Acknowledgements and Contributions:

UCLA – G. Andonian, S. Barber, B. O’Shea, O. Williams, A. Fukasawa, A. Valloni, K. Fitzmorris, P. Hoang, J. Harrison, J.B. Rosenzweig


BNL ATF – M. Babzien, M. Fedurin, K. Kusche, C. Swinson, ATF staff.


MPI – P. Muggli

Yale/Omega P – S. Schelkunov, T. C. Marshall, G. Sotnikov, J.L. Hirshfield

LANL – E. Simakov, D. Shegolkov

FNAL/NIU– P. Piot, D. Mihalcea
Dielectric Wakefield Acceleration (DWA)

Drive beam: Energy $\uparrow$, Charge $\uparrow$ Bunch length $\downarrow$ Emittance $\downarrow$

$$
\sigma_r = \left( \frac{\varepsilon N}{\gamma} \beta \right)^{1/2}
$$

$$
W_z(z) \approx \frac{Q}{a^2} \exp \left[-2 \left( \frac{\pi \sigma_z}{\lambda_n} \right)^2 \right] \cos(kz)
$$

Dielectric based accelerator advantages:
- design simplicity: no tight tolerances;
- scalability: GHz, THz
- 0.5-1.0 GV/m gradient
- maximal field magnitude at the center
- small transverse size allows for magnet integration
- reduced sensitivity to the beam break-up (BBU)

• Acceleration:
  - Two-beam acceleration (CLIC-type)
  - Collinear acceleration
  - Radiation

• Structure side:
  - Type of ceramics: loss, multipactor, thermal management, fabrication, charging
  - Power extraction, coupling
  - Tuning
  - HOM suppression

• Beam side:
  - Phase space manipulation
  - Bunch trains
  - Beam shaping for transformer ratio
  - Beam transport and BBU studies
Dielectric Wakefield Acceleration (DWA)

Drive beam: Energy ↑, Charge ↑, Bunch length ↓, Emittance ↓

\[ \sigma_r = \left( \frac{\varepsilon_N}{\gamma} \beta \right)^{1/2} \]

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Recent Dielectric Wakefield Structures Experiments

- 7.8GHz power extractor (40MW)
- 100MV/m
- 11.4GHz PETS: 40MW@100ns ASTA, SLAC
- Witness Acceleration
- Wake mapping
- Bragg structure
- Woodpile
- Enhanced Transformer Ratio: 3.4
- Tunable DWA structure
- 26GHz power extractor
- THz generation UCLA, Neptune
- GV/m FFTB
- GV/m FACET
- Chirp corrector
- Tunable THz
- Resonant excitation
- Second harmonic

Frequency Bands:
- 1GHz
- 10GHz
- 30GHz
- 100GHz
- 300GHz
- 1THz

Additional Information:
- AWA
- ATF BNL FACET SLAC
Motivation: Argonne Flexible Linear Collider

Short pulse – high gradient (efficiency optimization) – low cost
Technology required: Broadband couplers, power extractor demonstration..

Layout of the ANL 26GHz 250GeV Flexible Linear Collider

- 22ns rf pulse
- 120MV/m loaded gradient
- Machine Rep=50Hz

Energy booster linac

C.J. Jing, et. al. IPAC2012
Development of Dielectric-Based Wakefield Power Extractors

C-Band Wakefield Power extractor

• 30ns, 1MW & 10ns, 40MW 7.8GHz rf pulse produced

Dielectric-Loaded deceleration waveguide

TM$_{01}$-TE$_{10}$ coupler

rf output port

F. Gao et al. PRSTAB 11, 041301 (2008)

K-Band Wakefield Power extractor (Euclid SBIR Project)

