THz Electron Gun Development

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3/30/2016

Outline

- Motivation
- Experimental Demonstration of THz Acceleration
  - THz Generation
  - Accelerating Structure and Results
- Moving Forward
  - Parametric THz Amplifiers
  - THz Photo-Injector
- Conclusions

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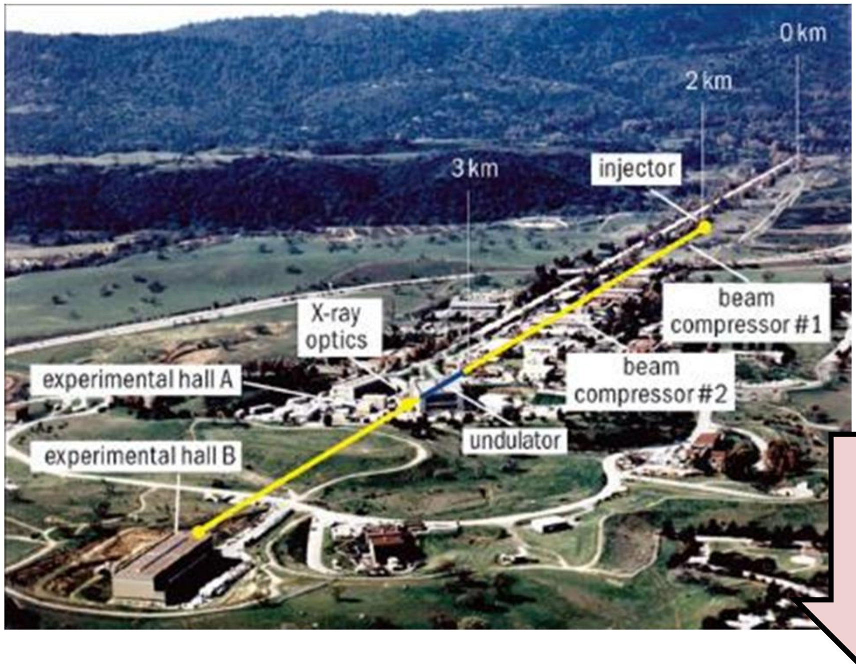
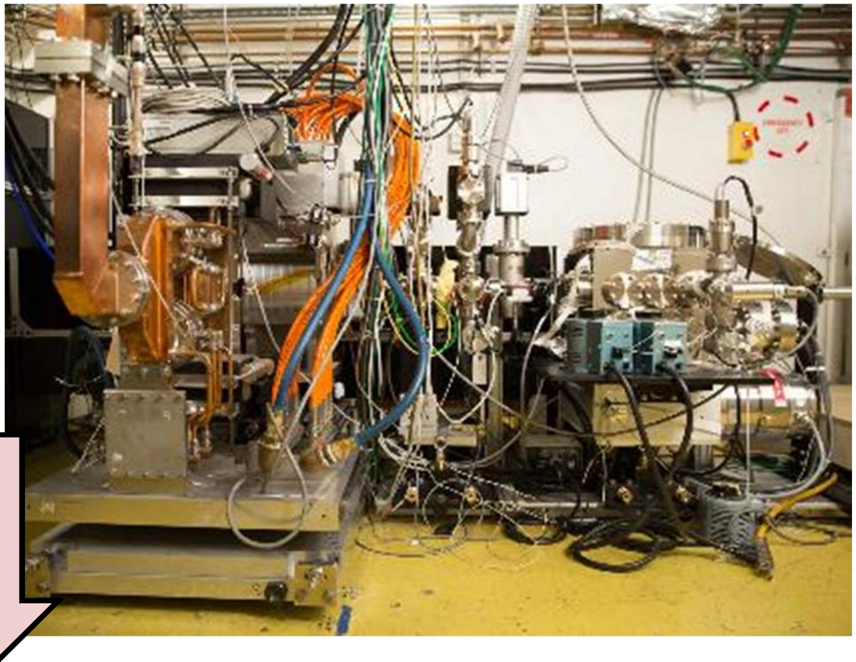
Ultrafast Science Enabled by Accelerators

- X-rays and electrons are used at SLAC for ultrafast science

Coherent X-rays from LCLS (2009)



Ultrafast Electron Diffraction (2015)

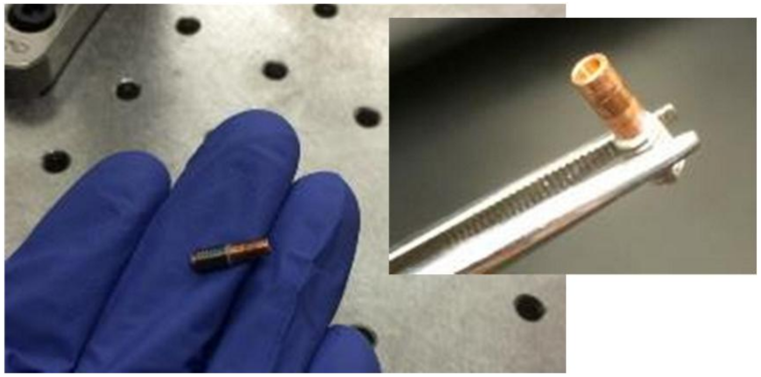


New Accelerators Providing Improved Performance?

Accelerators for the Next Generation of Ultrafast Science

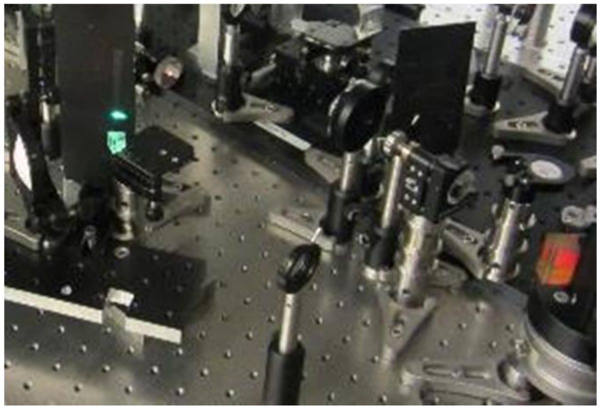
S-band Accelerators
30 MeV/m

THz Accelerators
GeV/m



Klystron Source
10s MW, μs, ~3 GHz

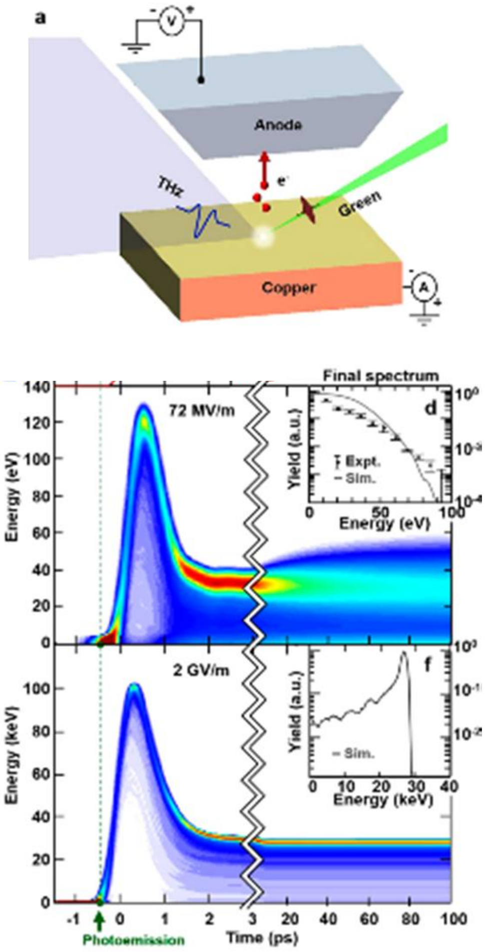
Optically-Driven THz Source
MW, ns, ~0.3 THz



Higher Frequencies Can Achieve Higher Gradients

SLAC

- Accelerating gradient is limited by breakdown (i.e. arcing or plasma formation)
- Breakdown threshold for surface electric field $E_s \propto f^{1/2}$
- Strongly focused THz pulses on metal surfaces have demonstrated operation with ~1 GV/m surface fields
- For electron gun, increased electric field at the emission surface improves emittance $\propto E_s^{1/2}$



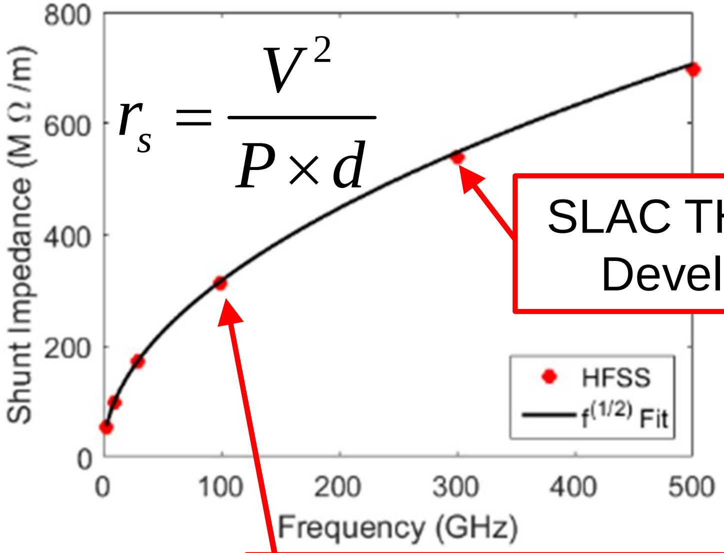
Huang, W. R., Nanni E. A., et al., *Nature Scientific Reports* 5 (2015).
Huang, W. R., Accepted for Talk, *CLEO* (2016).
Wimmer L. *et al.,* Nature Phys. 10, 432–436 (2014).

