



Single Pass High Efficiency THz FEL

A. Fisher¹, Y. Park¹, M. Lenz¹, A. Ody¹, R. Agustsson², T. Hodgetts²,
A. Murokh², and P. Musumeci¹

¹UCLA Department of Physics, Los Angeles, CA

²RadiaBeam Technologies, Santa Monica, CA

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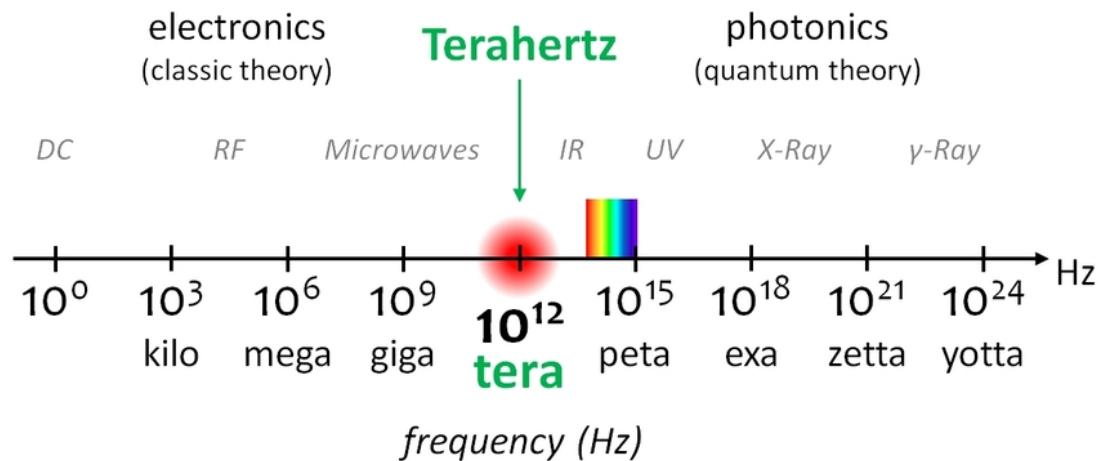
NAPAC
2022

Outline

- THz sources and FIR-FELs
- Waveguide “zero-slipage” condition
- Experiment design
- Beam and THz measurements
- Current work
- Summary

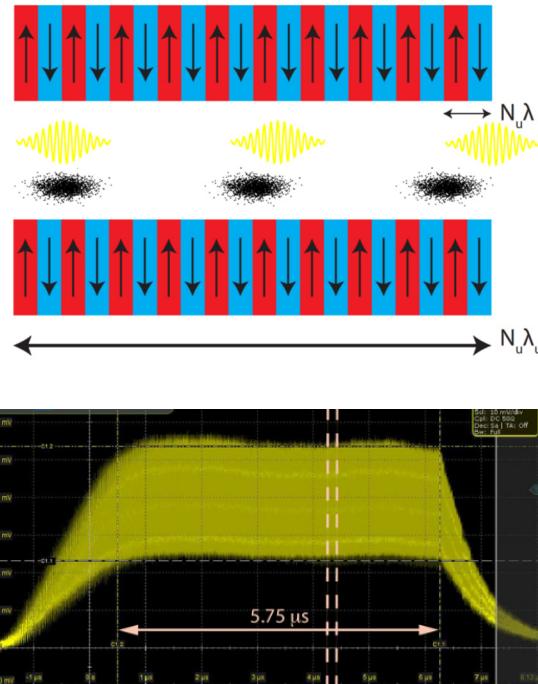
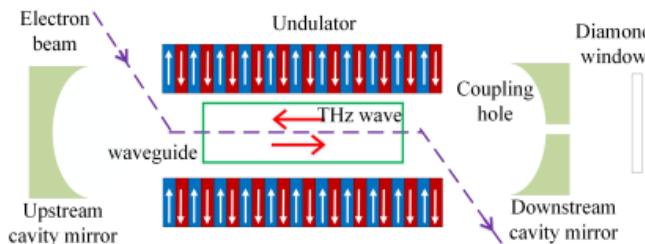
THz Gap

- Wide variety of applications
 - Time domain spectroscopy
 - Material science
 - Medical and security imaging
 - Communications
- Sources
 - Gyrotrons
 - Quantum cascade lasers
 - Laser-based sources
 - **Accelerator-based sources**