• 16ns, 1MW & 10ns, 20MW 26GHz rf pulse produced

Dielectric loaded deceleration waveguide

TM$_{01}$-TE$_{10}$ coupler

Downconverted signal

11.44 + 14.576 = 26.016 GHz

F. Gao et al. PRSTAB 11, 041301 (2008)

C. Jing et al. PAC’09

AWA ANL
### Dielectric PETS (for CLIC) Parameters

Using CLIC Beam: \( \sigma z=1\text{mm}, \ Q=8.4\text{nC}, \ T_b=83\text{ps} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq</td>
<td>11.994GHz</td>
</tr>
<tr>
<td>Effective Length</td>
<td>23cm</td>
</tr>
<tr>
<td>Beam channel</td>
<td>23mm</td>
</tr>
<tr>
<td>Dielectric wall thickness</td>
<td>2.582mm</td>
</tr>
<tr>
<td>Dielectric const.</td>
<td>3.75(Q Quartz)</td>
</tr>
<tr>
<td>Q</td>
<td>7318</td>
</tr>
<tr>
<td>R/Q</td>
<td>2.171k(\Omega)/m</td>
</tr>
<tr>
<td>Vg</td>
<td>0.4846c</td>
</tr>
<tr>
<td>Peak surface Gradient</td>
<td>(E_{</td>
</tr>
<tr>
<td>Steady Power</td>
<td>142MW</td>
</tr>
</tbody>
</table>
11.4GHz version is under high power rf test at SLAC

Currently conditioned to 40 MW, 100 ns (with the goal of 200ns)

Setup at SLAC ASTA facility
Planned two beam acceleration experiment @AWA

75MeV drive beam
- 16 bunches x 60nC/per bunch
- $\sigma_z = 2\,\text{mm}$

26GHz Stage I DWPE
- $a=3.5\,\text{mm}$; $b=4.53\,\text{mm}$; $\varepsilon=6.64$; $L=30\,\text{cm}$

65MeV drive beam
- $767\,\text{MW} \times 15\,\text{ns}$
- $26\,\text{GHz}$ rf

RF Power Generation

26GHz Stage II DLA
- $a=3\,\text{mm}$; $b=5.03\,\text{mm}$; $\varepsilon=9.7$; $V_g=11\%c$; $L=30\,\text{cm}$

Ez = 250MV/m

witness (10 MeV)
- $Q=1\,\text{nC}$, $\sigma_z=1\,\text{mm}$, $\varepsilon=1.5\,\text{um}$

witness (85 MeV)
Non-linear ferroelectrics for DWA

- BSTM – nonlinear ferroelectric
- Frequency tuning
- $\varepsilon(V_{DC})$ – fast, $\varepsilon(T)$ - slow
- Bench test ($T, V_{DC}$)
- Beam test ($T$)

Witness beam energy change

---

C. Jing et al. PRL, 106, 164802, April (2011)
Reducing the aperture...

\[ W_z(z) \approx \frac{Q}{a^2} \exp\left[-2\left(\frac{\pi \sigma_z}{\lambda_n}\right)^2\right]\cos(kz) \]
FFT B (2008)
– Fused silica tube, metallized OD=324um, ID = 100um, L=1cm
– SLAC beam $\sigma_z = 10 - 100$um, $\sigma_r = 10$um
– 16 GV/m maximum accelerating field achieved
– Metallization evaporated due to ohmic heating
– dielectric breakdown observed (maximum field on dielectric surface $\sim 27$ GV/m

Thompson et al PRL 100, 214801 (2008)

UCLA FACET DWA measurement (2013)
– Fused silica tube, metallized OD=640um, ID = 450um, L=10cm
– SLAC beam 3.2 nC, $\sigma_z = 30$um, $\sigma_r = 40$um
– $<\Delta E>=50$ MeV!
– Ez >1 GV/m

Courtesy G. Andonian
Being prepared for publication
Acceleration in slab symmetric DWA

- Structure:
  - SiO2, beam gap 240μm
  - Metal boundary
- BNL ATF
  - E = 59MeV, Q=500pC
  - Flat beam
  - Long bunch structure with two peaks
- CCR interferometry
  - Characterized first two modes
- Observe acceleration
- Robust start-to-end simulations for benchmarking

Projections + Simulations

ATF beam shaping

Linear energy chirp is required for this method

Wakefield mapping in planar DWA

- Diamond - Chemical vapor deposition (CVD)
  - Low loss tangent
  - High thermal diffusivity
  - High breakdown
- Rectangular waveguide
  - 6cm length; 200um x 1mm beam gap
- Experiment at BNL ATF
  - 57MeV, 70% charge transmission
  - Variable delay witness
- Results
  - Wakefield mapping (TM\textsubscript{11}-like mode, 0.25THz)
  - No damage to diamond after beam interaction

