Linear Electron Acceleration in THz Waveguides

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Acknowledgments

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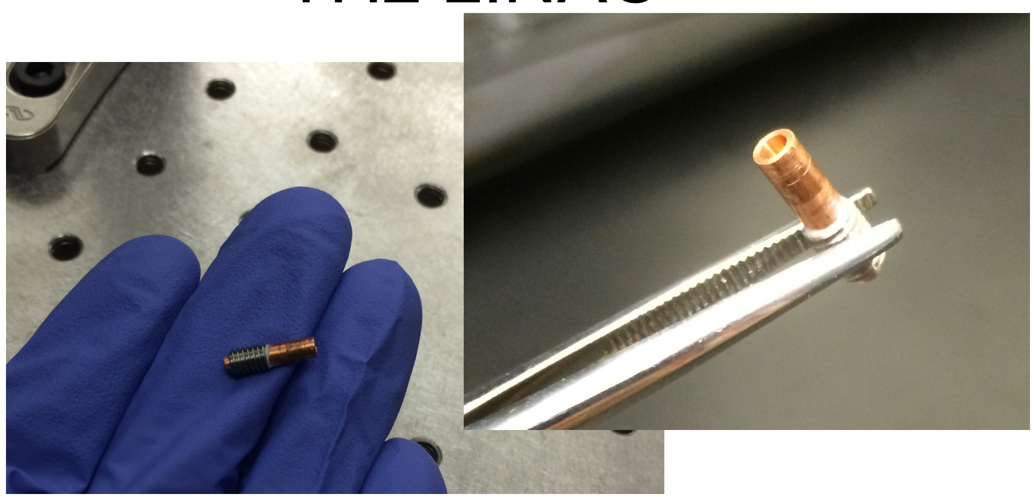
Outline

- Motivation
- THz Generation via Optical Rectification
- Accelerating Structures
- THz Accelerator
- Conclusions

Motivation

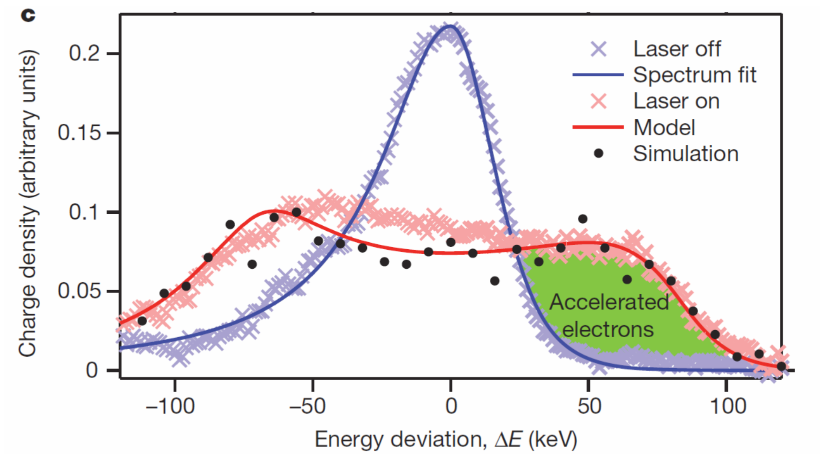
- High-gradient accelerators are attractive due to reduced size and improved electron beam quality
- Increasing operational frequency reduces complications from pulsed heating, breakdown and average power load
- Commercial IR laser can generate a 20 MW THz pulse
- Proof of concept: accelerate 60 keV electrons with THz pulse

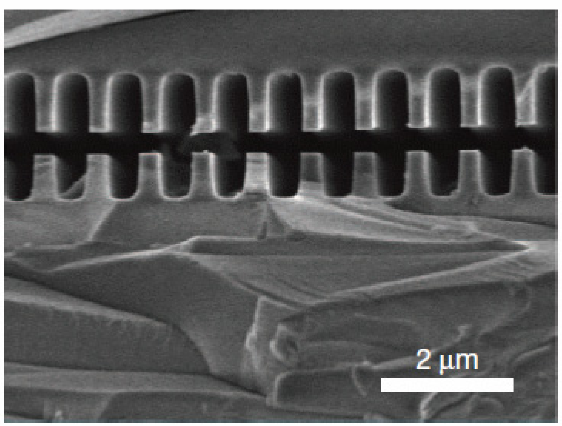
THz LINAC



Background

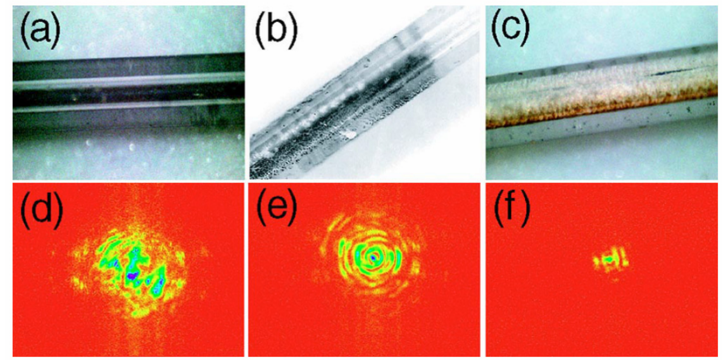
<u>Laser-Driven Acceleration</u>
Demonstrated 190 MV/m

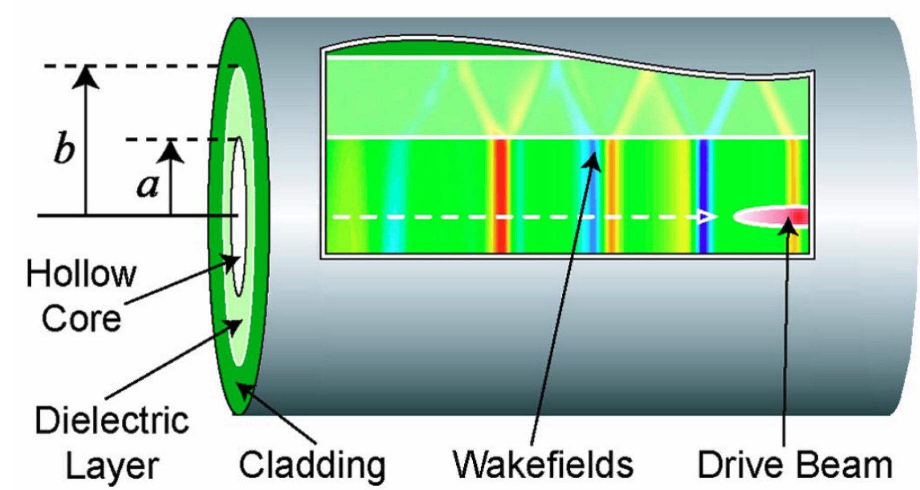




Peralta, E. A., et al., *Nature* 503.7474 (2013): 91-94.

<u>Dielectric Wakefield Acceleration</u>
Demonstrated 5.5 GV/m

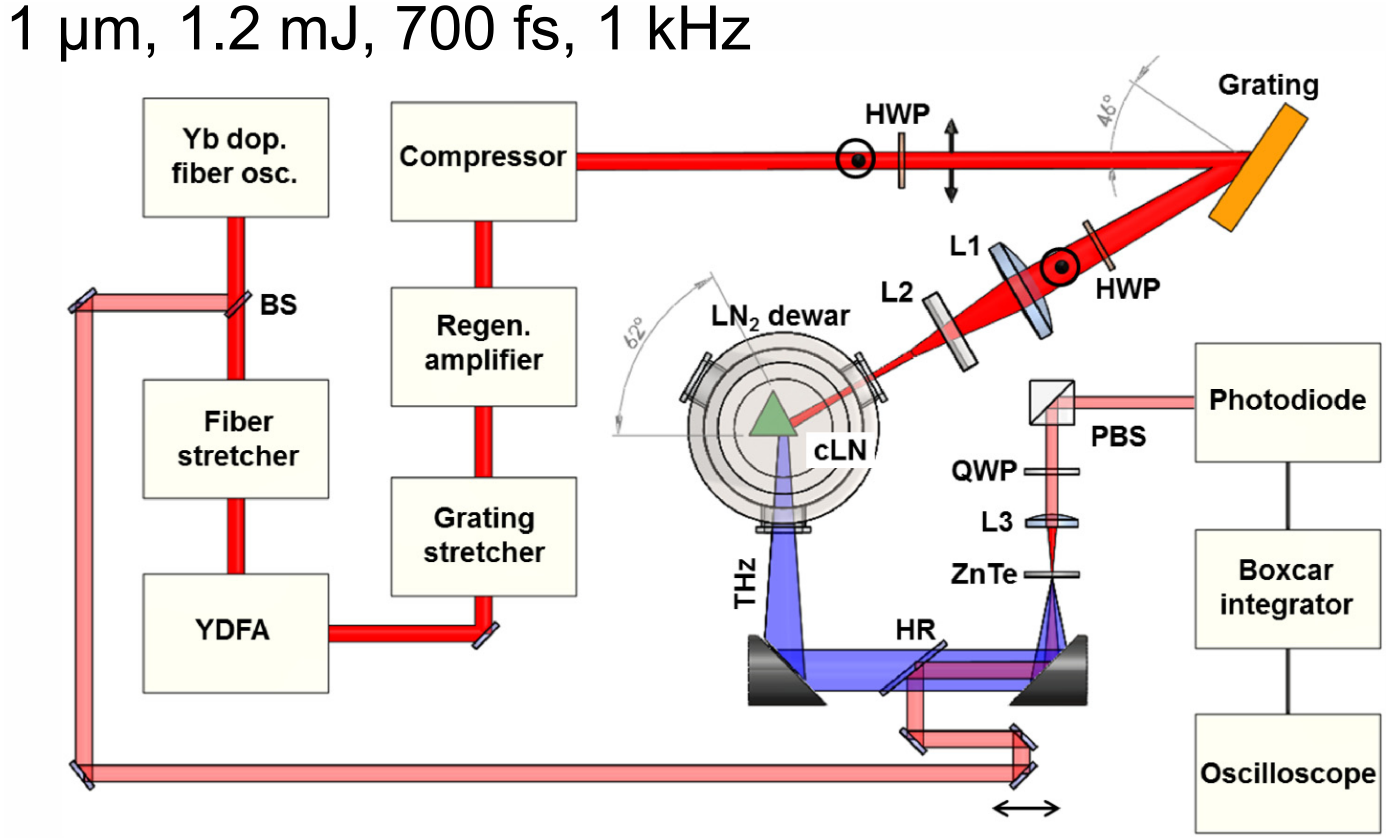




Thompson, M. C., et al., *Phys. Rev. Lett.* 100.21 (2008): 214801.

