THz Accelerators and Their Application to Ultrafast Electron Diffraction

Emilio A. Nanni

SLAC National Accelerator Laboratory, Stanford University

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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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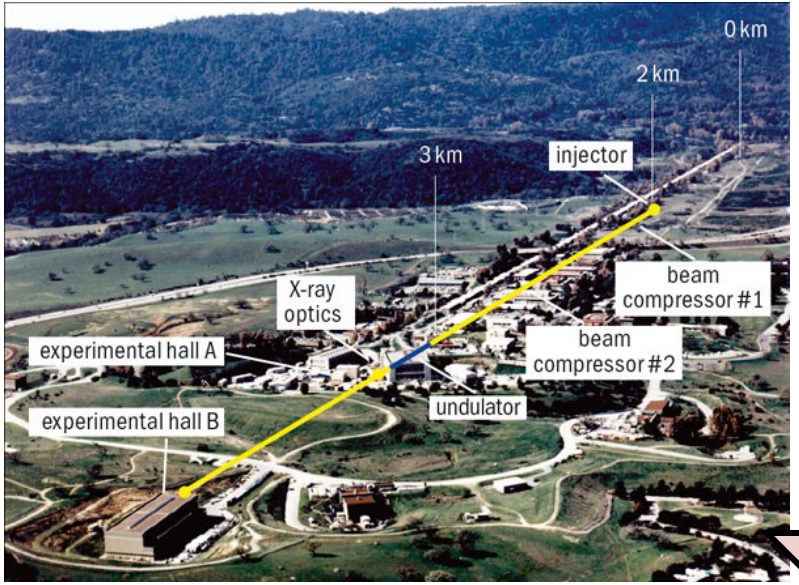
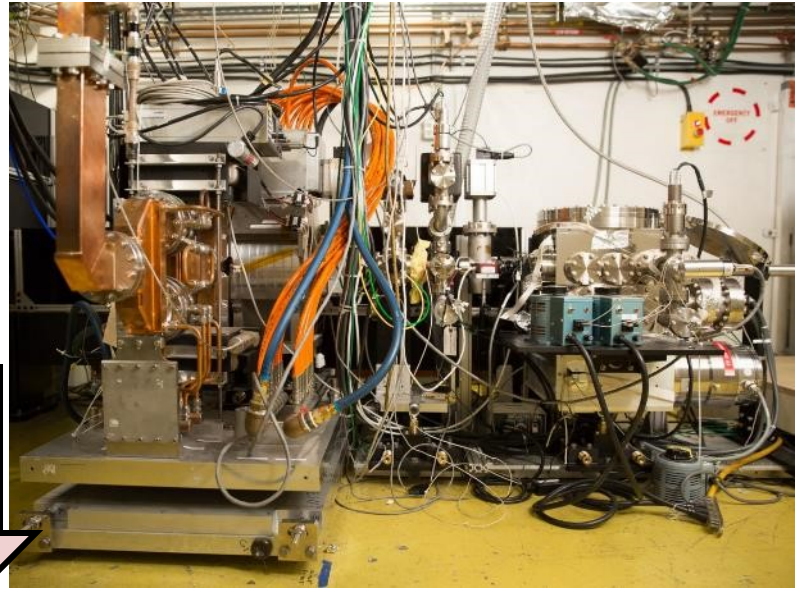
Accelerator Technology Drives Scientific Discovery

SLAC

Coherent X-rays from LCLS (2009)

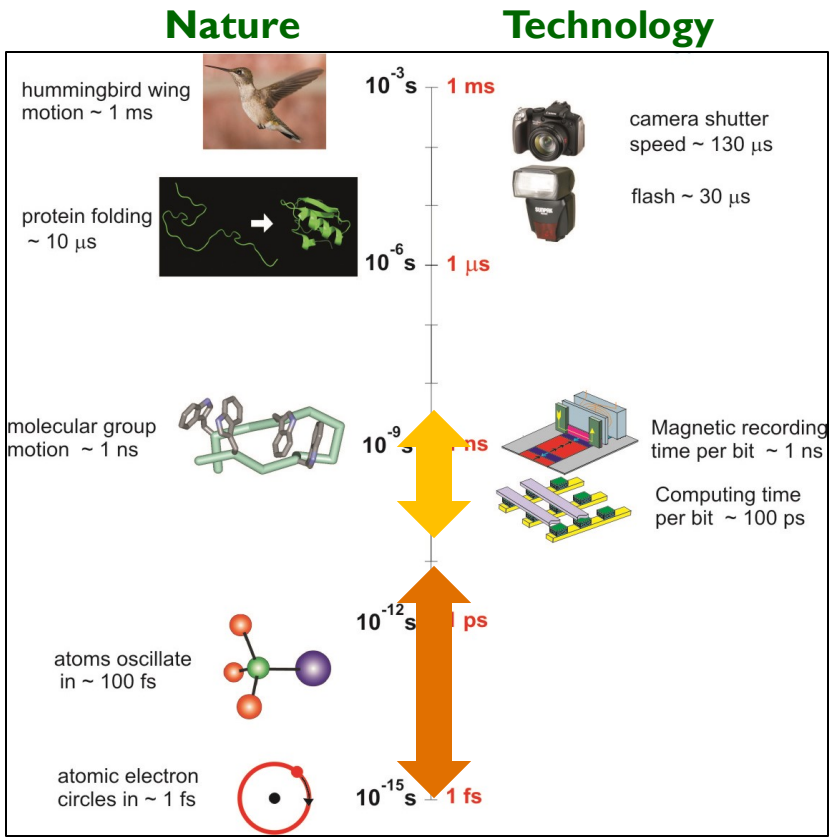


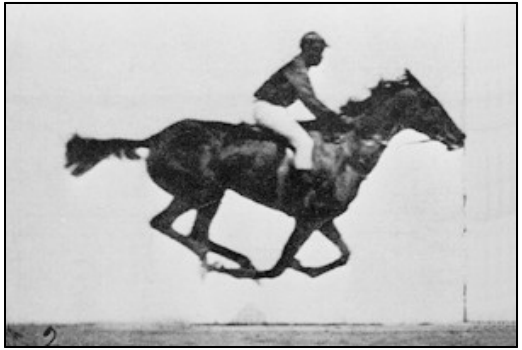
Ultrafast Electron Diffraction (2015)



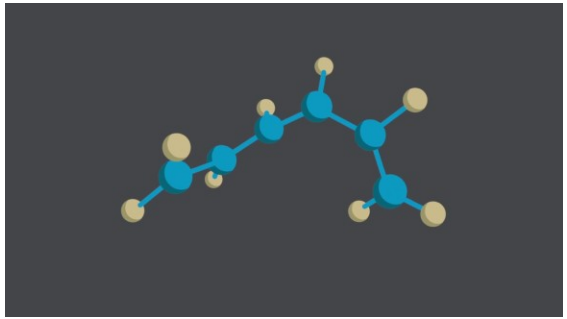
How do we develop the next generation of accelerators and what new science does this enable?

Ultra-fast and Ultra-small: The New Frontier





1 msec shutter speed



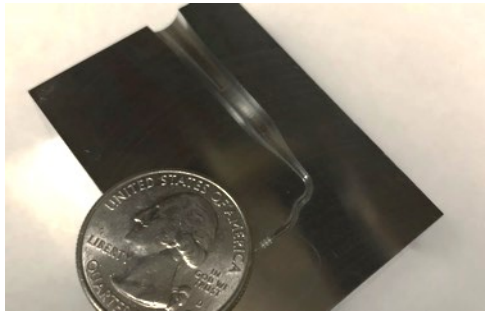
10-100 femtosecond shutter speed

Next Generation Accelerators in Pursuit of Compactness, Efficiency and Performance

SLAC

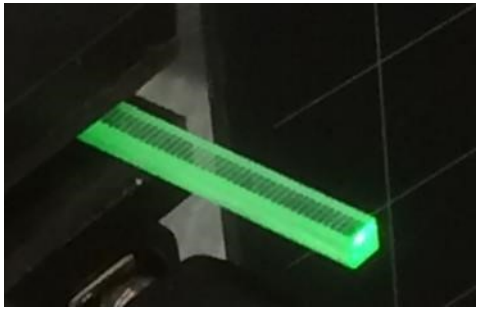
S-band Accelerators
30 MeV/m

mm-Wave/THz Accelerators
GeV/m



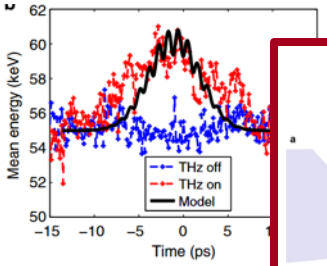
Klystron Source
10s MW, μs, ~3 GHz

mm-Wave/THz Sources
MW, ns, ~0.3 THz



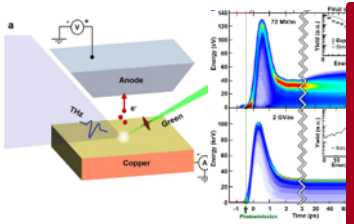
Rapid Development of THz Accelerator Technology

Acceleration



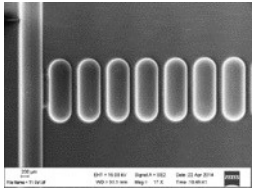
Nature Comm. 6 (2015):

Photoinjectors



Huang, W. R., et al., *Nature Scientific Rep.* 5 (2015).

Beam-Driven GV/m Fields



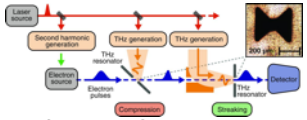
M. Dal Forno, et al., *PRAB* 19 (2016): 051302.

Deflectors and <1 fs Timing

afast O
2017)

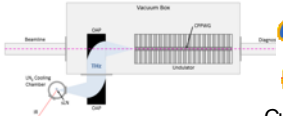
Growing International Community:

Zhao, et al. *PRX* 8.2 (2018): 021061.

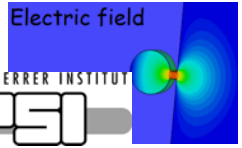


Kealhofer, et al. *Science* 352.6284 (2016)

Healy, et al., *UCMMT, 2017*

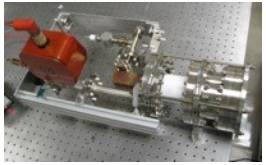


Curry, et al. arXiv:1708.06385 (2017).



M. Dehler, HG2017

Toward Externally Driven GeV/m Accel.



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

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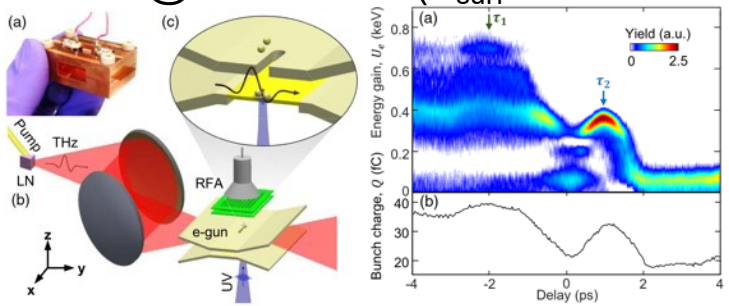
Higher Frequencies Can Achieve Higher Gradients

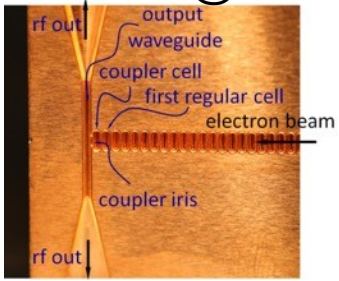
- Accelerating gradient is limited by breakdown (i.e. arcing or plasma formation)
- Breakdown threshold for surface electric field $E_s \propto f^{1/2}$
- Demonstrated operation with ~1 GV/m surface fields

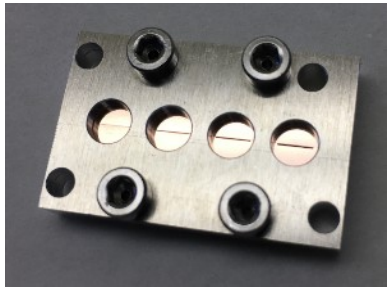
THz Guns @ MIT/DESY (E_{surf} ~ 300 MV/m)



W. R. Huang, et al., Optica 3, 1209-1212 (2016).

Beam Driven @ FACET (E_{surf} ~ GV/m)





M. Dal Forno, et al., *PRAB* 19.5 (2016): 051302.

Streaking @ SLAC UED (E_{surf} ~ 150 MV/m)

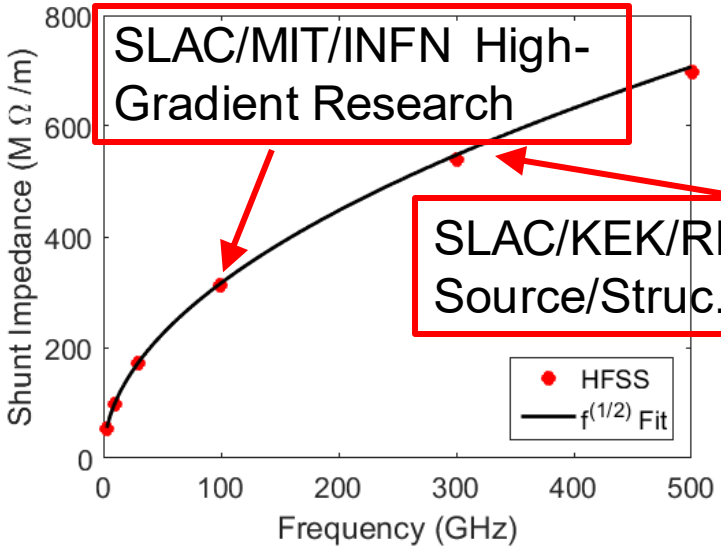
Other Examples:
Wimmer L. *et al.,* Nature Phys. 10, 432–436 (2014).
Nanni, E. A., et al. *Nature Comm.* 6 (2015): 8486.
Huang, W. R., et al., *Nature Scientific Reports* 5 (2015).