MIT CFEL SCIENCE

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

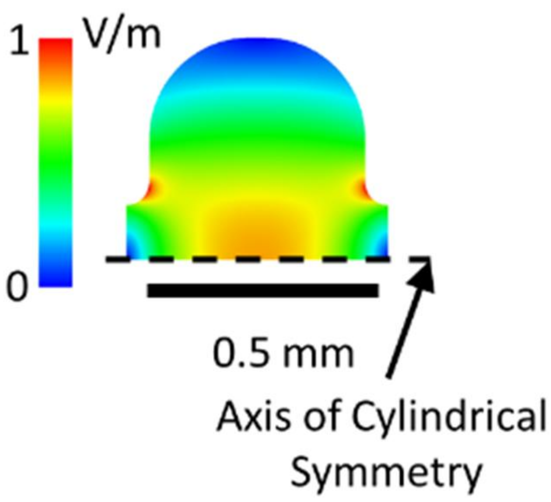


$$r_s = \frac{V^2}{P \times d}$$

SLAC THz Source Development

SLAC/MIT High-Gradient Research

~300 GHz Structure



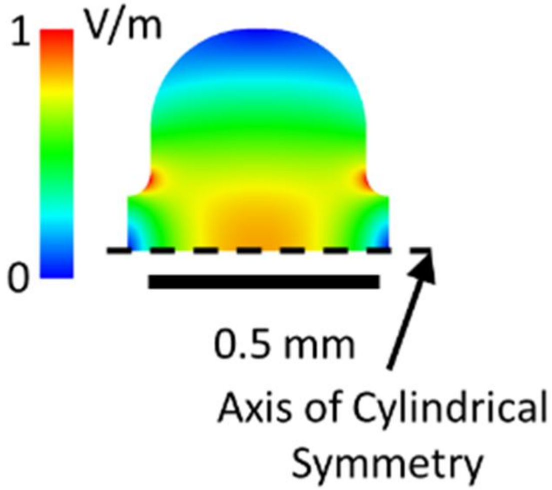
E. A. Nanni, et al., “mm-Wave Standing-Wave Accelerating Structures for High-Gradient Tests.” IPAC 2016

Comparison Between RF and THz Accelerators

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

Parameters for 100 MeV/m Gradient

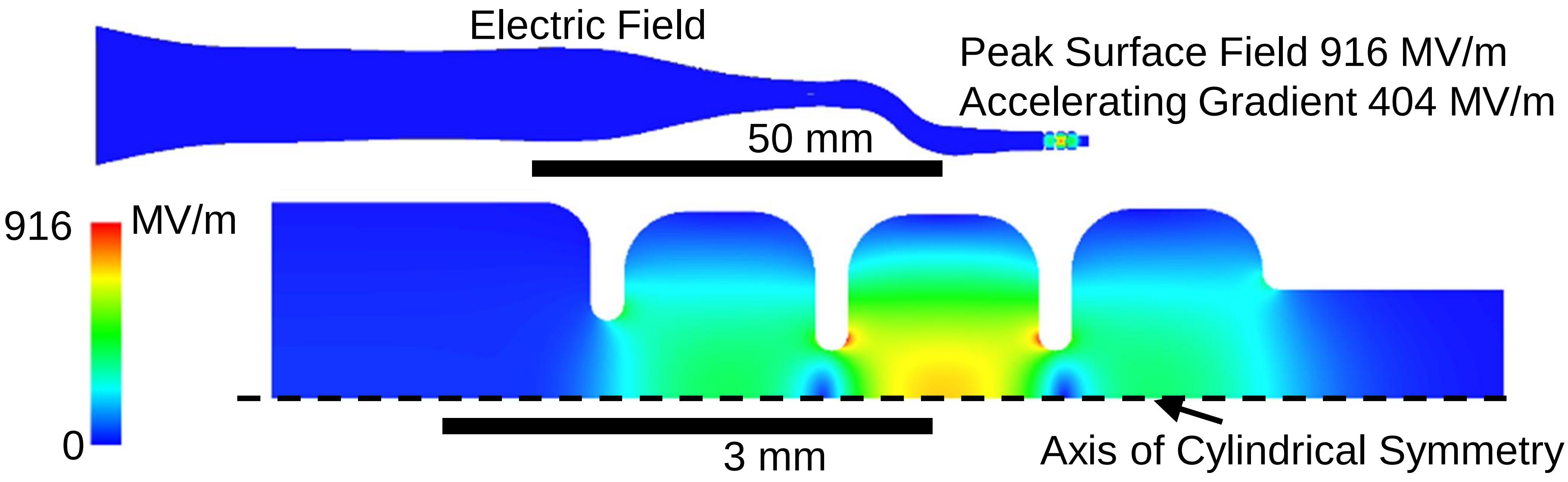
Frequency	3 GHz	300 GHz
Stored Energy [mJ]	8450	0.013
Q-value [x1000]	17.96	2.05
Shunt Impedance [MOhm/m]	55	514
Max. Mag. Field [MA/m]	0.3	0.3
Max. Electric Field [MV/m]	210	210
Fill Time [ns]	2000	2
Loss in 1 meter [MW]	181	19



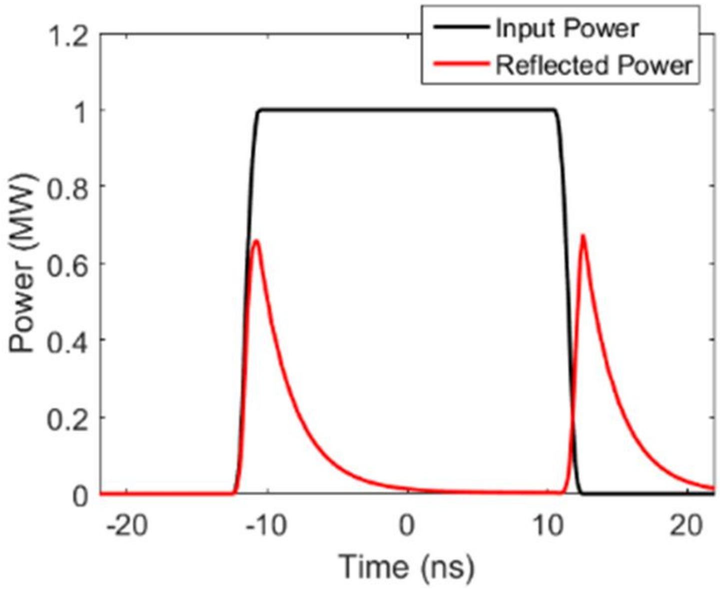
$P \times \tau$ decreases by 4 orders of magnitude

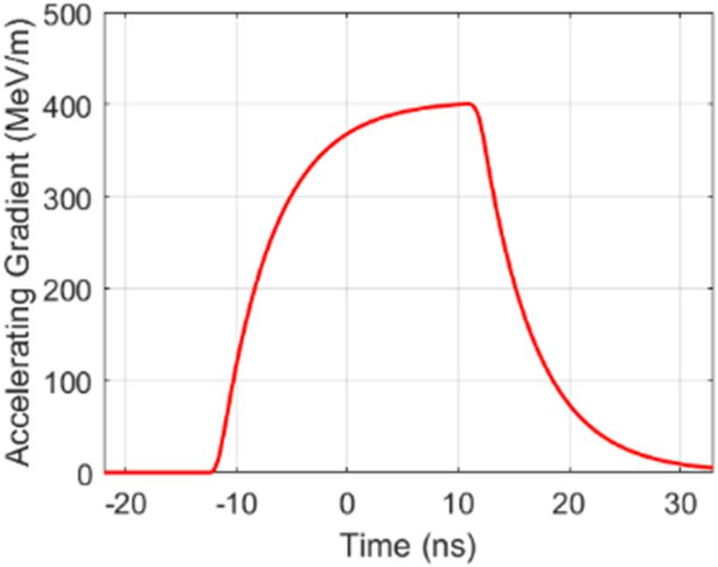
Potential to operate at 10s kHz vs 100s Hz

SLAC/MIT 110 GHz High-Gradient Research



Peak Surface Field 916 MV/m
Accelerating Gradient 404 MV/m

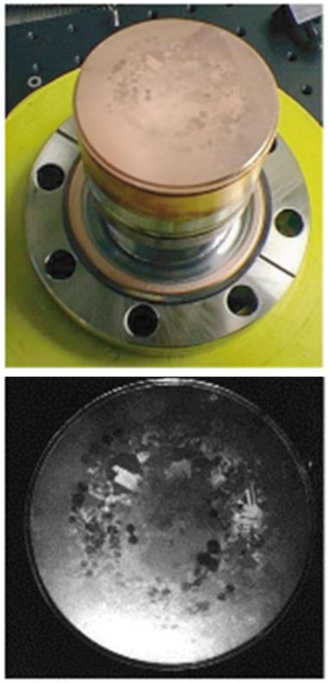




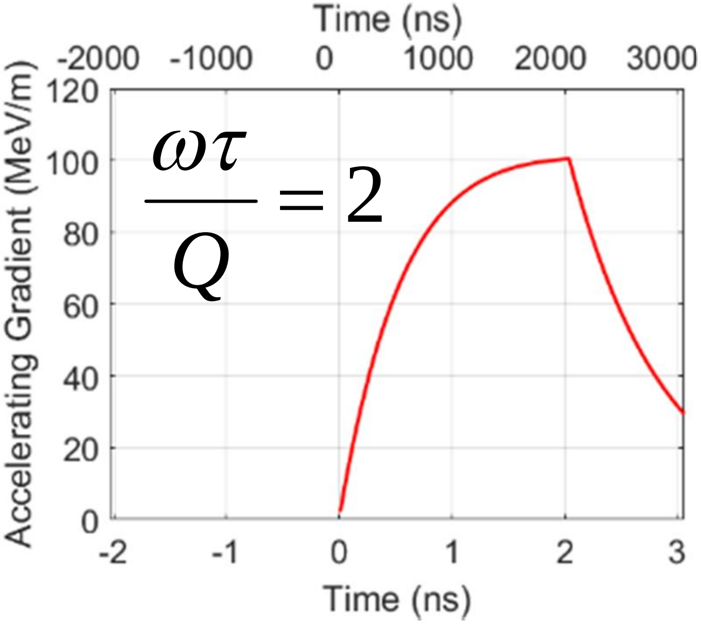
Pulsed Heating in High-Frequency Structures