THz Generation Setup

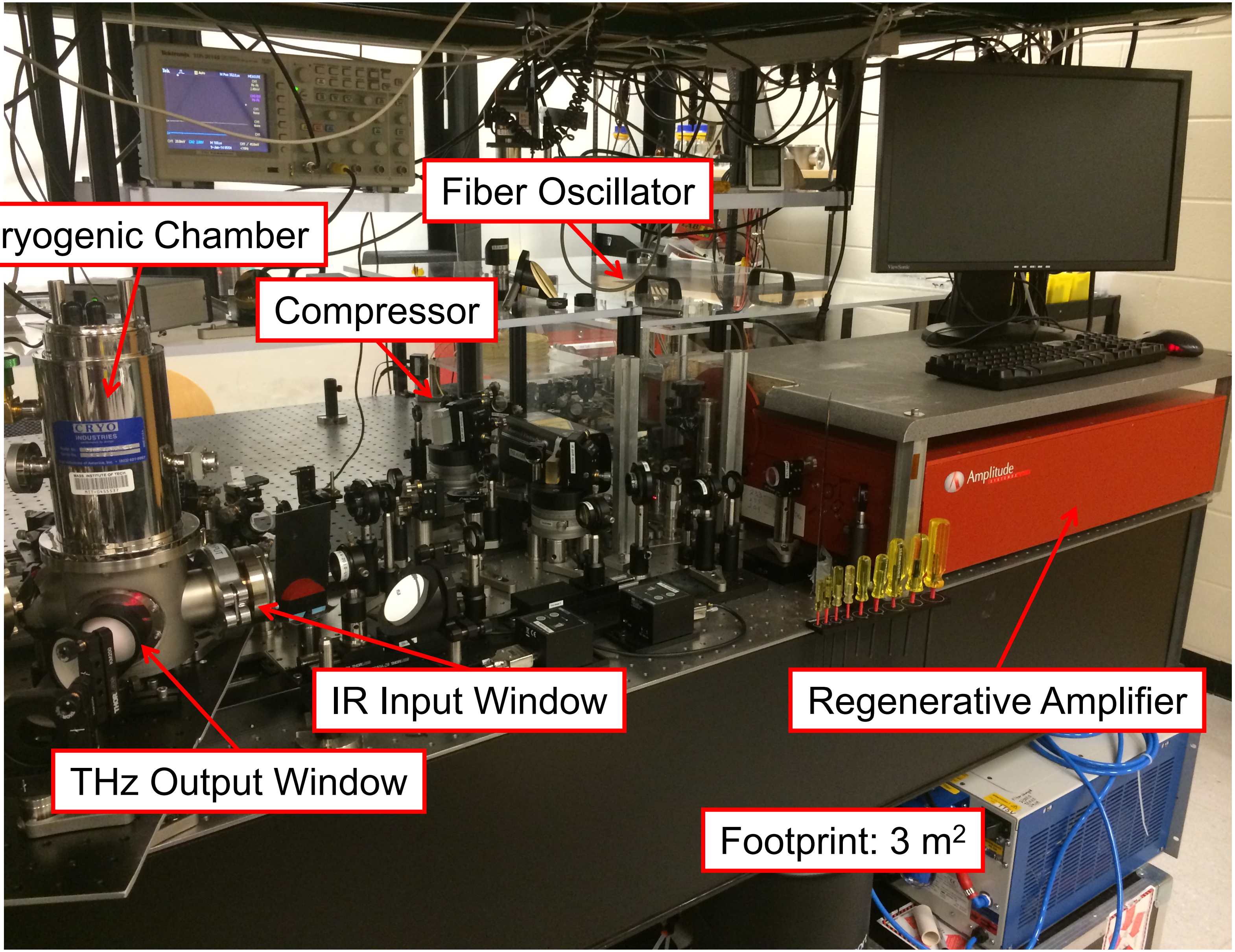
- Yb:KYW regenerative amplifier
  - 1 µm, 1.2 mJ, 700 fs, 1 kHz



- ~1% THz conversion efficiency with pulse front tilting and cryogenic cooling

Huang, W. Ronny, et al., *Journal of Modern Optics* ahead-of-print (2014): 1-8.

