Investigation of Optimization of Dielectric Terahertz Acceleration Structures

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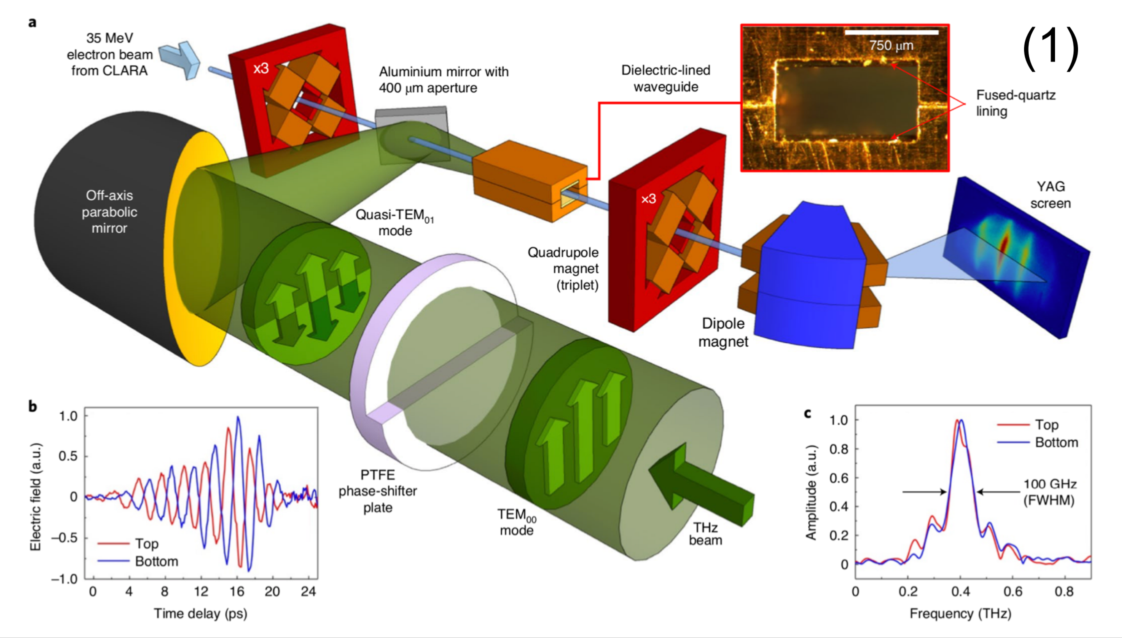
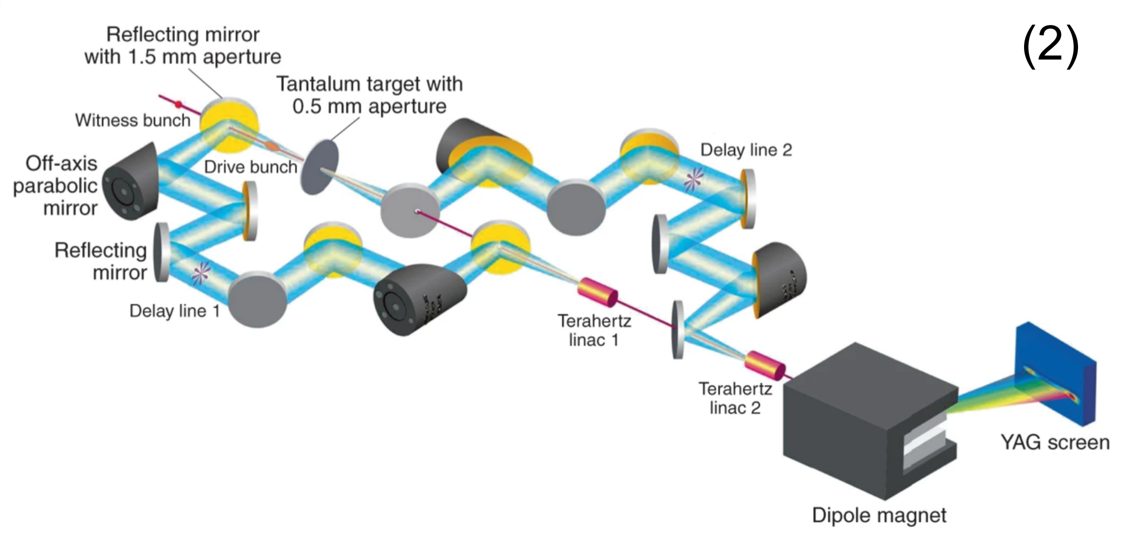
Advantages of THz Acceleration

- Moving to THz frequencies provides favorable scalings:
  - Higher surface EM fields and shunt impedance
    - Scales as $f^{1/2}$, for metallic structures
  - More efficient
  - Decrease in loss and fill time
- Results:
  - High gradients and peak electric fields are possible
  - Low emittance, high brightness beams
  - Allows operation at higher rep rate

Examples of THz Accelerators

- Current THz accelerators:
  - Use single cycle sources
  - Basic dielectric and metallic accelerating structures
  - Couple THz into the structure along the beam path





1) Hibberd, M.T. *et al.* Acceleration of relativistic beams using laser-generated terahertz pulses. *Nat. Photonics* (2020).
2) Xu, H. *et al.* Cascaded high-gradient terahertz-driven acceleration of relativistic electron beams. *Nat. Photonics* (2021).