- 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



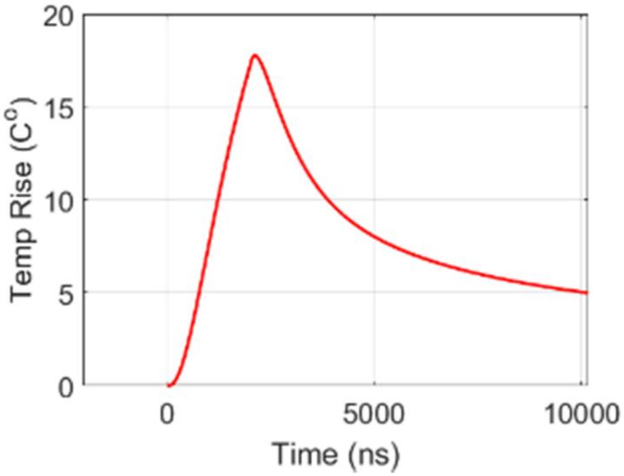
[3 GHz Structure]



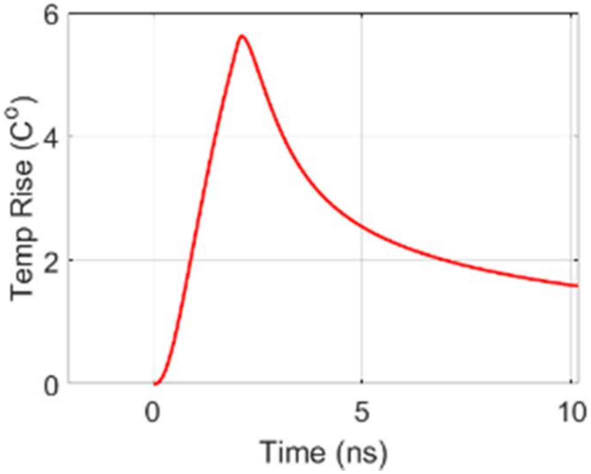
$$\frac{\omega\tau}{Q} = 2$$

[300 GHz Structure]

3 GHz Structure



300 GHz Structure



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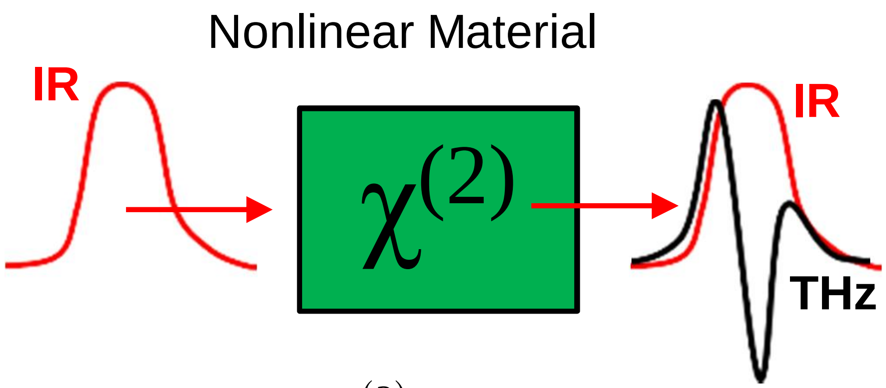
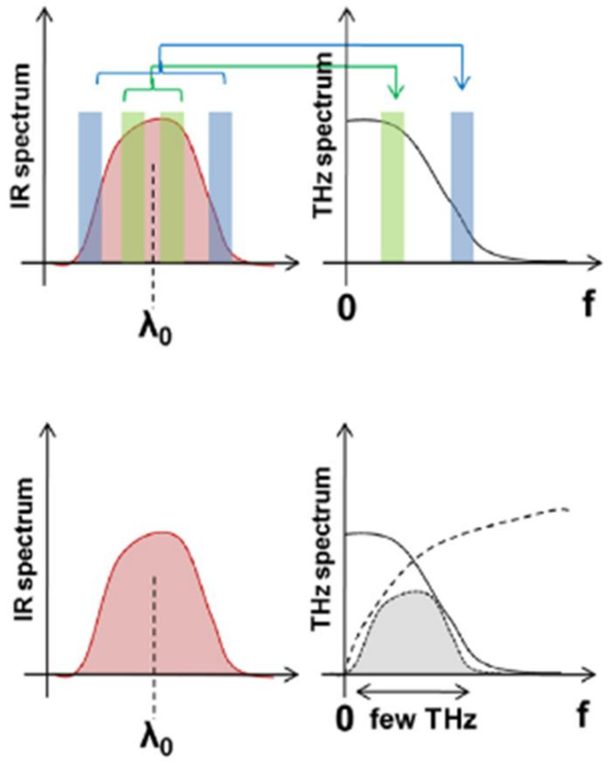
THz Generation via Optical Rectification (OR)

- Optical rectification (OR): difference frequency generation occurs between two spectral components of the same pulse
- OR occurs at frequencies which are within the bandwidth of the pulse $\Delta\omega > \Omega$

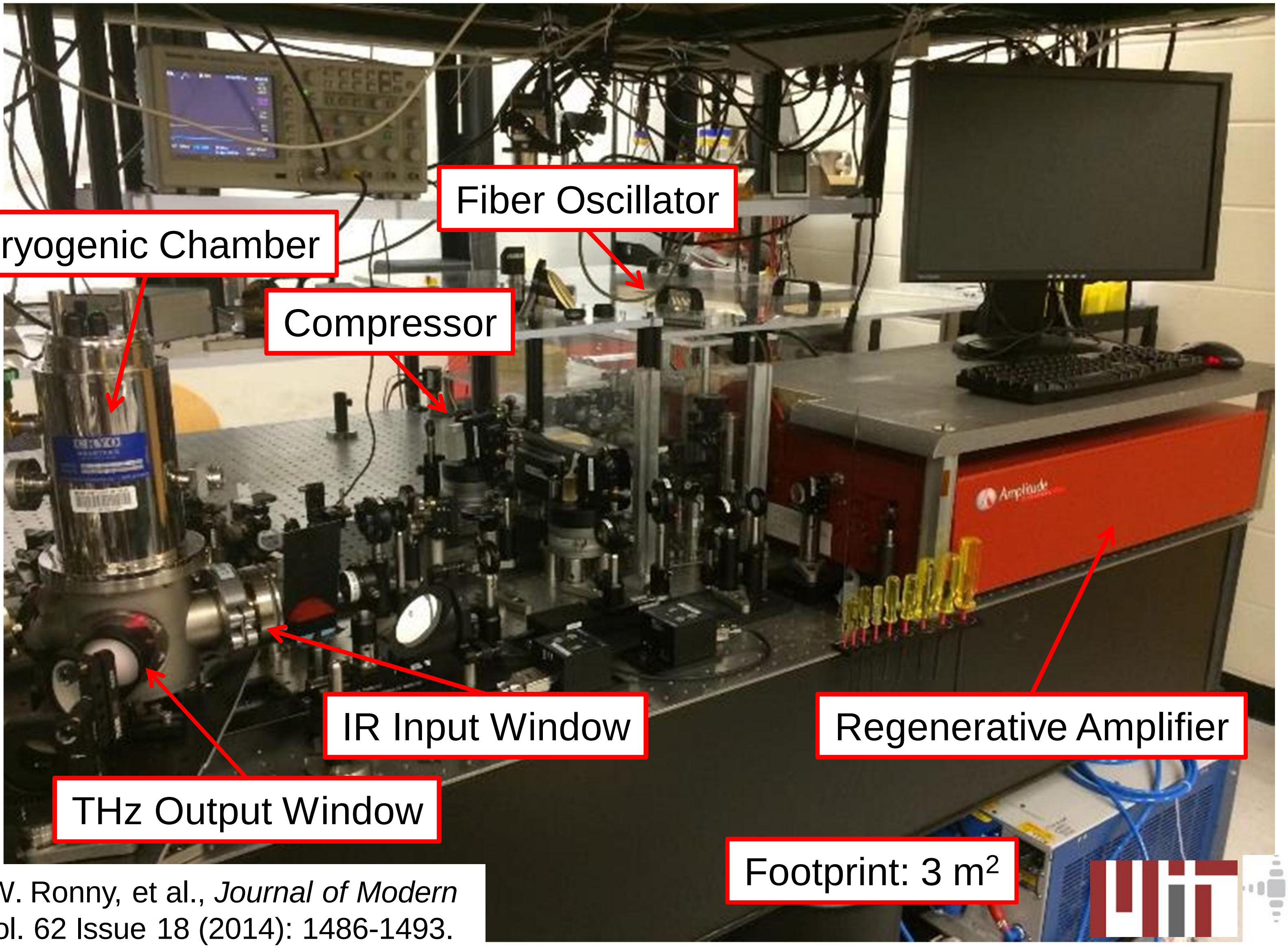


$$P_{\mathrm{NL}}(\Omega) = \varepsilon_0 \chi^{(2)} E(\omega) E^{*}(\omega - \Omega)$$

