RECENT PROGRESS OF SHORT PULSE DIELECTRIC TWO-BEAM ACCELERATION

JIAHANG SHAO

On behalf of the Argonne Wakefield Accelerator (AWA) facility
BACKGROUND AND MOTIVATION

- **Short pulse two-beam acceleration**
  - Approach to structure-based wakefield acceleration
  - High gradient acceleration (200-300 MV/m)

- Both structures can be optimized to obtain high power generation, high gradient acceleration, and high efficiency

A promising solution!

\[ E_0 = \sqrt{2\alpha Z_{eff} P_{in}} \] ~GW

\[ BDR \propto E^{30} \tau^5 \] ~20 ns

BACKGROUND AND MOTIVATION

- **Dielectric structure**
  - Slow-wave structure with simple geometry

- **Advantages**
  - Simple geometry
  - Small transverse size
  - No surface electric field enhancement
  - High group velocity: short pulse preferred

BACKGROUND AND MOTIVATION

- **Argonne Flexible Linear Collider (AFLC)**
  - A 3 TeV 30 MW machine based on short-pulse dielectric TBA

  ![Diagram of AFLC](image)

  - **Uniqueness**
    - High frequency (26 GHz), short rf pulse (~20 ns), high gradient (267 MV/m)
    - Modular design for flexible energy upgrade

BACKGROUND AND MOTIVATION

- **Argonne Wakefield Accelerator (AWA) facility**
  - A flexible, state-of-art testbed for future linear colliders

**Breakdown test-stand**
- Double emittance exchange (DEEX)
- Argonne cathode test-stand (ACT)

**Wakefield experimental area**
- Witness beam
  - 15 MeV, single bunch
  - 0.05-60 nC
- Drive beam
  - 70 MeV, up to 32 bunches
  - Max charge: 100 nC (single)
  - 600 nC (train)
BACKGROUND AND MOTIVATION

- **Argonne Wakefield Accelerator (AWA) facility**
  - Strong capability in research related to wakefield acceleration
  - **Over 15** collaborators and users

  D. Wang, et al., PRL 2016
  E. Simakov, et al., PRL 2016
  H. Zha, et al., PRAB 2016
BACKGROUND AND MOTIVATION

- **Argonne Wakefield Accelerator (AWA) facility**
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  ![Diagram with boxes and arrows]

  drive → Collinear
  drive+witness → TBA

  C. Jing, et al., to be published
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<thead>
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<th>Collinear</th>
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<td>Drive+Witness</td>
<td>TBA</td>
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<td>Drive+EEX</td>
<td>Bunch shaping Collinear</td>
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Q. Gao, et al., PRL 2018  
G.Ha, et al., PRL 2017  
A. Halavanau, et al., PRAB 2017  
G.Ha, et al., PRAB 2016
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<td>drive+EEX</td>
<td>Plasma Wakefield</td>
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Under investigation
**BACKGROUND AND MOTIVATION**

- **Argonne Wakefield Accelerator (AWA) facility**
  - Strong capability in research related to wakefield acceleration
  - **Over 15** collaborators and users

  - Drive
  - Drive+witness
  - Drive+EEX
  - Drive+EEX
  - Drive+EEX+witness
  - Collinear
  - TBA
  - Bunch shaping Collinear
  - Plasma Wakefield
  - Bunch shaping TBA

  Under investigation
BACKGROUND AND MOTIVATION

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J. Shao, et al., PRL 2016
J. Shao, et al., PRL 2015
S. Baryshev, et al., APL 2014
BACKGROUND AND MOTIVATION

- **Argonne Wakefield Accelerator (AWA) facility**
  - Strong capability in research related to wakefield acceleration
  - **Over 15** collaborators and users

- **Wakefield R&D**
  - Successful tests with metallic structures: **300 MW + 150 MeV/m** for single stage, **70 MeV/m** for two stages
  - Continuous effort in developing dielectric structures