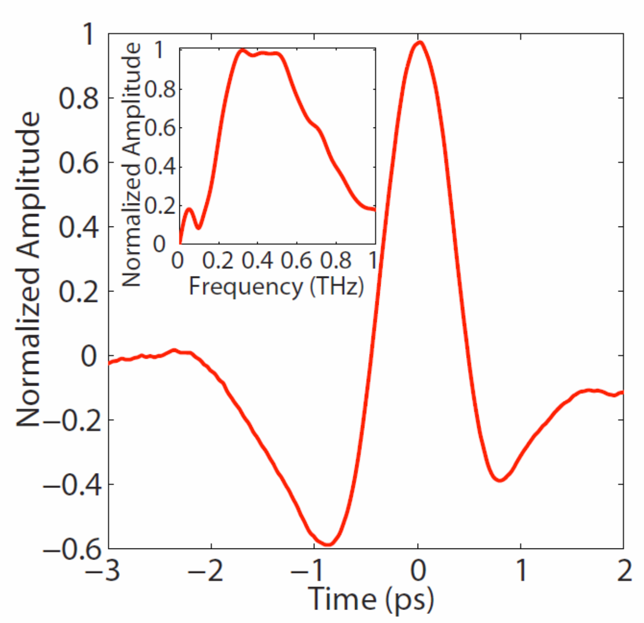
THz Generation Setup



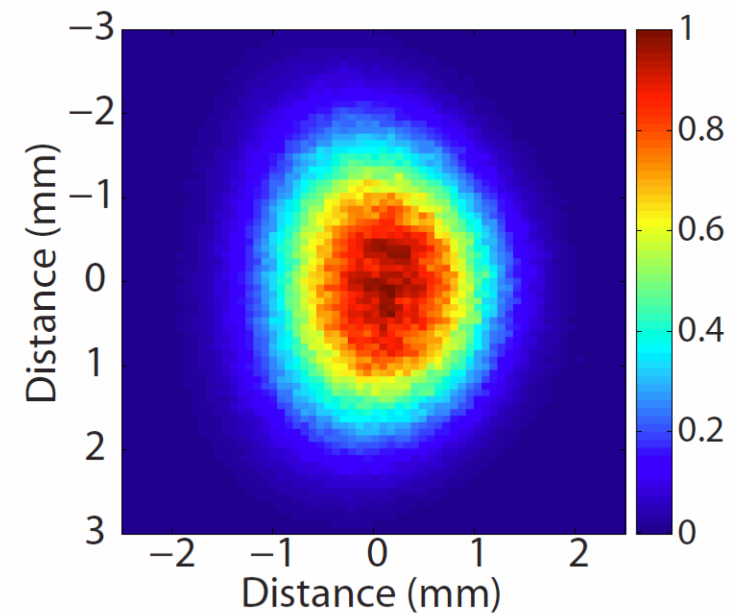
THz Pulse Properties

- 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

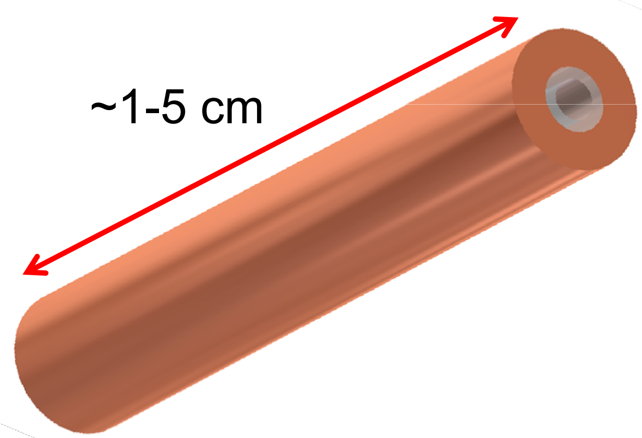


Transverse Intensity Profile



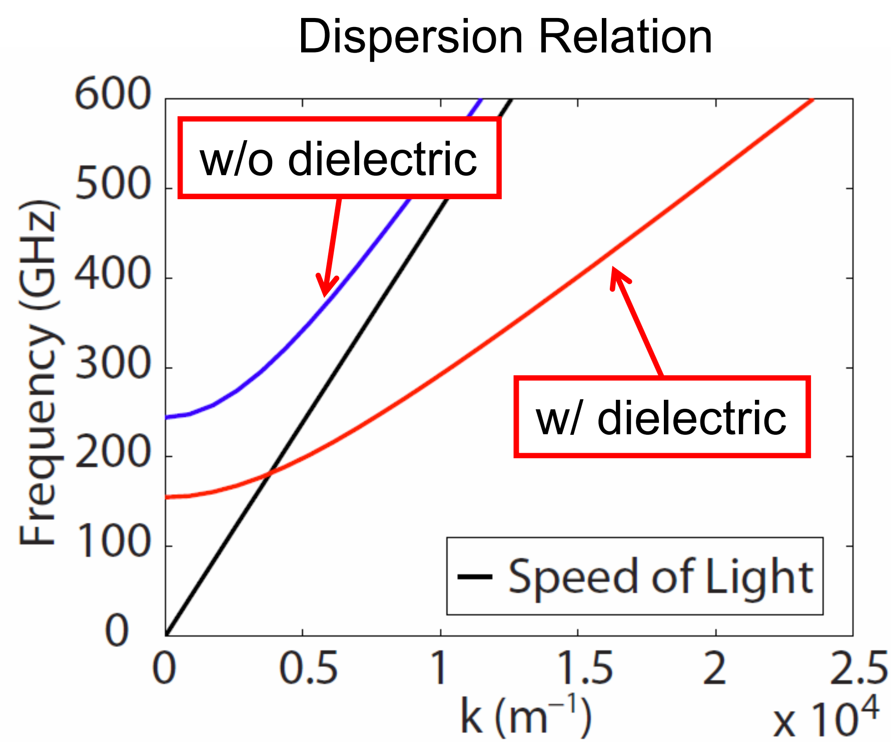
Dielectrically Loaded Circular Waveguide

- 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



Electro-Optic (EO) Sampling

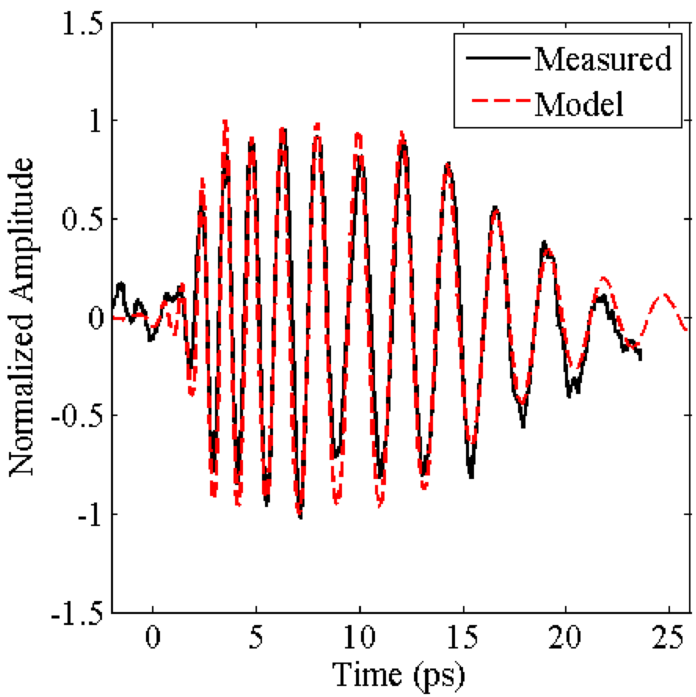
- THz waveguide is highly dispersive over a large bandwidth
- Dispersion in waveguides measured with EO sampling

<u>Waveguide Parameters</u>

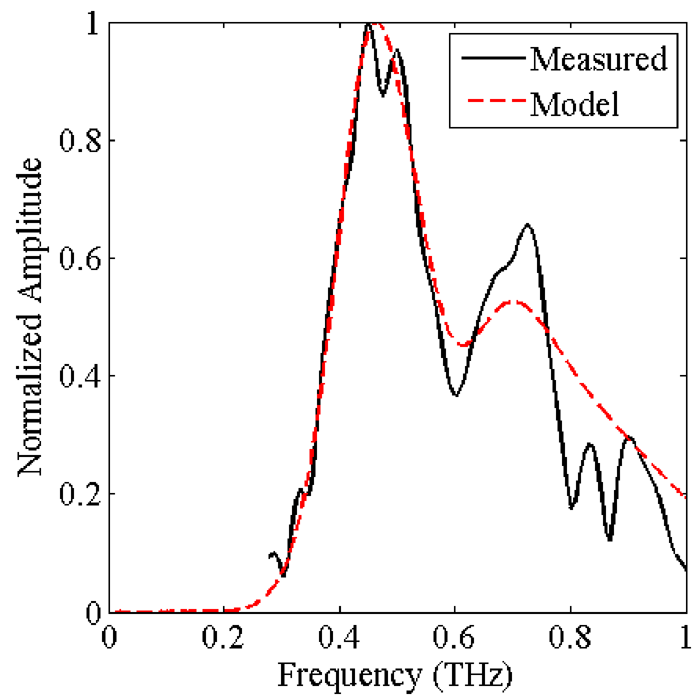
L = 4 cm

r_w = 474 μm

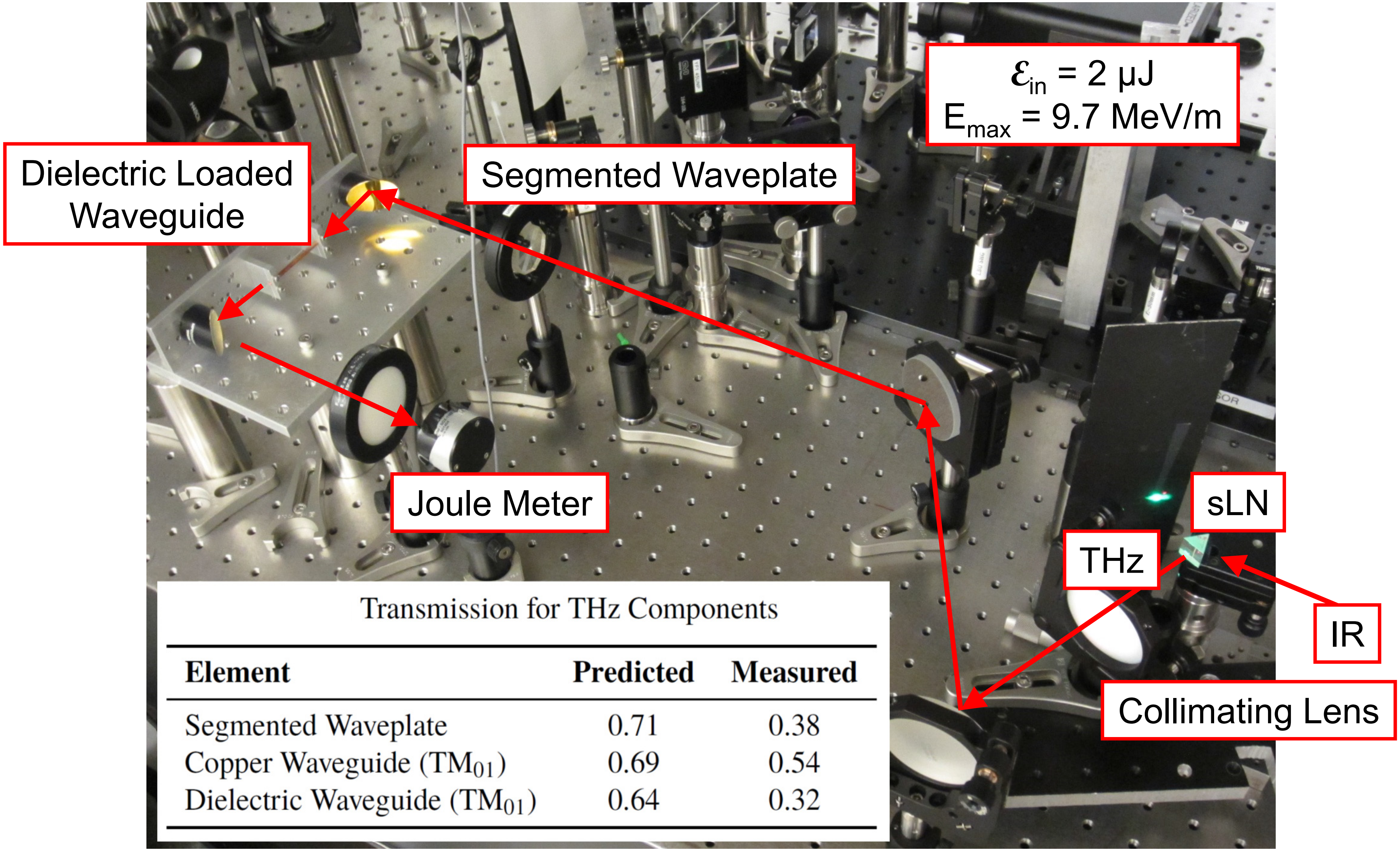
Electric Field



Frequency Spectrum



Transmission Measurements



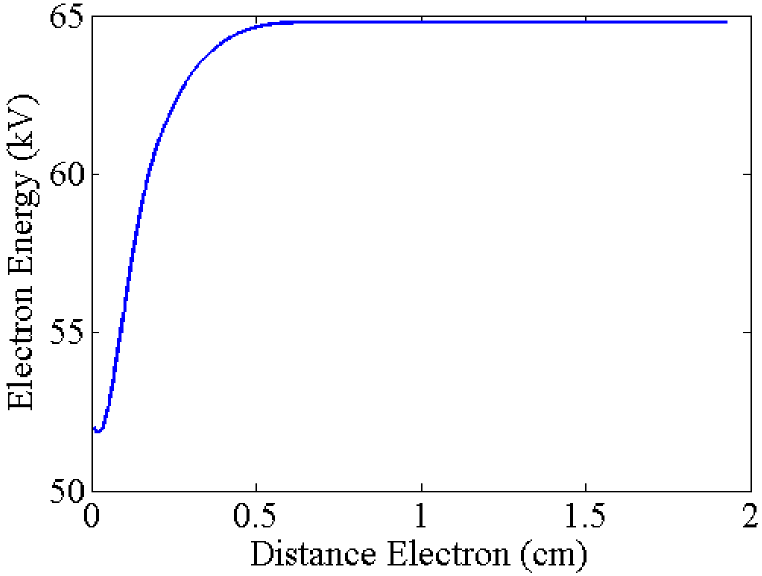
Transmission for THz Components

Element	Predicted	Measured
Segmented Waveplate	0.71	0.38
Copper Waveguide (TM_{01})	0.69	0.54
Dielectric Waveguide (TM_{01})	0.64	0.32

