Spatio-Temporal Structure in Intense Terahertz Pulses

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LINAC 2022 Liverpool (1 September 2022)

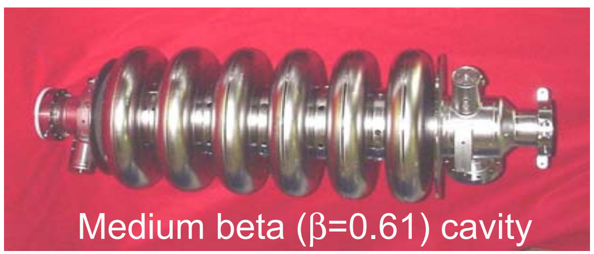
Outline

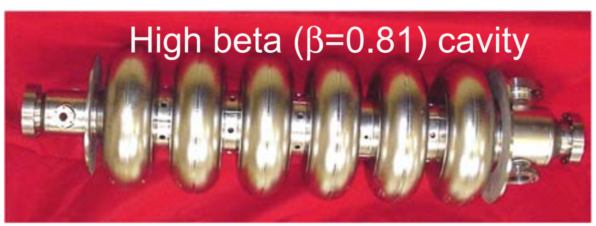
- Processing Superconducting Cavities for High Fields
  - Field Emission
  - Streamlining Field Emission Testing Terahertz Pulses
- Advanced Accelerator Applications of Terahertz Pulses
- Sub-cycle (Ultrabroadband) Terahertz Pulses
  - Generation
  - Conventional Detection
  - Spatiotemporal Detection
- Spatio-Temporal Effects
  - Carrier Phase/Gouy Phase
  - Intrinsic Spatial Chirp
  - A New Regime of Diffraction