Spectrum from Optical Rectification



THz Generation Setup



Fiber Oscillator

Cryogenic Chamber

Compressor

IR Input Window

Regenerative Amplifier

THz Output Window

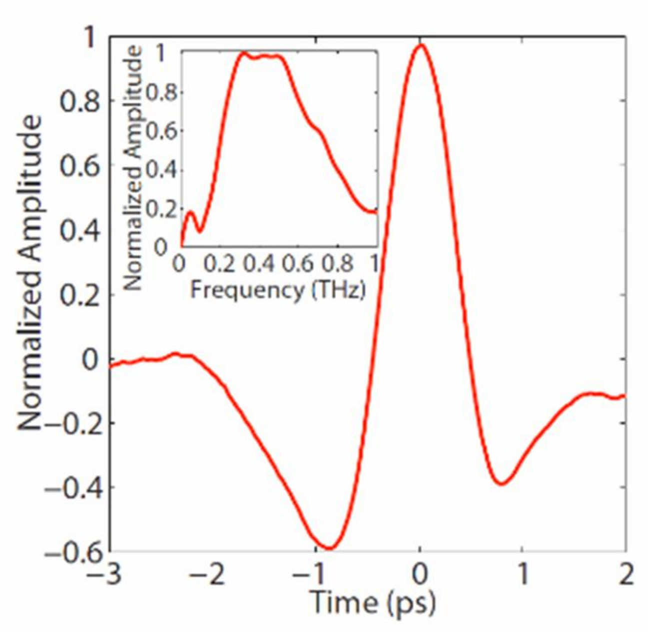
Footprint: 3 m^2

Huang, W. Ronny, et al., *Journal of Modern Optics* Vol. 62 Issue 18 (2014): 1486-1493.

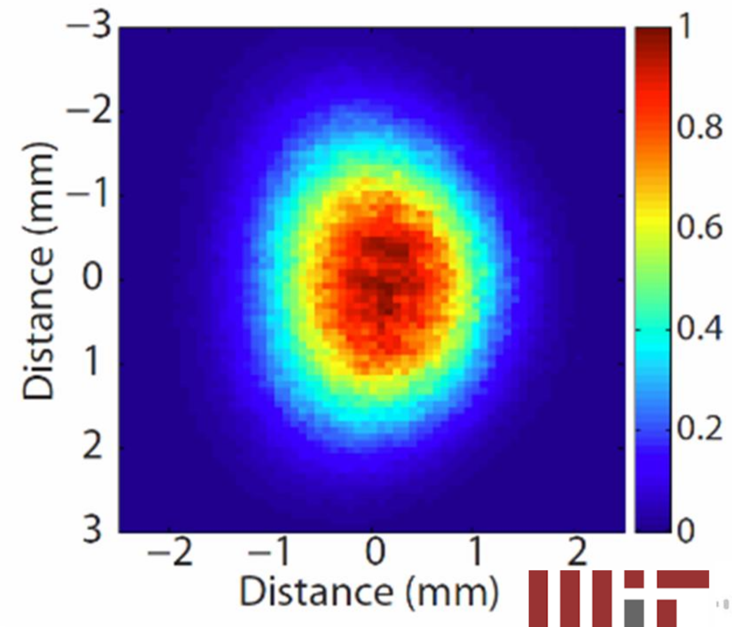
THz Pulse Properties

- Single cycle THz pulse (~2 ps) centered at 0.45 THz
- THz beam propagates in free space over significant distances due to high Gaussian content
- 10 µJ pulse measured ~1 m from source

Electric Field from EO Sampling



Transverse Intensity Profile



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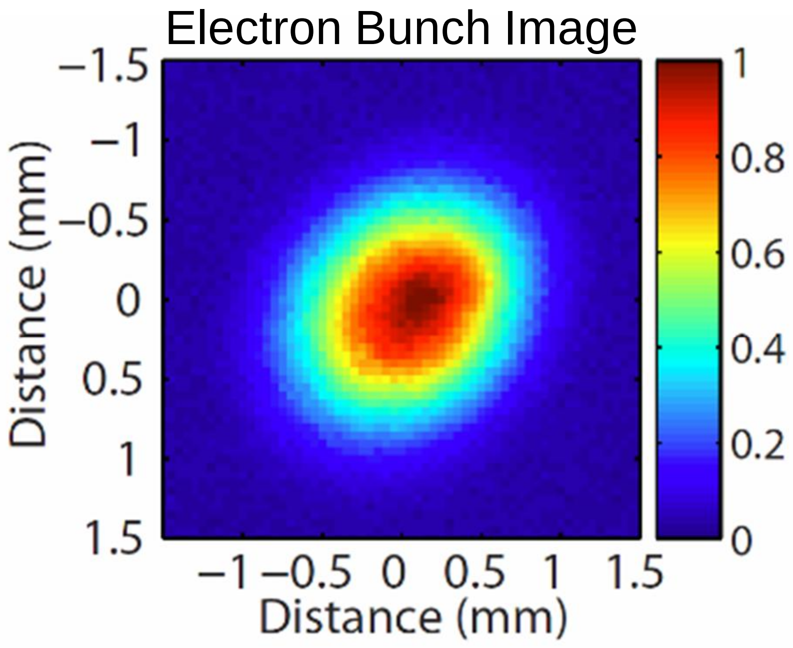
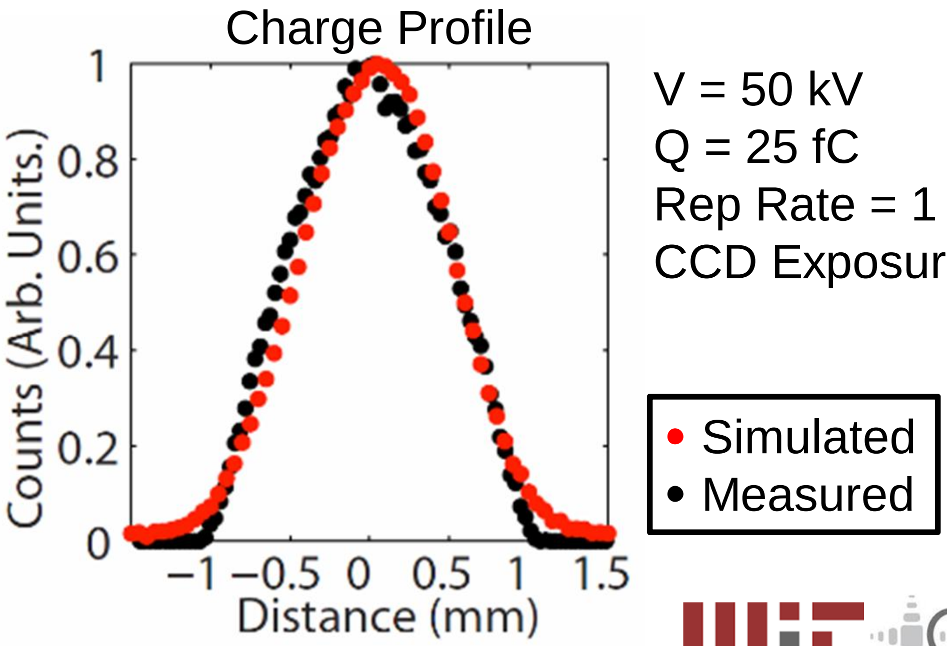
Electron Beam Parameters

- 60 kV DC photo-injector used as electron source
- Photoemission with UV pulse (quadrupled from 1030 nm IR)

UV Pulse = 0.7 µJ, 250 nm, 350 fs

- PARMELA is used to simulate from photo-emission to detection

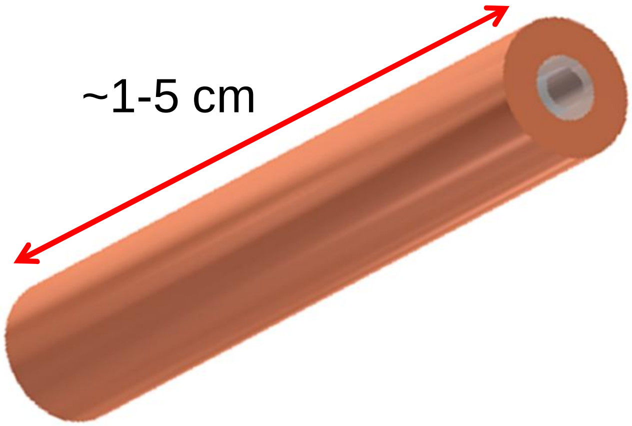

Electron Bunch Image


Charge Profile

V = 50 kV
Q = 25 fC
Rep Rate = 1 kHz
CCD Exposure = 2 s

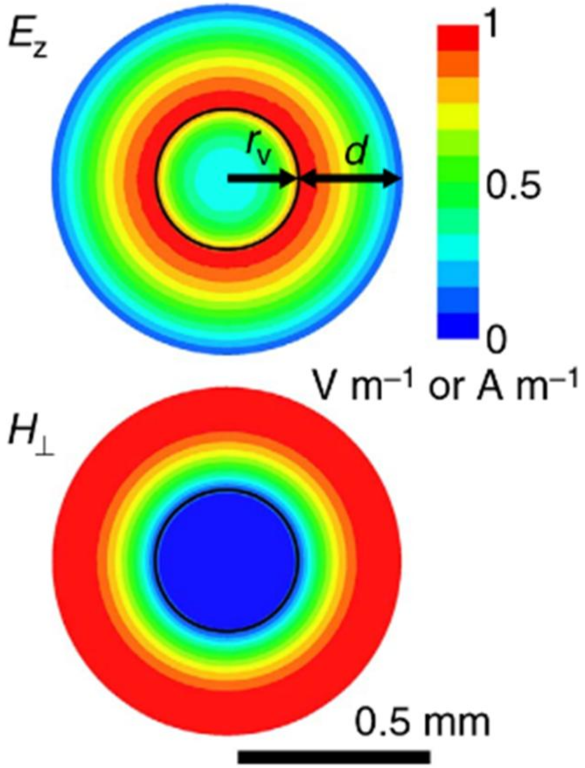
Dielectrically Loaded Circular Waveguide

