THz Accelerators and Their Application to Ultrafast Electron Diffraction

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RF Accelerator Technology Team
Outline

• Motivation
• Performance of THz Accelerators
• Structure Prototyping and Fabrication
• High-Power Test of Narrow-Band Structures
• Laser-Driven THz Accelerator Experiments
• Conclusions
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How do we develop the next generation of accelerators and what new science does this enable?
Ultra-fast and Ultra-small: The New Frontier

**Nature**
- Hummingbird wing motion ~ 1 ms
- Protein folding ~ 10 μs
- Molecular group motion ~ 1 ns
- Atoms oscillate in ~ 100 fs
- Atomic electron circles in ~ 1 fs

**Technology**
- Camera shutter speed ~ 130 μs
- Flash ~ 30 μs
- Magnetic recording time per bit ~ 1 ns
- Computing time per bit ~ 100 ps

1 msec shutter speed
10-100 femtosecond shutter speed
Next Generation Accelerators in Pursuit of Compactness, Efficiency and Performance

**S-band Accelerators**
30 MeV/m

**Klystron Source**
10s MW, µs, ~3 GHz

**mm-Wave/THz Accelerators**
GeV/m

**mm-Wave/THz Sources**
MW, ns, ~0.3 THz
Rapid Development of THz Accelerator Technology

**Impacting Diverse Areas of Accelerator Technology:**

- Precision Diagnostics and Beam Manipulation - <fs resolution
- Ultrafast Electron Diffraction - 100 fC, <10 fs
- X-ray Generation – few to 10s pC, low emittance
- High Current, High Luminosity >>10s pC, bunch trains

**Growing International Community:**

- Healy, et al., UCMMT, 2017
- Zhao, et al. PRX 8.2 (2018): 021061

**References:**

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Higher Frequencies Can Achieve Higher Gradients

- Accelerating gradient is limited by breakdown (i.e. arcing or plasma formation)
- Breakdown threshold for surface electric field $E_s \propto f^{1/2}$
- Demonstrated operation with $\sim 1$ GV/m surface fields

Other Examples:

THz Guns @ MIT/DESY ($E_{surf} \sim 300$ MV/m)

Beam Driven @ FACET ($E_{surf} \sim$ GV/m)

Streaking @ SLAC UED ($E_{surf} \sim 150$ MV/m)
Advantages of Operating at THz Frequencies

Additional advantages of high frequency structures:

- Shunt impedance increases as $f^{1/2}$
- RF pulse energy decreases as $f^{-2}$

Shunt Impedance for TM$_{01}$ π-mode Structures

SLAC/MIT/INFN High-Gradient Research

SLAC/KEK/RIKEN Source/Struc. Development

~300 GHz Structure

0.5 mm Axis of Cylindrical Symmetry
Comparison Between RF and THz Accelerators

- Scaling structure design from S-band to the THz range

**Parameters for 100 MeV/m Gradient**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>3 GHz</th>
<th>300 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>3 GHz</td>
<td>300 GHz</td>
</tr>
<tr>
<td>Stored Energy [mJ]</td>
<td>8450</td>
<td>0.013</td>
</tr>
<tr>
<td>Q-value [x1000]</td>
<td>17.96</td>
<td>2.05</td>
</tr>
<tr>
<td>Shunt Impedance [MOhm/m]</td>
<td>55</td>
<td>514</td>
</tr>
<tr>
<td>Max. Mag. Field [MA/m]</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Max. Electric Field [MV/m]</td>
<td></td>
<td>210</td>
</tr>
<tr>
<td>Fill Time [ns]</td>
<td>2000</td>
<td>2</td>
</tr>
<tr>
<td>Loss in 1 meter [MW]</td>
<td>181</td>
<td>19</td>
</tr>
</tbody>
</table>

$P \times \tau$ decreases by 4 orders of magnitude

Potential to operate at 10s kHz vs 100s Hz
Pulsed Heating in High-Frequency Structures

- Surface temperature rise during RF pulse causes damage
- Surface resistivity increases as $f^{1/2}$
- Cavity fill time drops dramatically


[3 GHz Structure]

\[ \frac{\omega \tau}{Q} = 2 \]

3 GHz Structure

300 GHz Structure

Must Understand this New Regime for Frequency, Pulse Length, Stored Energy
THz Metallic Accelerator Holds the Potential for High-Gradient Accelerators

- Increased shunt impedance and RF efficiency w/ THz metallic accelerators
- Investigate geometry, gradient, pulse length and materials
- Achieved peak surface field of 1.5 GV/m
- Next step evaluate performance without drive beam

What is the Real Scaling in Frequency for Breakdown Physics?