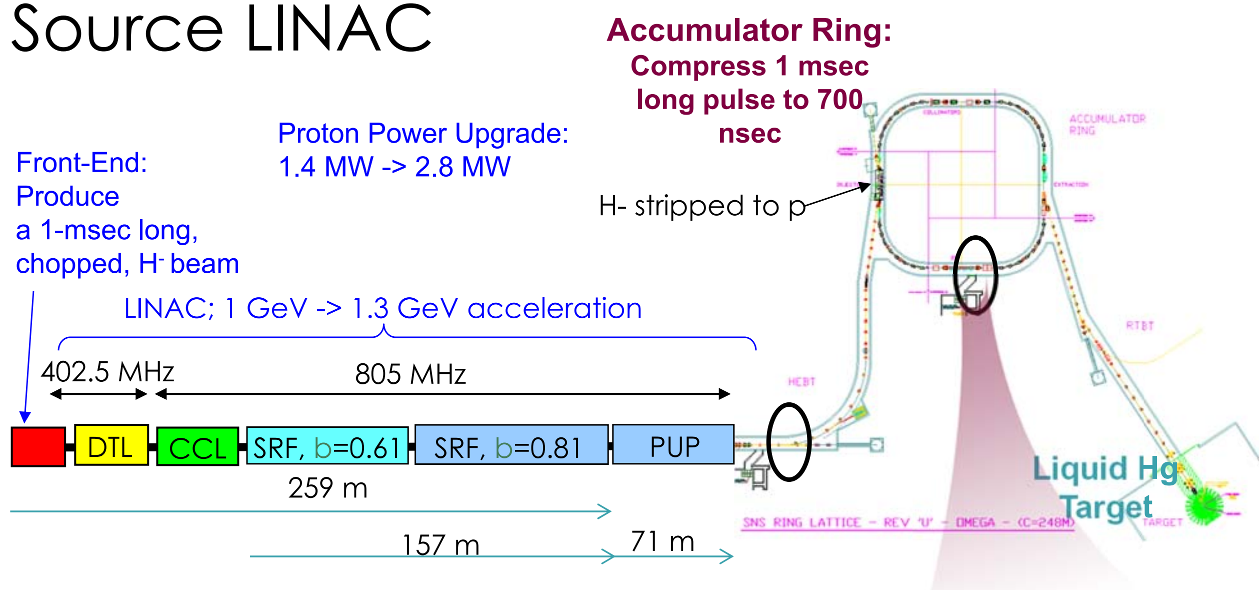
Spallation Neutron Source LINAC

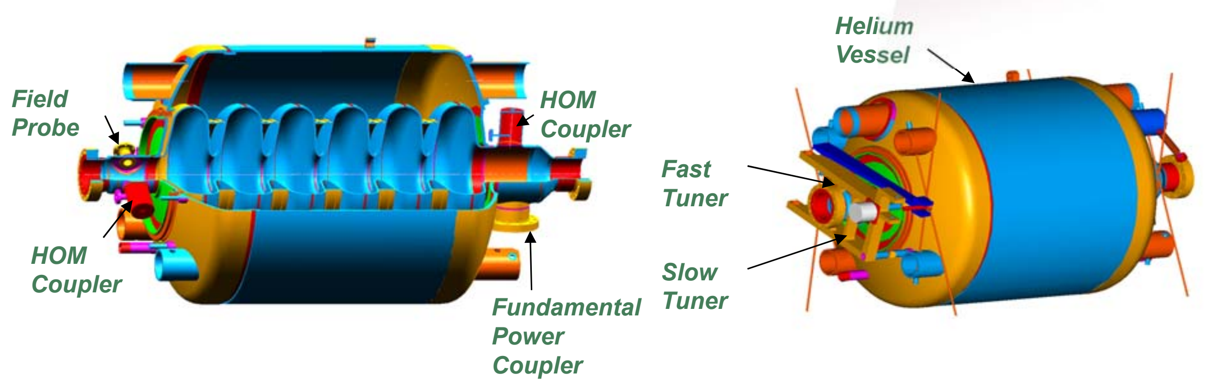
Bulk Ni

E_a=15.8 MV/m at β=0.81
E_a=10.2 MV/m at β=0.61
Q_o> 5e10^9 at 2.1 K


Medium beta (β=0.61) cavity

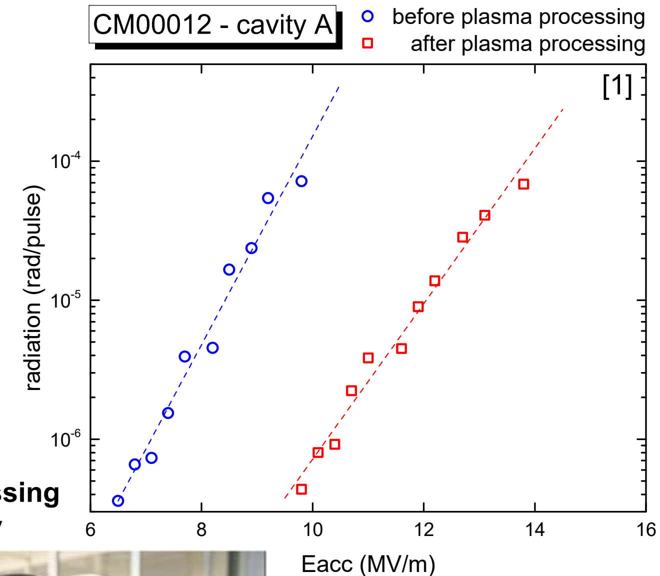

High beta (β=0.81) cavity



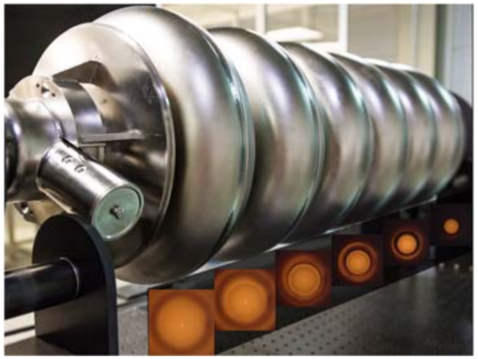


Improving Gradients via Cavity Processing

- High gradients supported by effective cavity processing techniques
- Field emission (FE) from cavity surface one of major limiting factors for accelerating gradient
  - FE electrons cause excessive heating and x-ray radiation
- Plasma cleaning an effective *in situ* technique for reducing field emission



Plasma Processing of a Cavity



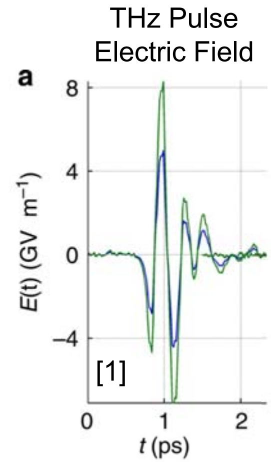
Plasma cleaning improves accelerating field by removing contaminants.

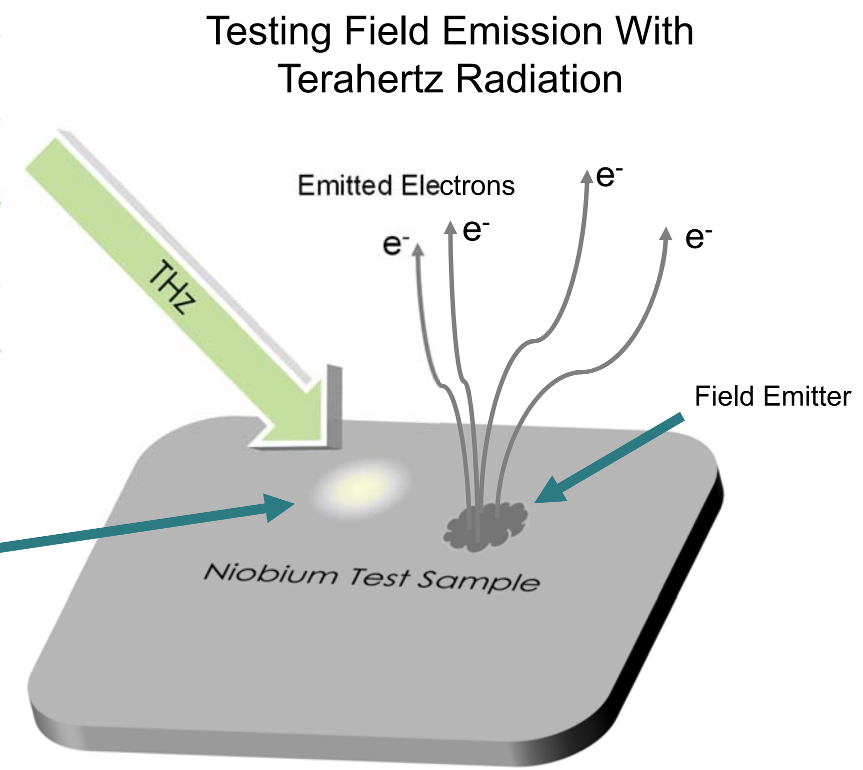
[1] M. Doleans *et al.* In-situ plasma processing to increase the accelerating gradients of superconducting radio-frequency cavities (2016) https://doi.org/10.1016/j.nima.2015.12.043