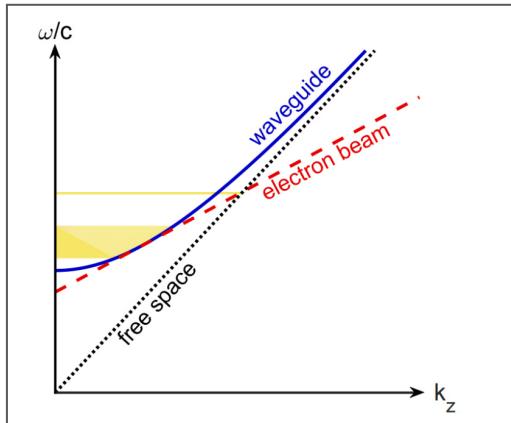
FIR-FELs

- FEL Resonance
 - $\lambda = \frac{\lambda_u}{2\gamma^2} (1 + K_{rms}^2)$
- Gain limited by slippage and diffraction
 - Low peak power
 - Narrow bandwidth
- Oscillators
 - Outcoupling
 - Electron sources



Waveguide “zero-slipage”

- Match radiation group velocity to average e-beam velocity
- No limitations on bunch length
 - Increase beam current
 - Using bunching factor to seed interaction

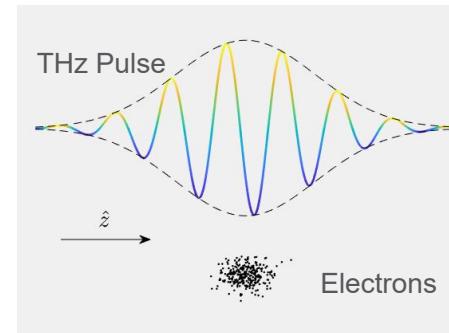


Constraints

$$\text{Waveguide: } \frac{\omega^2}{c^2} = k_z^2 + k_{\perp}^2$$

$$\text{FEL phase resonance: } k_z + k_u = \frac{\omega}{c\beta_z}$$

$$\text{Zero-slipage: } c\beta_z = c^2 \frac{k_z}{\omega} = v_g$$

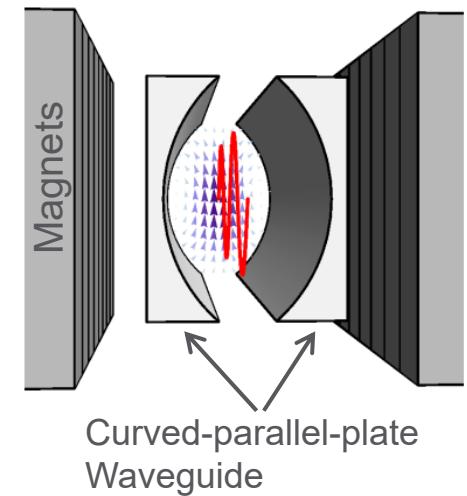
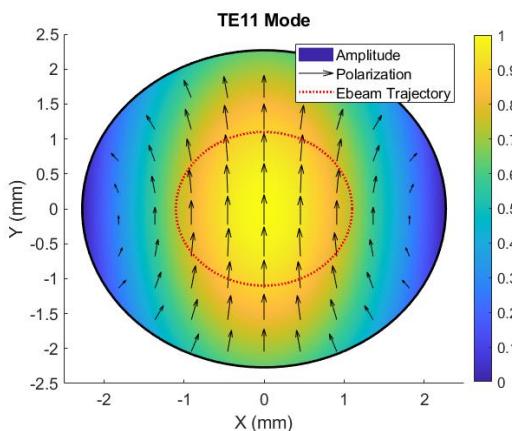