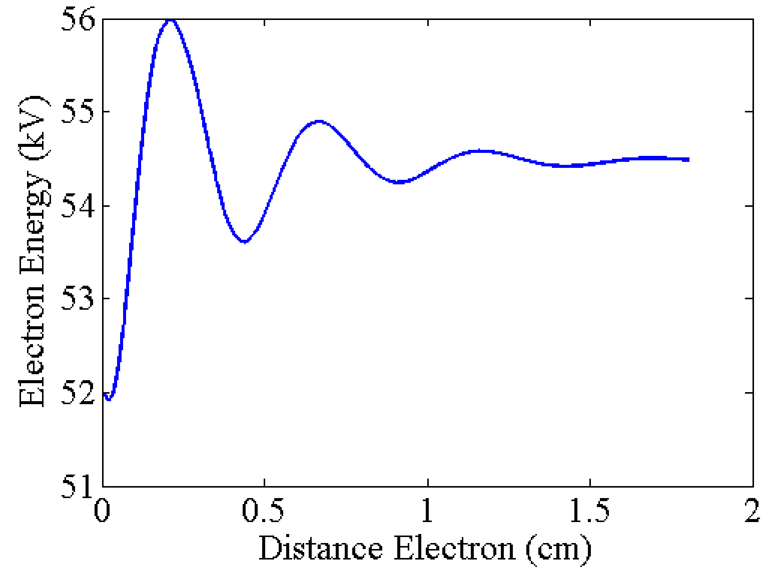
THz Acceleration Modeling

- Time domain acceleration of a single particle
- Small change in field has big impact due to low particle energy