- Traveling wave structure is best for coupling broad-band single cycle pulse
- Phase-velocity matched to electron velocity with thickness of dielectric



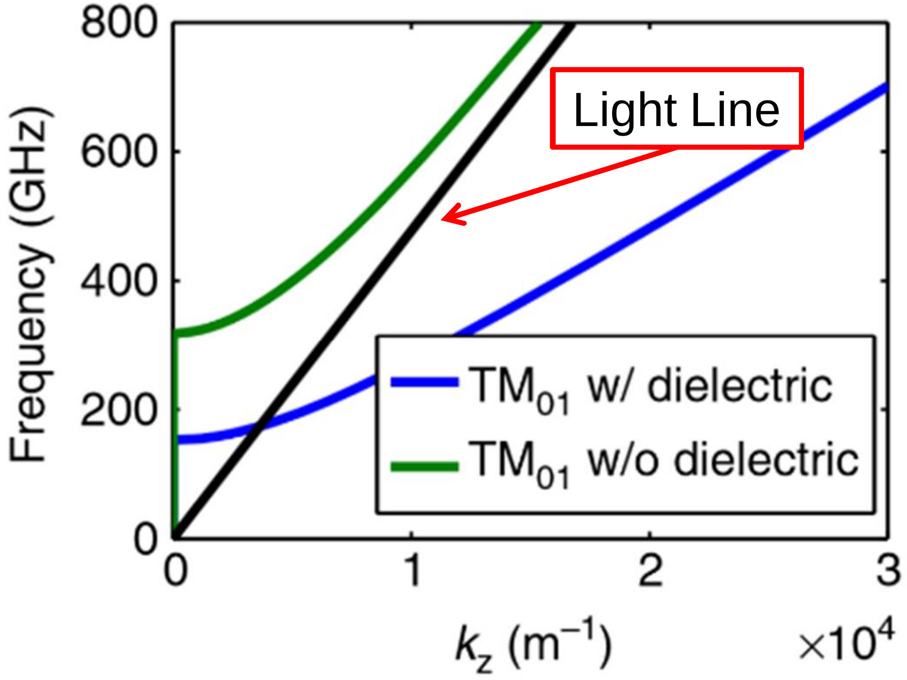
Copper Inner Diameter = 940 µm

Fused Silica Inner Diameter = 400 µm

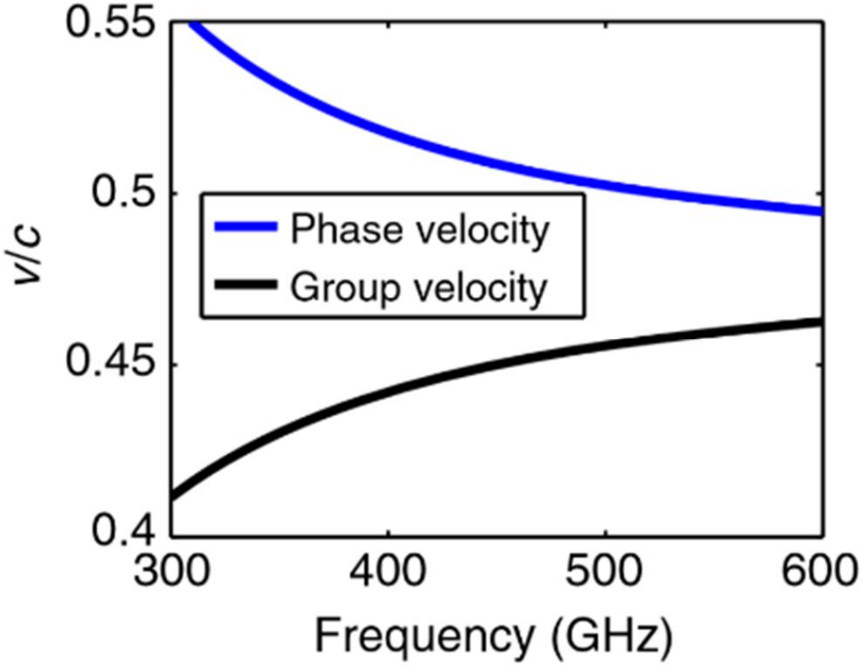


Dispersion in Dielectrically Loaded Waveguide

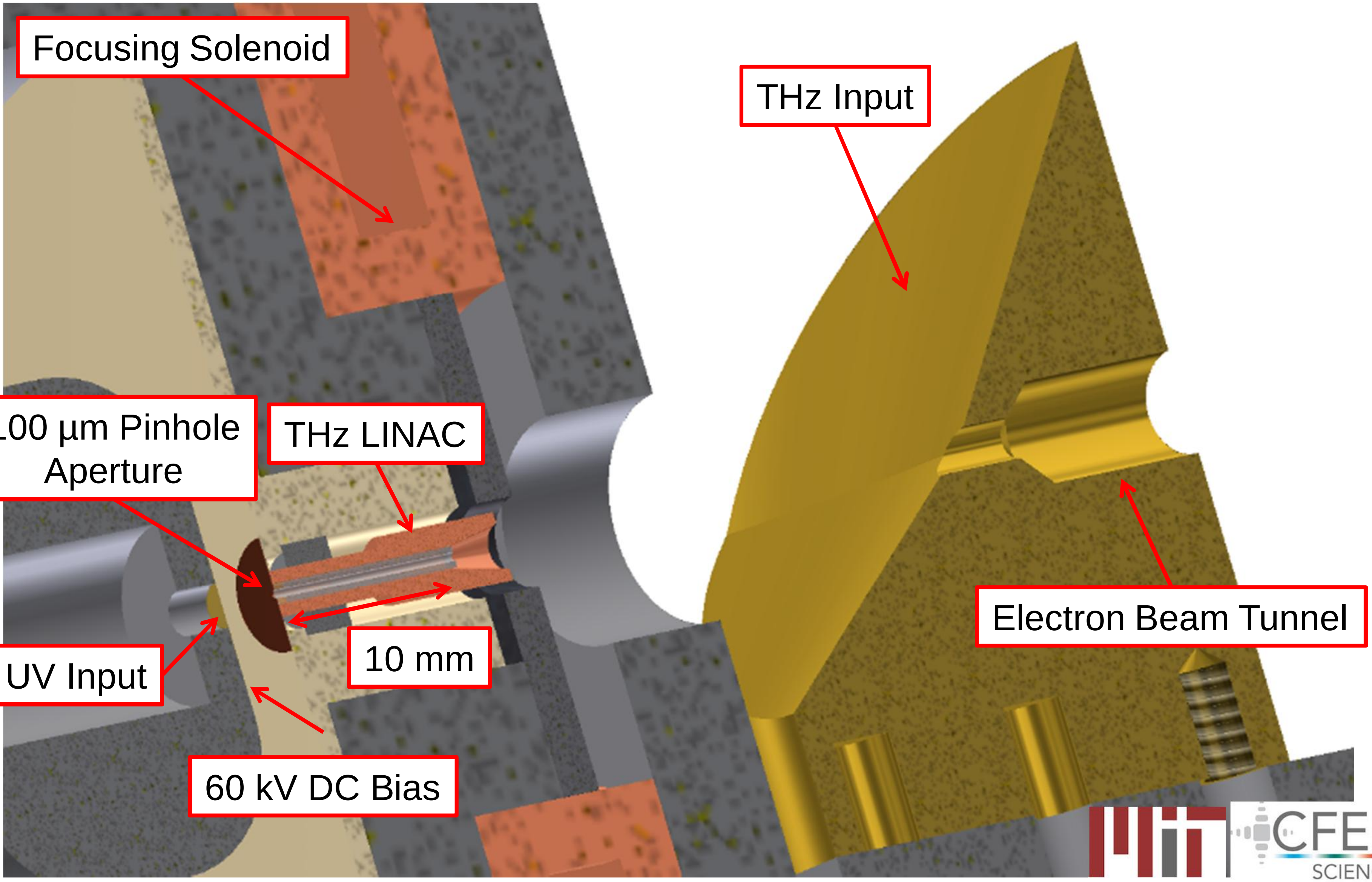
- Thick dielectric required to achieve desired phase velocity
- Waveguide is dispersive for wide bandwidth of THz pulse


