High Frequency, High Gradient Dielectric Wakefield Acceleration Experiments at SLAC and BNL

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Scaling the accelerator in size

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

**Resonant dielectric laser-excited structure** (with HFSS simulated fields)

- GV/m allows major reduction in size, cost
- To jump to GV/m, mm-THz may be better:
  - Beam dynamics, breakdown scaling
  - Must have new source...
Promising paradigm for high field accelerators: wakefields

- Coherent radiation from bunched, $\nu \sim c$, e$^-$ beam
  - *Any slow-wave* environment
  - Powers exotic schemes: plasma, dielectrics
- Resonant or non-resonant (*short pulse*) operation
- High average power beams can be produced
  - Tens of MW, beats lasers...
- Intense beams needed by many fields
  - X-ray FEL
  - X-rays from Compton scattering
  - THz sources
Schematic of wakefield-based collider

(concept borrowed from W. Gai…)

• Similar to original CLIC scheme
• Study for plasma wakefield accelerator
  • $\gamma\gamma$ due to charge asymmetry in PWFA
  • Not a problem for DWA…
The dielectric wakefield accelerator

- **High accelerating gradients: GV/m level**
  - Dielectric based, low loss, short pulse
  - Higher gradient than optical?
  - Unlike plasma, charged particles in beam path...

- **Use wakefield collider schemes**
  - CLIC style modular system
  - *Afterburner* (energy multiplier) possible for existing accelerators

- **Spin-offs**
  - High power THz radiation source (e.g. E. Chiadroni)

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**Coherent Cerenkov scaling**

\[
\frac{dU}{dz} \propto k_{\text{max}}^2 \propto \sigma_z^{-2}
\]

\[
\frac{dU}{dz} \propto \int (n - 1)kdk \propto k_{\text{max}}^2
\]
Dielectric Wakefield Accelerator
Overview

- Electron bunch ($\beta \approx 1$) drives wake in cylindrical dielectric structure
  - Dependent on structure properties
  - Generally multi-mode excitation
- Wakefields accelerate trailing bunch
- Mode wavelengths (quasi-optical)
  \[ \lambda_n \approx \frac{4(b - a)}{n} \sqrt{\varepsilon - 1} \]
- Peak decelerating field
  \[ eE_{z,\text{dec}} \approx -\sqrt{\frac{4N_br}{8\pi}} m_ec^2 \left( \frac{\varepsilon \sigma}{\varepsilon - 1} + a \right) \]
  Extremely good beam needed
- Transformer ratio (unshaped beam)
  \[ R = \frac{E_{z,\text{acc}}}{E_{z,\text{dec}}} \leq 2 \]
T-481: Test-beam exploration of breakdown threshold

- 1st ultra-short, high charge beams
- Beyond pioneering work at ANL...
  - Much shorter pulses, small radial size
  - Higher gradients...
- Leverage off E167 PWFA
- Goal: breakdown studies
  - Al-clad fused SiO₂ fibers
    - ID 100/200 µm, OD 325 µm, L=1 cm
  - Avalanche v. tunneling ionization
  - Beam parameters indicated $E_z \leq 12 \text{GV/m}$ can be excited
    - 3 nC, $\sigma_z \geq 20 \mu\text{m}$, 28.5 GeV
- 48 hr FFTB run

T-481 “octopus” chamber
Methods and Results

- Multiple tube assemblies
- Scanning of bunch lengths for wake amplitude variation
- Vaporization of Al cladding... dielectric more robust
- Observed breakdown threshold (field from simulations)
  - 13.8 GV/m surface field
  - 5.5 GV/m deceleration field
  - Multi-mode effect?
- Correlations to post-mortem inspection

- Longer bunch
- Ultrashort bunch
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.
Beam Observations and Analysis

