Survey of Advanced Dielectric Wakefield Accelerators

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Argonne National Laboratory

2007 Particle Accelerator Conference
Outline

- Dielectric Wakefield Acceleration experiments (more references in Proceedings paper)
- Argonne has been a major contributor (Euclid Techlabs)
- Yale / Omega-P / Columbia / Kharkov Institute collaboration
- UCLA / SLAC / USC / LLNL / Euclid Techlabs collaboration
First Demonstration of Dielectric Wakefield Acceleration

- Argonne Accelerator Test Facility (AATF) in late 1980s

- 20 MeV drive beam (1 - 5 nC), and 16 MeV witness beam from the same thermionic RF gun

- Detailed mapping of wake potential (160 keV)

- Lesson: polymer based dielectrics charge up; ceramics are fine
- 14 MeV drive beam (10 – 100 nC), and 4 MeV witness beam from distinct photocathode RF guns
- Bunch train generation: four bunches of 10 nC
Wakefield Acceleration at AWA

- Collinear wakefield acceleration: 15 MV/m
- First TBA with dielectric loaded structures: 3.5 MV/m deceleration in Stage I, 7 MV/m acceleration in Stage II
91 GHz Planar Dielectric Wakefield Accelerator at SLAC


- Planar dielectric structure in a ring resonator circuit.
- Dielectric slab: $0.3 \times 0.8 \times 25.4 \text{ mm}^3$ alumina, $\varepsilon = 9.5$
- Structure: $a = 360 \ \mu\text{m}$, $b = 660 \ \mu\text{m}$, $w = 800 \ \mu\text{m}$
- Beam: 300 MeV, 100 ns, 0.5 A, 11.4 GHz ($\times 8$)
- Measurements: 20 MV/m, 200 kW, 42 MΩ/m
New AWA Drive Beamline

Drive Gun | Linac & Beam Optics | Wakefield Structure
---|---|---
ICT1 | YAG1 | YAG2 | YAG3 | YAG4 | ICT2 | YAG5
GV | GV | Slits | BPM | BPM | BPM | BPM

4.5 m

Single bunch operation
- \( Q = 1-100 \) nC (reached 150 nC)
- 15 MeV, 2 mm bunch length (rms), emittance < 200 mm mrad (at 100 nC)
- High Current: \( \sim 10 \) kA

Bunch train operation
- 4 bunches x 10 nC
- 64 bunches x 50 nC \( \rightarrow \) 50 ns long (future)
### Experimental Setup for High Gradient Tests

**WF signal**

**RF field probe (- 60 dB)**

**Monitor for breakdown**

**Infer Gradients from MAFIA**

<table>
<thead>
<tr>
<th>SW Structure</th>
<th>#1 C10-102</th>
<th>#2 C10-23</th>
<th>#3 C5.5-28</th>
<th>#4 Q3.8-25.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Cordierite</td>
<td>Cordierite</td>
<td>Cordierite</td>
<td>Quartz</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>4.76</td>
<td>4.76</td>
<td>4.76</td>
<td>3.75</td>
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<tr>
<td>Freq. of TM01n</td>
<td>14.1 GHz</td>
<td>14.1 GHz</td>
<td>9.4 GHz</td>
<td>8.6 GHz</td>
</tr>
<tr>
<td>Inner radius</td>
<td>5 mm</td>
<td>5 mm</td>
<td>2.75 mm</td>
<td>1.9 mm</td>
</tr>
<tr>
<td>Outer radius</td>
<td>7.49 mm</td>
<td>7.49 mm</td>
<td>7.49 mm</td>
<td>7.49 mm</td>
</tr>
<tr>
<td>Length</td>
<td>102 mm</td>
<td>23 mm</td>
<td>28 mm</td>
<td>25.4 mm</td>
</tr>
<tr>
<td>Wakefield Gradient</td>
<td>0.45 MV/m/nC</td>
<td>0.5 MV/m/nC</td>
<td>0.91 MV/m/nC</td>
<td>1.33 MV/m/nC</td>
</tr>
</tbody>
</table>
Wakefield Measurements: Structure #1  (C10-102)

46 nC → 21 MV/m
MAFIA Simulation of Structure #1 (C10-102)

Snapshots of wakefield amplitude
Wakefield Measurements: Structure #2 (C10-23)

Measured and simulated $E_r$ probe signals

Measured and simulated $E_r$ probe signals

86 nC $\rightarrow$ 43 MV/m 😊
Wakefield Measurements: Structure #3 (C5.5-28)

Er of Wakefield Signal @ 86 nC single bunch

Power Spectrum

86 nC → 78 MV/m
MAFIA Simulation of Structure #3 (C5.5-28)

E-field pattern

$W_z > 1 \text{MV/m} @ 1 \text{nC for 10GHz Structure}$
Wakefield Measurements: Structure #4 (Q3.8-25.4)

75 nC → 100 MV/m  😊😊
Dielectric Loaded Structures at AWA: Steadily Increasing Accelerating Gradients

- The 1990s: ~10 MV/m
- Structure #1 (Summer 2005): 21 MV/m
- Structure #2 (Winter 05/06): 43 MV/m
- Structure #3 (Summer 2006): 78 MV/m
- Structure #4 (Spring 2007): 100 MV/m

Next Steps:
- Test more structures
- Cesium telluride photocathodes (long, high charge bunch trains)
- Additional klystron (thanks to B. Carlsten, S. Russell, and DOE !!)
- Complete new RF gun
- Restore two-beam-accelerator capability
An Example of Two-Beam Accelerator (Future Goal)

• Drive beam: 64 bunches of 50 nC, each separated by one RF period, generating a 50 ns long RF pulse.