Terahertz Field Emission Test Stand - Concept

- Few-THz range well-suited for probing on sub-mm scales

- THz sources can achieve extremely high electric field strength (few GV/m)
  - Highest available THz fields are generated using short-pulsed lasers
  - Enough to induce field emission on SRF surfaces

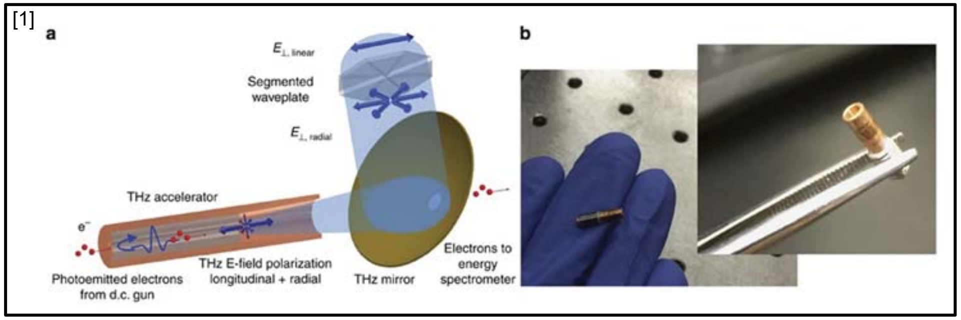




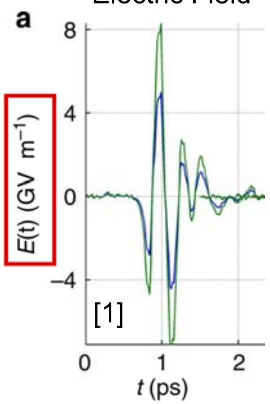
[1] Shalaby, M., Hauri, C. Demonstration of a low-frequency three-dimensional terahertz bullet with extreme brightness. *Nat Commun* **6,** 5976 (2015).

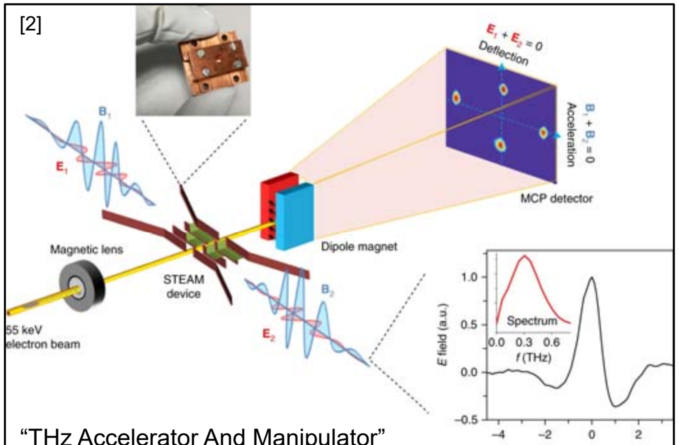
THz-Based Particle Acceleration – Ions/Protons?

- High peak fields an interesting prospect for compact acceleration
  - Sub-picosecond timing with optical pulses
  - Submillimeter length scales
  - Reduced field emission
- Pulsed THz technology undergoing rapid increases in field strength and efficiency
- Optical THz technology is becoming more reliable and accessible
- Little investigation into Ion/proton acceleration – how slow a wave is possible?