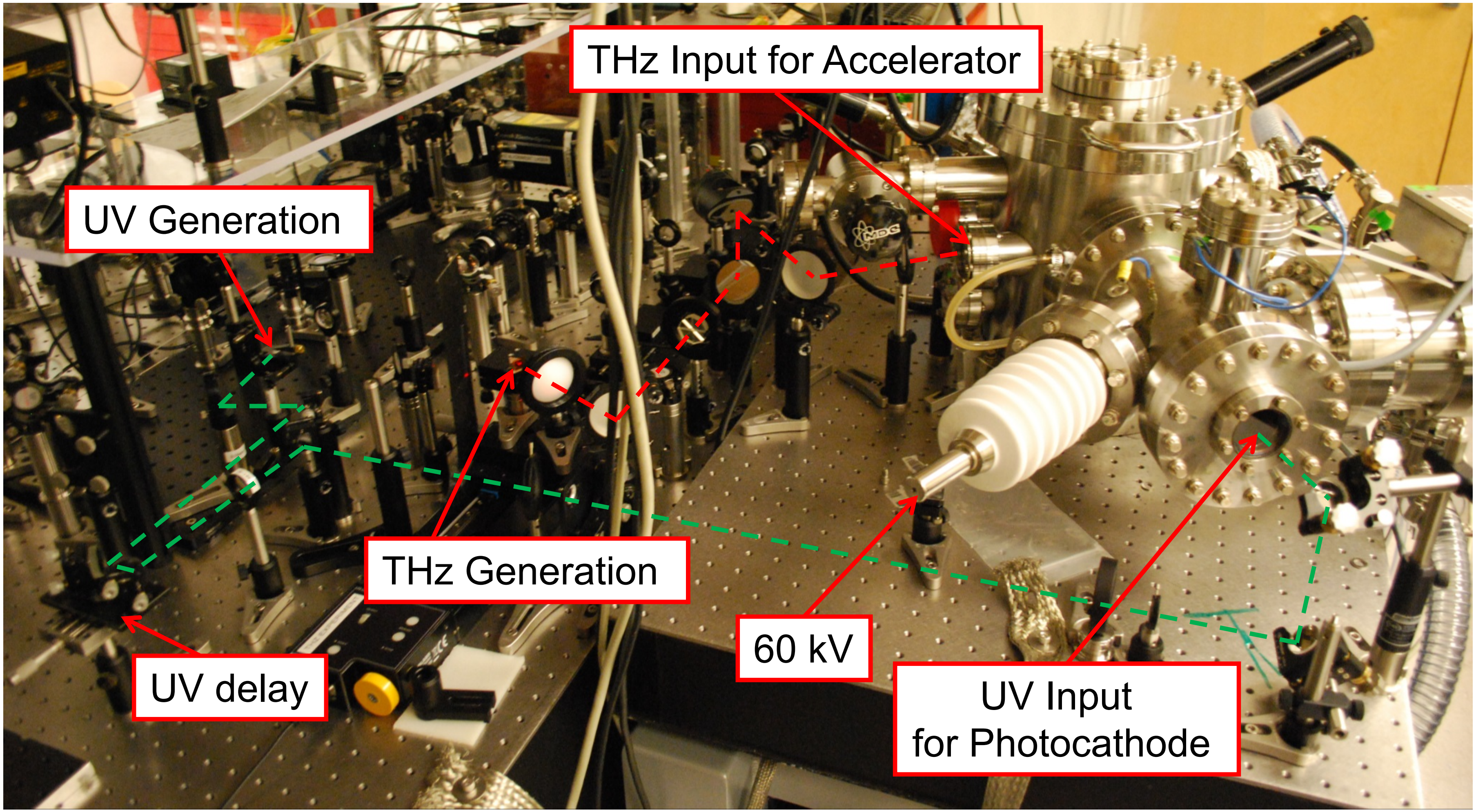
2 μJ THz
10 MeV/m, 13 kV Acceleration



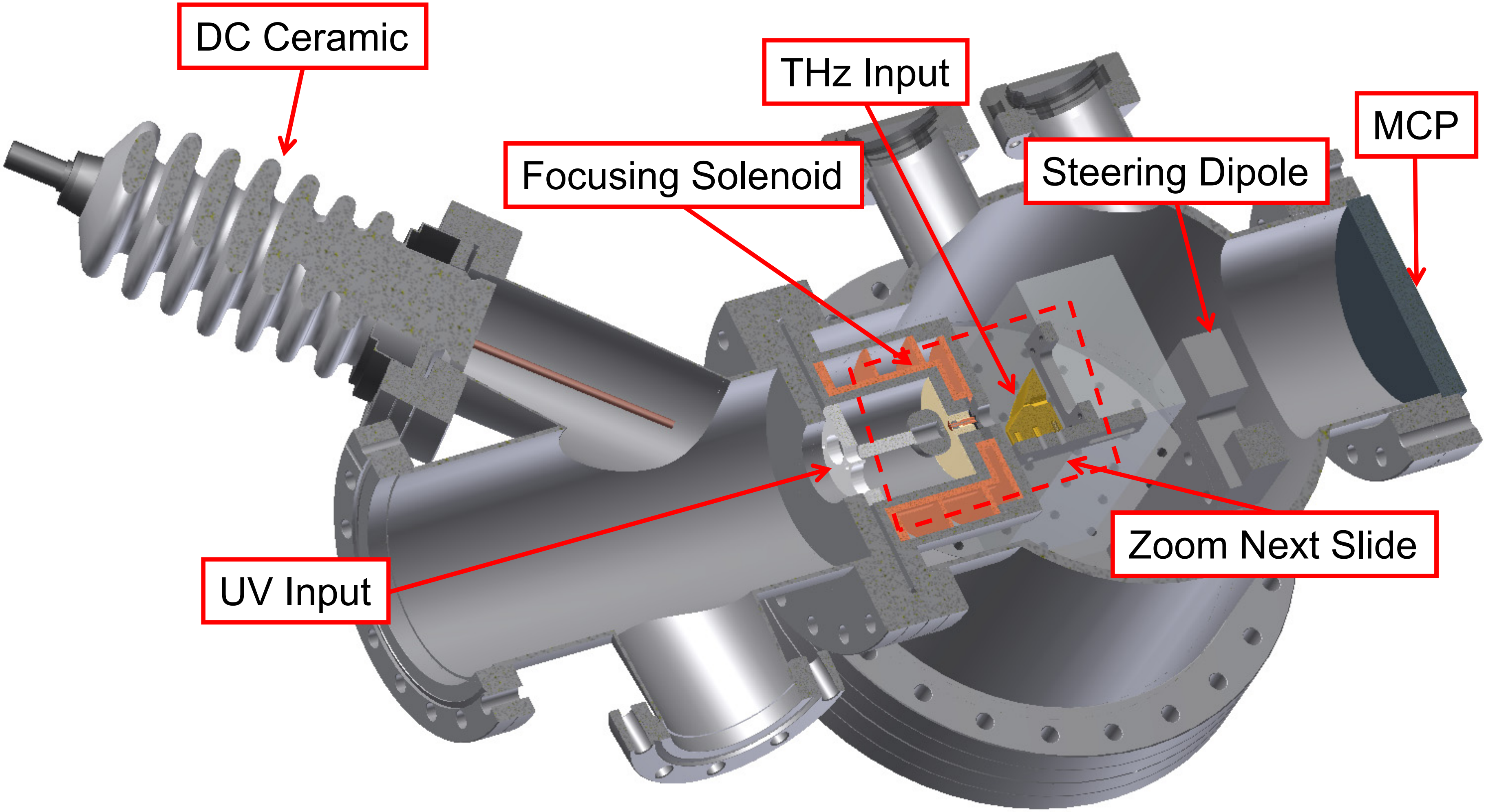
0.5 μJ THz
5 MeV/m, 2.5 kV Acceleration



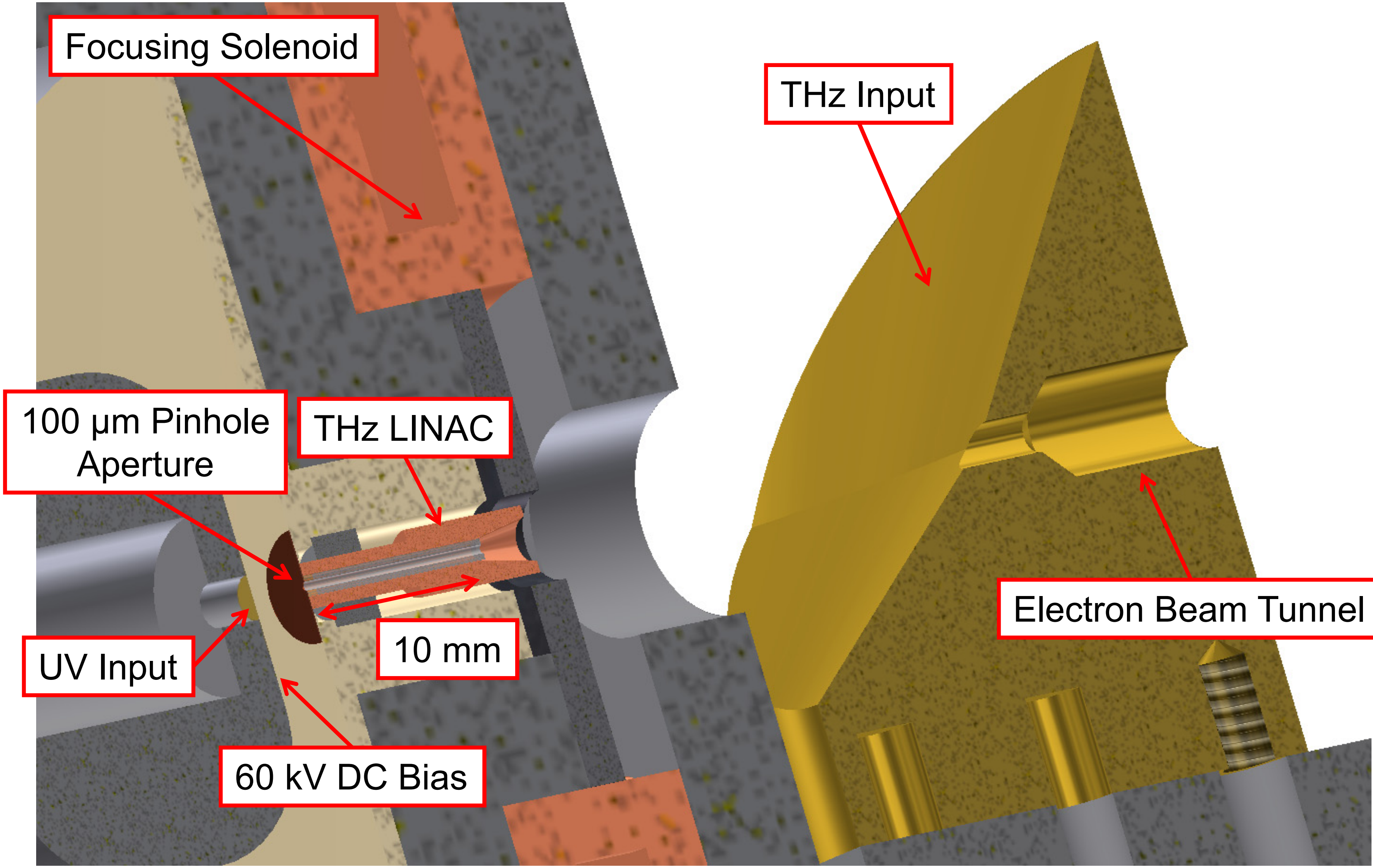
THz Acceleration Chamber



DC Gun and THz LINAC



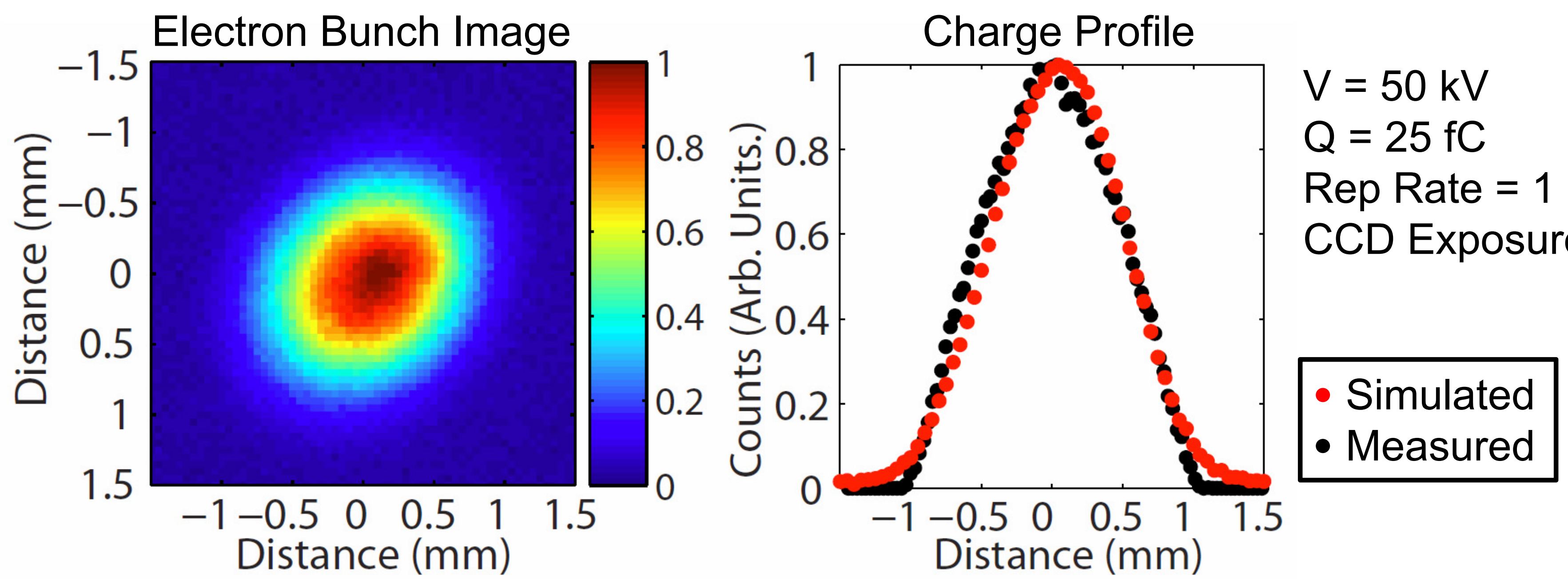
DC Gun and THz LINAC



Electron Beam Parameters

- Electron beam imaged on a microchannel plate (MCP) detector
- Solenoid is optimized to focus electron bunch at MCP
- PARMELA is used to simulate from photo-emission to detection

