</td>
</tr>
<tr>
<td>Total Linac Length</td>
<td>km</td>
<td>33.3</td>
</tr>
</tbody>
</table>

Calculator from E. Colby

Based on multibunch trains
Other optimizations possible (slab structures)
Conclusions

- Very promising technical approach in DWA
  - Physics surprisingly forgiving thus far
  - Looks like an accelerator!
- FACET should provide critical test-bed
- Linear collider system presents new challenges
  - Unique problems of short $\lambda$, wakefields
  - Develop straw man now!