High-Power High-Gradient Testing of mm-Wave Standing-Wave Accelerating Structures

Emilio A. Nanni

*IPAC 2018*

5/1/2018
## Acknowledgements

<table>
<thead>
<tr>
<th>SLAC</th>
<th>MIT</th>
<th>INFN-LNF</th>
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<tbody>
<tr>
<td>Valery Dolgashev</td>
<td>Sam Schaub</td>
<td>Bruno Spataro</td>
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<td>Jeff Neilson</td>
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<td>Andy Haase</td>
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<td>Sami Tantawi</td>
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<td>Chris Pearson</td>
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Support by:

[Image of Support by]

U.S. Department of Energy
Office of Science
Outline

• Motivation
• mm-Wave Structure for High Gradient Tests
• Structure Prototyping and Fabrication
• Cold-Test Results for Accelerator Structure
• Conclusions
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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 mm-Wave/THz Accelerator Technology

Rapid Development of mm-Wave/THz Accelerator Technology

**Acceleration**


**Photoinjectors**

Rapid Development of mm-Wave/THz Accelerator Technology

Acceleration


Photoinjectors


Beam-Driven GV/m Fields

Rapid Development of mm-Wave/THz Accelerator Technology

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**Deflectors and <1 fs Timing**

Rapid Development of mm-Wave/THz Accelerator Technology

Acceleration


Photoinjectors


Beam-Driven GV/m Fields


Deflectors and <1 fs Timing


Toward Externally Driven GeV/m Accel.
Rapid Development of mm-Wave/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

Acceleration


Photoinjectors


Beam-Driven GV/m Fields


Deflectors and <1 fs Timing


Growing International Community:


Healy, et al., UCMMT, 2017

Toward Externally Driven GeV/m Accel.


M. Dehler, HG2017
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
Higher Frequencies Can Achieve Higher Gradients

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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

- 300 GHz Structure

E. A. Nanni, et al., IPAC 2016
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Shunt Impedance for $\text{TM}_{01}$ $\pi$-mode Structures

E. A. Nanni, et al., IPAC 2016
Comparison Between RF and THz Accelerators

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

### Parameters for 100 MeV/m Gradient

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<td>Stored Energy [mJ]</td>
<td>8450</td>
<td>0.013</td>
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<td>Q-value [x1000]</td>
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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

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Must Understand this New Regime for Frequency, Pulse Length, Stored Energy
Outline

• Motivation
• mm-Wave Structure for High Gradient Tests
• Structure Prototyping and Fabrication
• Cold-Test Results for Accelerator Structure
• Conclusions
- Increased shunt impedance and RF efficiency w/ mm-wave 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

Observation of Damage:

Input coupler, cells 1-7, no damage
Cells 15-23, fist signs of damage

Acc. gradient 0.3 GV/m
$E_{\text{peak}}$ 0.64 GV/m
Pulse Length ~2.3 ns

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

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)

Electric Field

Frequency = 110.12 GHz  $Q = 1572$

Magnetic Field

Axis of Cylindrical Symmetry
S-Parameters for ‘Single-Cell’ Structure for $a/\lambda = 0.105$ and 1 MW of Dissipated Power

- Measure forward/reflected power through free space direction coupler and coupled power through diagnostic port
## Single Cell Parameters and Pulsed Heating

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* *20 ns 1 MW Pulse*
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**High Power Switch or Frequency Tuning to Select Pulse Length**
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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 8 assemblies consisting of 22 separate RF structures
  - Focus is structural integrity, RF performance, frequency shifts
Comparison of Assembly Techniques

• Assembly from halves makes RF performance insensitive

• 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
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Structure Fabrication for High Gradient Test at 110 GHz

• First test with split-cell and diffusion bonding

Applying Advanced Metrology for Close Loop Manufacturing
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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 of S_11 vs Frequency (GHz) with π-mode highlighted.](image_url)
110 GHz High Gradient Structure Assembly Complete

Vacuum Pump Out

Dark Current Port

Diffusion Bonded 110 GHz Structure

Diagnostic Window

High Power Window
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

Schaub, Jawla
6.75 in.

Nanni, Neilson, Jawla, Schaub
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 - π-mode 110.1 GHz, $S_{11} \approx -25$ dB, $S_{21} \approx -40$ dB

Moving Forward to Test @ MIT, Target 1 MW Dissipated >400 MeV/m
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
- Quasi-optical coupling and transport demonstrated
- Integration with MW source now underway
Questions?