Challenges of THz Acceleration and Advantages of Dielectric Accelerators

- Challenges :
  - Spectral properties of high-field THz sources make coupling difficult
  - THz transport results in significant beam losses
- Dielectric accelerator structures reduce these losses because:
  - THz radiation can be coupled laterally into the structure
  - ohmic losses are reduced in dielectric materials
- Advanced machining methods allow complex geometries in dielectric accelerators
  - Structure geometry can be optimized using simulation and optimization tools

Simulation of Dielectric THz Accelerator Structures

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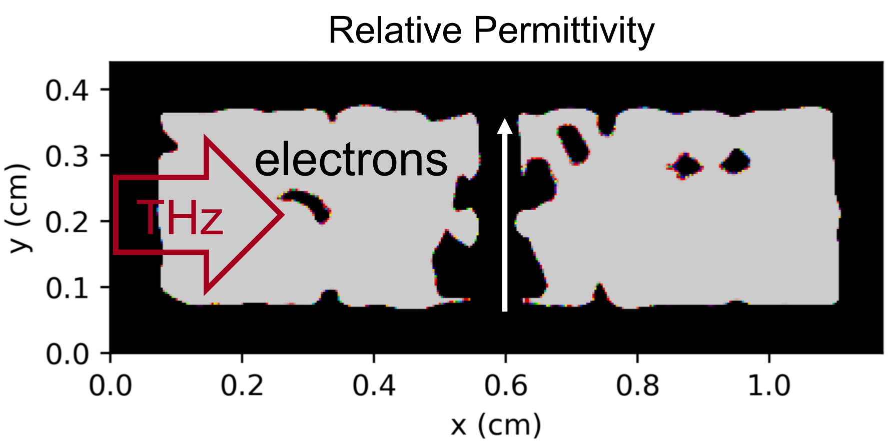
- Simulations carried out in an electromagnetic simulation and automatic differentiation package called Ceviche
  - Developed at Stanford
- Ceviche provides two core electromagnetic simulation tools for solving Maxwell's equations:
  - finite-difference frequency-domain (FDFD)
  - finite-difference time-domain (FDTD)
- Optimization of structures (i.e. maximizing accelerating gradient) can also be carried out

- https://github.com/fancompute/ceviche
- https://arxiv.org/abs/1908.10507

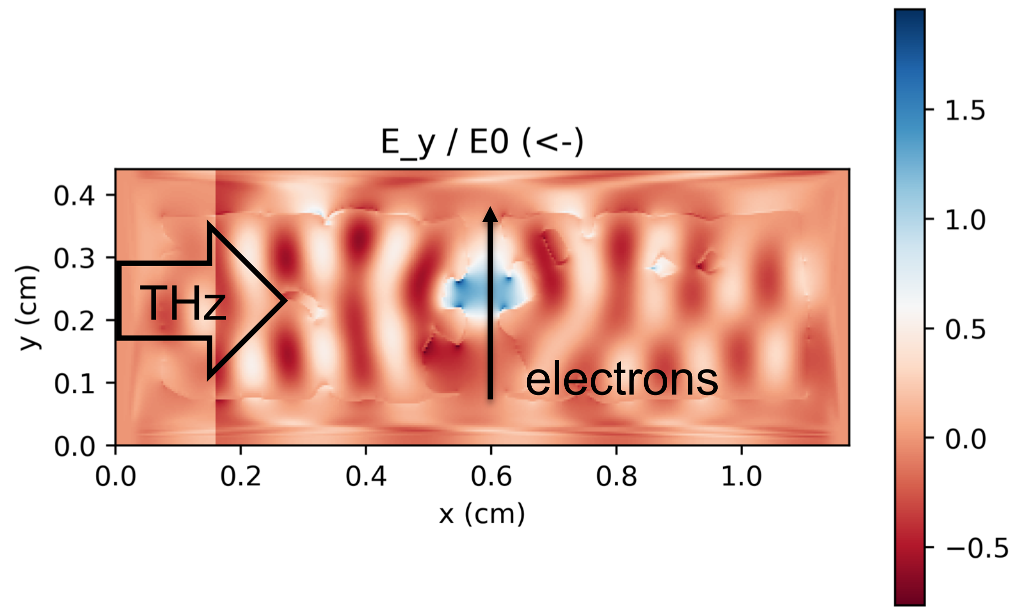
ceviche

Preliminary Frequency Domain Simulation Results

- 94 GHz CW incident from left side of structure
- All dielectric accelerator
- Single period
- Boundary: perfectly-matched absorbing layer (PMLs)
- Shunt Impedance: $9.98\times10^5\ \Omega/m$