Dispersion Relation

Light Line


Group and Phase Velocity

DC Gun and THz LINAC



Focusing Solenoid

THz Input

100 µm Pinhole Aperture

THz LINAC

Electron Beam Tunnel

UV Input

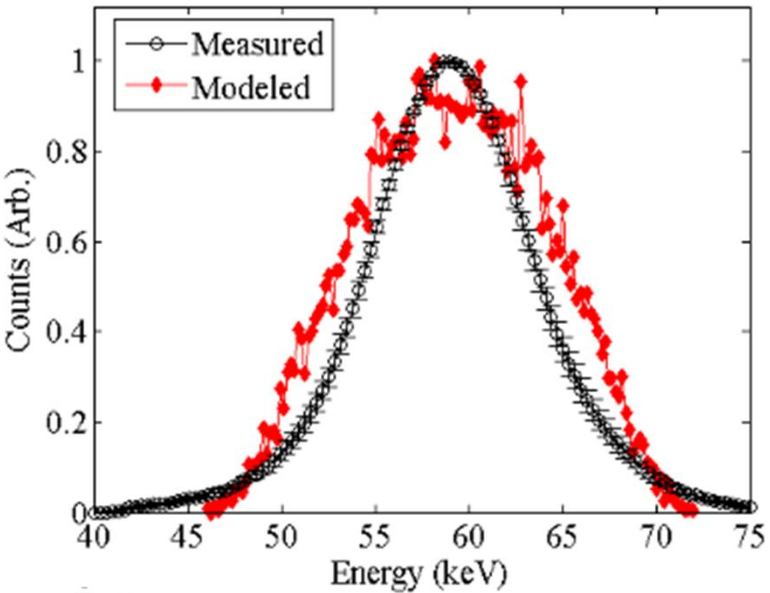
10 mm

60 kV DC Bias

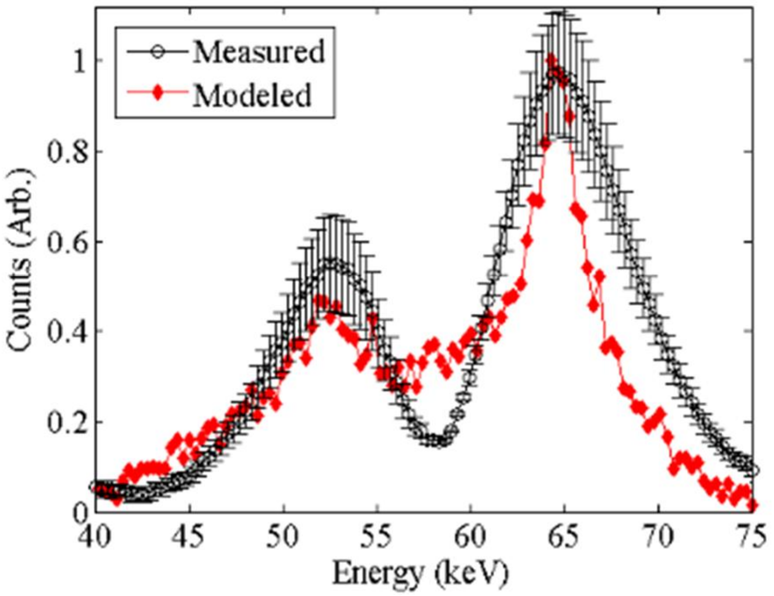
Electrons Accelerated by THz Pulse

- Measured energy spectrum for 59 keV start energy
- Modeled on-axis electric field of 8.5 MV/m
- Electron bunch $\sigma_z = 45\ \mu m$

THz Off



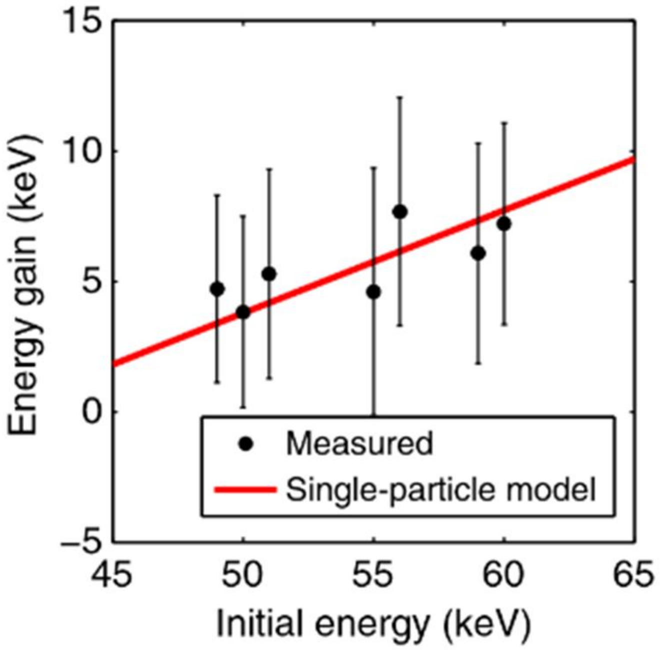
THz On

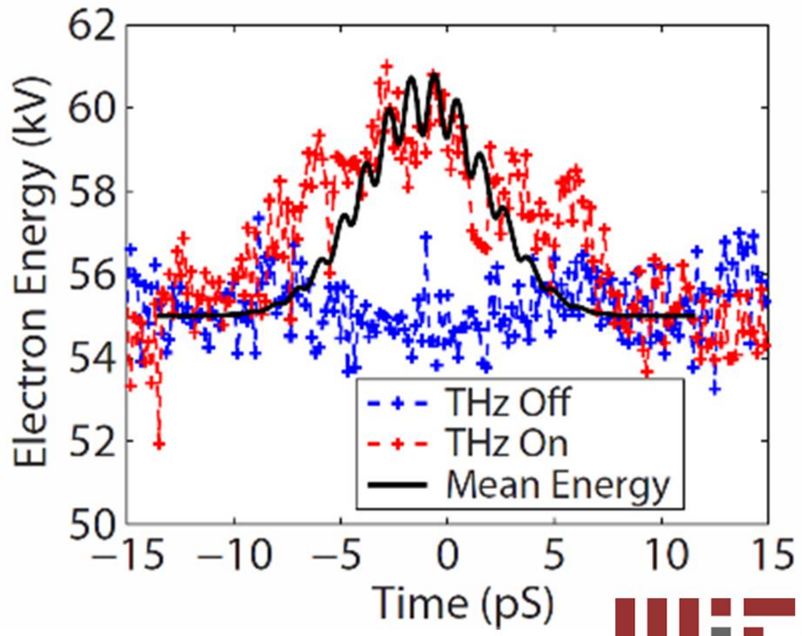


Nanni, et al. Nature Communications 6, 8486 (2015).

Optimizing THz Acceleration

- Energy gain depends on initial electron energy and arrival time of THz pulse
- Increase in energy decreases phase slippage
- Single particle model with 8.5 MV/m electric field or accelerating gradient of 2.5 MeV/m for 3 mm





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Future Directions @ SLAC

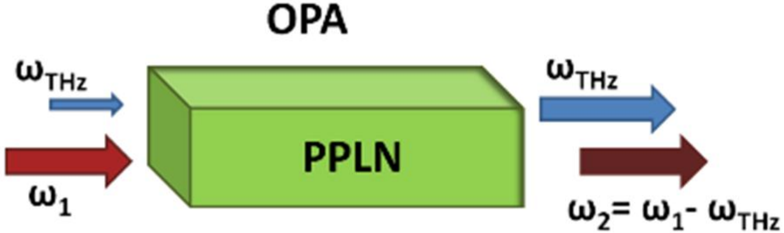
- How do we extend this work to achieve high-gradients >100 MeV/m?
- Standing wave accelerating structures reduce peak power to achieve high gradient
  - Require narrow-band, nanosecond THz pulses
  - Amplifier would be best source to control THz pulse
- Coherently amplified narrow-band THz source
  - ns IR pump lasers are cheap and compact with pulsed energies from 100 mJ – 1 J , 0.1-1 kHz
  - A THz optical parametric amplifier meets our requirements and under development at SLAC

Optical Pump:1064 nm, 250 mJ, 120 Hz,10 ns

Approach to Operating OPAs at THz Frequencies

- Long nonlinear crystal length is required to achieved high conversion efficiency
- Phase mismatch avoided by periodic poling of nonlinear media

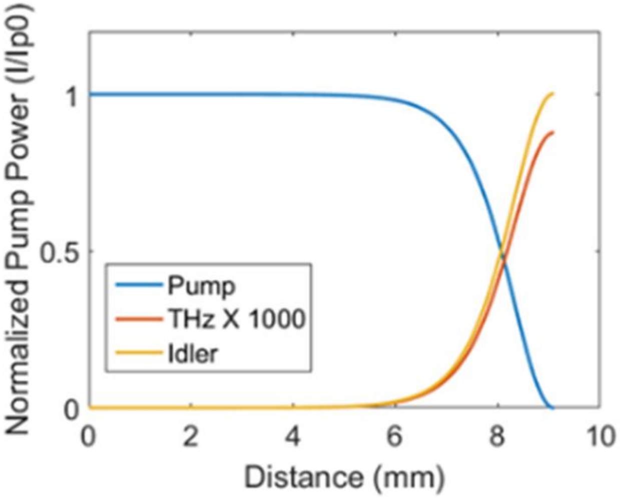
Optical Pump:1064 nm, 250 mJ, 120 Hz,10 ns