Consequences

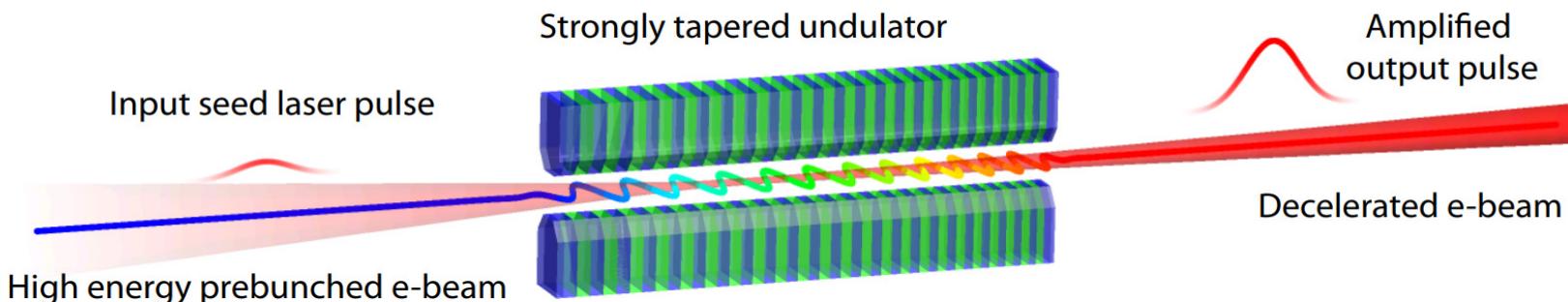
- Frequency tunability
 - Planar and helical geometries
- E-beam trajectory
 - $\frac{r_{traj}}{R} = \frac{1}{1.8412} \frac{K}{\sqrt{1+K^2}} \leq 0.54$
- Field Tuning
 - $r_{traj} = 1.1 \text{ mm}$, gap $\approx 7 \text{ mm}$
 - Mode amplitude

Meter-Scale Terahertz-Driven Acceleration of a Relativistic Beam

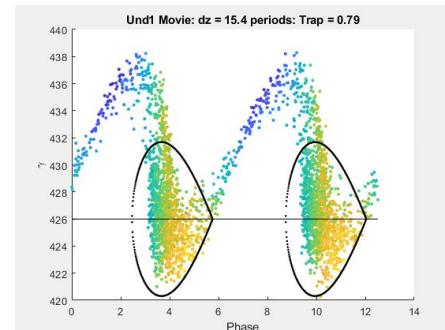
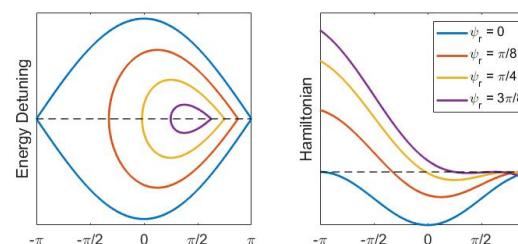
E. Curry, S. Fabbri, J. Maxson, P. Musumeci, and A. Gover
Phys. Rev. Lett. **120**, 094801 – Published 28 February 2018



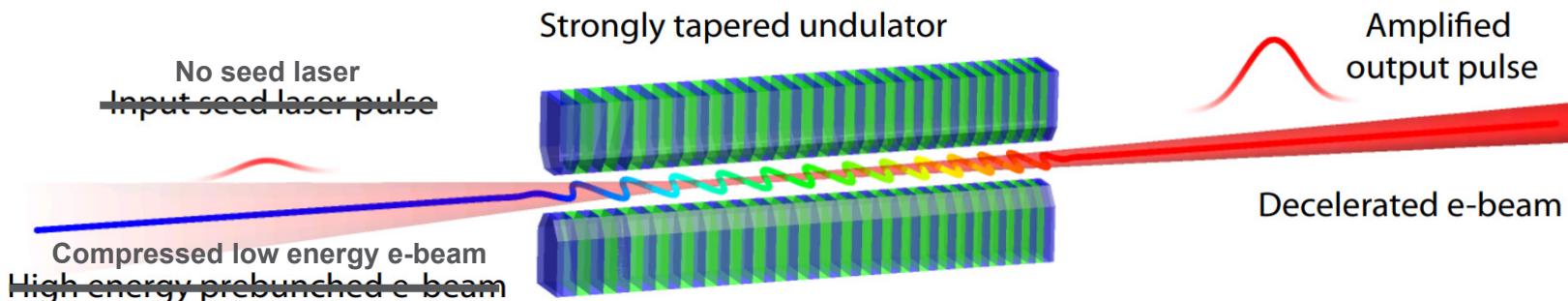
Tapering Enhanced Stimulated Superradiant Amplification (TESSA)