• Stage I (28 cm long): 2a=11 mm, 2b=22 mm, $\varepsilon = 4.6$, 45 MV/m deceleration field, generating 500 MW (flat top).

• Stage II (85 cm long): 2a= 6mm, 2b= 11 mm, $\varepsilon = 20$, 112 MV/m acceleration field, yielding a total acceleration of 95 MeV.
Two Beam Accelerator Design

<table>
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<tr>
<th></th>
<th>Drive</th>
<th>Witness</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (mm)</td>
<td>6.02</td>
<td>3.00</td>
</tr>
<tr>
<td>b (mm)</td>
<td>11.17</td>
<td>5.406</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>4.6</td>
<td>20</td>
</tr>
</tbody>
</table>

Frequency (GHz)

S11 (dB)
Development of a 7.8 GHz Power Extractor (deceleration structure + coupler)

dielectric = cordierite
**7.8GHz Power Extractor**

Detected voltage signal 
(q = 66nC, $\sigma_z$=2mm)

Spectrum of the signal 
(q = 66nC, $\sigma_z$=2mm)

Generated power vs. charge 
(single bunch test)

- Measured results
- Theoretical value
**Bunch Train through Power Extractor**

*Figure: Laser beam splitter*

*Figure: Spectrum of voltage signal*

*Figure: Wakefield superposition observed*

- **Bunch 1**, $q = 1.32 \text{nC}$
- **Bunch 2**, $q = 1.26 \text{nC}$
- **Bunch 3**, $q = 1.11 \text{nC}$
- **Bunch 4**, $q = 1.15 \text{nC}$
- **Bunch 1&2**, $q_{\text{total}} = 2.87 \text{nC}$
- **Bunch 3&4**, $q_{\text{total}} = 2.56 \text{nC}$
- **Bunch 1&2&3&4**, $q_{\text{total}} = 5.54 \text{nC}$
Wakefield Transformer Ratio Enhancement Experiment at AWA*

- Transformer ratio limited: Wakefield theorem says: A trailing beam cannot gain more than twice of the drive beam peak energy loss in a collinear wakefield scheme if the drive beam is longitudinal symmetric distributed, which results in the accelerated beam can not gain much due to the limited drive beam energy.

- The asymmetric bunch distribution will beat R<2 limit---the principal goal of this experiment is to demonstrate this idea.


Reference: Schutt et. al., Nor Ambred, Armenia, (1989)

* This work is a collaboration with Euclid Techlabs, LLC. The results were published in Phys. Rev. Lett. 98 (2007) 144801. This work was supported by DoE SBIR funding.
Measurements

This is measured wakefield transformer ratio enhancement! Transform Ratio R was enhanced for two ramped bunches is 3 in theory and 2.3 in measurement.
HG two-beam wake field accelerator using a two-channel rectangular dielectric structure*

J.L. Hirshfield$^{1,2}$, T.C. Marshall$^{2,3}$, V.P. Yakovlev$^2$, G.V. Sotnikov$^{2,4}$, C.B. Wang

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$^2$Omega-P, Inc.
$^3$Columbia University
$^4$Kharkov Institute of Physics and Technology

*Research sponsored by US DoE, DHEP
Features of a two-beam dielectric wake field accelerator (DWFA):

- High adjustable transformer ratio $T \gg 2$;
- Wall slots and bunch location that may help suppress HOM's;
- Simple but precise fabrication of planar dielectric elements;
- Continuous coupling of energy from drive to accelerated bunch;
- No need for coupling/transfer structures;
- Continuous pumpout of narrow channels through wall slots;
- High accelerating fields in the single bunch mode.
E-169: Wakefield Acceleration in Dielectric Structures

A proposal for experiments at the SABER facility

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$^\gamma$University of Southern California
$^\delta$Lawrence Livermore National Laboratory
$^\varepsilon$Euclid TechLabs, LLC

Collaboration spokespersons
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
  \[ eE_{z,\text{dec}} \approx -4N_b \frac{m_e c^2}{\alpha \sqrt{\varepsilon-1}} \]

- Transformer ratio
  \[ R = \frac{E_{z,\text{acc}}}{E_{z,\text{dec}}} \leq 2 \]

Design Parameters: \( a, b, L_d, \varepsilon, N_b, \sigma_z \)

Ez on-axis, OOPIC

Extremely good beam needed
Goal: breakdown studies
- Al-clad fused silica fibers
  - ID 100/200 μm, OD 325 μm, L=1 cm
- Avalanche v. tunneling ionization
- Beam parameters indicate ≤
- 30 GeV, 3 nC, $\sigma_z \geq 20$ μm
Significant and steady progress being made in the development of Dielectric Wakefield Accelerators!