DWA with Bragg-like boundaries

- Modal confinement
  - Constructive interference
  - Alternating dielectric layers
  - Eliminate metal cladding

- DWA: SiO₂, 240μm beam gap
  - Bragg layers SiO₂, ZTA
  - Assembled at UCLA

- BNL ATF experiment
  - 50MeV, 100pC, σt~1ps

- Results
  - \( \lambda = 1.4\text{mm} \) (210GHz)
  - Energy chirp mitigation
  - Confirmed with simulation
  - Submitted to PRL

Beam Energy

Interferogram

FFT

OOPIC Sims

Courtesy G. Andonian, UCLA
Woodpile Experiment

- Extension of Bragg to 3d
  - Photonic structures
  - Studies in laser coupling
- Woodpile structure
  - Sapphire rods for woodpile (125μm)
  - 240μm beam gap
  - Hand Assembled at UCLA
  - Matching horn incorporated in structure
- BNL ATF
  - 50MeV, 100pC
- Results under study
  - Scaled GALAXIE structure fabricate by *laser assisted etching* of sapphire

CST Simulations

Interferogram FFT

Scaled Galaxie

ATF BNL
Two-beam acceleration in THz?
Two-channel structures

Measured at the AWA

Collinear Acceleration, Transformer Ratio

Transformer Ratio: \[ TR = \frac{E_{\text{max gain}}}{E_{\text{max loss}}} \]

Using this method, TR = 3.4 was demonstrated experimentally at AWA, ANL

C. Jing et. al. PRL, 98, 144801, April (2007)
C. Jing et. al. PR ST-AB, 14, 021302, Feb. (2011)
Energy-doubling of the Advanced Superconducting Test Accelerator (ASTA) using a DWFA module

- Flat-beam photoinjector
- Phase-space-exchanger current shaping

Courtesy of P. Piot, NIU / FNAL
Application for high efficiency dielectric collinear wakefield acceleration: soft X-Ray FEL example

A Schematic of a FEL facility based on a 2.4 GeV DWA

C. Jing, J. Power, and A. Zholents
ANL/APS/LS-326 (2011)
Dielectric wakefield accelerator project at LANL

- The pre-conceptual design for Matter-Radiation Interactions in Extreme (MaRIE) future signature facility is underway at LANL, with the design of the 12 GeV electron linear accelerator being one of the main research goals.

- A dielectric wakefield accelerator (DWA) has a potential to be employed as a future afterburner for the MaRIE linac if the energy spread in the witness bunch can be made below $10^{-4}$.

- Energy spread in the witness bunch can be made very small if the shape of the witness bunch is properly customized.

*Courtesy of E. Simakov (Smirnova), LANL*
Shaping electron bunches with an Emittance Exchanger

- A double triangular drive bunch and a trapezoidal witness bunch can be cut out from a single Gaussian shaped bunch with a specially shaped mask.

- An Emittance Exchanger (EEX) in either double-dogleg or a chicane configuration can convert the shaped x-y distribution into the shaped t-y distribution of electrons.

A schematic of a bunch shaping beamline: mask is followed by an EEX in a double-dogleg configuration.

*Courtesy of E. Simakov (Smirnova), LANL*
Energy Chirp Correction Experiment at ATF

Self-deceleration!