- Demonstrate realizable THz accelerating structure
- Power with stand-alone RF source – Experimental test underway at MIT with 1 MW gyrotron oscillator
- Direct comparison w/ X-band breakdown studies

Need to Develop High-Power High-Frequency Sources for Practical Applications
S-Parameters for ‘Single-Cell’ Structure for $a/\lambda = 0.105$ and 1 MW of Dissipated Power

- Measure forward/reflected power through free space directional coupler and coupled power through diagnostic port

Beam waist $1.65 \lambda$

Field on horn aperture

Standing-Wave Cavities

Medium: Electric Field 916 MV/m

Gaussian Beam Input

Te11 to TM01

50 mm
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Prototyping of mm-Wave Structures

- Assembly of structure and impact on RF and high gradient performance is a key concern
- Prototyping effort to test assembly using diffusion bonding and/or brazing
- Completed tests on 12 assemblies consisting of ~40 RF structures
  - Focus is structural integrity, RF performance, frequency shifts
Comparison of Assembly Techniques

• Assembly from halves makes RF performance insensitive to defects
• Local features significantly different

Diffusion Bond
Limited Braze Foil
Isolated + Limited Braze Foil
Details of Isolated + Limited Brazed Assembly

- New techniques and approaches needed for fabrication
- Successfully adapted split-cell approach to mm-Wave/THz range
- Braze foil tailored to cavity shape to control volume
Structure Fabrication for High Gradient Test at 110 GHz

- First test with split-cell and diffusion bonding

Applying Advanced Metrology for Close Loop Manufacturing

Pre-Bonding SEM

Mode Converter and Cavities

RF Diagnostic Port

TM$_{01}$ Input

Gaussian Beam Input
110 GHz High Gradient Structure Assembly Complete
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Efficient Excitation of THz Accelerating Structures

- Avoid lossy waveguides with quasi-optical transport and couplers

Measured back-propagated field in the cut plane of the assembly

Free-space Gaussian beam coupled to structure

Versatile Topology Compatible with New Structures and Different Frequencies
Results from Quasi-Optical Transport Test

- Gaussian beam launcher used to test excitation
- Matches design - $\pi$-mode 110.1 GHz, $S_{11} \approx -25$ dB, $S_{21} \approx -40$ dB

First Quasi-Optical Coupling into Narrow-Band Accelerating Structure
Laser-Triggered Semiconductor Switch for Pulse Shaping

- Short tunable pulse lengths few-100s nanoseconds at MIT
- Quasi-optical coupling also demonstrated on high power setup

Measured Pulse After Switch

Picard, Schaub
High-Power Testing of 110 GHz Accelerating Structures

• Achieved 225 MeV/m Gradient (<100k pulses)
• Breakdowns observed after power increased and rapidly process away
• MIT improving transport, coupling, diagnostics (now approaching 600 kW – upgrades planned to 800 kW)

Mm-Wave Relativistic Electron Source

Two cell π mode structure with 50 μm radius copper tip
On-axis coupling from 110 GHz gyrotron source
Maximum field on the tip is 3.8 GV/m for 500 kW input power
Future Work: THz-Driven Electron Gun

This gun will demonstrate the feasibility of using normal conducting, THz accelerating structures to create compact, high gradient electron sources.

**Next Steps**

- Full assembly completed and tuned
- High power tests will begin soon
- Results will be focused on characterizing electron beam: energy (350 keV), energy spread, current
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Exploring New Frontiers of THz Acceleration with Laser-Driven THz Sources

Single-Cycle THz Source Experiments

- Experimental stepping stone
- Successfully demonstrated <fs streaking diagnostic at SLAC UED
- Pursuing compression of electron bunch down to a femtosecond

Narrow-Band THz Source Experiments

- Developing structure for test with 100 ps 100 kW source (w/ Minamide RIKEN)

THz Driven Electron Bunch Compression is Key Technology for sub-Femtosecond Resolution

- THz transverse deflector demonstrated sub-fs timing accuracy
  - Electron bunch length and jitter limit timing resolution for UED (low counts)
- Electron bunch compressor could reduce bunch length
- Laser-generated THz synchronized with beam; compression interaction stabilizes time-of-arrival

Longitudinal phase space simulations in GPT:

THz Compressor

THz Pulse

Initial Beam

ΔE

MeV Electron Bunch

THz Structure

Gap δz

Initial Beam

THz

ΔE

MeV Electron Bunch

THz Compressor

Initial Beam

ΔE

MeV Electron Bunch

THz Structure

Gap δz

Chirped Beam

Compressed Beam

... drift
THz Compression Experiment Integrated with Operating Ultrafast Electron Diffraction Facility

- Operated with few fC of charge and 2-3.5 MeV, nominal UED operating point - fields in structure ~100 MV/m
- Bunch characterized with THz transverse deflector

THz Driven Compression Experimental Setup

*setup diagram not-to-scale
Performance of THz Electron Bunch Compressor: Single Shot Bunch Length Measurement

- Uncalibrated data with fit performed by mapping Gaussian bunch onto measured streak profile.