Advantages of Operating at THz Frequencies

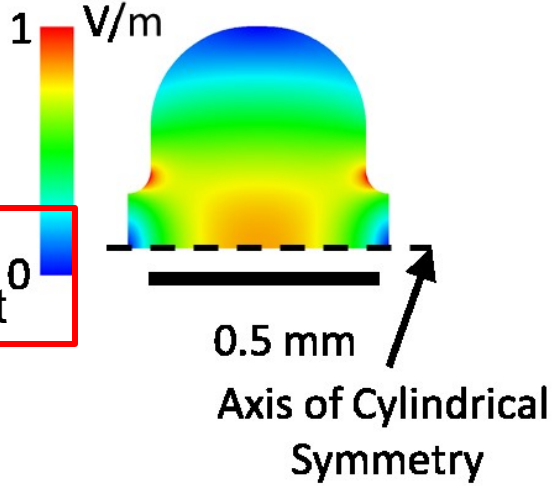
Additional advantages of high frequency structures:

- 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

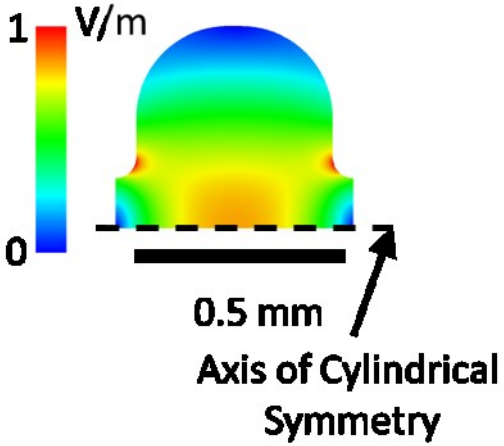


Comparison Between RF and THz Accelerators

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

Parameters for 100 MeV/m Gradient

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

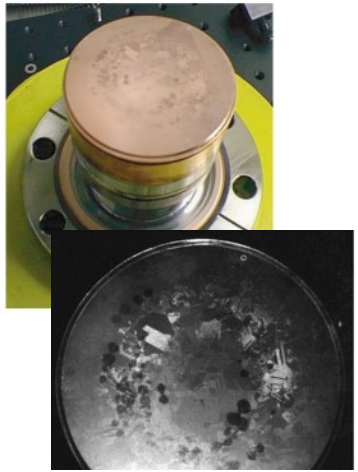


$P \times \tau$ decreases by 4 orders of magnitude
Potential to operate at 10s kHz vs 100s Hz

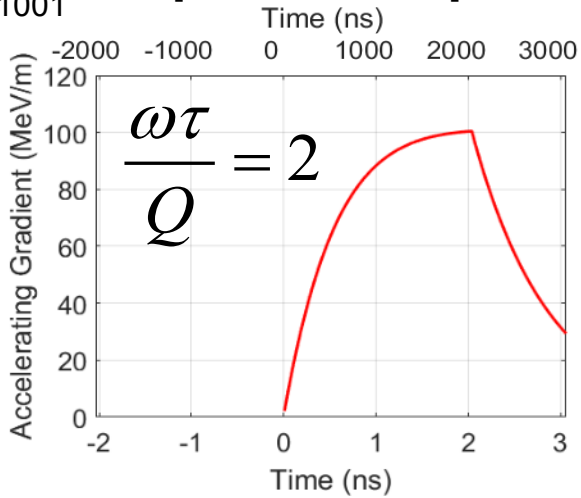
Pulsed Heating in High-Frequency Structures

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

Pritzkau, et al., Phys. Rev. STAB 2002
Laurent, et al. *PRSTAB* 14.4 (2011): 041001

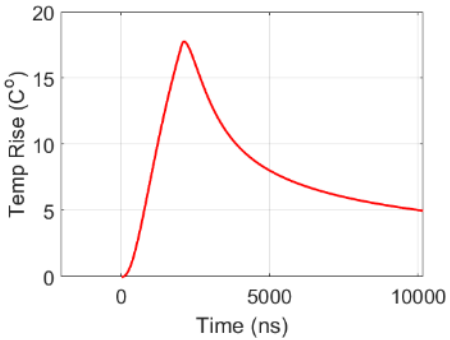


[3 GHz Structure]

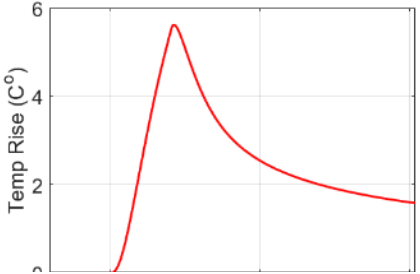


$$\frac{\omega\tau}{Q} = 2$$

3 GHz Structure



300 GHz Structure

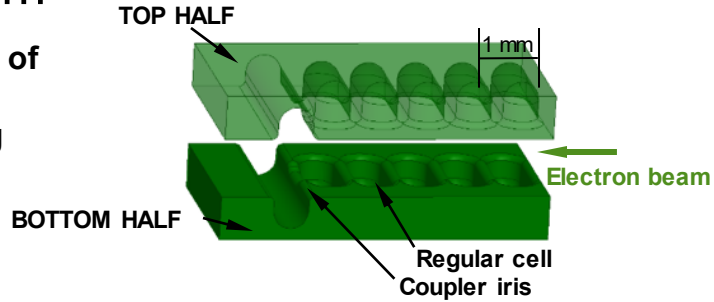


Must Understand this New Regime for Frequency, Pulse Length, Stored Energy

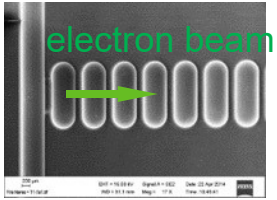
THz Metallic Accelerator Holds the Potential for High-Gradient Accelerators

- 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

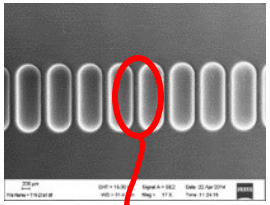
Solid model of the 100 GHz accelerating structure



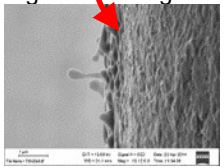
Observation of Damage:



Input coupler, cells 1-7, no damage

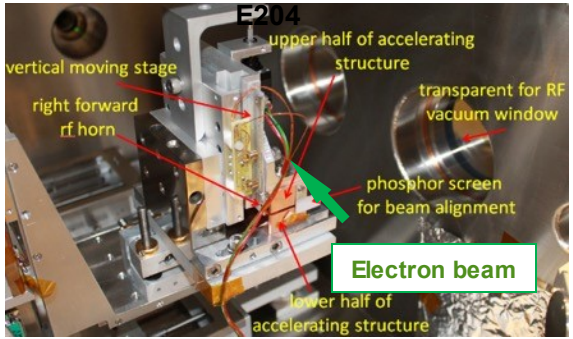


Cells 16-23, fist signs of damage



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

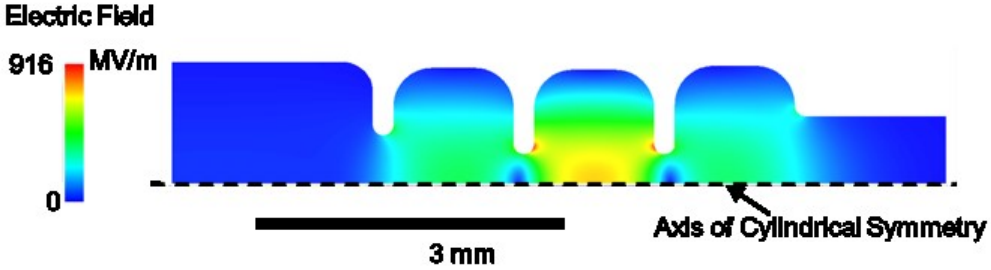
Experimental setup with copper accelerating structure – FACET E204

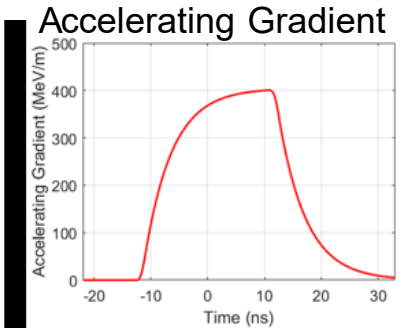


Dal Forno, Massimo, et al. *PRAB* 19.1 (2016): 011301.

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

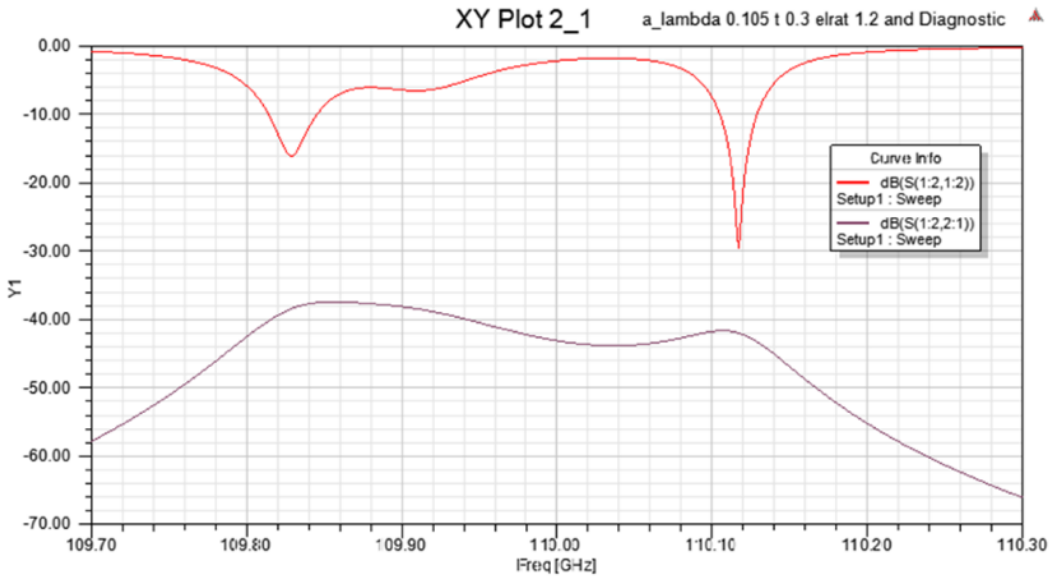




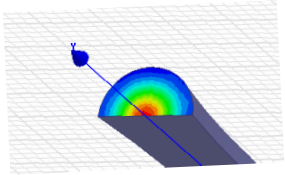
Need to Develop High-Power High-Frequency Sources for Practical Applications

S-Parameters for 'Single-Cell' Structure for a/λ = 0.105 and 1 MW of Dissipated Power

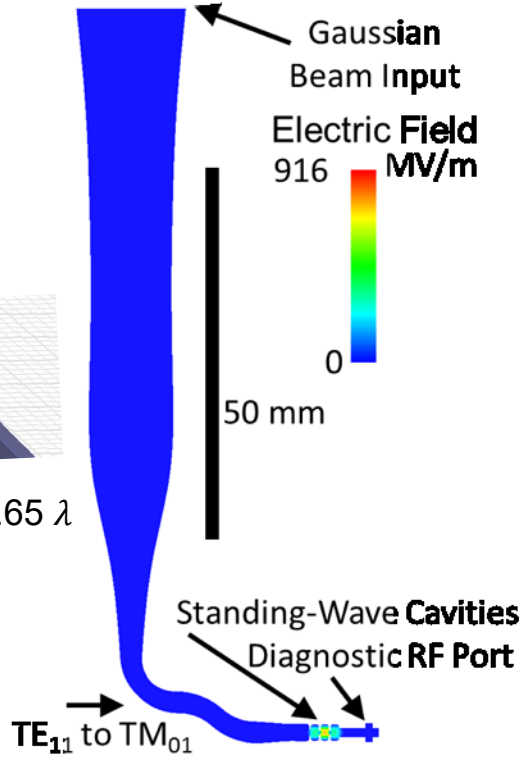
- Measure forward/reflected power through free space directional coupler and coupled power through diagnostic port



Field on horn aperture



Beam waist 1.65 λ



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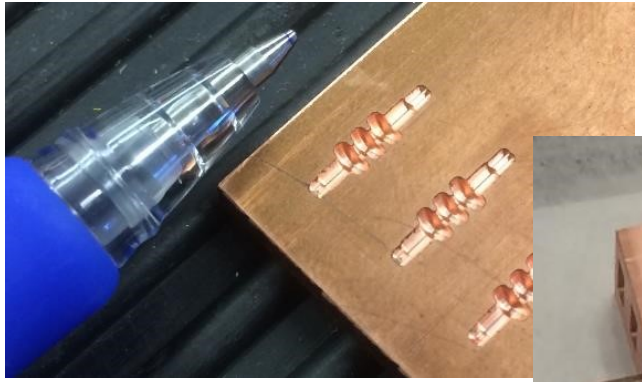
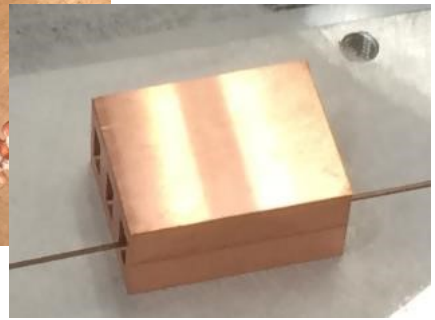
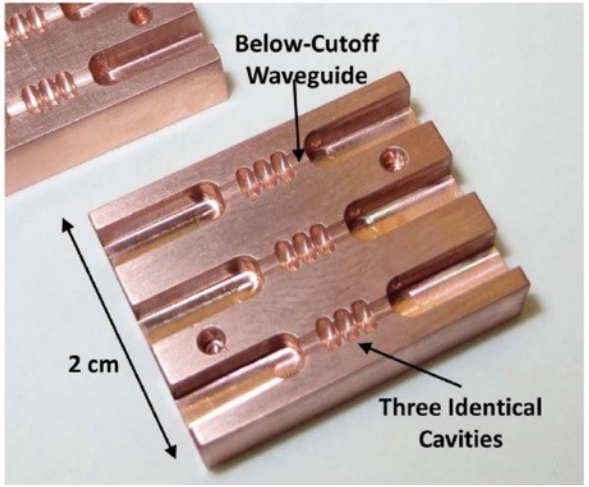
Prototyping of mm-Wave Structures