C. Jing, et al, *To be published*
SHORT PULSE DIELECTRIC TBA IN K-BAND
-- A PROTOTYPE IN AFLC
STRUCTURE OVERVIEW

- Prototypes for the basic TBA pair in AFLC

<table>
<thead>
<tr>
<th></th>
<th>POWER EXTRACTOR</th>
<th>ACCELERATOR</th>
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</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>26 (20 x 1.3)</td>
<td>26 (20 x 1.3)</td>
</tr>
<tr>
<td>ID / OD (mm)</td>
<td>7 / 9.068</td>
<td>3 / 5.026</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>6.64 (Frosterite)</td>
<td>9.8 (Alumina)</td>
</tr>
<tr>
<td>Cu coating</td>
<td>No</td>
<td>Yes, 100 µm</td>
</tr>
<tr>
<td>Group velocity</td>
<td>0.25 c</td>
<td>0.1115 c</td>
</tr>
<tr>
<td>r/Q (Ω/m)</td>
<td>9788</td>
<td>21983</td>
</tr>
<tr>
<td>Q</td>
<td>2950</td>
<td>2295</td>
</tr>
<tr>
<td>r (MΩ/m)</td>
<td>28.9</td>
<td>50.5</td>
</tr>
</tbody>
</table>

J. Shao, et al., in Proc. IPAC’2017, 3305-3307, 2017
HIGH POWER GENERATION

- **2009**: low charge
  - Low charge 16-bunch train, 2 MW generated power

- **2016-2017**: high charge
  - High charge 4-bunch train, **55 MW** generated power

Higher attenuation and surface damage
Mechanism under investigation
MAIN BEAM ACCELERATION

- Successful demonstration of short pulse dielectric TBA
  - 1.8 MeV acceleration, 28 MeV/m average gradient

- Structure inspection
  - No structure damage was observed after the high power test
SHORT PULSE HIGH POWER GENERATION IN X-BAND
-- BEYOND 100 MW
STRUCTURE OVERVIEW

- **A X-band Structure to obtain high power at AWA**
  - Large iris: ensure good transmission with high charge, minimize damage from beam irradiation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>11.7 (9 x 1.3)</td>
</tr>
<tr>
<td>ID / OD (mm)</td>
<td>14.99 / 18.79</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>9.8 (Alumina)</td>
</tr>
<tr>
<td>Cu coating</td>
<td>Yes, 1 μm</td>
</tr>
<tr>
<td>Group velocity</td>
<td>0.1959 c</td>
</tr>
<tr>
<td>r/Q (Ω/m)</td>
<td>4320</td>
</tr>
<tr>
<td>Q</td>
<td>3392</td>
</tr>
</tbody>
</table>

J. Shao et al., in *Proc. IPAC’2018, TUPML007, 2018*
HIGH POWER TEST

- **Low charge**
  - Perfect agreement between simulation and measurement

\[ \sqrt{P} = \sqrt{\frac{\omega r}{4 Q v g} \frac{F}{1 - \beta_g} Q_b} \]

- **High charge**
  - **90 MW** for 4-bunch train, **105 MW** for 8-bunch train
STRUCTURE COATING DAMAGE

- Sign of structure damage during high power test
  - Gradual degrading performance

- Structure inspection
  - Transmission drops from -2.5 dB (before) to -32.5 dB (after)
  - **Dielectric survive**, severe damage to the thin copper coating
STRUCTURE COATING DAMAGE

- **Sign of structure damage during high power test**
  - Gradual degrading performance

- **Structure inspection**
  - Transmission drops from -2.5 dB (before) to -32.5 dB (after)
  - **Dielectric survive**, severe damage to the thin copper coating

Thick copper coating (>100 μm) is critical for dielectric structures!
DIELECTRIC DISK ACCELERATOR -- EFFICIENCY IMPROVEMENT
### Structure Overview

<table>
<thead>
<tr>
<th></th>
<th>DLA</th>
<th>DDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>ID (mm)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>9.8</td>
<td>50</td>
</tr>
<tr>
<td>Dielectric loss tangent</td>
<td>$1\times10^{-4}$</td>
<td>$5\times10^{-4}$</td>
</tr>
<tr>
<td>Group velocity</td>
<td>0.11 c</td>
<td>0.16 c</td>
</tr>
<tr>
<td>$r/Q$ (kΩ/m)</td>
<td>21.8</td>
<td>32.5</td>
</tr>
<tr>
<td>Q</td>
<td>2295</td>
<td>6430</td>
</tr>
<tr>
<td>r (MΩ/m)</td>
<td>50.0</td>
<td>208.8</td>
</tr>
<tr>
<td>Input power (GW)</td>
<td>1.22</td>
<td>0.96</td>
</tr>
<tr>
<td>$\eta_{rf\text{-beam}}$ (%)</td>
<td>~9</td>
<td>~13</td>
</tr>
<tr>
<td>$E_{\text{max}}$ (MV/m)</td>
<td>365</td>
<td>660</td>
</tr>
<tr>
<td>Beam loading (%)</td>
<td>15.5</td>
<td>17.1</td>
</tr>
</tbody>
</table>