THz Pulse Electric Field





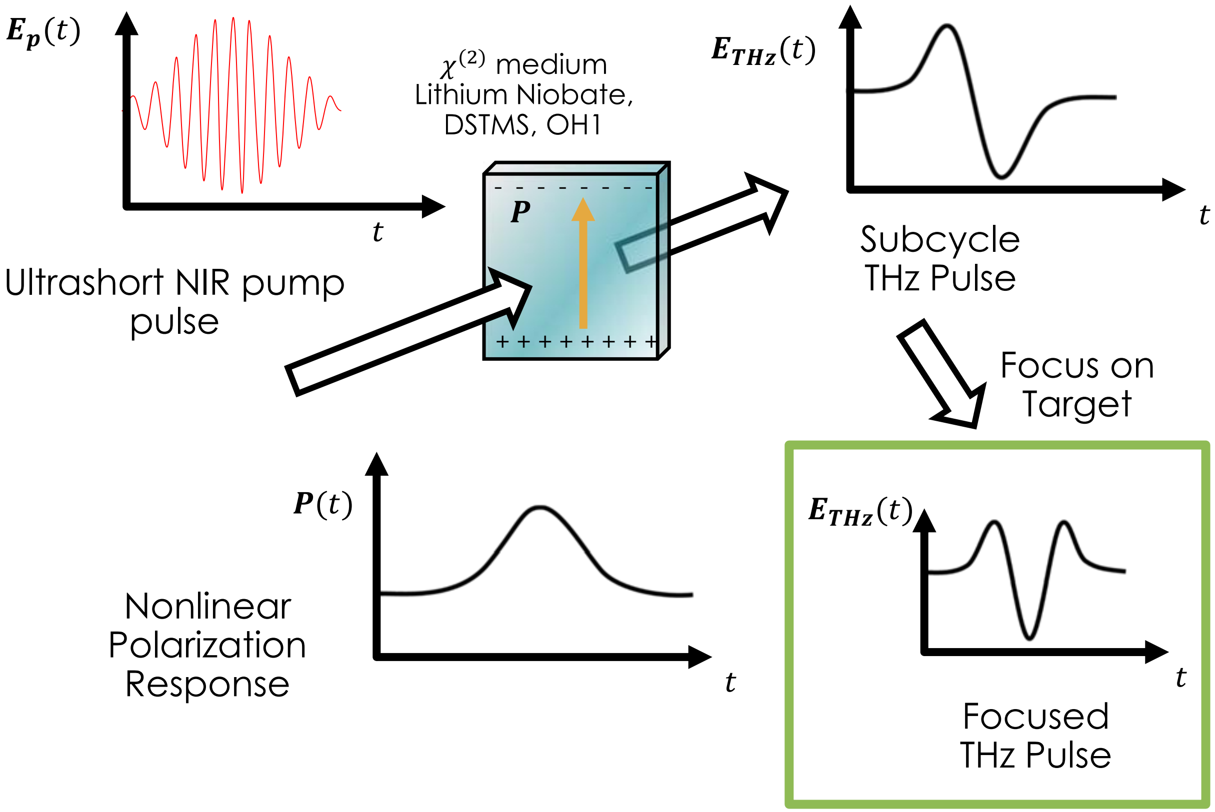
“THz Accelerator And Manipulator”

[1] Emilio A. Nanni et al. Terahertz-driven linear electron acceleration *Nature Communications* **volume 6**, Article number: 8486 (2015)

[2] Zhang, D., Fallahi, A., Hemmer, M. et al. Segmented terahertz electron accelerator and manipulator (STEAM). Nature Photon 12, 336–342 (2018). ISSN 1749-4893

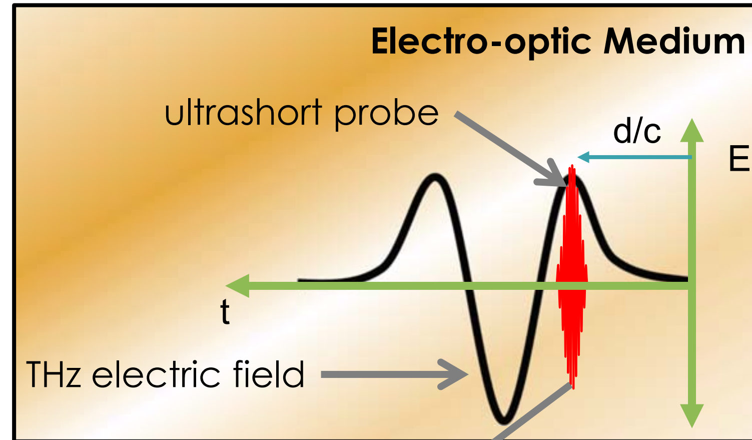
Optical Rectification of Ultrashort Laser Pulses

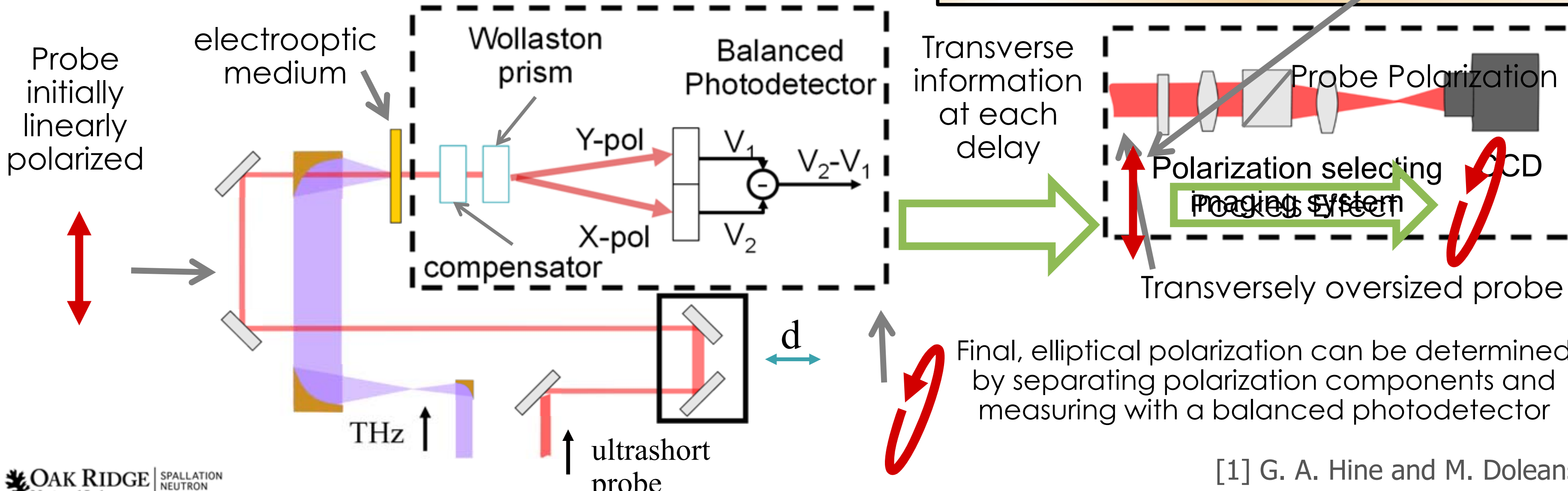
- Nonlinear response of THz generating crystals produces quasi-static polarization
- Polarization locally radiates electromagnetic pulse up to THz frequencies
- Collection of polarization sites acts like phased antenna array, producing directed THz pulsed beam
- THz frequencies can be propagated in free space and focused onto target