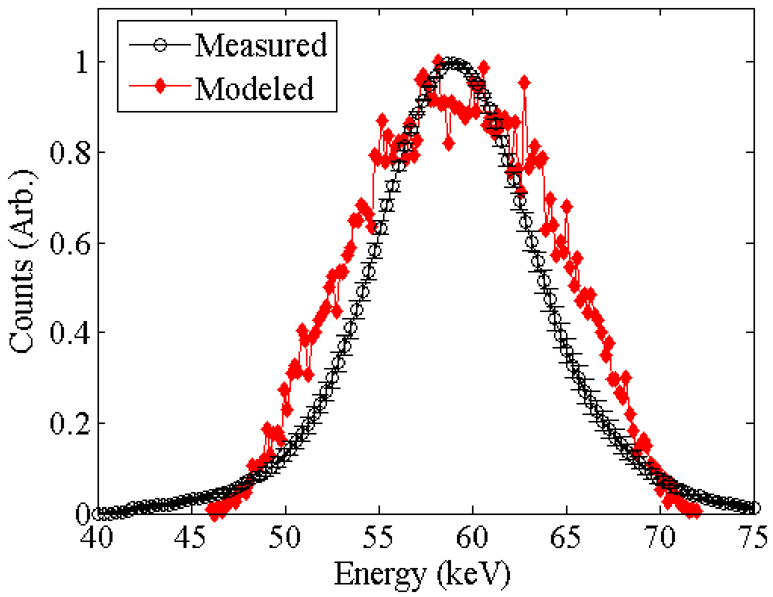
UV Laser = 0.7 μJ, 250 nm, 350 fs



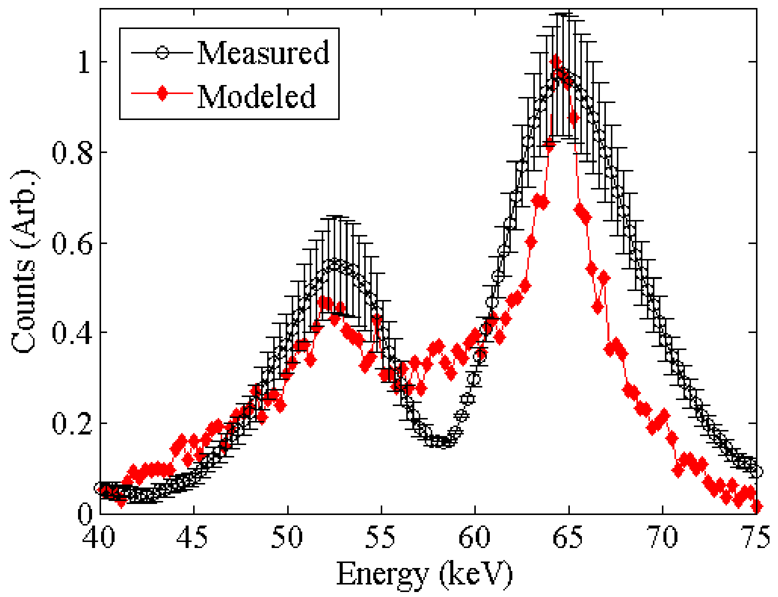
Energy Spectrum

- Measured energy spectrum for 59 keV start energy
- Modeled on-axis gradient of 4.9 MeV/m
- Electron bunch $\sigma_z = 45\ \mu m$

THz Off

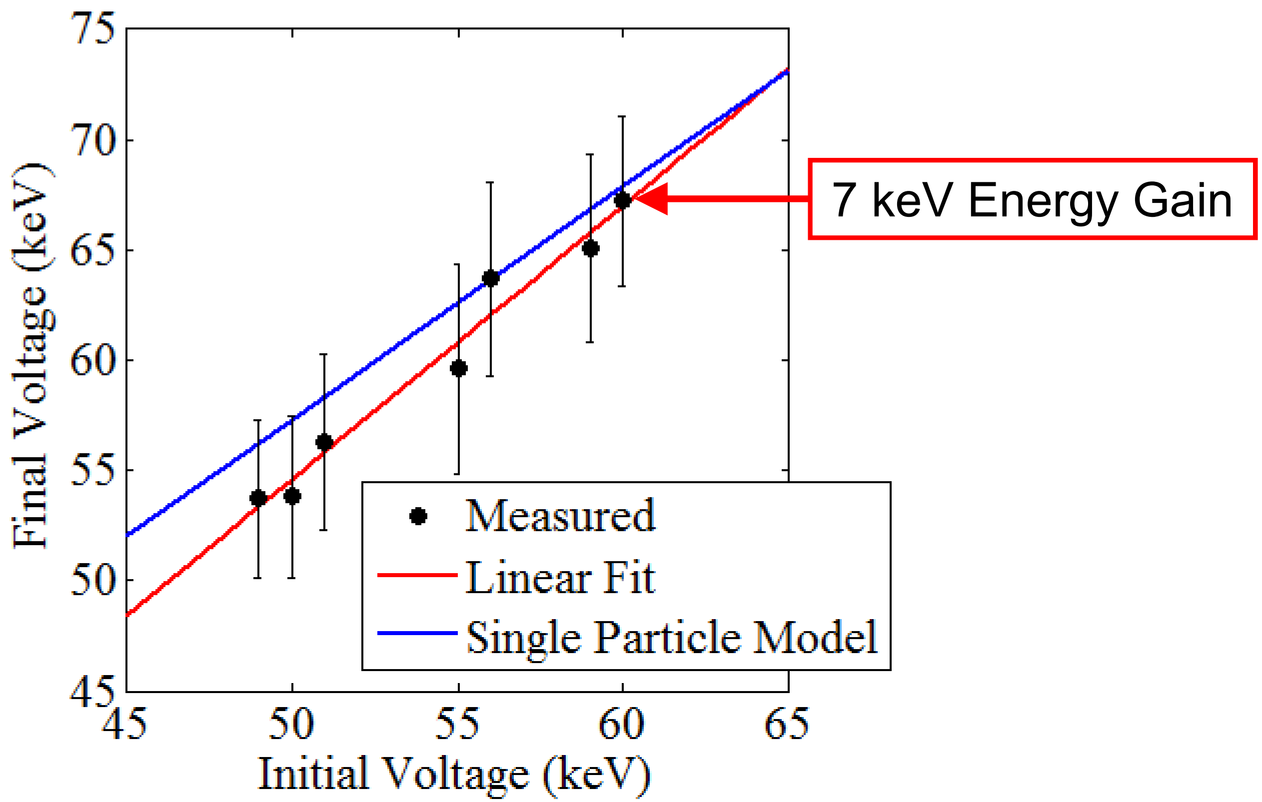


THz On



Energy Gain vs Voltage

- Energy gain depends on initial electron energy
- Increase in energy decreases phase slippage
- Single particle model with 5 MeV/m gradient

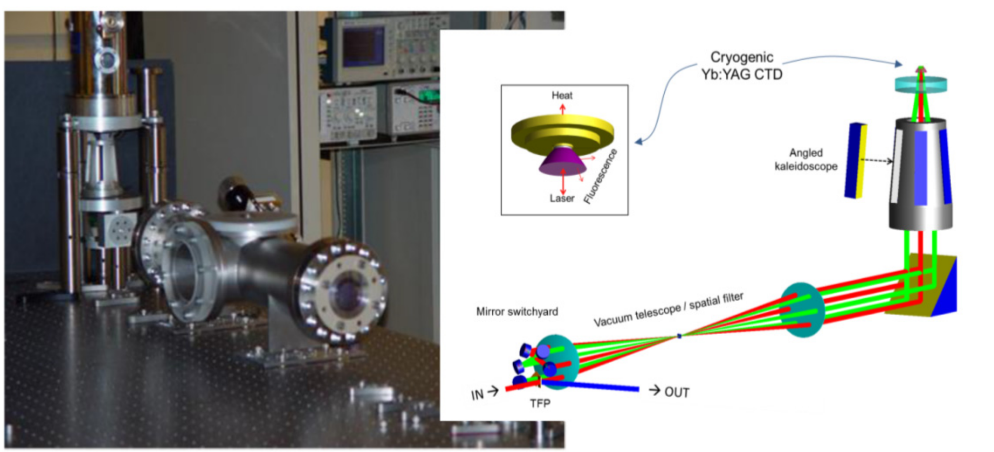


Future Work

- Extending THz acceleration to GeV/m and relativistic particles
  - Improvements to IR laser pulse energy (100 mJ – 1 J) with cryo-YAG or cryo-YILF multi-pass amplifiers
  - High energy accelerator development underway using single and multi-cycle pulses

Demonstrated cryo-YAG amplifier

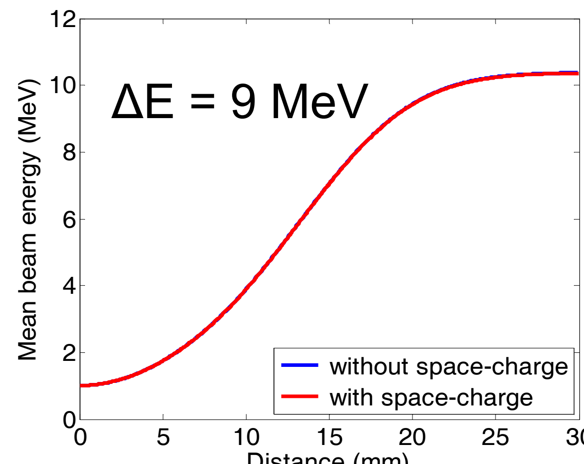
60 mJ IR pulse, uncompressed



Zapata, L., et al., CLEO, SM1F.1, 2014.

Modeling THz Acceleration

10 cycle, 10 mJ pulse, 0.74GeV/m



Wong, Liang Jie, et al., *Optics express* 21.8 (2013): 9792-9806.