- Advantages of (DDA) over (DLA) for short pulse TBA
  - High efficiency (~45% improvement with $2\pi/3$ mode)
  - Easier machining and tuning for high frequency and constant gradient

J. Shao et al., in *Proc. IPAC’2018, TUPML005*, 2018
ONGOING RESEARCH

- **PETS driven X-band prototype**
  - Test brazing between dielectric and copper
  - Demonstrate machining and tuning
  - High power test to reach ultra-high surface field (nosecone for 600 MV/m)
AFLC EFFICIENCY MAP

\[ \eta_{\text{AC-beam}} = 9.4\% \]

297 MW

\[ \eta_{\text{Lband rf}} = 55\% \]

klystrons

\[ \eta_{\text{Lband rf - drive}} = 86\% \]

Drive beam

\[ \eta_{\text{drive - Kband rf}} = 77\% \]

DPETS

\[ \eta_{\text{waveguide}} = 95\% \]

Main linac

\[ \eta_{\text{rf-main}} = 27\% \]

Drive beam dumps

Main beam

27.8 MW

Only rf power is taken into consideration
AFLC EFFICIENCY MAP

η_{AC-beam} = 9.4\%  \quad \rightarrow \quad 13.4\%  

297 MW \quad \rightarrow \quad 207 MW

AC power

- η_{AC - L\text{band rf}} = 55\%
- η_{L\text{band rf - drive}} = 86\%

klystrons

Drive beam

- η_{drive - K\text{band rf}} = 77\%

DPETS

- η_{waveguide} = 95\%

Main linac

- η_{rf-main} = 27\%  \quad \rightarrow \quad 39\%

Main beam

DDA

Only rf power is taken into consideration
AFLC EFFICIENCY MAP

$\eta_{AC-beam} = 9.4\%$

297 MW → 13.4% → 207 MW → 20.1% → 138 MW

- AC power
- $\eta_{AC-Lband\;rf} = 55\%$
- Klystrons

- Lband rf - drive $= 86\%$
- Drive beam

- $\eta_{drive-Kband\;rf} = 77\%$
- DPETS

- Waveguide $= 95\%$
- Main linac

- $\eta_{rf-main} = 27\%$ → 39% → 58% → 27.8 MW
- Drive beam dumps

- Main beam + Main beam shaping

Only rf power is taken into consideration
AGNL EFFICIENCY MAP

**AC power**

- $\eta_{AC\text{-}beam} = 9.4\%$
- $\eta_{AC\text{-}L\text{band rf}} = 55\%$
- $\eta_{L\text{band rf\text{-}drive}} = 86\%$
- $\eta_{\text{drive - Kband rf}} = 77\%$
- $\eta_{\text{waveguide}} = 95\%$
- $\eta_{\text{rf\text{-}main}} = 27\%$

**Drive beam**

- 297 MW
- 207 MW
- 138 MW
- 84 MW

**DDA**

- + Main beam shaping
- + High efficiency klystron

**Main linac**

- Drive beam dumps
- 27.8 MW

Only rf power is taken into consideration
SUMMARY

- **Short pulse dielectric TBA**
  - A promising candidate which may meet the requirements of high gradient, high efficiency, and low fabrication cost of a future linear collider

- **Short pulse dielectric TBA at AWA**
  - K-band: 55 MW generated power, 28 MeV/m acceleration
  - X-band: 105 MW generated power

- **Dielectric disk structure**
  - An alternative structure to remarkably improve the efficiency
  - 33% AC to main beam efficiency with other advanced technologies
FUTURE STUDY

- **Dielectric power extractor**
  - High power test with thick coating
  - Other limiting factors
- **Dielectric accelerator**
  - High power test for higher gradient
  - DDA
- **Short pulse TBA**
  - Full staging with kicker and septum
ACKNOWLEDGEMENT

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