- 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



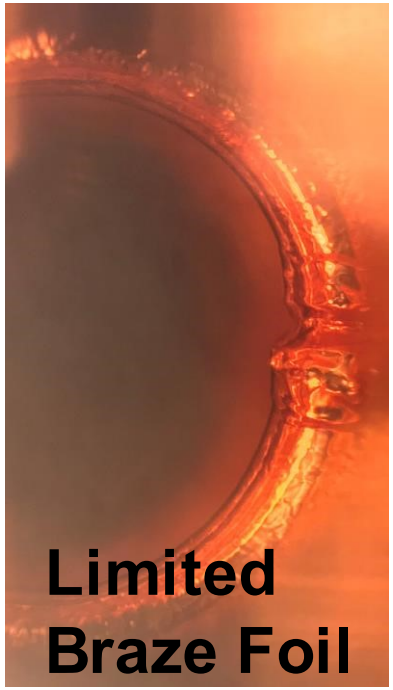


Coaxial Probes



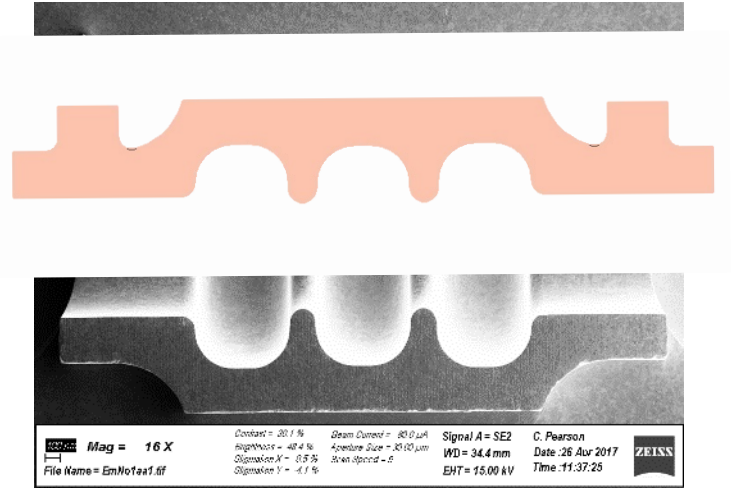
Comparison of Assembly Techniques

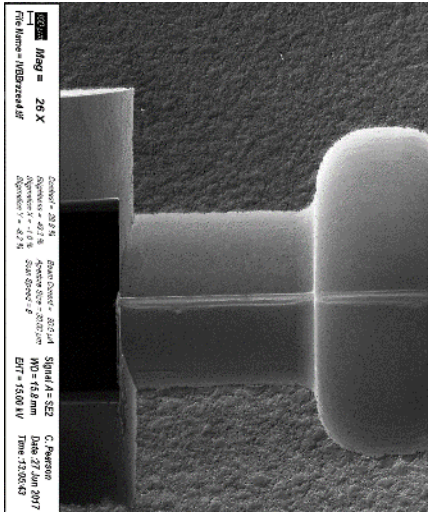
- Assembly from halves makes RF performance insensitive to defects
- Local features significantly different

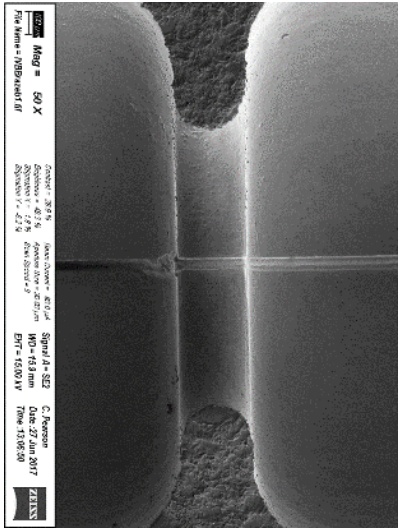


Details of Isolated + Limited Brazed Assembly

- 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



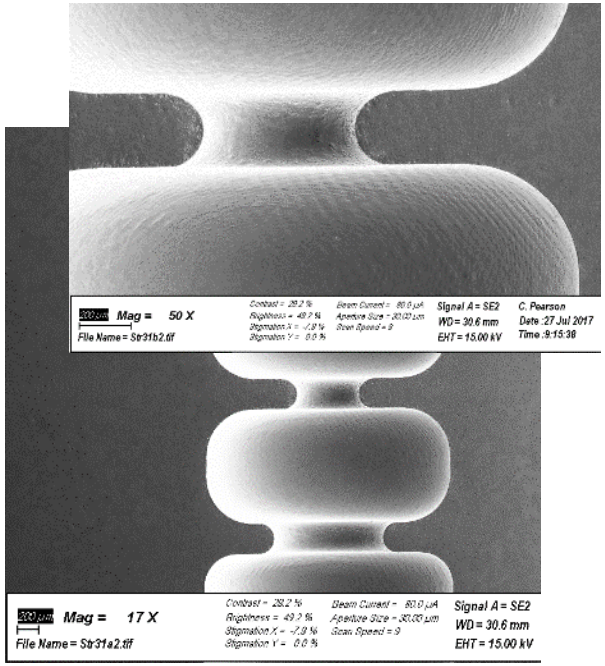




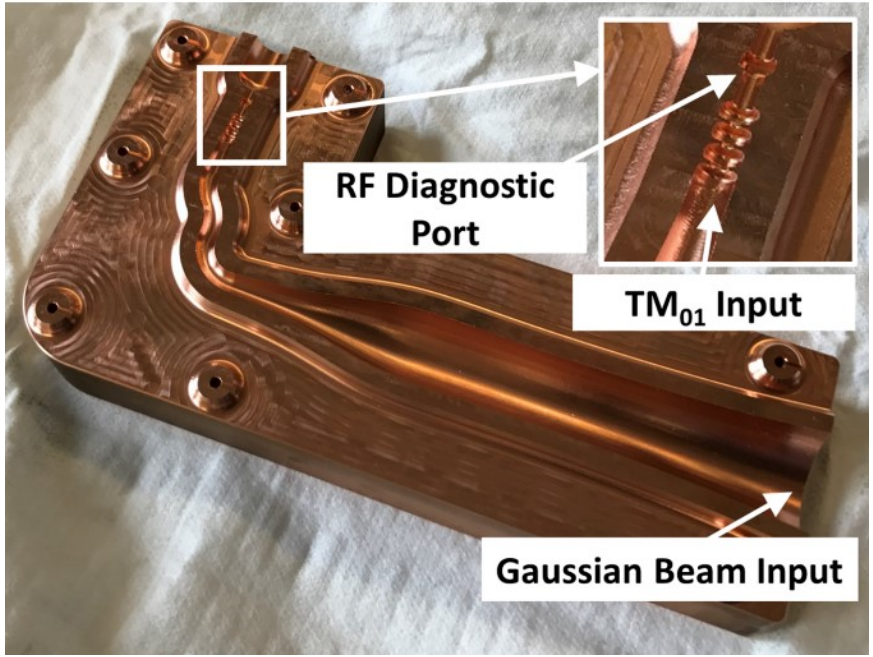
Structure Fabrication for High Gradient Test at 110 GHz

- First test with split-cell and diffusion bonding

Pre-Bonding SEM



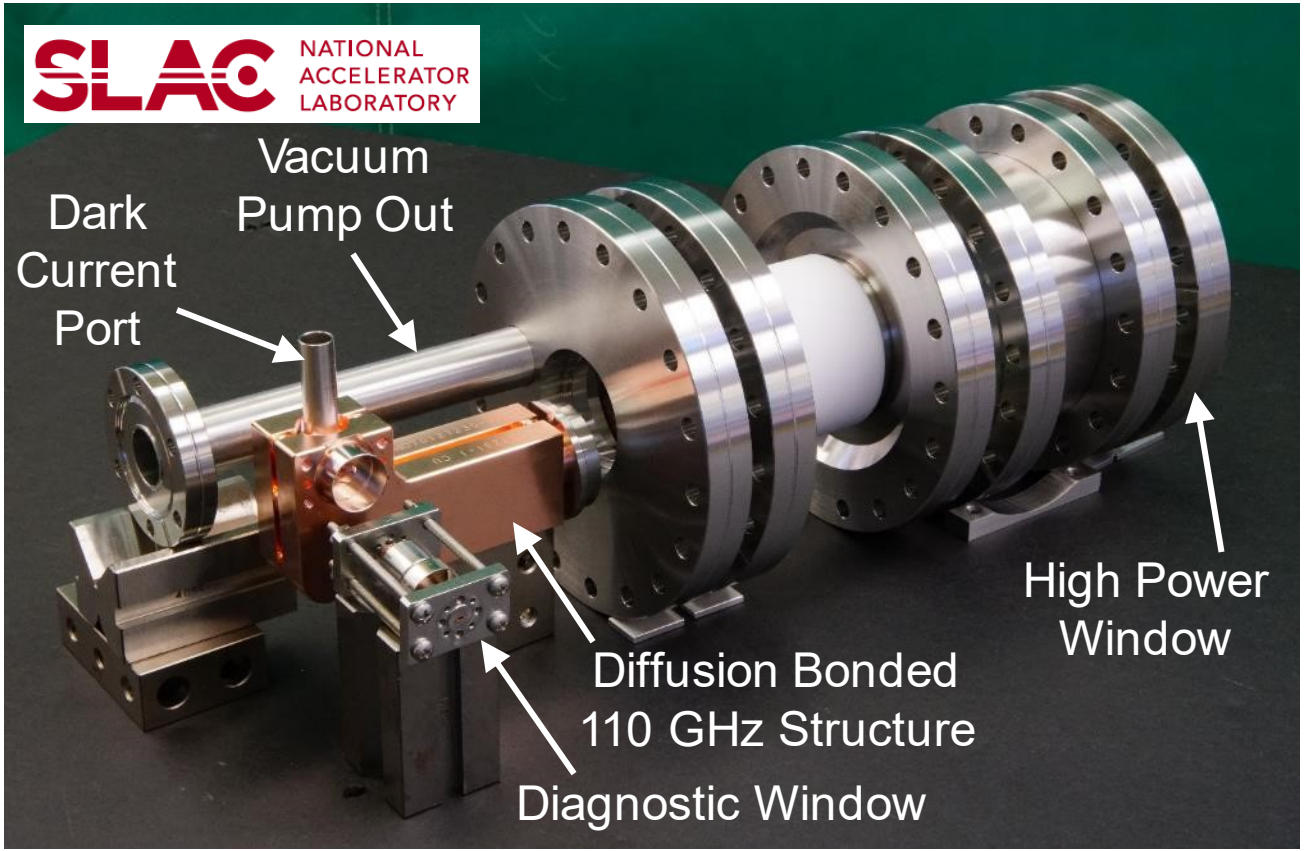
Mode Converter and Cavities



Applying Advanced Metrology for Close Loop Manufacturing

a/λ=0.105

110 GHz High Gradient Structure Assembly Complete



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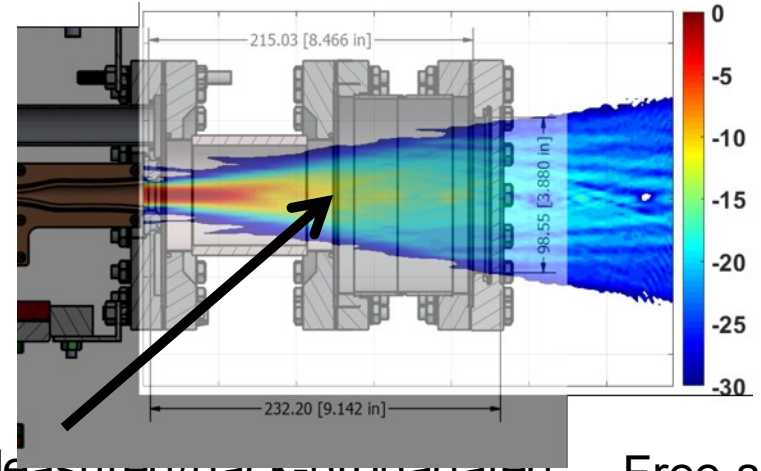
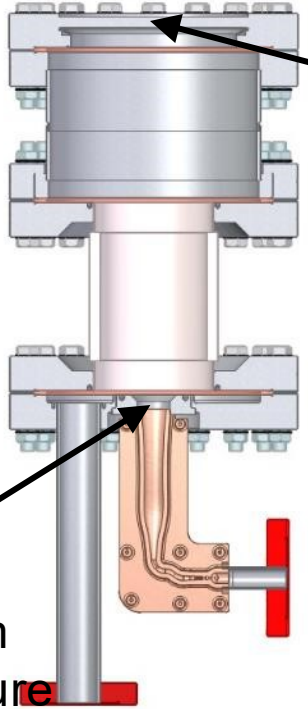
Efficient Excitation of THz Accelerating Structures