- Periodically poled Lithium Niobate (PPLN)
  - Low loss $\alpha_{THz} < 3\ \text{cm}^{-1}$,High nonlinear index $d_{eff} \approx 25$ pm/V

OPA Parameters:

Frequency	0.26 THz
Length	9 mm
Poling Period	440 µm
THz Input Power	10 mW

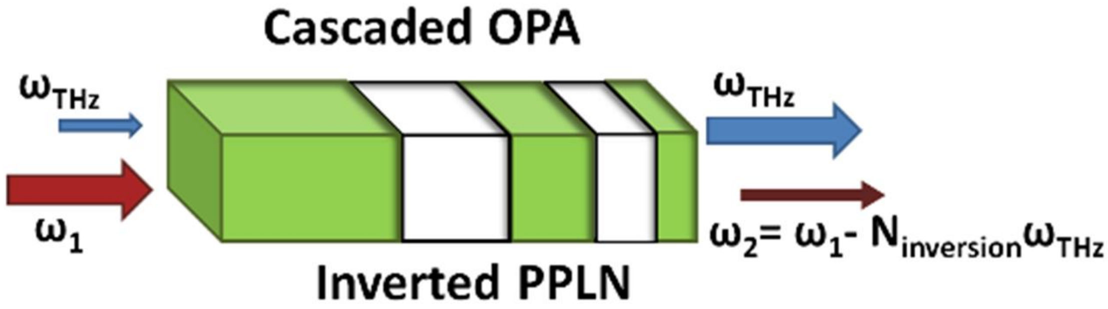


THz OPA Performance:

Efficiency	~0.1%
Peak Power	22.5 kW
Gain	55 dB

Approach to High Efficiency and MW Peak Power

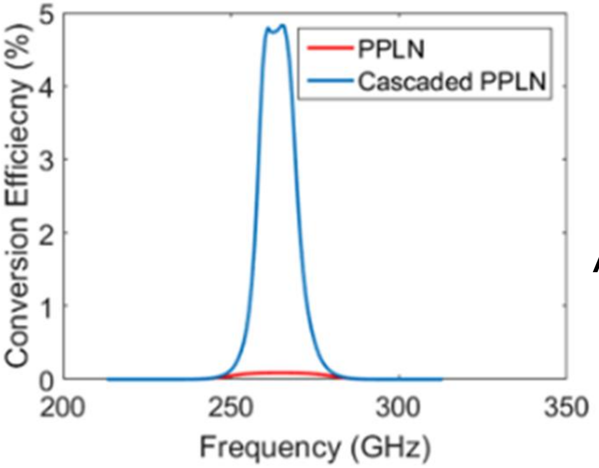
- >99% of the energy is at the idler frequency $\omega_2=\omega_1-\omega_{THz}$
- Invert poling period, use idler as a new pump signal



- Poling period is inverted every time pump is depleted

OPA Parameters:

Frequency	0.26 THz
Length	33 mm
Poling Period	440 µm
Poling Inversions	40
THz Input Power	10 mW



OPA Performance:

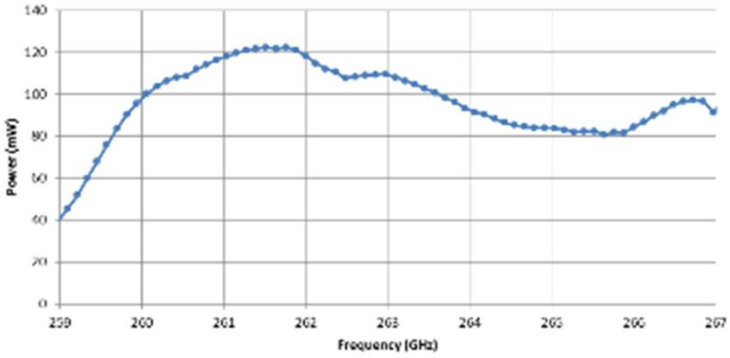
Efficiency	4.8%
Peak Power	1.2 MW
Average Power	1.4 W
Gain	71 dB
Bandwidth	20 GHZ

Expanding Capabilities in THz Range

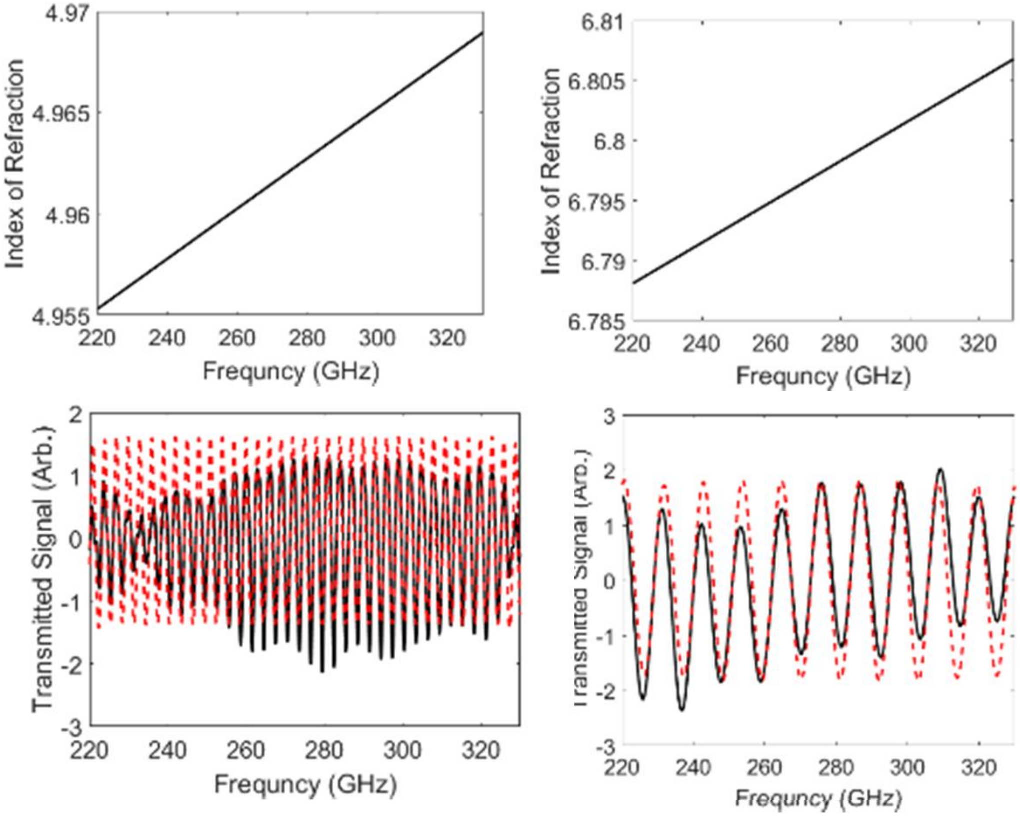
SLAC

- Laser system installation, solid-state source testing, THz component testing
- Precision dielectric constant measurements of Lithium Niobate

AMC 573 Output Power Versus Frequency



n_e=4.961, n_o=6.796 @263 GHz



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Challenges for RF Guns at High Frequency

- A standing wave gun could prove difficult in the THz range
- Energy gain per cell decreases with increasing frequency

$$\mathcal{E}_{1/2\ \mathrm{Cell}} \approx E_0 \left\langle \sin\theta \right\rangle_{\pi/2\to 0} \lambda / 4$$

Best Case!

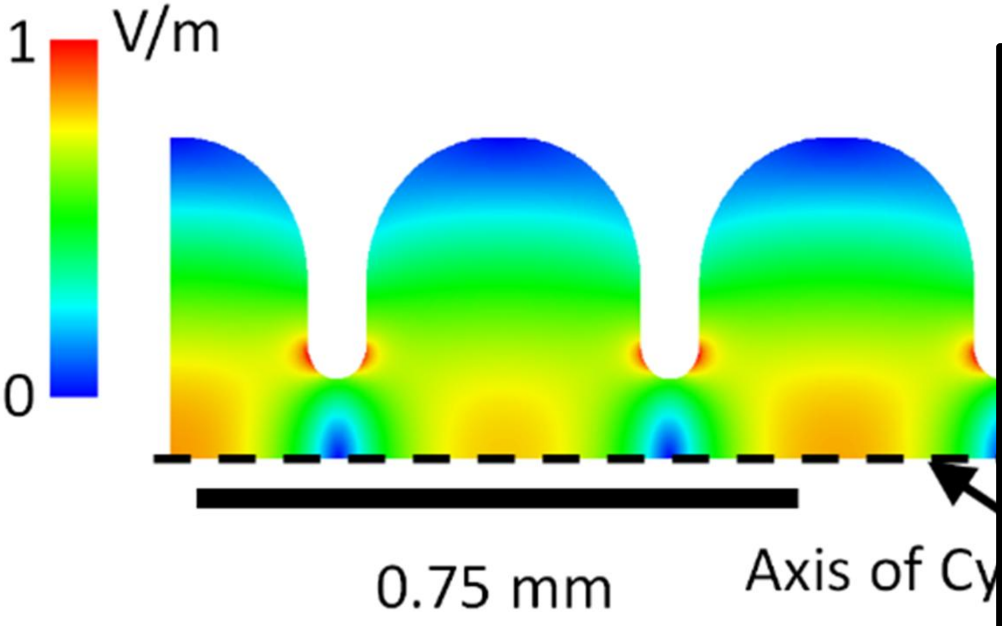
- Need energy to be high enough to limit phase slippage
  - Improved beam quality
  - Longer subsequent cavities, more energy gain
  - Practical limit to number of cells

$$\mathcal{E}_{1/2\ \mathrm{Cell}} \approx 100\ \mathrm{keV} \quad E_0 \approx 0.63\ \mathrm{GeV/m} \quad \lambda \approx 1\ \mathrm{mm}$$

