Wakefield Acceleration in Dielectric Structures

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The Physics and Applications of High Brightness Electron Beams

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Scaling the accelerator in size

- **Lasers** produce copious power (\(\sim J, >TW\))
  - 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, $\nu \sim c, e^-$ 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 drive beam extraction structure

CLIC wakefield-powered resonant scheme

CLIC 30 GHz, 150 MV/m structures

(concept borrowed from W. Gai…)

Initial Electron Pulse
4.6 A - 2 GeV - 16μs

Delay Line
39 m

Drive Beam Accelerator
Accelerating Structures 937 MHz

Combiner Ring
78 m

Main Beam Accelerator Units

Transfer Structures - 30 GHz

D. B. Decelerator Unit
The dielectric wakefield accelerator

- High 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
The "wake" mechanism: coherent Cerenkov radiation

Cerenkov angle

Radiation

Maximum frequency favored, minimum bunch length
Dielectric Wakefield Accelerator

Overview

- Electron bunch ($\beta \approx 1$) drives *Cerenkov wake* in cylindrical dielectric structure
- Dependent on structure properties
- Multimode excitation
- Wakefields accelerate trailing bunch
- Mode wavelengths (quasi-optical)

**Design Parameters**

- Peak decelerating field
- Transformer ratio (unshaped beam)

*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 $\mu$m, OD 325 $\mu$m, $L=1$ cm
  - Avalanche v. tunneling ionization
  - **Beam parameters indicate $E_z \leq 11$ GV/m can be excited**
    - 3 nC, $\sigma_z \geq 20$ $\mu$m, 28.5 GeV
- 48 hr FFTB run
Breakdown Limits on Gigavolt-per-Meter Electron-Beam-Driven Wakefields in Dielectric Structures

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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.
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

ultrashort bunch

longer bunch
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Dielectric inner diameter ($2a$)</td>
<td>100 µm</td>
</tr>
<tr>
<td>Dielectric outer diameter ($2b$)</td>
<td>324 µm</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 µm</td>
</tr>
<tr>
<td>RMS bunch radius ($\sigma_r$)</td>
<td>10 µm</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. Ischebecker$^\beta$, R. Iverson$^\beta$, A. Kanareykin$^\varepsilon$, 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$^\beta$

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Collaboration spokespersons
E-169 Motivation

- Take advantage of unique experimental opportunity at SLAC
  - FACET: ultra-short intense beams
  - Advanced accelerators for high energy frontier
  - Plasma and dielectric wakefields 1st in line
- 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 $\sigma_r \sim 100$ μm ($a = 250$ μm)
- Single mode operation
  - Two tubes, different $b$, THz frequencies
- Horn-launched quasi-optical transport
- Autocorrelation in Michelson interferometer

![Measured Power Spectrum](image)
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

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

<table>
<thead>
<tr>
<th>(\sigma_z)</th>
<th>(\geq 20 \mu m)</th>
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<tr>
<td>(\sigma_r)</td>
<td>(&lt; 10 \mu m)</td>
</tr>
<tr>
<td>(U)</td>
<td>25 GeV</td>
</tr>
<tr>
<td>(Q)</td>
<td>3 - 5 nC</td>
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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

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<td>&lt; 10 µm</td>
</tr>
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<td>$E_b$</td>
<td>25 GeV</td>
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<td>$Q$</td>
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FACET beam parameters for E169: acceleration case

* Longitudinal E-field

Momentum distribution after 33 cm (OOPIC)
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 $lowv_g$

- Low charge gives smaller, shorter beams
  - Can even replace large Q driver
- Use periodic DWA structure in $\sim \pi$-mode

Example: SiO$_2$-diamond structure
Analytical and simulation approach to zero VG structure

- Write matrix treatment of Ez and its derivative
- Evaluate through period, make phase advance $\mu = \pi$
- Check, optimize with OOPIC
Initial multi-pulse experiment: uniform SiO$_2$ DWA at BNL ATF

- Exploit Muggli’s pulse train slicing technique
  - 400 $\mu$m spacing, micro-Q=25 pC, $\sigma_z=80$ $\mu$m
  - DWA dimensions: $a=100$ $\mu$m, $b=150$ $\mu$m
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

Alternate species: e+

- Positrons have different issues
- Polarity of electric field pulls electrons out of material
  - Highest radial electric at driver
- Breakdown could be enhanced
  - Fundamental physics issue
- Unique opportunity at FACET
Conclusions

- Very promising technical approach in DWA
  - Physics surprisingly forgiving thus far
  - Looks like an accelerator!
- FACET and ATF provide critical test-beds
- Need to explore more:
  - Breakdown, materials
  - Advanced geometries