Triangular-shaped (current) beam with energy chirp

wake from $\Delta z = 210\mu, 300\mu$ ID / $400\mu$ OD quartz tube

Spectrometer image of the original beam

Spectrometer image after chirp corrector

Chirp corrector – passive wakefield tube: dielectric loaded waveguide

Spectrometer image of a beam that passed through the structure

Experimental results:
triangular current with chirp

S. Antipov, et al, prepared for publication

Gap ~ 2.8mm, 2.7mm, 1.9mm, 1mm
100% charge transmission
54pC total charge, ~160keV corrected
~60keV/m/mm/pC – chirp correction number
Say, 300pC beam with $\sigma_z = 100\mu$m, goes through 1m of chirp corrector $\rightarrow$ 1.8 MeV corrected

Dielectric chirp corrector @ ATF, BNL – May, 2013
Corrugated chirp corrector @ PAL-ITF – August, 2013
Corrugated chirp corrector @ ATF, BNL – September, 2013
Beam-based THz sources

UCLA Neptune

CCR as a tunable THz source
Q~200pC, E=14MeV, σ_z~200μm,
Varied outer radius
(b=350μm,400μm), L=1cm
~10μJ of THz, narrowband

A. Cook, et al., PRL 103, 095003 (2009)
Resonant excitation of higher-order modes

- Structure: SiO$_2$ tubes (Al coating, 100μm)
- Pulse train
  - Sextupole correction to mitigate chromatic aberrations
- Resonant wake excitation, CCR spectrum measured
  - Excited with 190 μm spacing (2$^{\text{nd}}$ “harmonic”=$\text{TM}_{02}$)
  - Suppression of fundamental
- Developed techniques to characterize structures

UCLA FACET DWA Measurements

- DWA: 10cm long, SiO2
- Robust Cu coating
- FACET beam parameters
  - \( Q = 3.2 \text{nC}, E = 20.5 \text{GeV} \)
  - \( \sigma_x = \sigma_y = 20 \mu\text{m}, \sigma_z = 45 \mu\text{m} \)
- Results:
  - \( \langle \Delta E \rangle = 50 \text{ MeV!} \)
  - \( E_z > 1 \text{ GV/m} \)
  - 0.4 THz: \( \sim 135 \text{mJ}, \text{BW}=0.4\%, \text{0.22GW} \)
  - 1.2 THz: \( \sim 40 \text{mJ}, \text{BW}=0.3\%, \text{0.14GW} \)

![Energy Loss in Tube](image)

![Interferogram and FFT](image)

*Courtesy G. Andonian, UCLA, in prep for publication*
Beam based THz source

1 nC beam generates wakefield and loses 1 MeV = 1 mJ of energy generated in a pulse!
Observation of energy modulation at ATF

Periodic self-deceleration!

**simulation**

- **a**
  - Beam current (red)
  - Self-wake (blue)
  - $z$, cm

- **b**
  - Energy, MeV
  - Red: no structure
  - Blue: with structure

- **c**
  - Energy histogram

**Measurement: spectrometer**

- **A**
  - Original chirped beam
- **B**
  - 0.95 THz structure
- **C**
  - 0.76 THz structure

---


ATF BNL
Sub-picosecond bunch train production at ATF

PM chicane is used to convert energy modulation into density modulation

CTR interferometry shows that THz periodicity can be tuned by energy chirp

We proposed a high power terahertz radiation source based on this scheme (electron beam wakefields). A third stage, yet another dielectric tube will be installed after chicane to coherently extract THz power from the bunch train.

High power beam-based THz source

**ATF (0.8nC / 2.4mm)**
- 6 MW peak, 0.7THz, 160ps pulse, 1%BW, 1.4mJ pulse

**AWA (20nC / 6.3mm)**
- 0.5 GW peak, 0.3THz, 320ps pulse, 1%BW, 155mJ pulse

**Stage I**
- Energy modulation via self-wakefield

**Stage II**
- Chicane energy modulation conversion to bunch train
- D. Xiang et al. PRL. 108, 024802 (2012)
- S. Antipov, et al., PRL. 111, 134802 (2013)

**Stage III**
- THz radiation wakefield structure

---

**Measured beam spectrum**
- Energy chirped rectangular beam

**Measured beam spectrum**
- Energy modulated rectangular beam

**Bunch train frequency content**
- Tunable 100% source: Range: 0.3-1.5 THz
- Pulse bandwidth: 1%
- Energy in pulse: ~ mJ

Flexible: each step has a tuning range
Summary

• A large number of exciting experiments on DWA had been reported by several groups
• GHz, THz
• High gradient acceleration
• High power THz radiation
• Two beam acceleration
• Transformer ratio
• ... and more to come