Schaub, Jawla

- Avoid lossy waveguides with quasi-optical transport and couplers

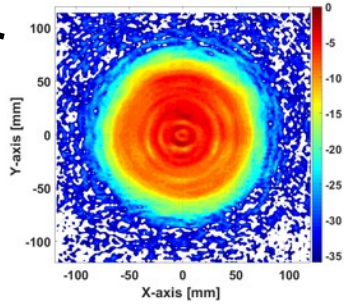


Measured/back-propagated field in the cut plane of the assembly

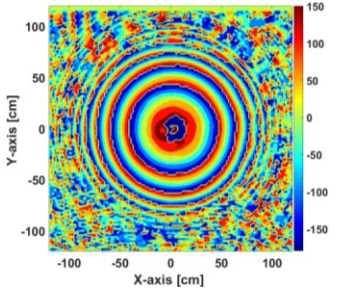


Free-space Gaussian beam coupled to structure

Measured Amplitude



Measured Phase

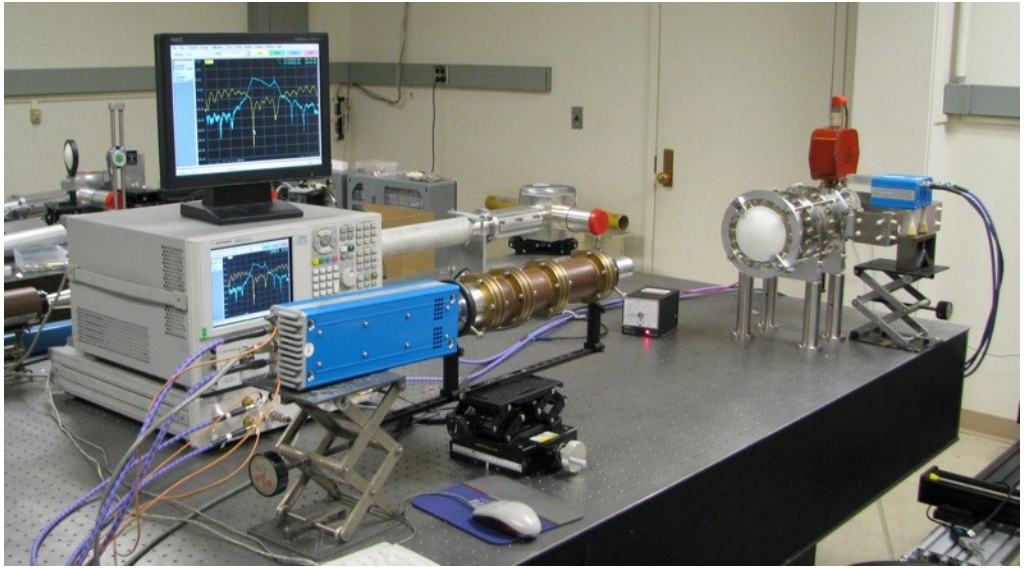


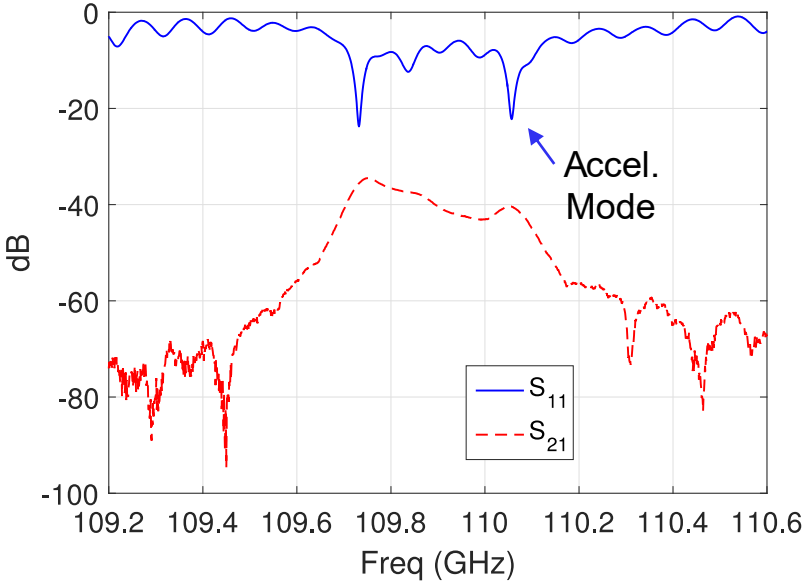
Versatile Topology Compatible with New Structures and Different Frequencies

Results from Quasi-Optical Transport Test

Schaub, Jawla

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

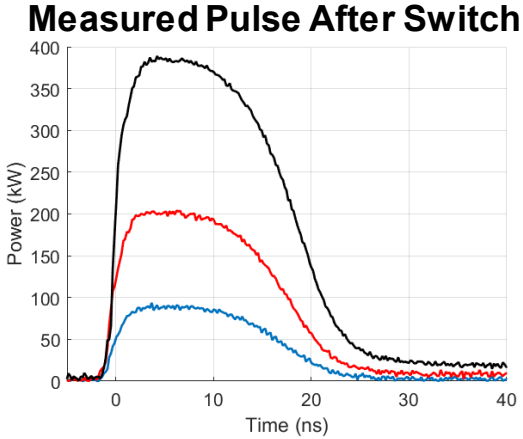


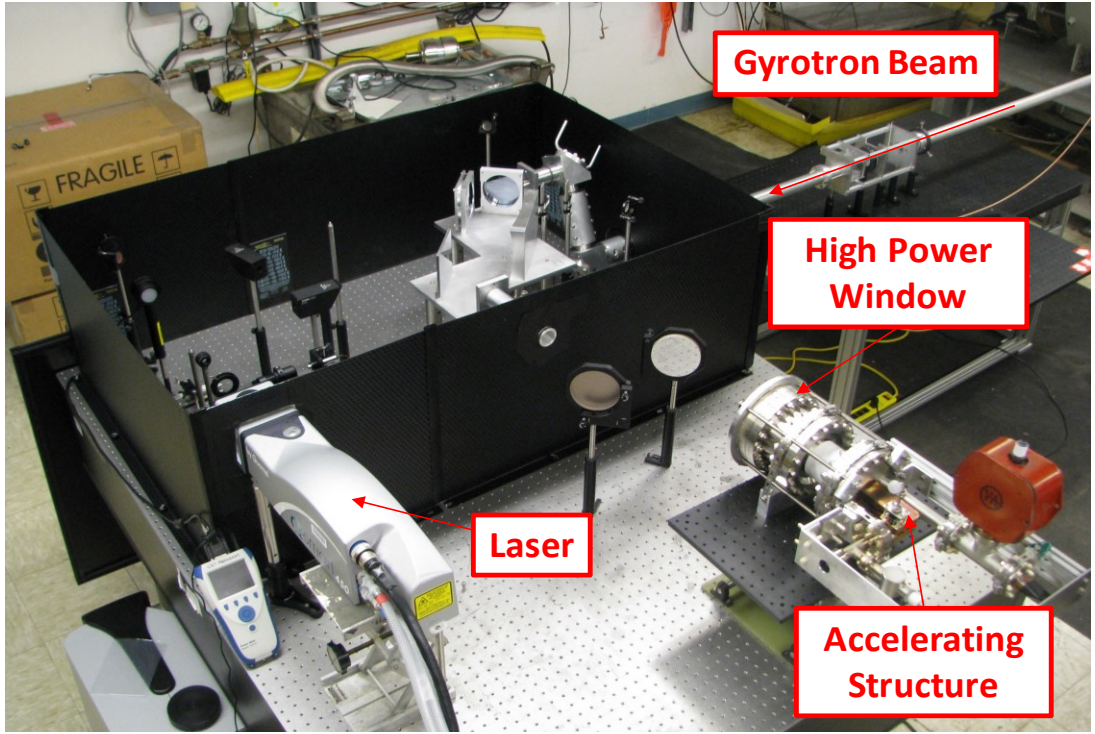


First Quasi-Optical Coupling into Narrow-Band Accelerating Structure

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

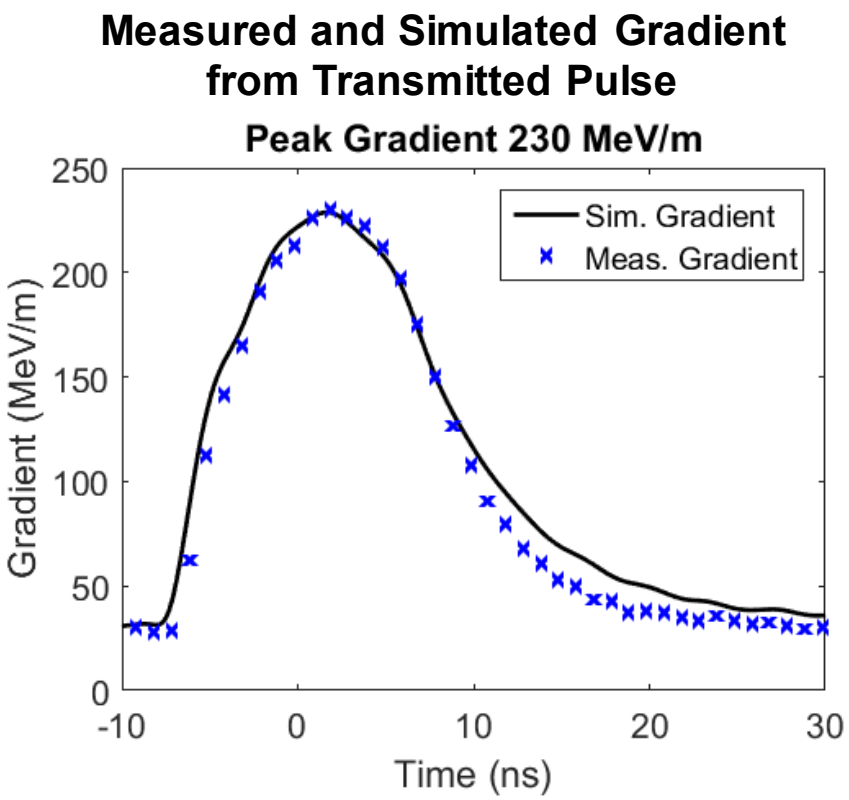




Picard, Schaub

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)



520 MV/m Surface Electric Field

Othman, et al. *Applied Physics Letters* 117.7 (2020): 073502.

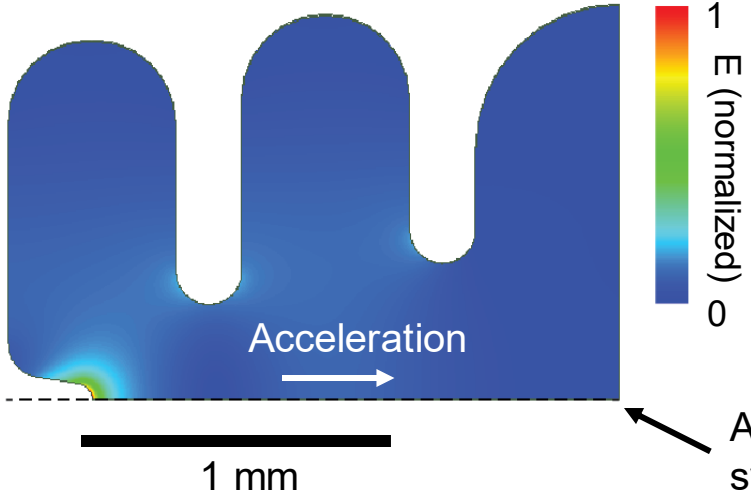
Mm-Wave Relativistic Electron Source

Two cell π mode structure with 50 μm radius copper tip

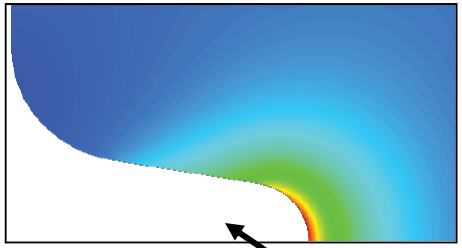
On-axis coupling from 110 GHz gyrotron source

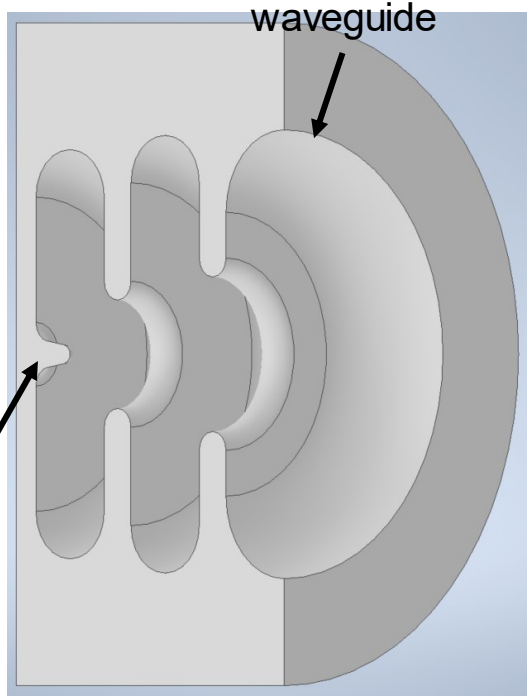
Maximum field on the tip is 3.8 GV/m for 500 kW input power