2+1D Electro-optic Sampling[1]

- THz electric field changes polarization of ultrashort probe
  - The change in polarization of an ultrashort probe depending on its timing within the THz field

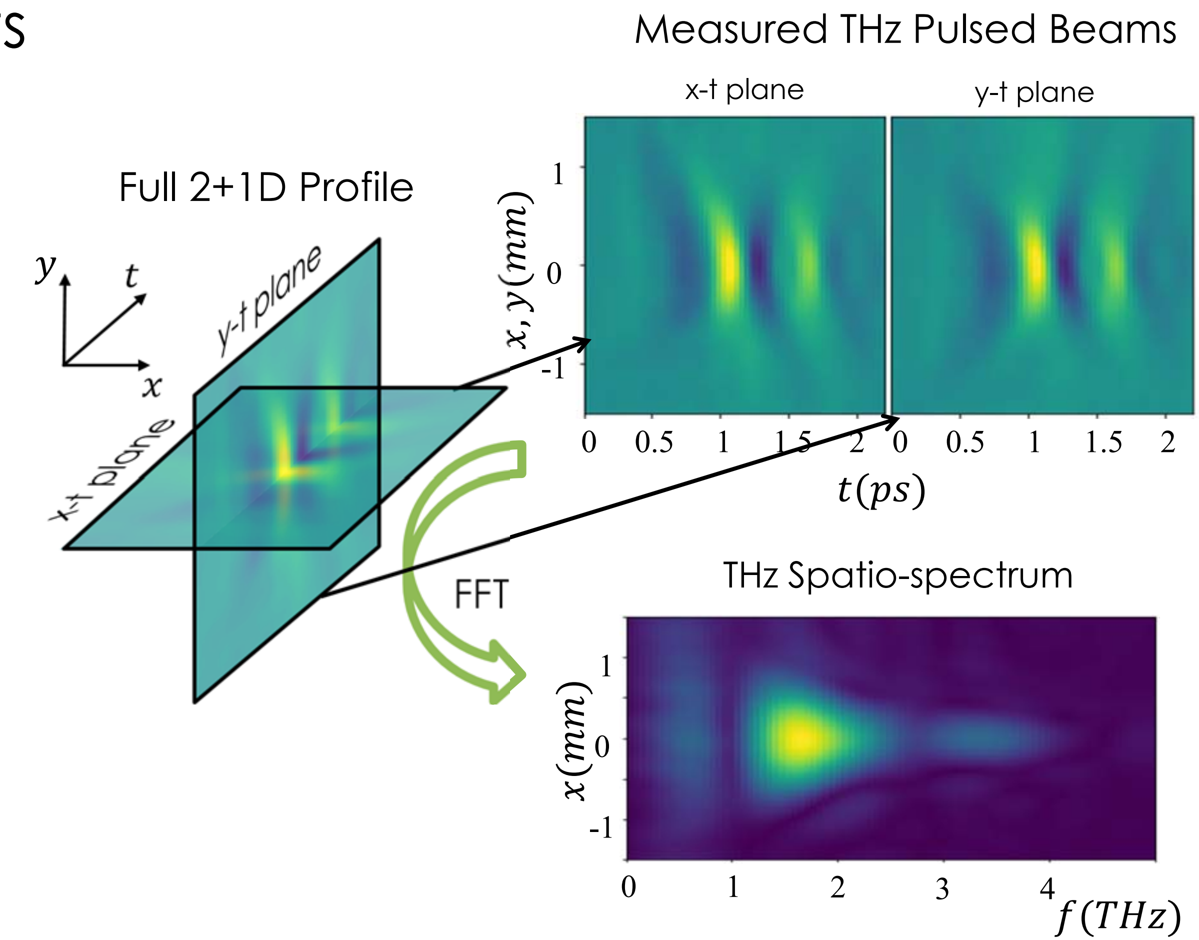




[1] G. A. Hine and M. Doleans
Phys. Rev. A **104**, 032229 – Published 30 September 2021

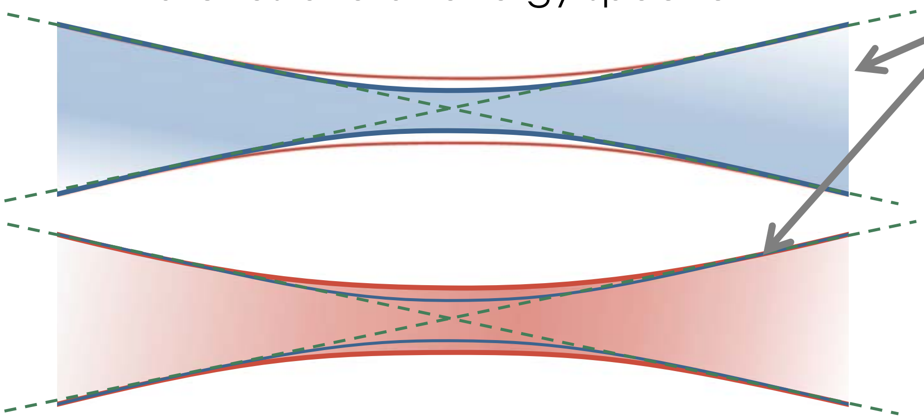
Interpreting Results

- Full spatiotemporal profile has 2-transverse and 1-temporal dimension.
- Transverse slices reveal spatio-temporal/spectral correlations
- Provides a complete characterization of the pulse according to Huygens principle
- Can be easily propagated according to the wave equation