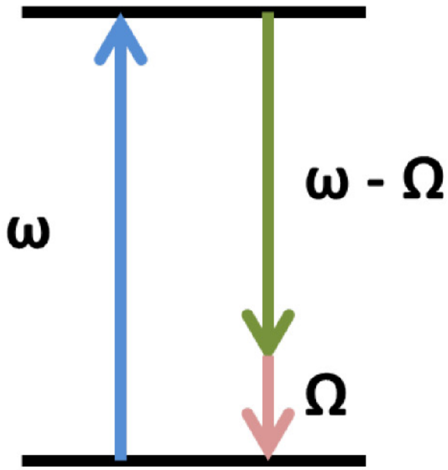
Conclusions

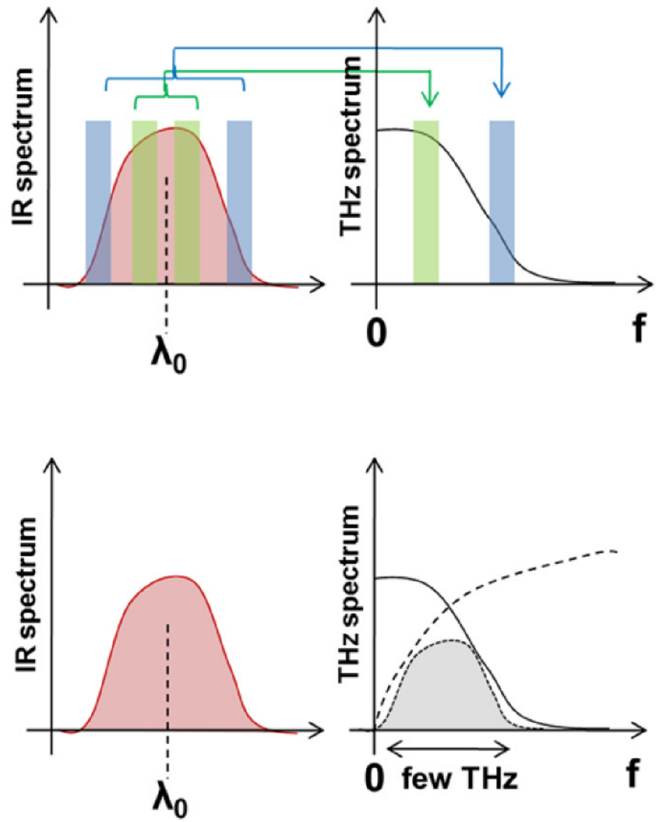
- First demonstration acceleration in a waveguide with optically generated THz pulse
- Maximum observed acceleration 7 keV
  - 25 fC per bunch, 1 kHz repetition rate
- 4.9 MeV/m gradient achieved in electron acceleration experiment
- THz accelerator performance limited by long UV pulse (350 fs)
- ~1% conversion efficiency THz pulse
  - 10 μJ single-cycle pulse produced at source

Extra Slides

THz Generation

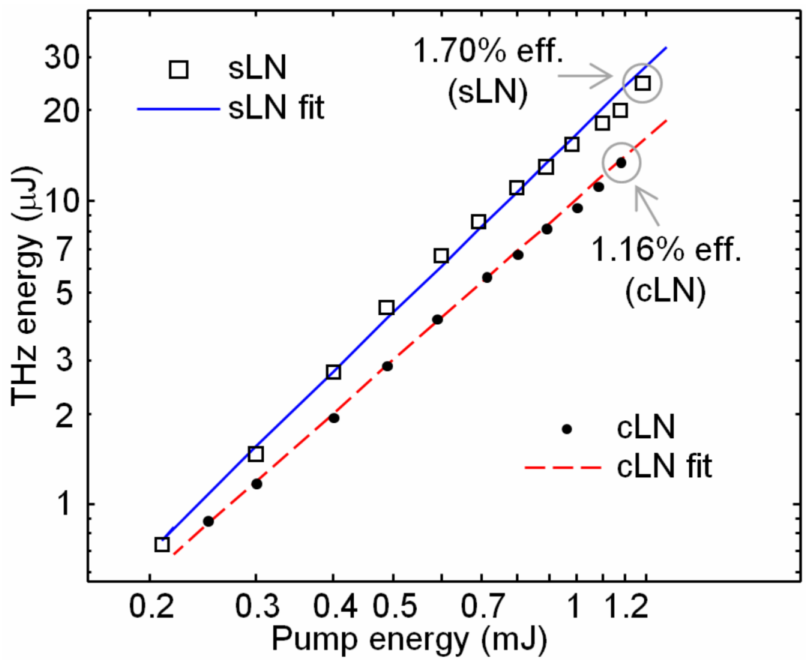
- THz generation via optical rectification of IR pulses
- Optical rectification: intra-pulse difference frequency generation

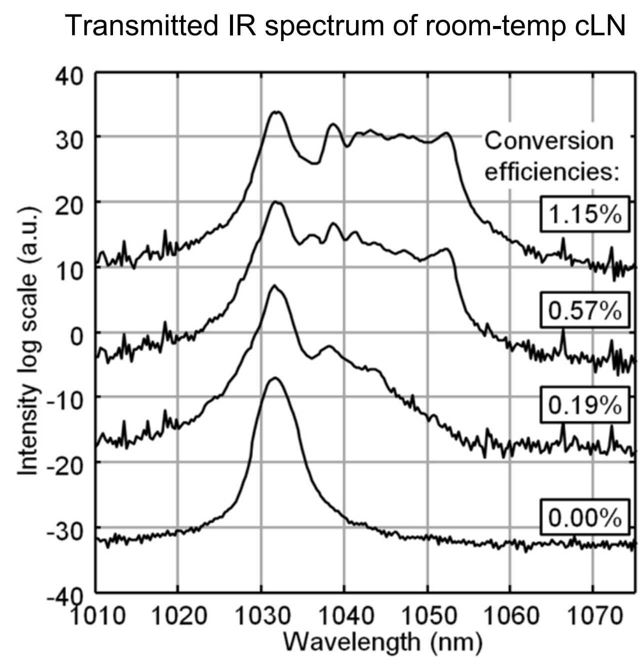




THz Generation Efficiency

- Conversion efficiency of 1.7% in room temperature sLN
- Cascaded IR pulse is associated with high conversion efficiency

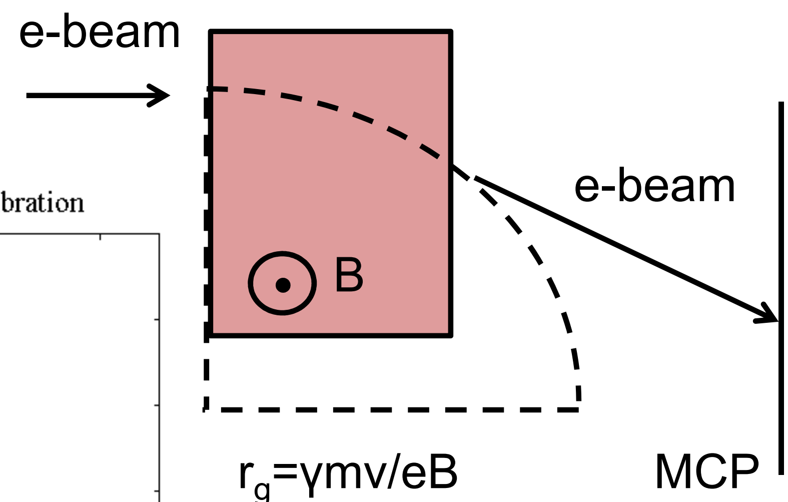


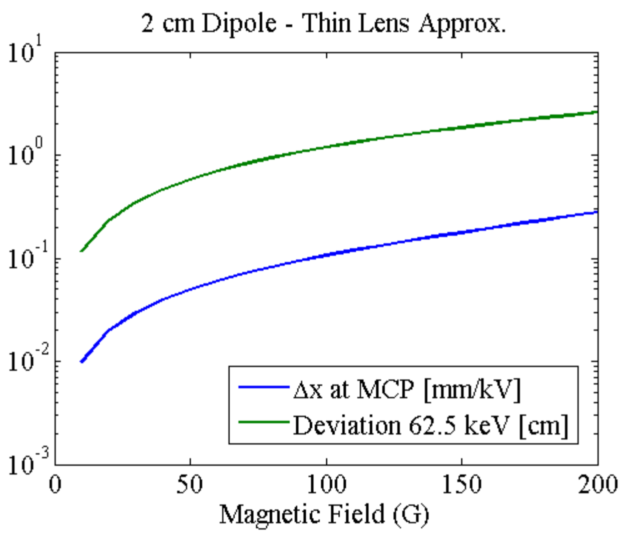


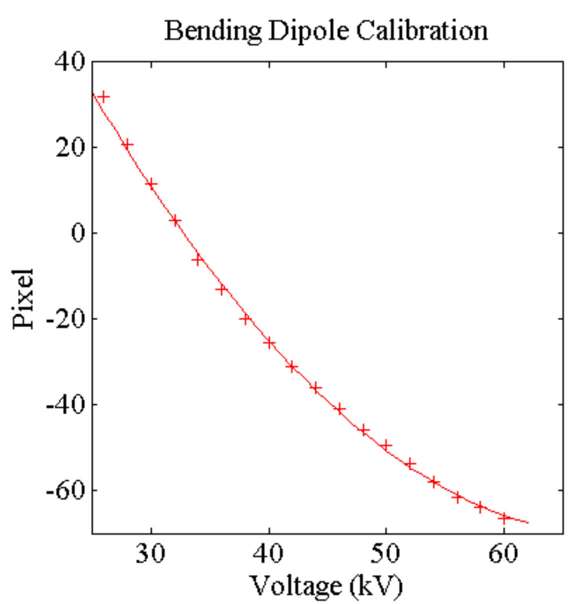
Huang, Shu-Wei, et al., Optics letters 38.5 (2013): 796-798.