π mode field (vacuum

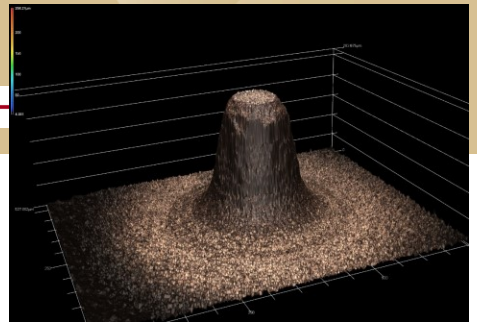


Field enhancement at





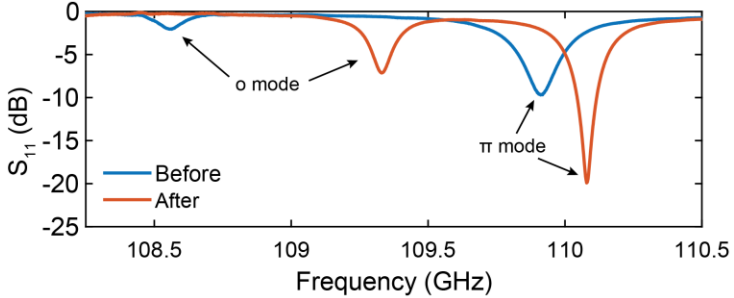
Future Work: THz-Driven Electron Gun

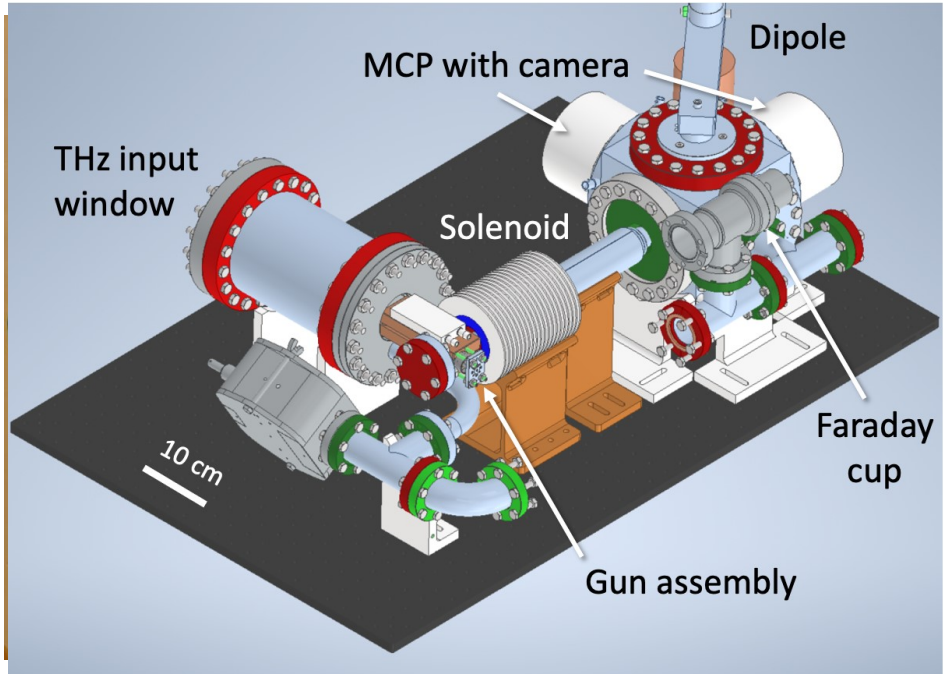


This gun will demonstrate the feasibility of using normal conducting, THz accelerating structures to create compact, high gradient electron sources.

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





Outline

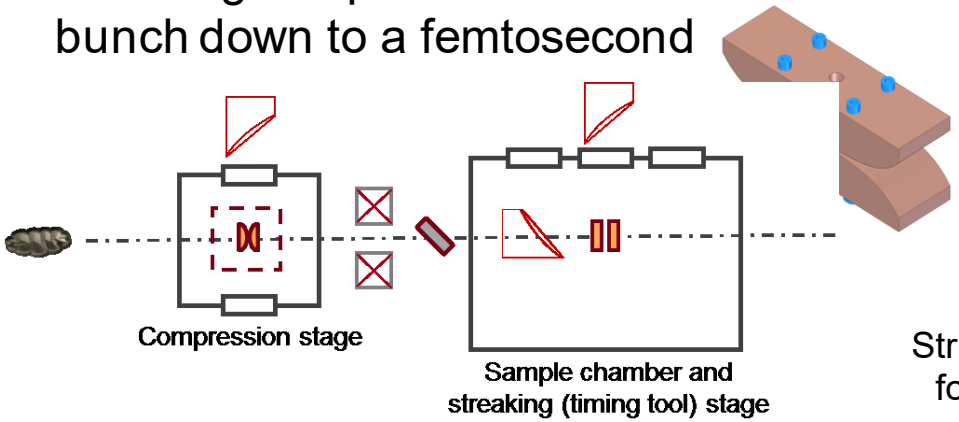
- Motivation
- Performance of THz Accelerators
- Structure Prototyping and Fabrication
- High-Power Test of Narrow-Band Structures
- Laser-Driven THz Accelerator Experiments
- Conclusions

Exploring New Frontiers of THz Acceleration with Laser-Driven THz Sources

SLAC

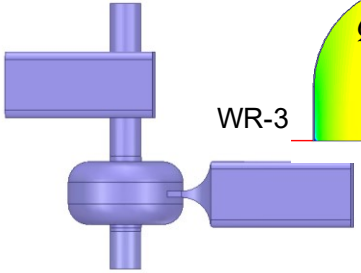
Single-Cycle THz Source Experiments

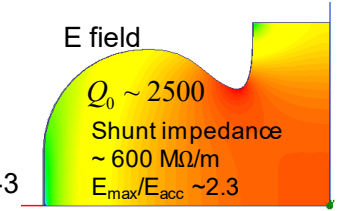
- Experimental stepping stone
- Successfully demonstrated <fs streaking diagnostic at SLAC UED
- Pursuing compression of electron bunch down to a femtosecond



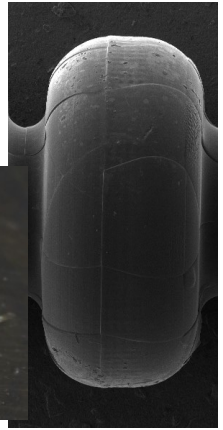
Narrow-Band THz Source Experiments

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





3D Printing Accelerating Structures at 300 GHz for Electro-Forming

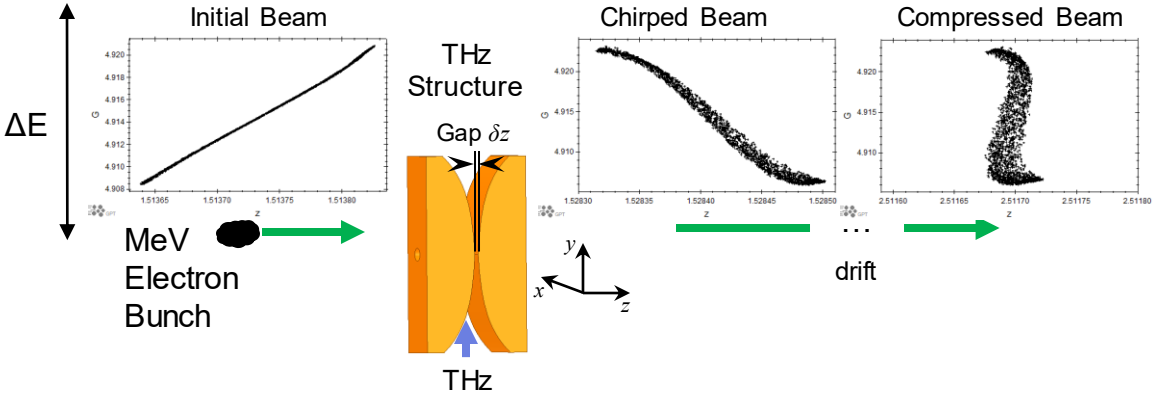


Othman, et al. *Opt. Express 27, 23791-23800* (2019)
Snively, et al. *Phys. Rev. Lett. 124, 054801* (2020)

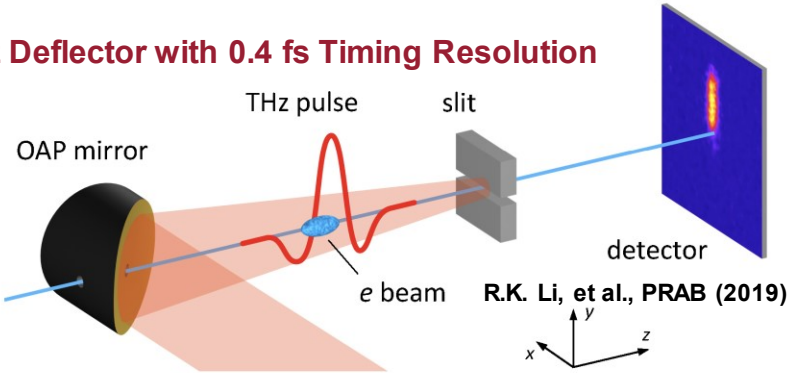
THz Driven Electron Bunch Compression is Key Technology for sub-Femtosecond Resolution

- 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:

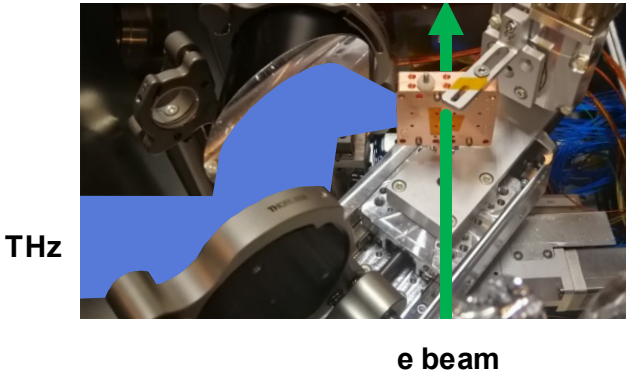


THz Deflector with 0.4 fs Timing Resolution



R.K. Li, et al., PRAB (2019)

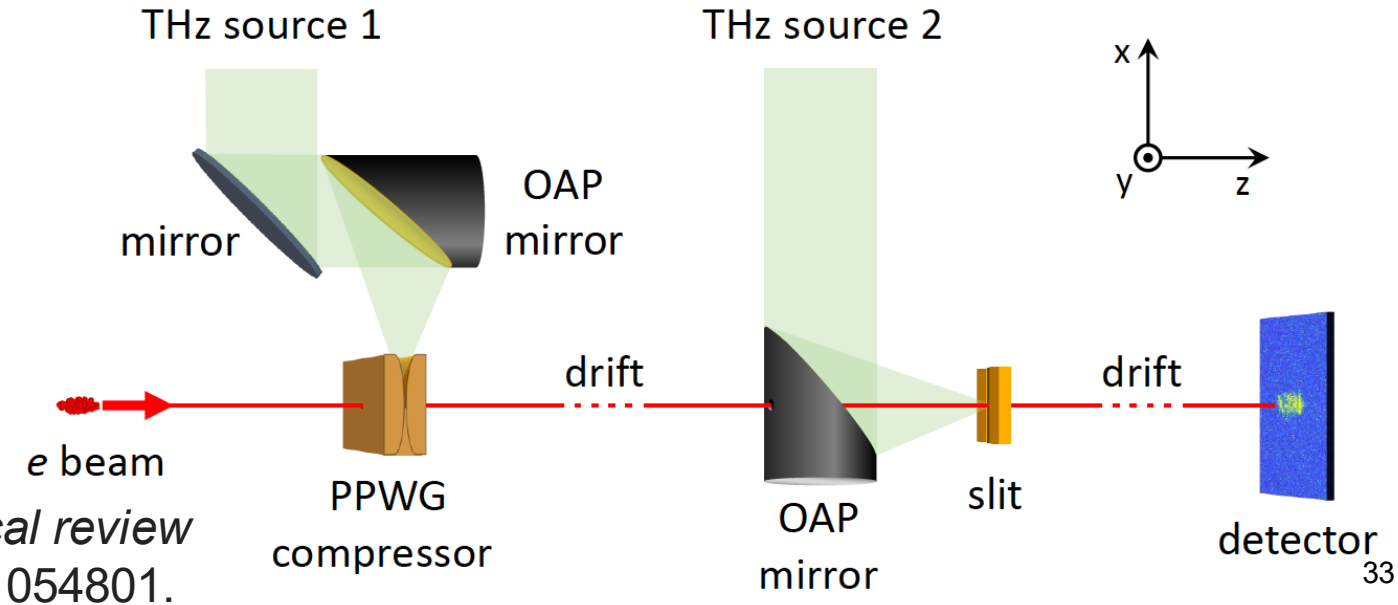
THz Compressor



THz Compression Experiment Integrated with Operating Ultrafast Electron Diffraction Facility

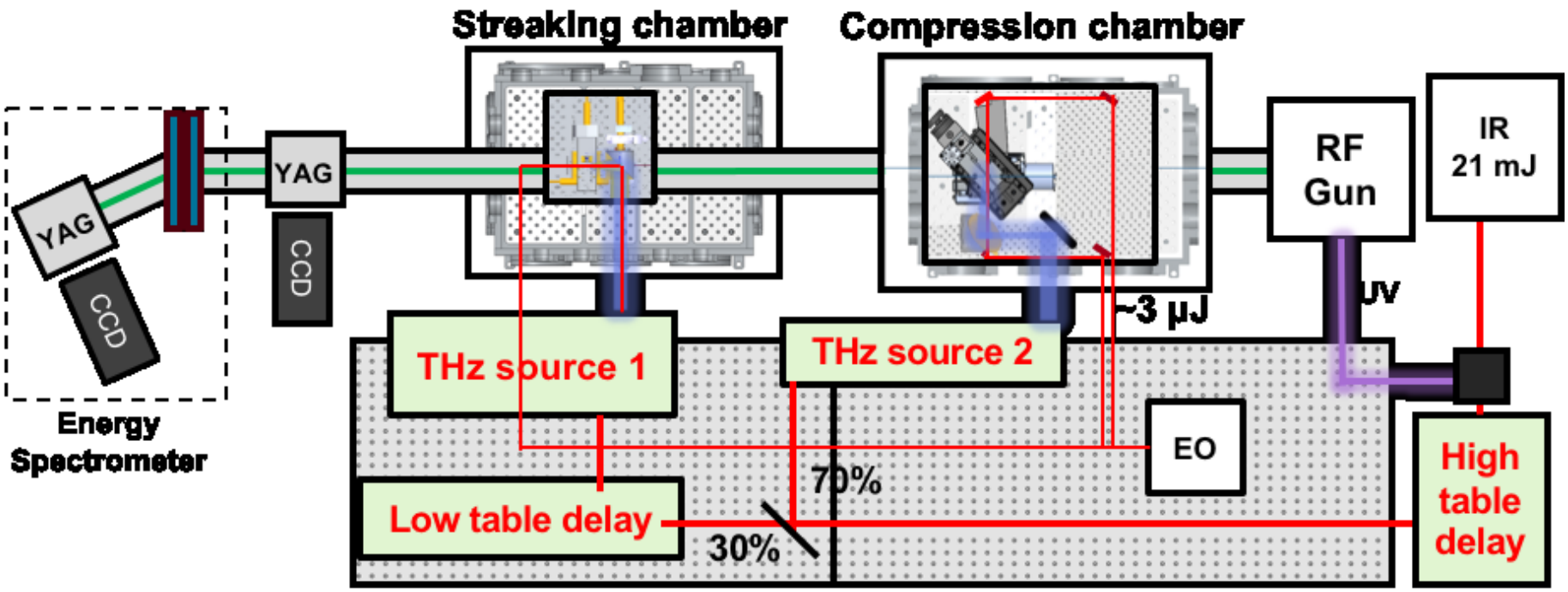
- Operated with few fC of charge and 2-3.5 MeV, nominal UED operating point - fields in structure ~100 MV/m
- Bunch characterized with THz transverse deflector

Experimental Setup for THz Compressor and THz Deflector



Snively, et al. *Physical review letters* 124.5 (2020): 054801.