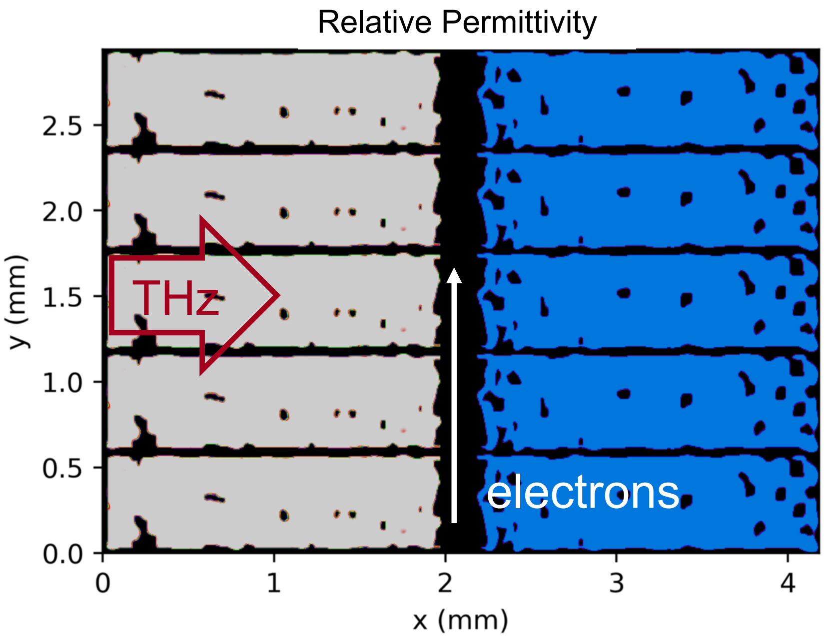


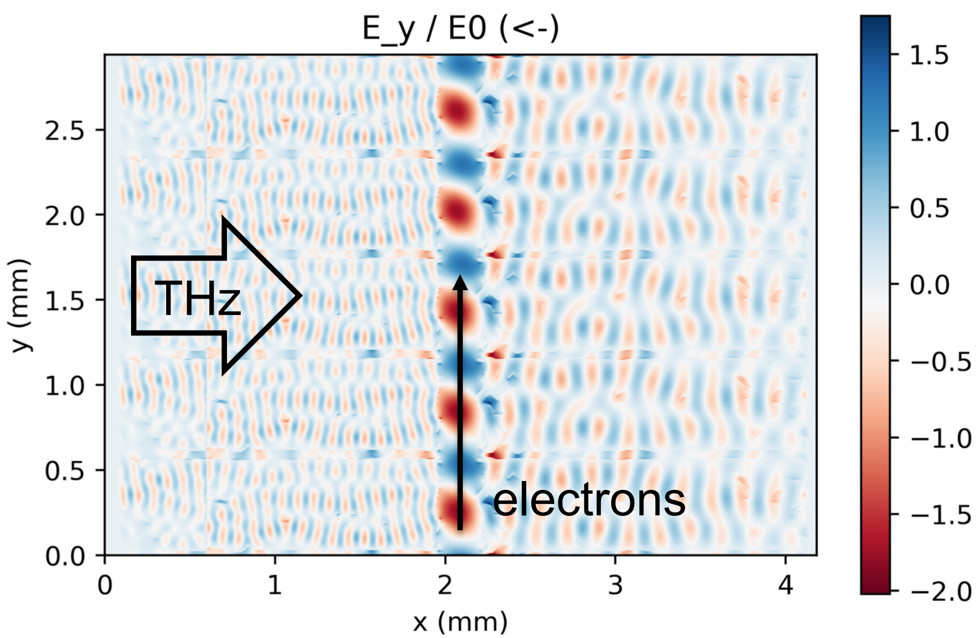
- gray = dielectric, $\varepsilon_r = 9$
- black = vacuum, $\varepsilon_r = 1$



Preliminary Frequency Domain Simulation Results

- 0.5 THz CW incident from left side
- Half lithium niobate half silicon dielectric accelerator structure
- 5 periods
- Boundary: periodic
- Shunt Impedance: $7.15\times10^{7}\ \Omega/\text{m}$