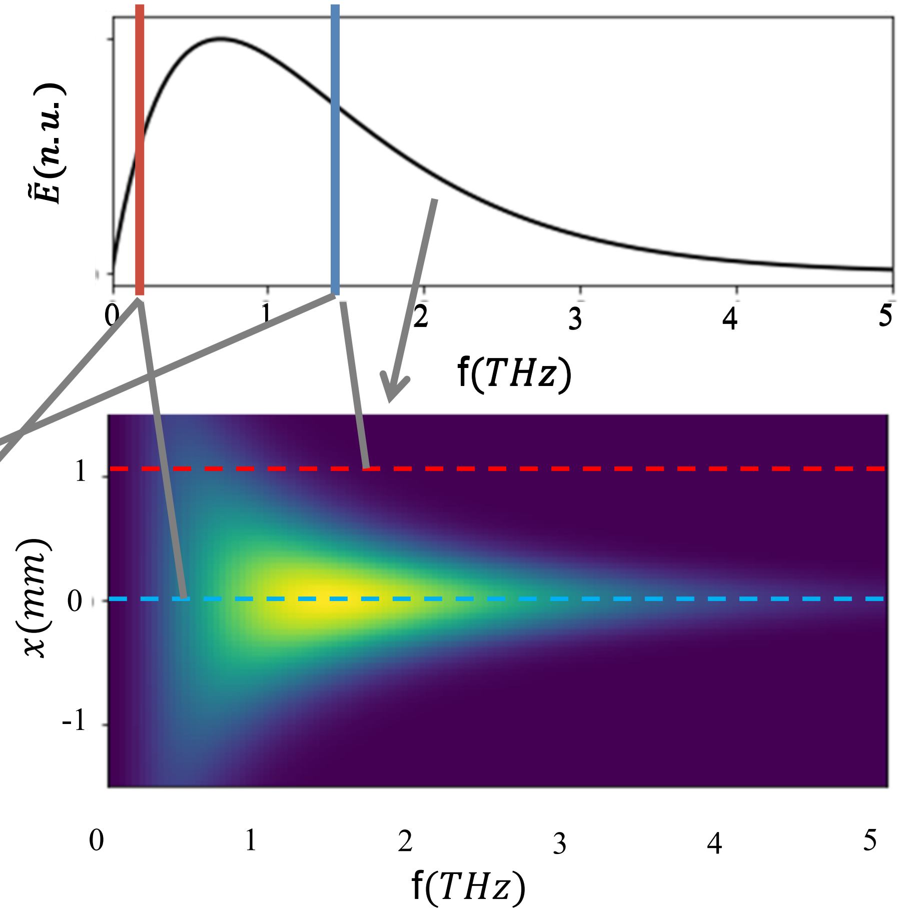


Focusing of Ultrabroadband Light

- Build spatio-spectrum from an (uncorrelated) spectrum
  - Gaussian profiles with flat phase fronts
  - Spot size inversely proportional to frequency
  - Total energy in each frequency matches overall energy spectrum