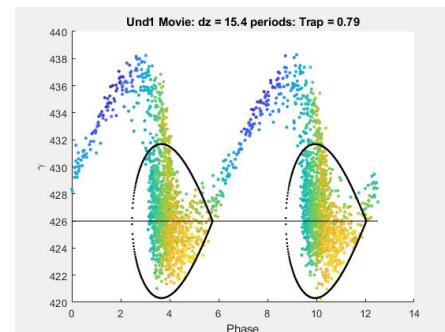
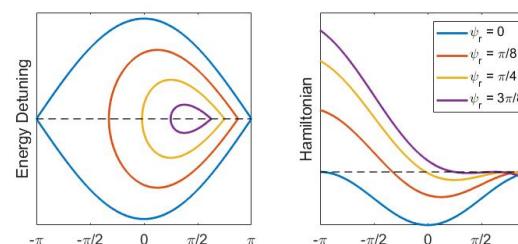
- Taper undulator to maintain high gradient deceleration past saturation
 - J Duris *et al* 2015 *New J. Phys.* **17** 063036
 - Cannot vary period and maintain zero-slipage
- FASTGREENS experiment
 - Target 10% efficiency at 515 nm



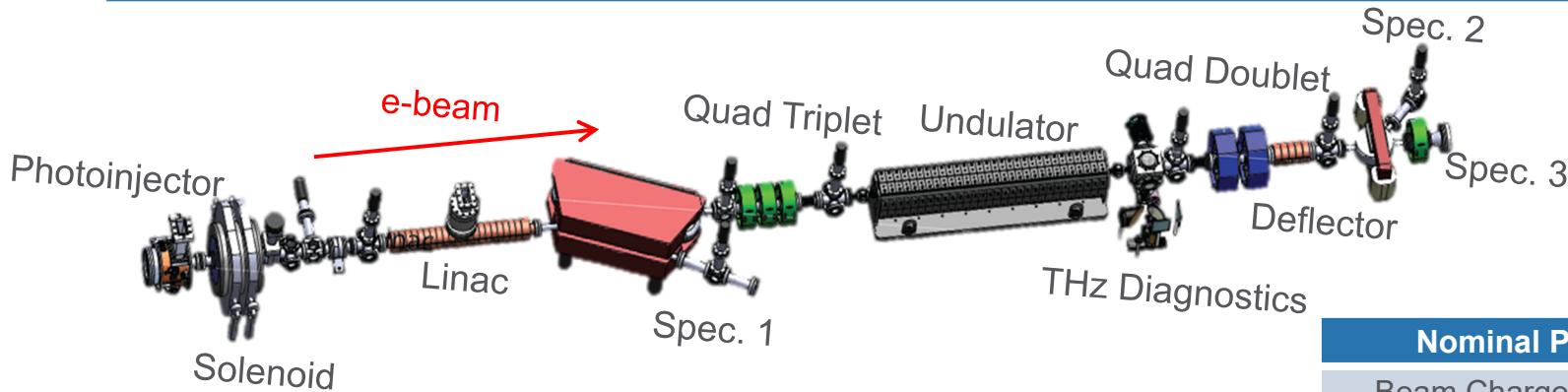
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Pegasus Beamlime (UCLA)

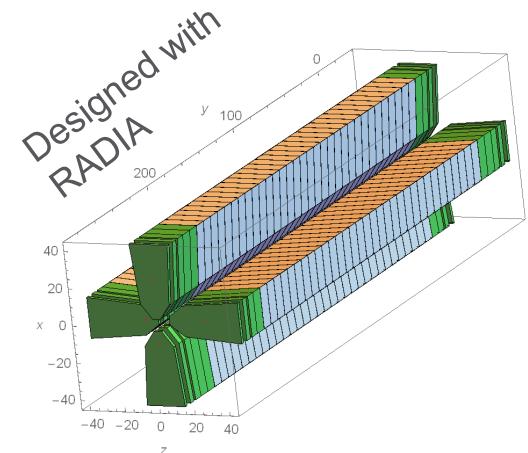
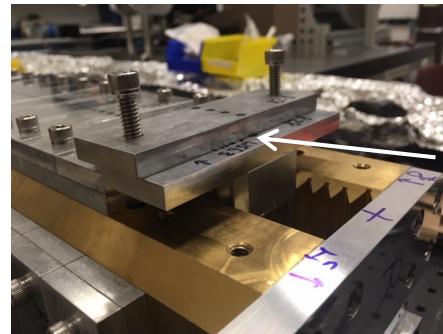
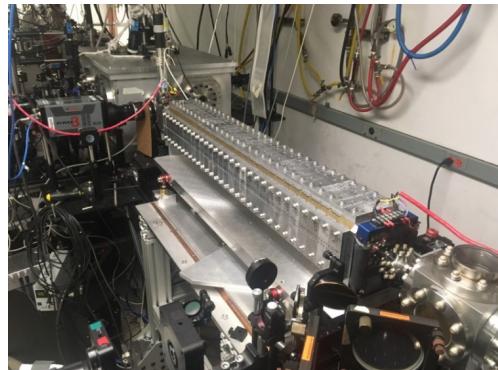