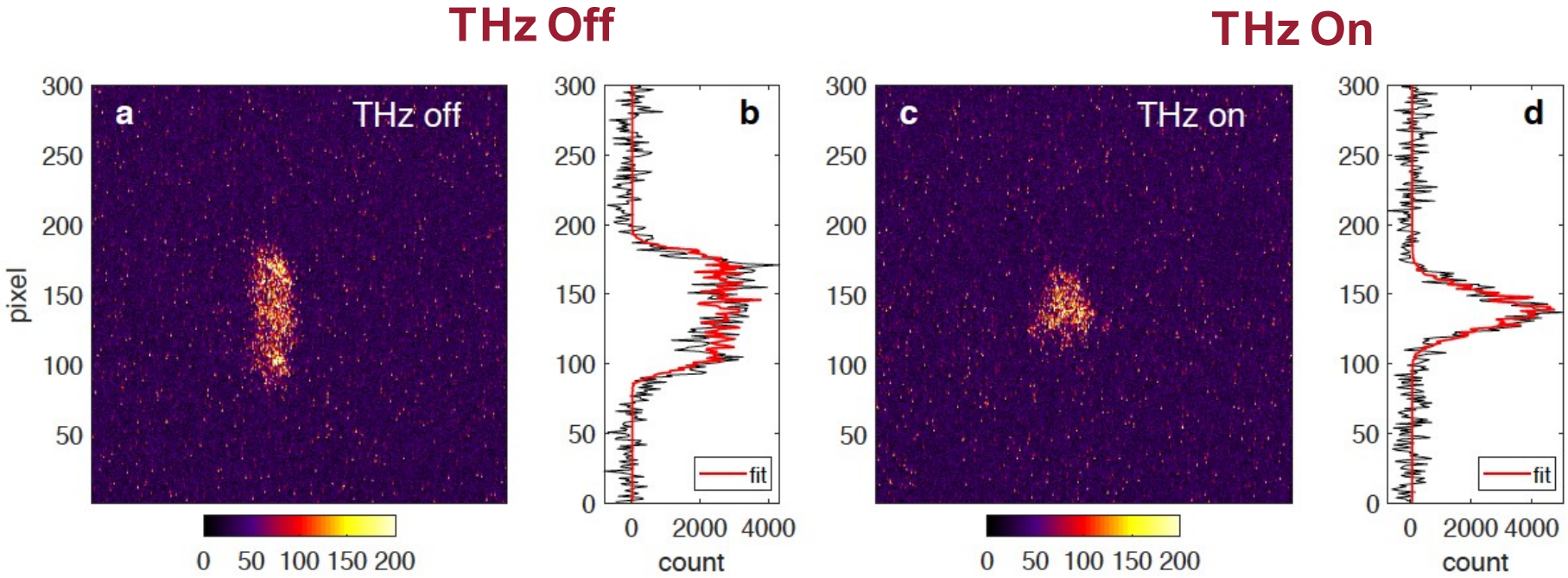
THz Driven Compression Experimental Setup



*setup diagram not-to-scale

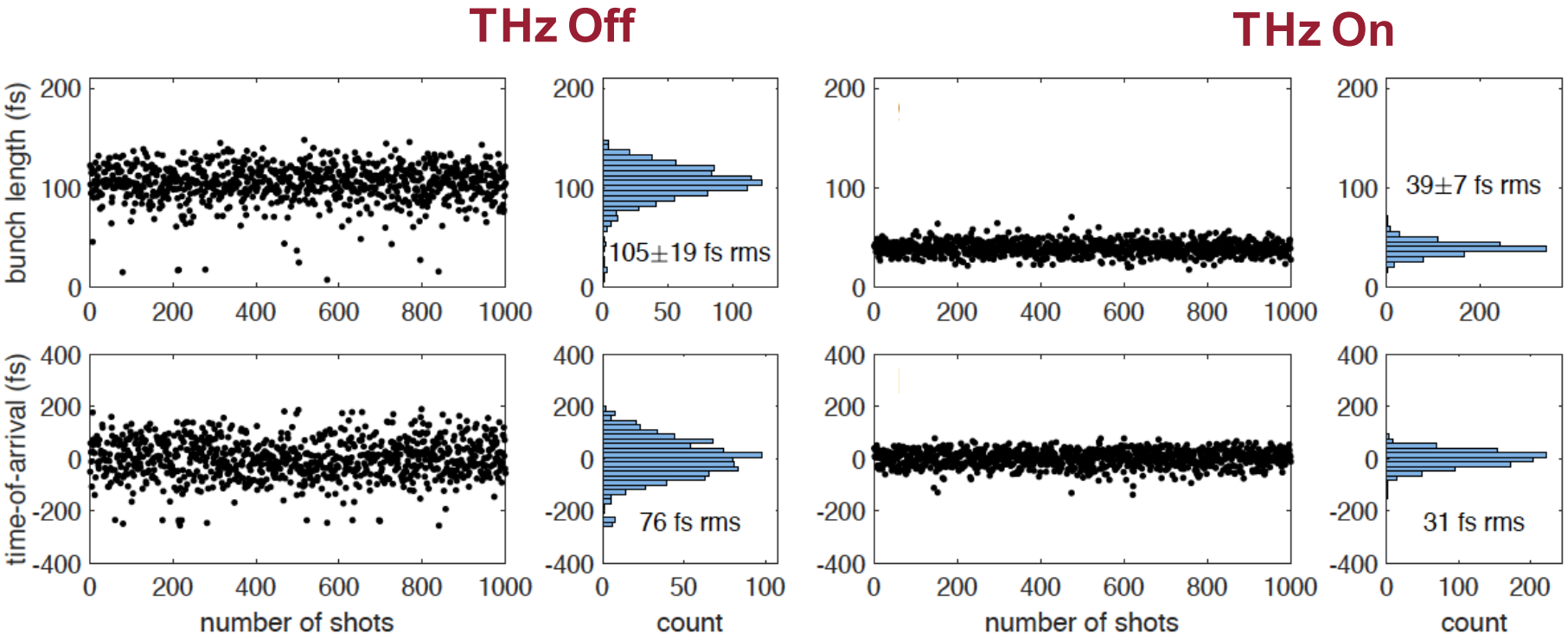
Performance of THz Electron Bunch Compressor: Single Shot Bunch Length Measurement

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



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

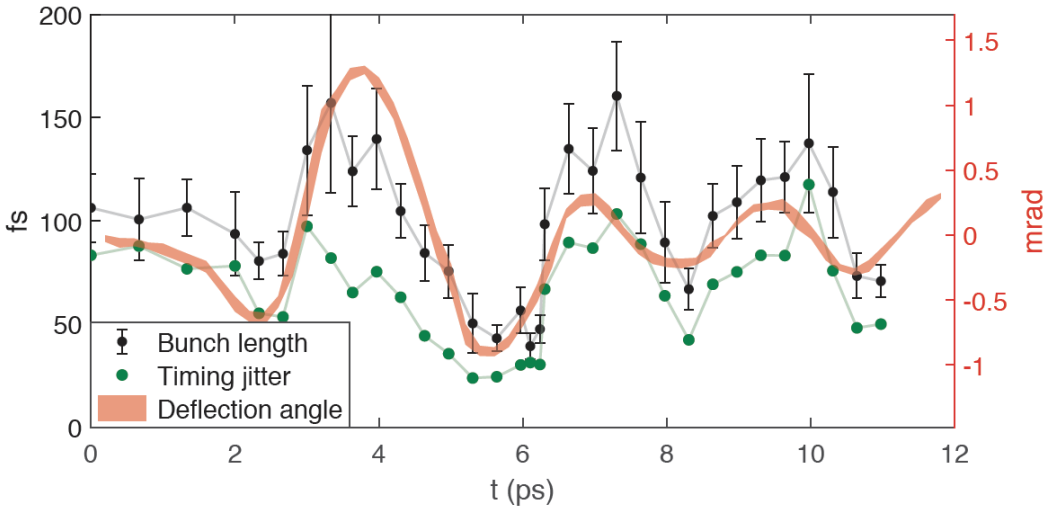
- Bunch length reduced by ~3X and jitter by >2X



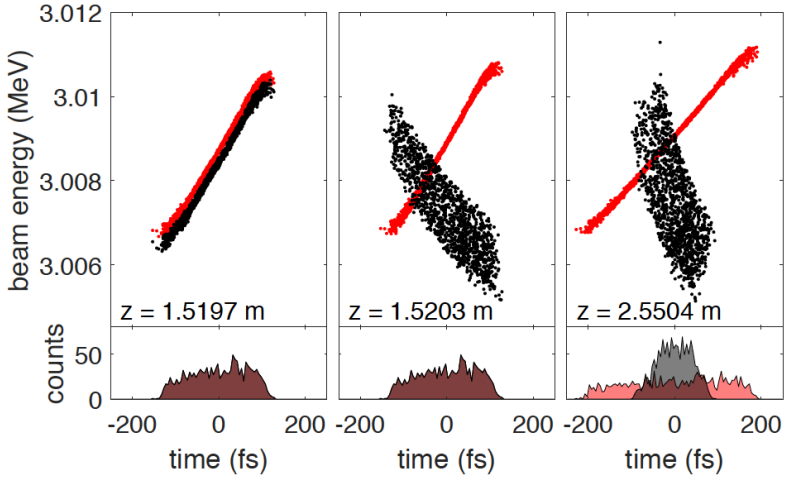
Performance of THz Electron Bunch Compressor: Stable Operation Allows for Full Characterization

- Measurements at multiple energies now being modeled and analyzed (500k images collected in 2 weeks)

Performance vs THz Delay



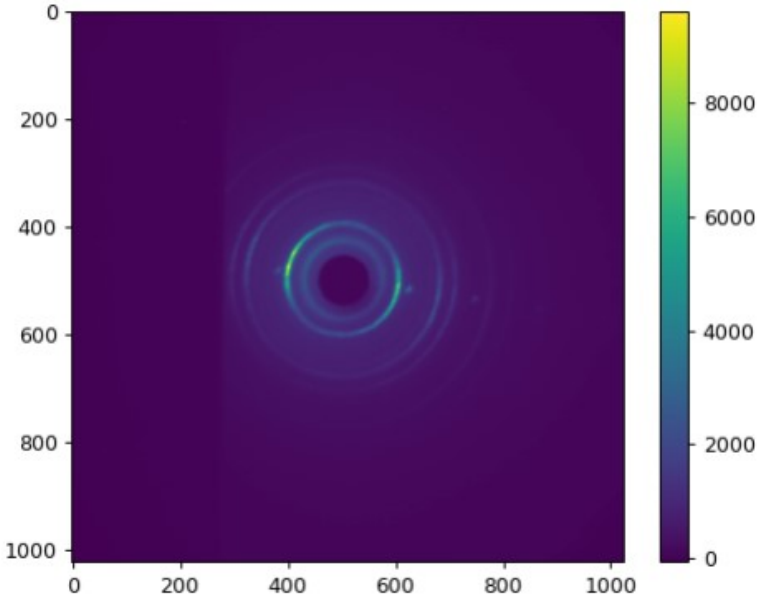
GPT Compression Model



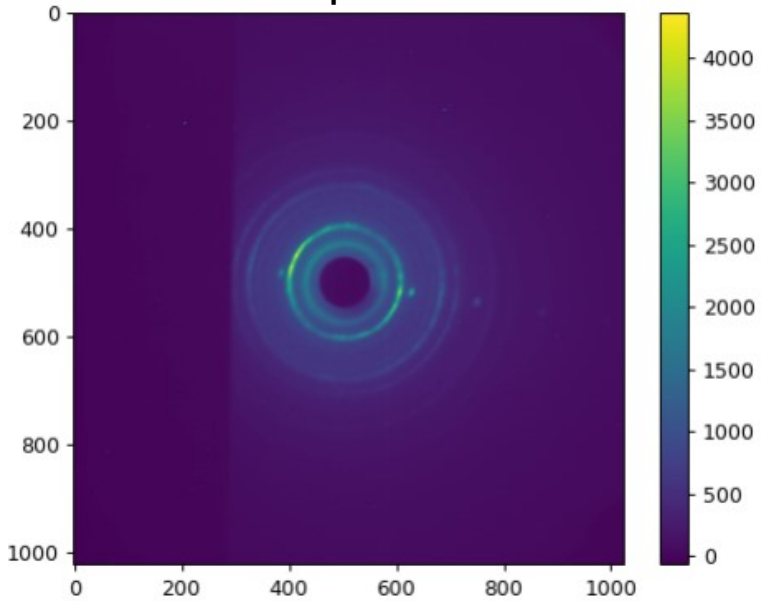
THz Compressed Bunch Preserves Resolution