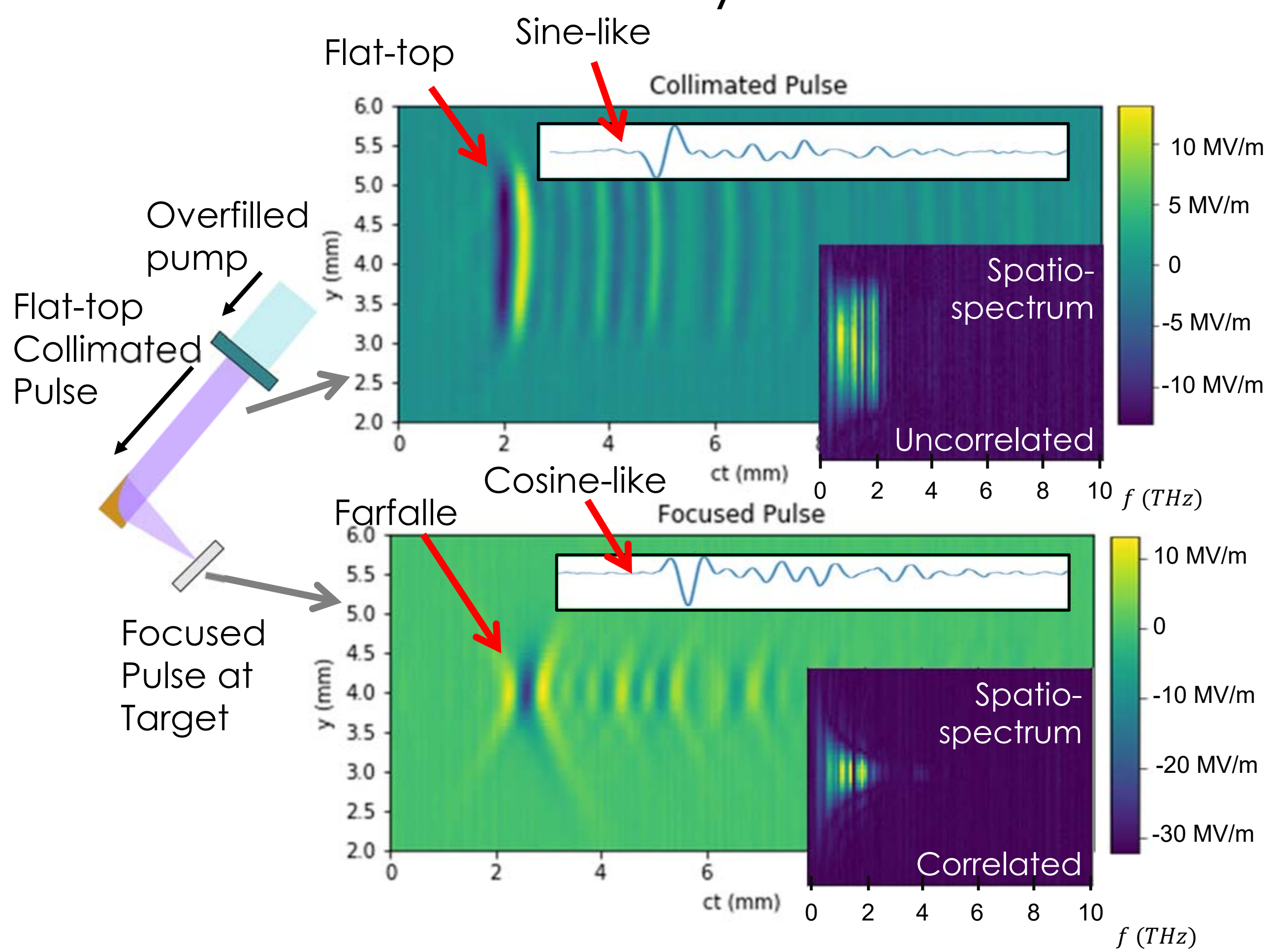


Theoretical Spatio-spectrum

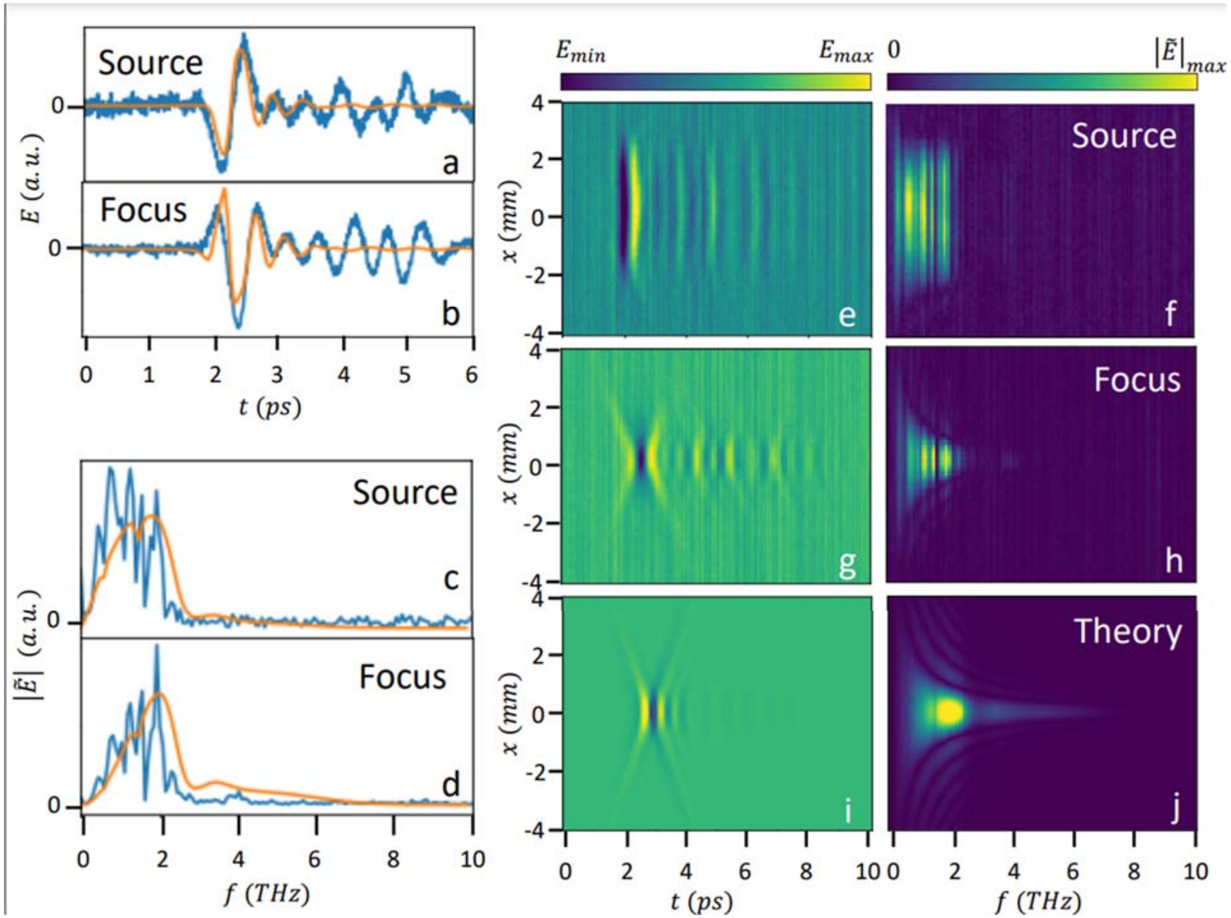


Transformation of an Uncorrelated Sub-cycle Pulse

- Transport of THz pulsed beams complicated by spatio-temporal propagation effects
- Initially uncorrelated pulsed beam develops spatio-temporal correlations when focused or allowed to propagate long distances
- Carrier envelope phase (CEP) sensitive to focusing and transport conditions.
  - Sine-like and cosine-like pulsed beams can be produced

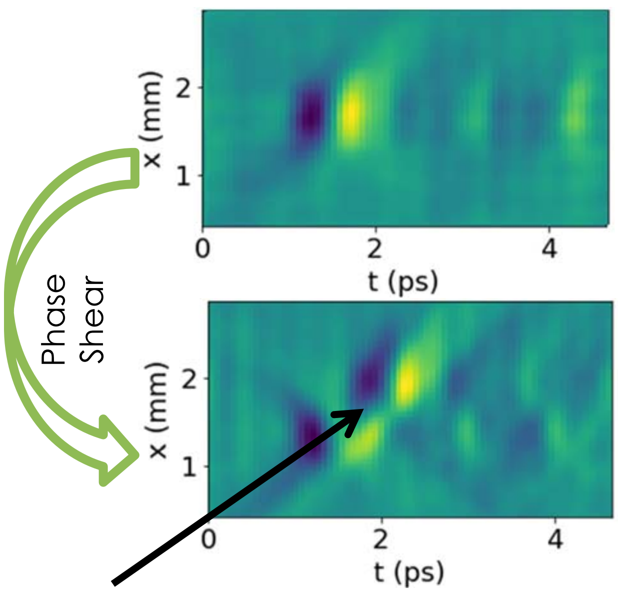


Transformation of an Uncorrelated Sub-cycle Pulse

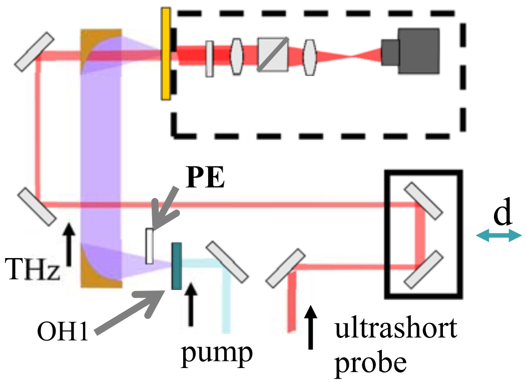


Formation of Optical Vortices from Stepped Optics

- Spatio-temporal effects of refraction – phase shear by group delay



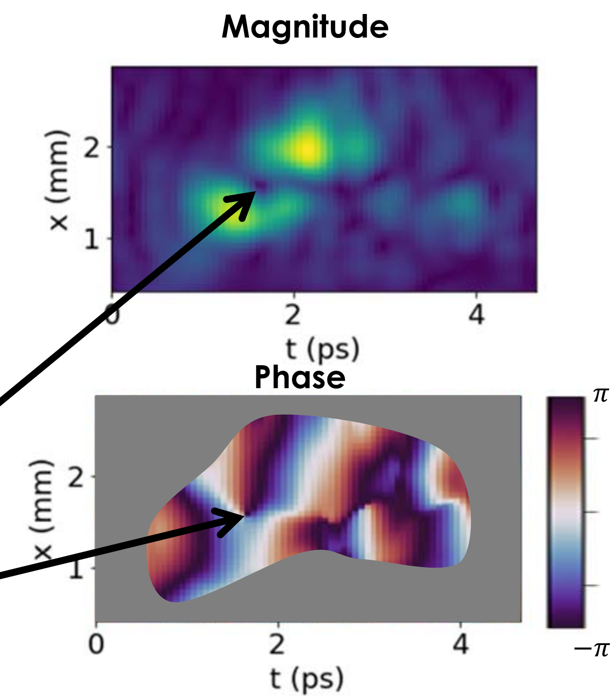
Phase defect?



Analytic Representation

Phase defect

- Stepped optics can cause robust amplitude nulls



Thanks to the team

Superconducting RF at SNS

Sang-Ho Kim/Marc Doleans

Rong-Li Geng
Ralf Afanador
Debra Barnhart
Steve Gold
John Mammosser
Paolo Pizzol
Danny Vandygriff

Former Undergraduates

Victor Suarez: Georgia Tech

Elaina Truhart: U. of Cincinnati

Summary/Questions

- THz pulses with large electric fields could have various applications for current and future accelerator technology
- Subcycle (ultrabroadband) terahertz pulses exhibit complex and sometimes exotic behavior even with ordinary circumstances
- Spatiotemporal measurements of THz pulses are a powerful characterization tool, providing significantly more complete information than conventional (temporal) methods