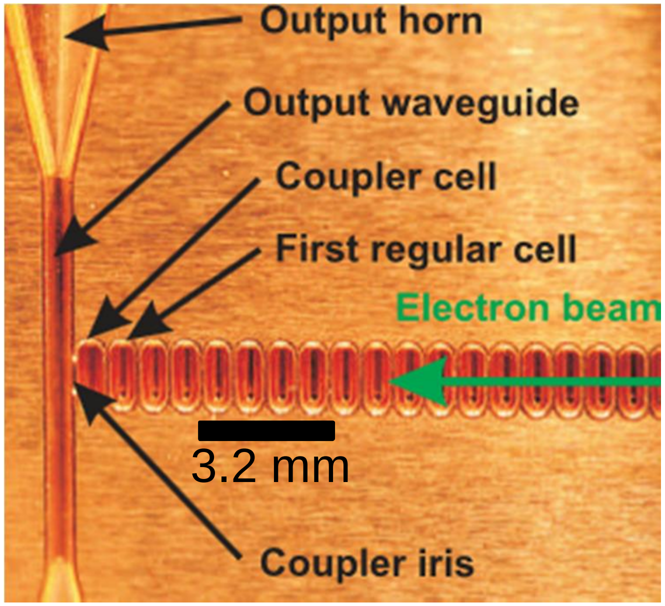
$$f \approx 300\ \mathrm{GHz}$$

THz Electron Gun for Ultrafast Science

- 3.5 cell RF photo-injector at 263 GHz
- Target exit energy of 1 MeV for UED applications
- Cavity cell lengths optimized to avoid phase slippage



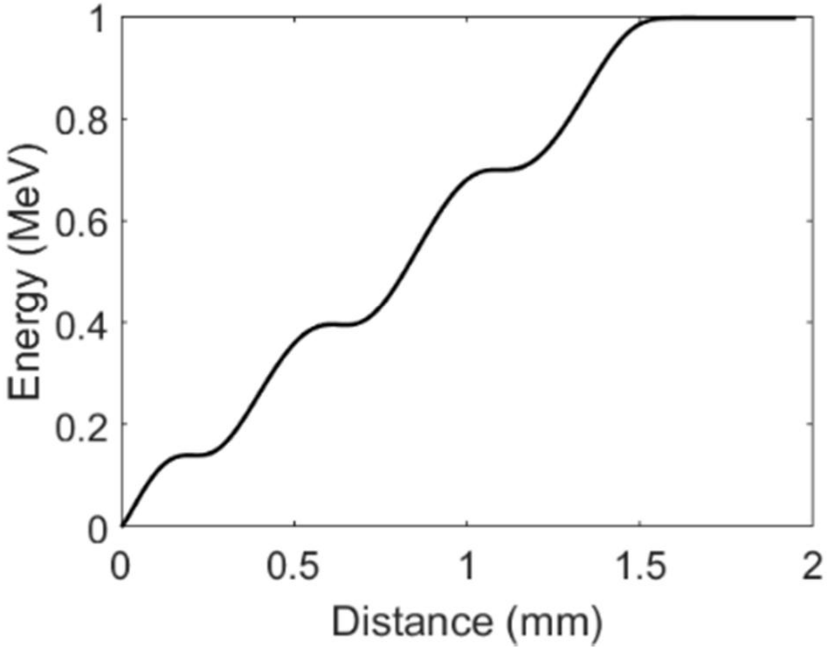
Demonstrated Fabrication

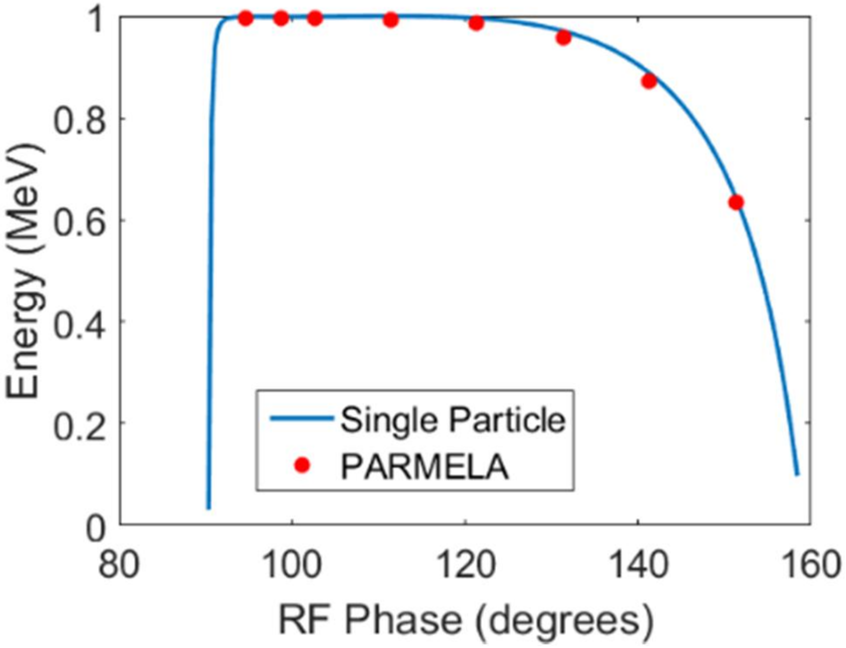


Dal Forno, et al. PRSTAB (2016)

Energy Gain in Electron Gun

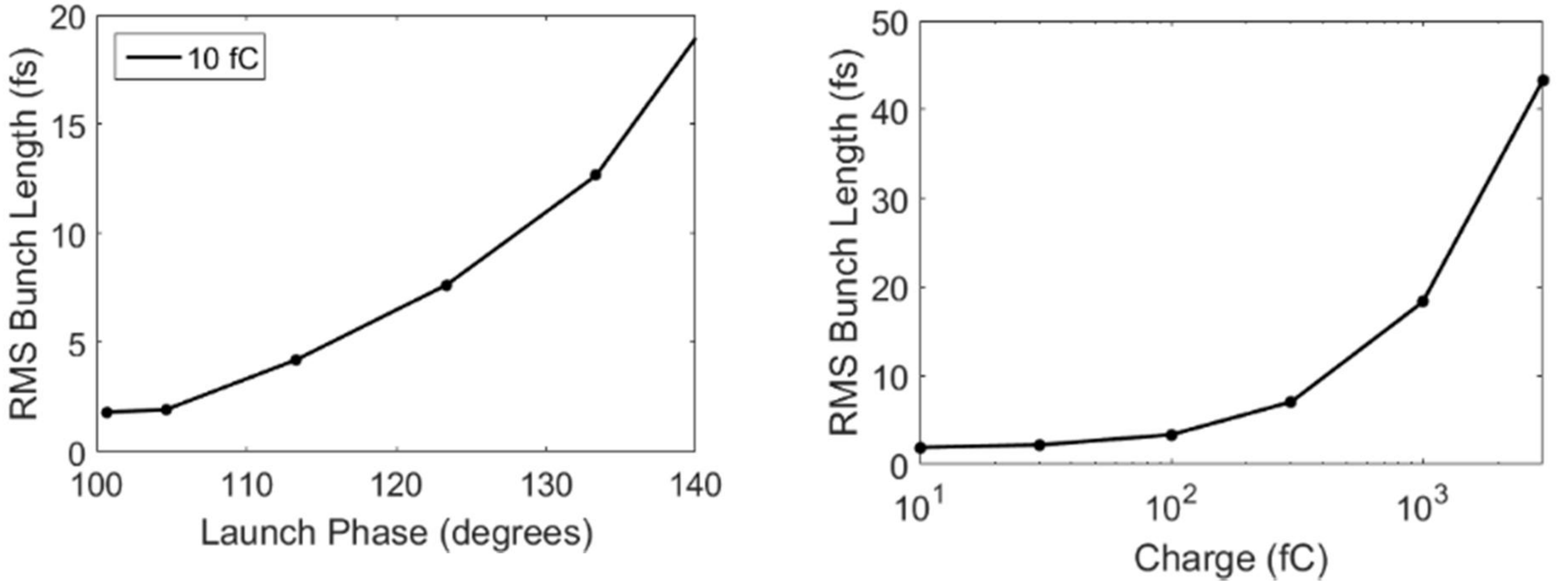
- 1 MW, 2 ns pulse required to achieve 1MeV exit energy
- Peak surface field of ~1 GV/m


Energy vs. Distance


Exit Energy

Femtosecond Electron Bunch Production

Electron Bunch Parameters at Gun Exit



- For 100 fC, 4 fs, electron bunch:
  - Initial Transverse Emittance 3 nm-rad
  - Final Transverse Emittance 7 nm-rad
  - x_{rms}=14 micron, 0.02% energy spread

Conclusions

- Development of efficient narrow-bandwidth THz sources needed to make THz accelerators practical
- THz OPAs can provide pulse frequency, bandwidth and length needed for many applications
- THz photo-injector: 1 MeV, <10 fs, 10 micron, 100 fC electron bunch with 2 mJ THz pulse
  - Ideal for ultrafast electron diffraction
  - Order of magnitude improvement over state-of-the-art in timing resolution, charge and energy spread
- THz accelerators powered by optical sources have the potential to enable compact high-gradient accelerators

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Questions?