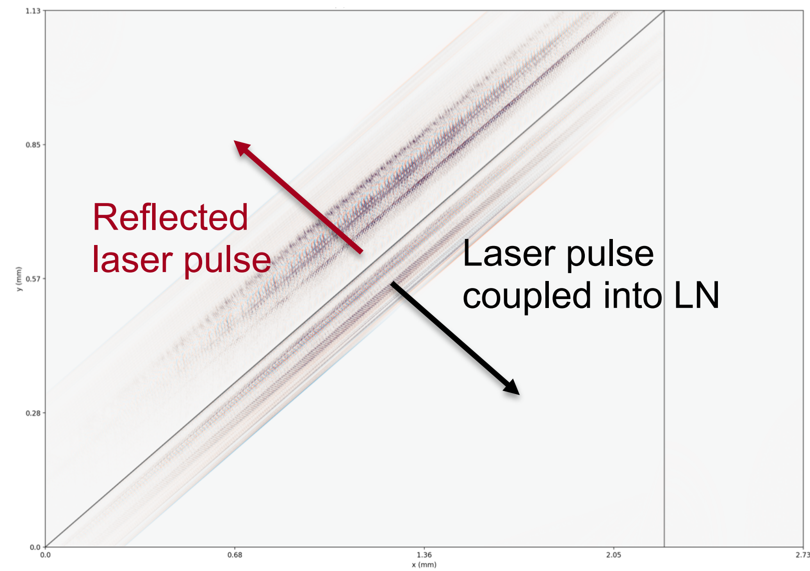


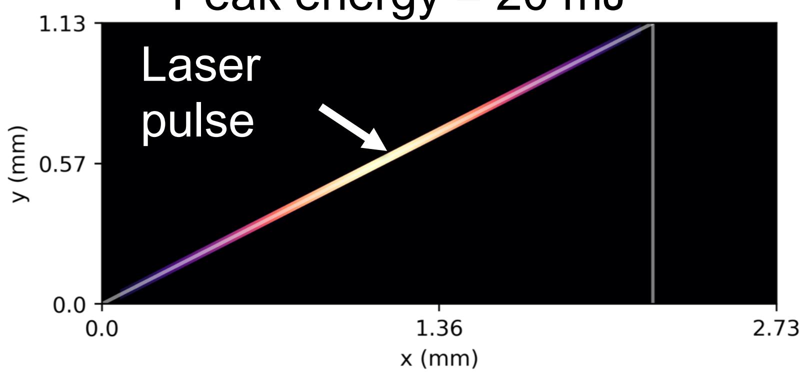


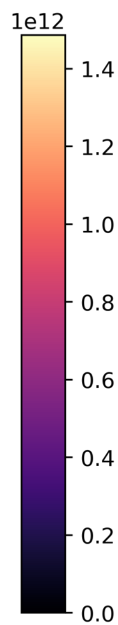
- gray = $LiNbO_3$, $\varepsilon_r = 42.5$
- blue = silicon, $\varepsilon_r = 11.7$
- black = vacuum, $\varepsilon_r = 1.0$

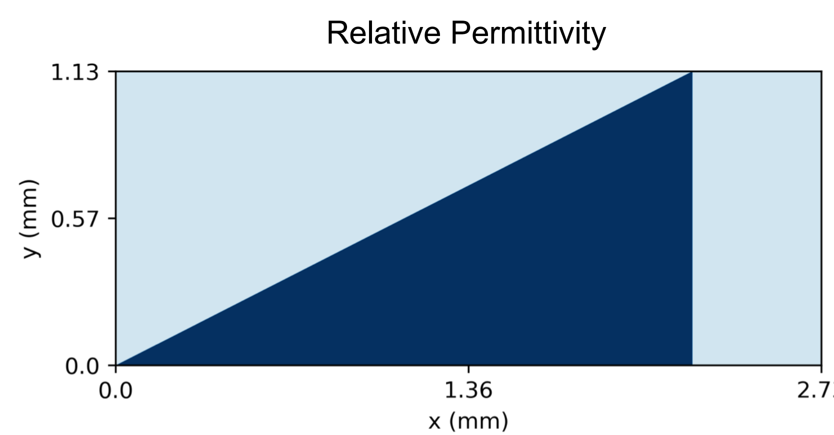
Future Work: Modeling of THz Generation in LN

- Accurate modeling of THz near field will improve and inform dielectric THz accelerator design and optimization
- Time domain simulation, $\lambda/4$ spatial resolution
- t = 9.63×10^{-13} sec
- Laser parameters:
  - $\lambda = 800$nm
  - Time duration = 30 fs
  - Peak energy = 20 mJ









- Dark blue = $LiNbO_3$, $\varepsilon_r = 5.0$
- Light blue = air, ε_r = 1