Energy Spectrometer

- A magnetic dipole is used to steer the electron beam in an energy dependent manner
- Resolution limit set by drift distance and pixel size



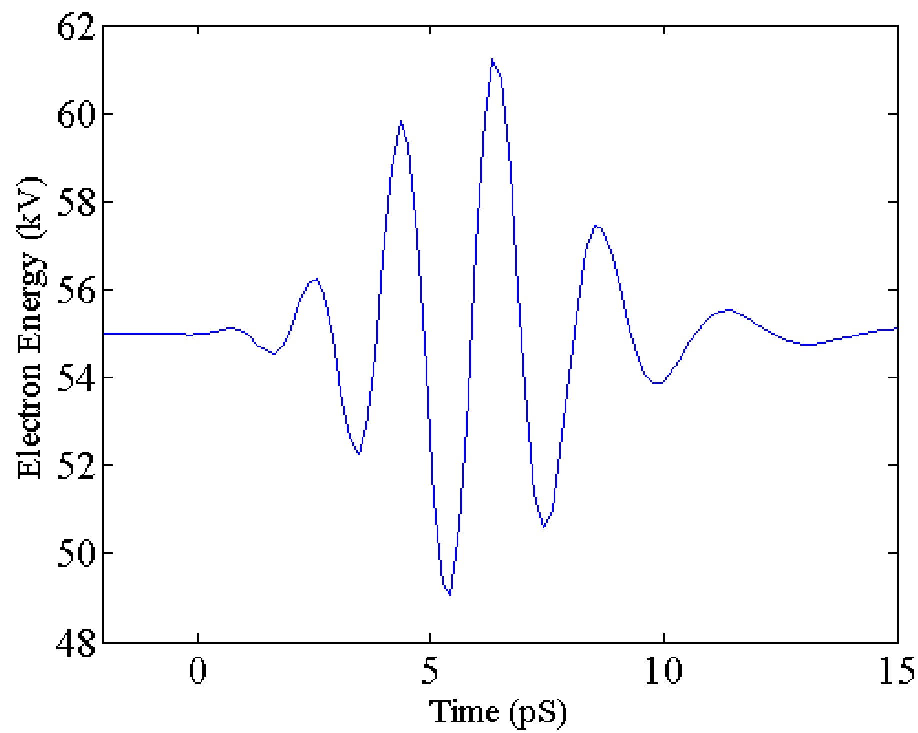




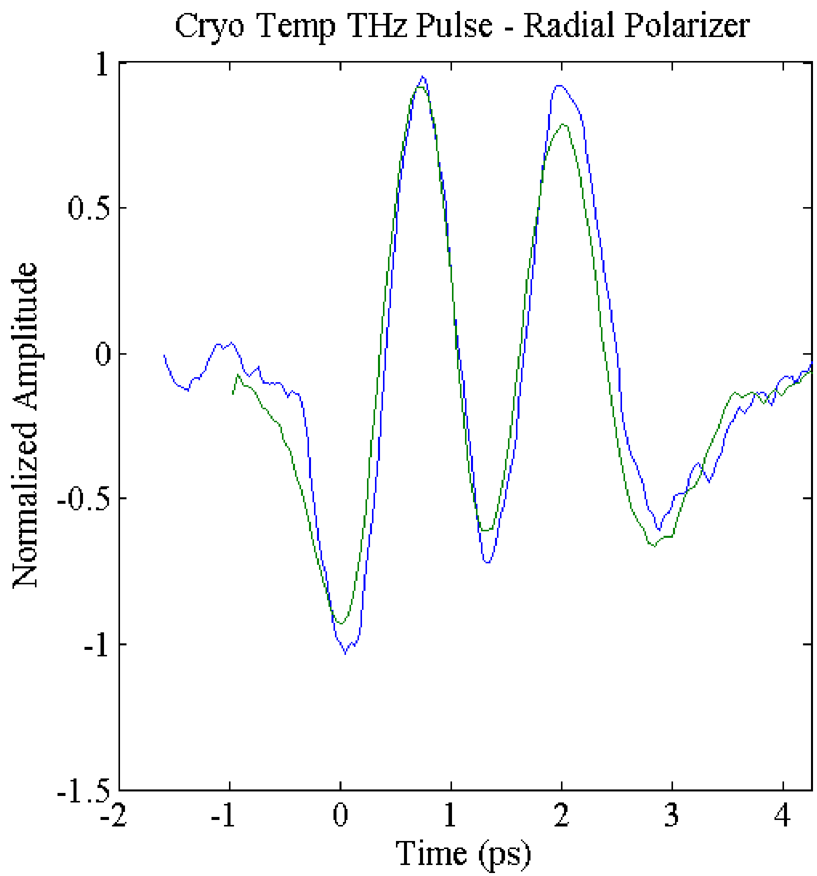
Modeled Acceleration vs UV Delay

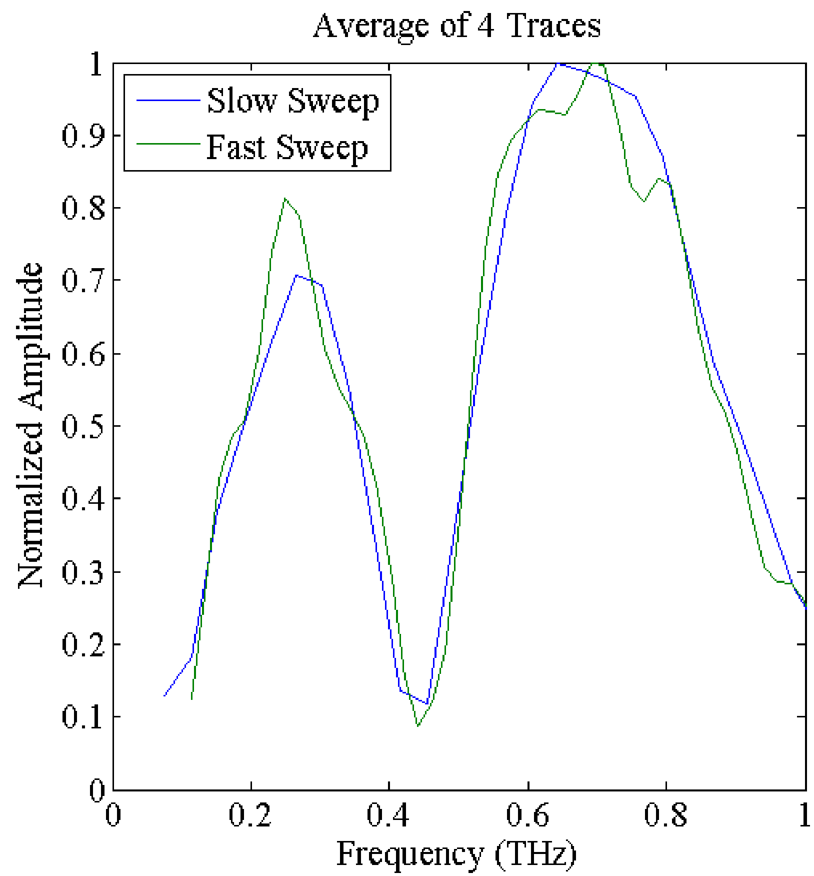
- Due to propagation in waveguide THz pulse suffers from dispersion
- Acceleration very sensitive to input spectrum

$E_{on\text{-}axis}$ = 5 MeV/m
Peak at Input
E_{beam} = 55 keV



Radial Polarizer w/ Cryo Pulse



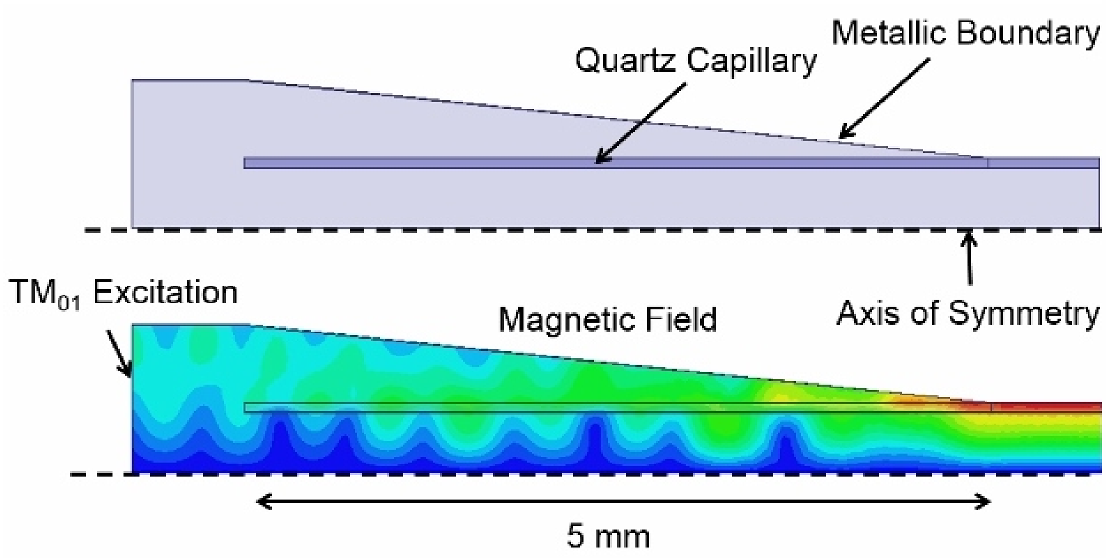


EO sampling should be insensitive to radial polarization at 450 GHz
Notch in spectrum is radially polarized

Dielectrically Loaded Horn

- Coupling of THz into waveguides with dielectrically loaded structure that is simple to fabricate

Dielectrically Loaded Horn



Coupling into TM_{01} - HFSS