View end of dielectric tube; frames sorted by increasing peak current

Breakdown determined by benchmarked OOPIC simulations

Breakdown limit: 5.5 GV/m decel. field

Multi-mode excitation — short, separated pulses — gives better breakdown dynamics
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Collaboration spokespersons
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
    - Slab structure (permits higher $Q$, low wakes)
    - Radial and longitudinal periodicity…
  - Varying tube dimensions
    - Impedance change
    - Breakdown dependence on wake pulse length

- Awaits FACET construction
  - Reapproval needed
  - Add AWA group to collaboration
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
  - Extremely narrow line width in THz
    - Higher power, lower width than THz FEL
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E-169 at FACET: Acceleration

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

- Phase 3: Accelerated beam quality
  - ✓ Witness beam
  - ✓ Alignment, transverse wakes, BBU
  - ✓ Group velocity & EM exposure \( t = \frac{L}{c - v_g} \)
  - ✓ Positrons. Breakdown is different?

| FACET beam parameters for E169: acceleration case |
|------------------|-----------------|
| \( \sigma_z \)   | 50-150 \( \mu \)m |
| \( \sigma_r \)   | < 10 \( \mu \)m   |
| \( E_b \)        | 25 GeV           |
| \( Q \)          | 3 - 5 nC         |

Longitudinal E-field

Momentum distribution after 33 cm (OOPIC)
E-169 at FACET: Acceleration

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Witness beam, acceleration and BBU
A High Transformer Scenario using Dielectric Wakes

- How to reach high energy with DWAs?
- Enhanced transformer ratio with *ramped beam*
- Does this work with *multi-mode* DWA?
- Scenario: 500-1000 MeV ramped driver; 5-10 GeV FEL injector in <10 m
A FACET test for light source scenario

- Beam parameters: $Q=3 \text{nC}$, ramp $L=2.5 \text{ mm}$, $U=1 \text{ GeV}$
- Structure: $a=100 \text{ \mu m}$, $b=100 \text{ \mu m}$, $\varepsilon=3.8$
- Fundamental $f=0.74 \text{ THz}$
- Performance: $E_z>\text{GV/m}$, $R=9-10$ (10 GeV beam)
- Ramp achieved at UCLA. Possible at ATF, FACET?
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Ramped beam using sextupole-corrected dogleg compression

Multipulse operation: control of group velocity

- **Multiple pulse beam-loaded operation** in linear collider, needs low $v_g$

- Low charge gives smaller (low $\varepsilon$), shorter beams
  - Can even replace large Q driver
  - Use *periodic DWA* structure in $\sim \pi$-mode, resonant excitation

Example: SiO$_2$/diamond structure
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Example: SiO$_2$/diamond structure
Initial multi-pulse experiment: uniform SiO$_2$ DWA at BNL ATF

- Exploit Muggli pulse train slicing technique


Correlated energy chirp from linac

Nguyen, NIMA 96 P. Emma, PRL 04
First results from BNL multi-pulse experiments

- Array of 1 cm tubes
  - Si02, diamond!
  - 325-660 μm λ
- Operation of pulse train with both chirp signs
  - Sextupole correction used
  - CTR autocorrelation
- Single bunch wakes observed
- Next: resonant wake excitation, CCR

4-drive + witness in spectrometer

CTR autocorrelation and FFT
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CTR autocorrelation and FFT

Single drive spectrum shows acceleration and deceleration
To a GV/m: multiple pulse DWA experiment at SPARC/X (LNF)

- Uses laser comb technique
- Bunch periodicity: 190 µm (0.63 ps)
  - 0.5 of BNL case
  - Scaled structure
- 125 pC/pulse @ 750 MeV
- 4 pulses + witness
- 1 GV/m, energy doubling in <70 cm
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>1.1 GV/m wakes in scaled DWA@SPARX
Conclusions

- Very promising technical approach in DWA
  - Physics surprisingly forgiving thus far
  - Looks like an accelerator!
  - Many open questions still to resolve for GV/m

- Pushing towards applications
  - Linear collider: multi-pulse
  - FEL: booster for reaching hard X-rays in few m

- Expect rapid experimental progress
  - 1st ATF; then FACET, SPARC/X...