Polycrystalline Bismuth

uncompressed

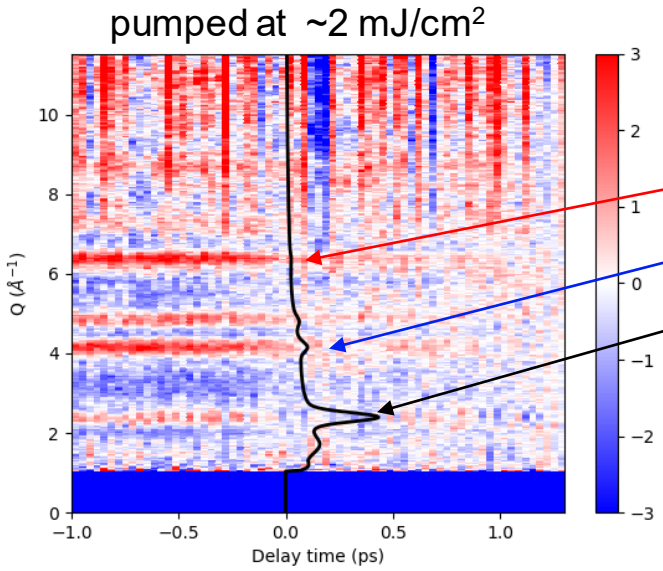


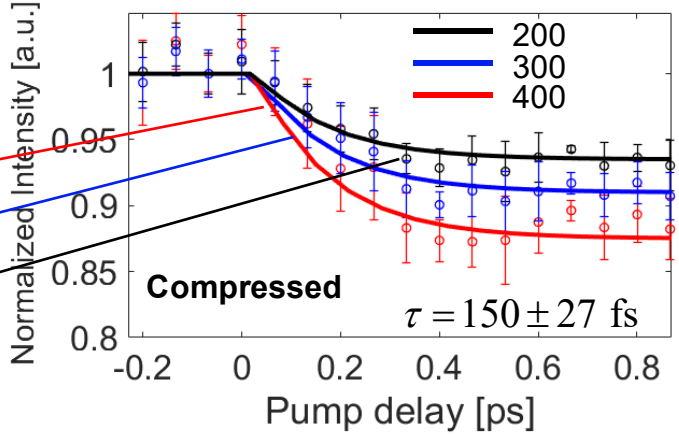
compressed

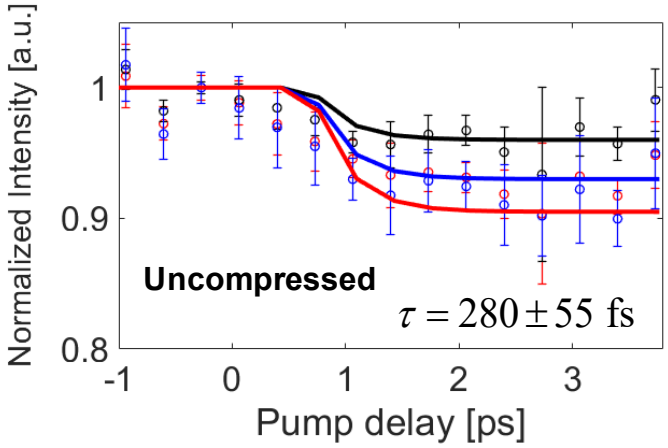


Othman, et al. *arXiv:2104.05691* (2021)

Debye-Waller Heating







- Different time scales associated with the Bi are observed
- Temporal resolution < 100 fs

Challenges:

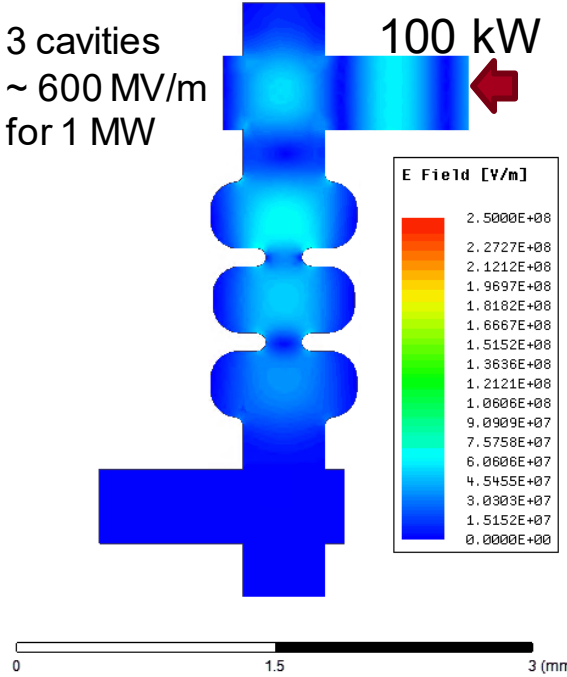
Timing drift, pointing stability, background, Q range & resolution

$$\Delta t = \sqrt{\Delta t_{\text{pump}}^2 + \Delta t_{\text{bunch}}^2 + \Delta t_{\text{jitter}}^2 + \Delta t_{\text{drift}}^2 + \ldots}$$

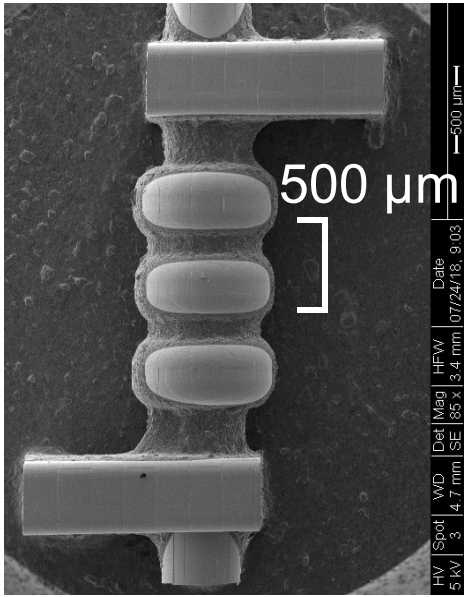
Bridging the Gap Between Single-Cycle and Quasi-CW Excitation for Optimized High-Field Performance

- 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
  - 3 cavities
  - ~ 600 MV/m for 1 MW

Single-cell 300 GHz structure



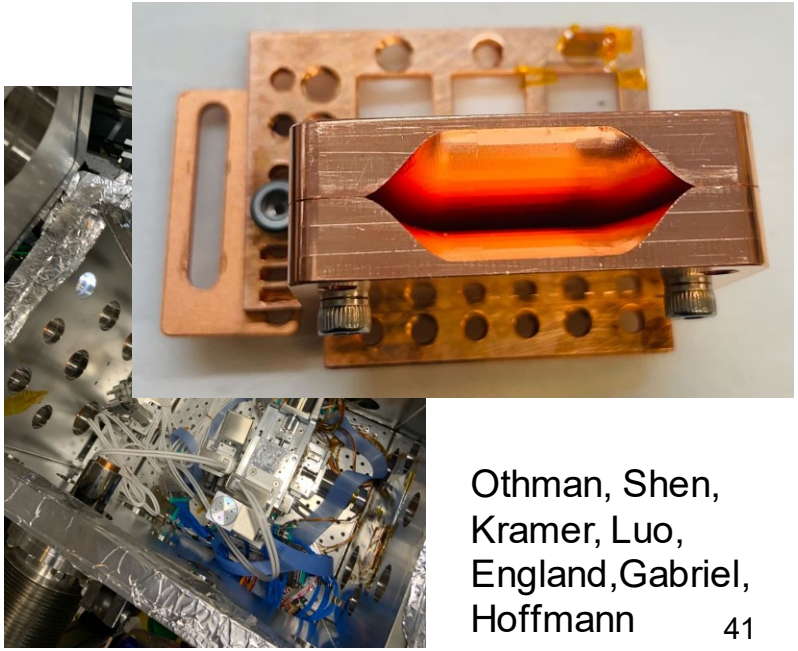
3D printed prototype



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



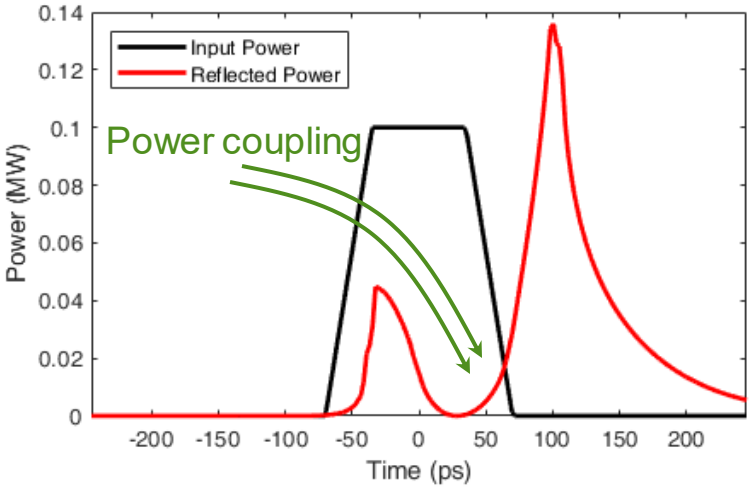
Othman, Shen, Kramer, Luo, England,Gabriel, Hoffmann

Questions?

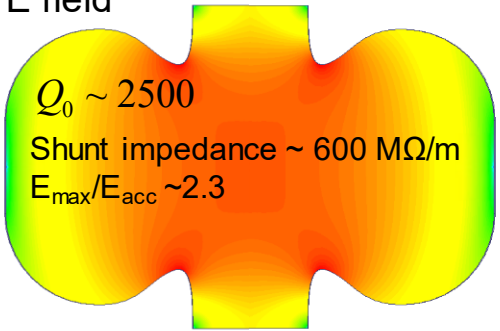
300 GHz Single Cell Accelerating Structure

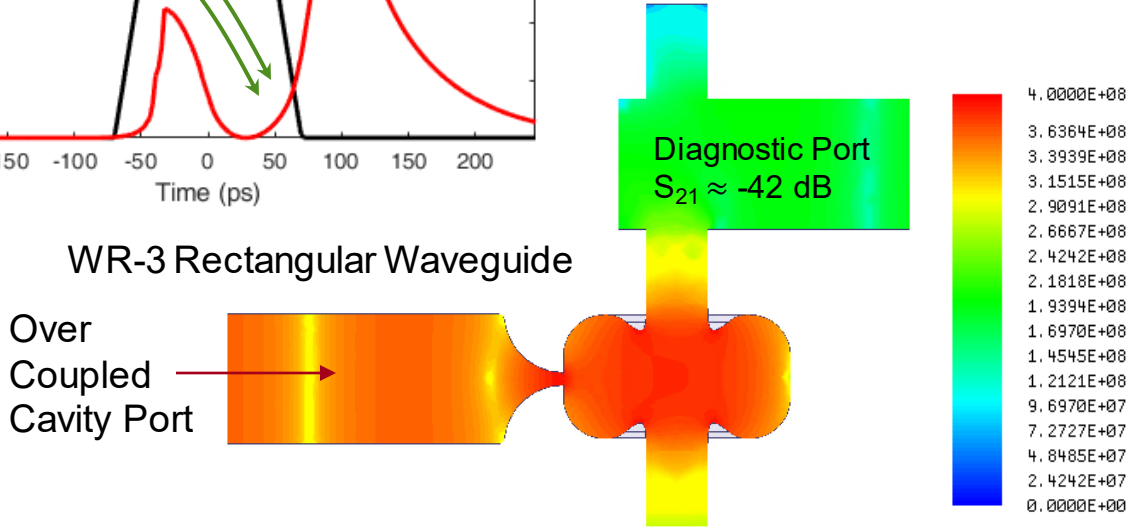
- Narrowband THz laser-based sources capable of producing 100s ps pulses
- Utilizing over-coupled scheme to demonstrate high gradient

$$Q_0 / Q_e \sim 17$$



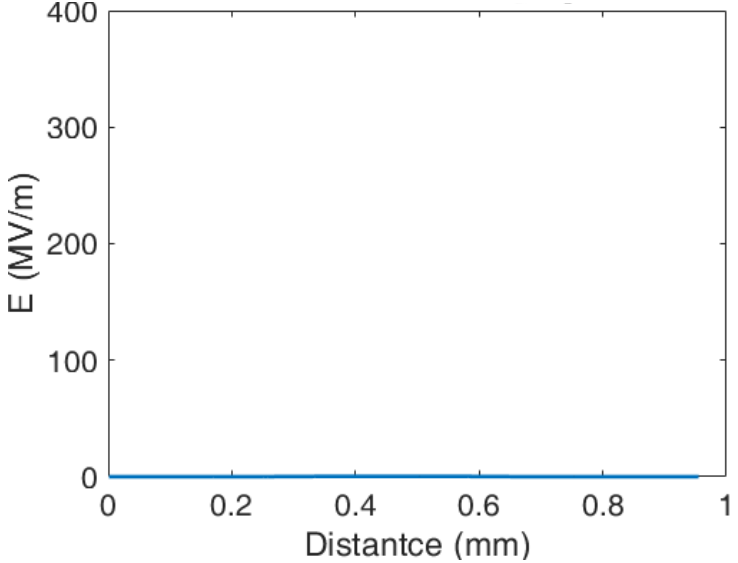
E field





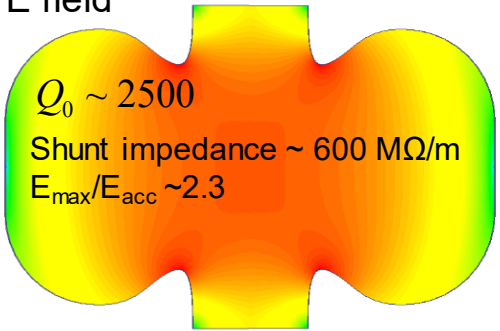
300 GHz Single Cell Accelerating Structure