THz Off

THz On
Performance of THz Electron Bunch Compressor: Bunch Length and Timing Jitter

- Bunch length reduced by ~3X and jitter by >2X

**THz Off**

- Bunch length: 105 ± 19 fs rms
- Time-of-arrival: 76 fs rms

**THz On**

- Bunch length: 39 ± 7 fs rms
- Time-of-arrival: 31 fs rms
Performance of THz Electron Bunch Compressor: Stable Operation Allows for Full Characterization

- Measurements at multiple energies now being modeled and analyzed (500k images collected in 2 weeks)
• Different time scales associated with the Bi are observed
• Temporal resolution < 100 fs

Challenges:
Timing drift, pointing stability, background, Q range & resolution

\[ \Delta t = \sqrt{\Delta t_{\text{pump}}^2 + \Delta t_{\text{bunch}}^2 + \Delta t_{\text{jitter}}^2 + \Delta t_{\text{drift}}^2 + \ldots} \]
Bridging the Gap Between Single-Cycle and Quasi-CW Excitation for Optimized High-Field Performance

- Laser-driven THz sources can produce high power pulses on 100s ps timescale
- Pursuing pulse-compression of electron-beam sources for very efficient nanosecond pulses
- Nanosecond time scale preserves high-shunt impedance of structures
Conclusions

- mm-Wave/THz accelerating structures have shown the promise of high gradient achieving GV/m fields
- Understanding the performance of structures at high-frequency and high-field is needed for adoption
- Advanced manufacturing techniques deliver expected RF performance for mm-Wave/THz accelerating structures
- Demonstrating quasi-optical coupling/transport and high field operation with stand-alone RF source demonstrated

Ongoing: Attempt to perform first UED measurement requiring THz time-stamping

Othman, Shen, Kramer, Luo, England, Gabriel, Hoffmann
Questions?
300 GHz Single Cell Accelerating Structure

- Narrowband THz laser-based sources capable of producing 100s ps pulses
- Utilizing over-coupled scheme to demonstrate high gradient

\[ Q_0 / Q_e \sim 17 \]

\[ Q_0 \sim 2500 \]
Shunt impedance \( \sim 600 \, \text{M}\Omega/m \)
\[ E_{\text{max}} / E_{\text{acc}} \sim 2.3 \]
• Narrowband THz laser-based sources capable of producing 100s ps pulses

• Utilizing over-coupled scheme to demonstrate high gradient

• Efficient coupling for short pulses
300 GHz Single Cell Accelerating Structure

- Narrowband THz laser-based sources capable of producing 100s ps pulses

- Utilizing over-coupled scheme to demonstrate high gradient

Developing structure for high gradient test with 100 kW, 100 ps laser generated source (w/ RIKEN)

100 kW power

Shunt impedance ~ 600 MΩ/m

$E_{\text{max}}/E_{\text{acc}} \sim 2.3$

Over Coupled Cavity Port

WR-3 Rectangular Waveguide

$Q_0 \sim 2500$

$Q_0/Q_e \sim 17$

$S_{21} \approx -42 \text{ dB}$
Field Distribution for $a/\lambda = 0.105$ and 1 MW of Dissipated Power – 400 MeV/m Effective Gradient

- Structure designed for comparison with X-band studies
- $E_{\text{max}}/E_{\text{acc}} \sim 2.25$

Iris Thickness (mm)

**A0.286-T0.2-Cu**

Iris Aperture Radius (mm)

**Frequency = 110.12 GHz  Q = 1572**

Electric Field

776 MV/m

Magnetic Field

1.27 MA/m

Axis of Cylindrical Symmetry
MIT 1 MW Pulsed Gyrotron Oscillator at 110 GHz

- RF sources limited in mm-wave range
- MIT 1 MW gyrotron oscillator at 110 GHz with up to 3 µs pulses and frequency tunability

## Single Cell Parameters and Pulsed Heating

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissipated Power [MW]</td>
<td>1</td>
</tr>
<tr>
<td>Peak Surface Electric Field [MV/m]</td>
<td>916</td>
</tr>
<tr>
<td>Peak Surface Magnetic Field [MA/m]</td>
<td>1.13</td>
</tr>
<tr>
<td>Effective Accelerating Gradient [MeV/m]</td>
<td>404</td>
</tr>
<tr>
<td>Accelerating Gradient in Central Cell [MeV/m]</td>
<td>419</td>
</tr>
<tr>
<td>Peak Surface Poynting Vector [W/µm^2]</td>
<td>549</td>
</tr>
<tr>
<td>S/H^2 [Ohm]</td>
<td>430</td>
</tr>
<tr>
<td>Pulsed Heating (20 ns Input)* [°C]</td>
<td>156</td>
</tr>
</tbody>
</table>

*Pulsed Heating (20 ns 1 MW Pulse)

**High Power Switch or Frequency Tuning to Select Pulse Length**

![Graph showing Temp Rise vs. Time (ns)]

*20 ns 1 MW Pulse*
Cold-Test Results for of Diffusion Bonded Structure

- RF performance of cavities, mode converter, diagnostic port, high/low-power window complete
- Frequency within 0.01% of target @ 110.07GHz – thermal tuning to match MW gyrotron

![Graph showing frequency response](image)

**π-mode**

Successful Diffusion Bond