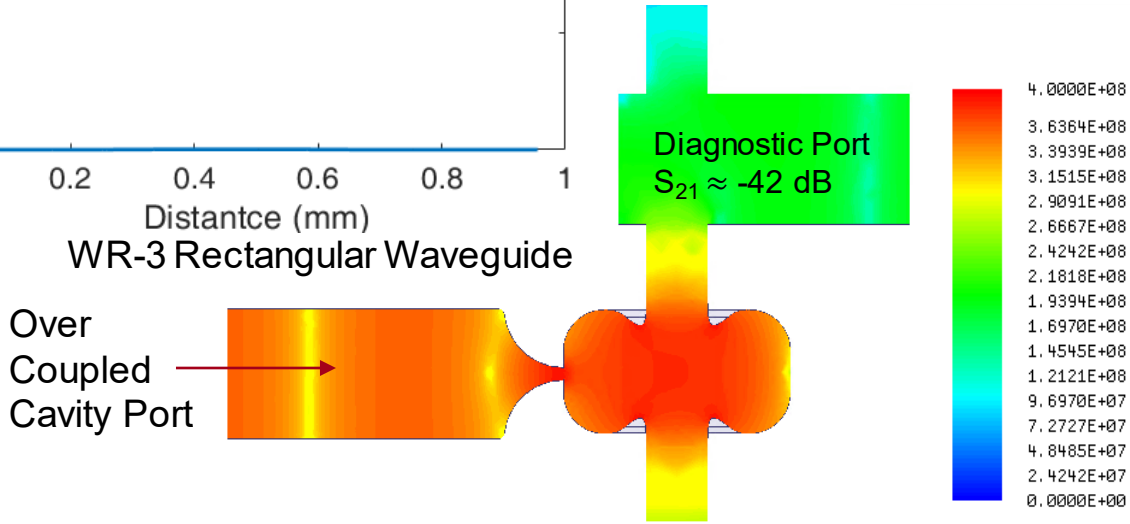
- Narrowband THz laser-based sources capable of producing 100s ps pulses
- Utilizing over-coupled scheme to demonstrate high gradient
- Efficient coupling for short pulses



WR-3 Rectangular Waveguide

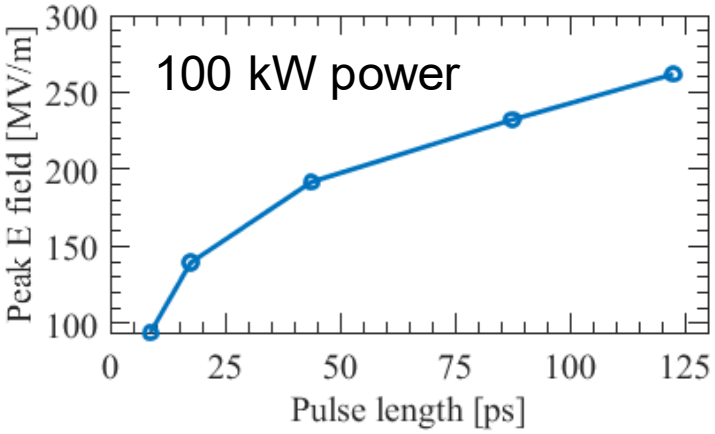
E field



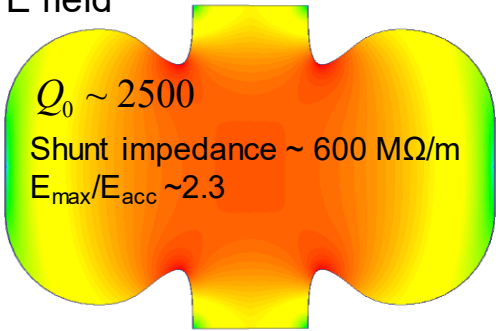


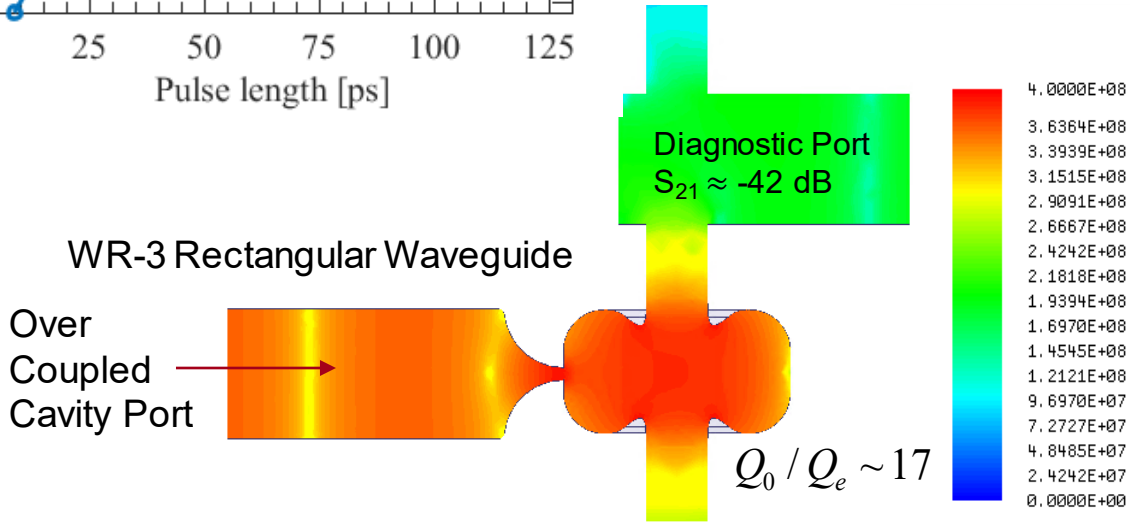
300 GHz Single Cell Accelerating Structure

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



E field





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

Field Distribution for a/λ = 0.105 and 1 MW of Dissipated Power – 400 MeV/m Effective Gradient

- Structure designed for comparison with X-band studies
- E_{max}/E_{acc} ~2.25

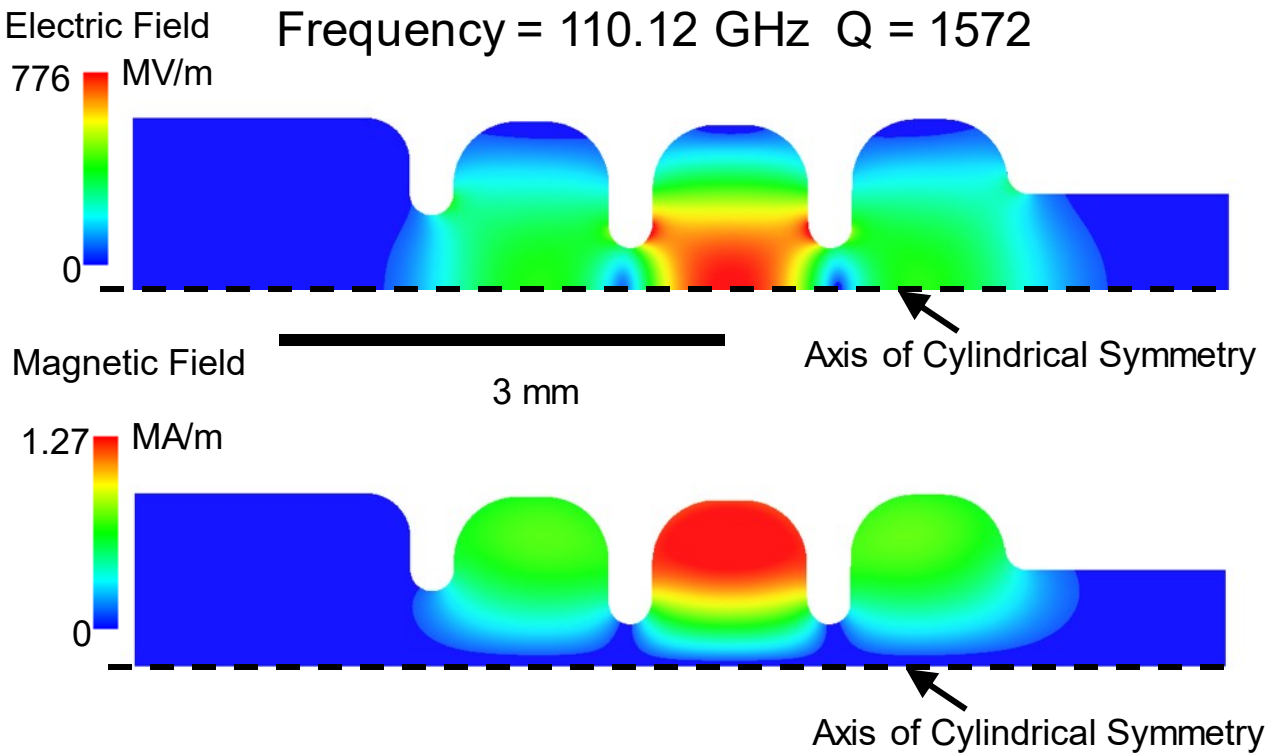
Iris Thickness (mm)

↓

A0.286-T0.2-Cu

↑

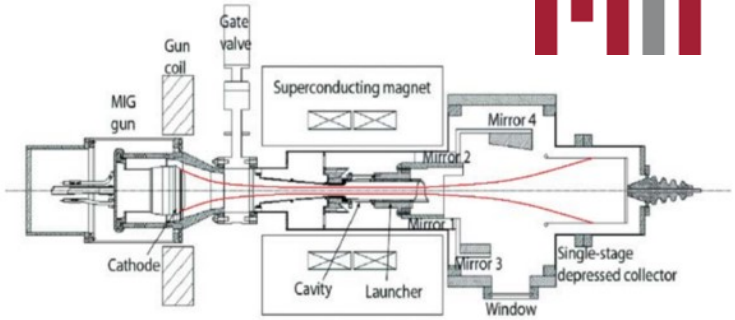
Iris Aperture Radius (mm)

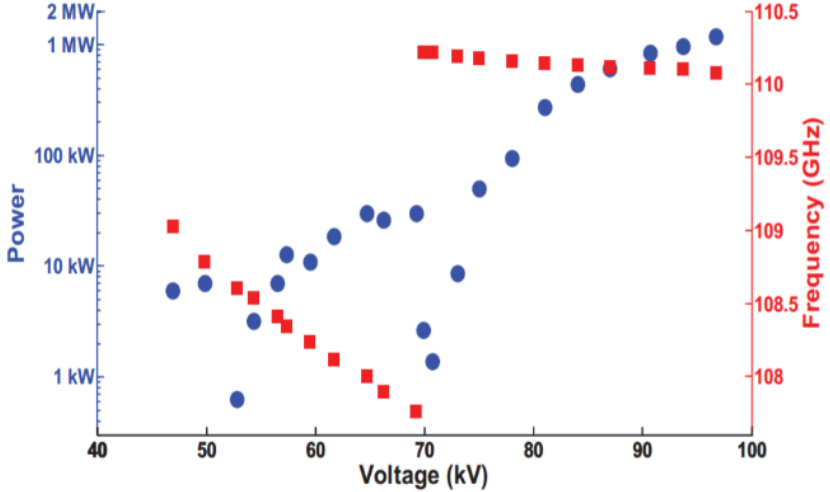


MIT 1 MW Pulsed Gyrotron Oscillator at 110 GHz

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

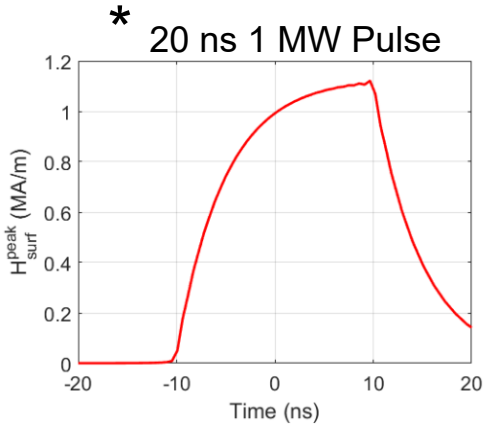
Tax, David S., et al. "Experimental study of the start-up scenario of a 1.5-MW, 110-GHz gyrotron." *IEEE Transactions on Plasma Science* 41.4 (2013): 862-871.

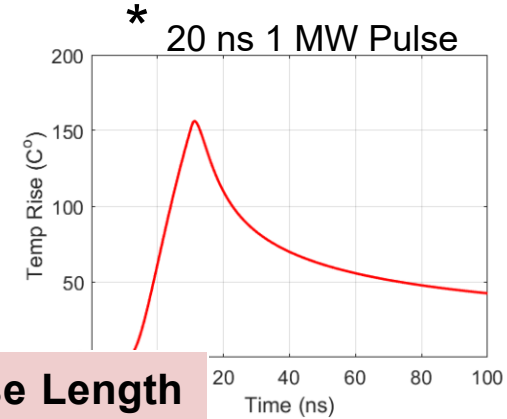




Single Cell Parameters and Pulsed Heating

	A0.286-T0.2-Cu-110GHz
Dissipated Power [MW]	1
Peak Surface Electric Field [MV/m]	916
Peak Surface Magnetic Field [MA/m]	1.13
Effective Accelerating Gradient [MeV/m]	404
Accelerating Gradient in Central Cell [MeV/m]	419
Peak Surface Poynting Vector [W/μm²]	549
S/H² [Ohm]	430
Pulsed Heating (20 ns Input)* [°C]	156





High Power Switch or Frequency Tuning to Select Pulse Length

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