- Spec. 2 and Spec. 3 are high and low resolution, respectively
- Undulator vacuum pipe doubles as waveguide
- Advanced photocathodes, laser shaping

Nominal Parameters	
Beam Charge	200 pC
Norm. Emittance	2 mm-mrad
Beam Energy	5.5 MeV
Undulator Field	0.73 T
Undulator Period	3.2 cm
Waveguide Radius	2.27 mm
Frequency	160 GHz

THESEUS Undulator design

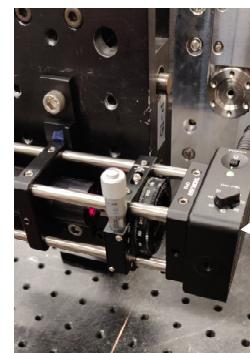
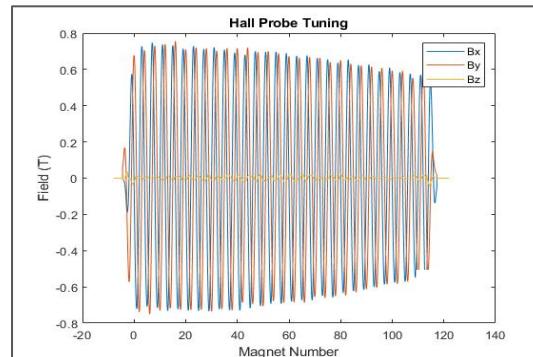
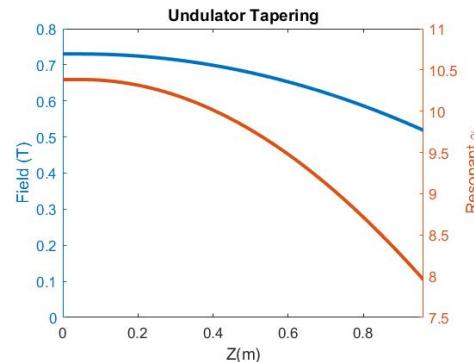
- Commissioned for TESSA Experiment
- Helical geometry composed of two permanent magnet Halbach arrays
- 28 full periods
- Individual magnet tuning capability



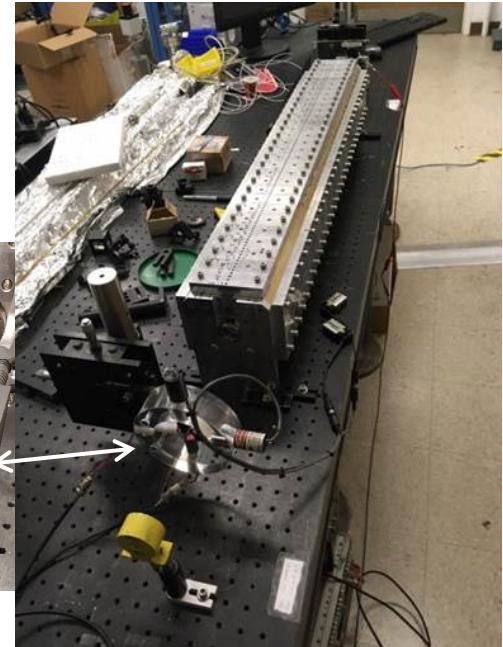
Tuning
screws

Undulator Tuning

- Measured fields with 3-axis Hall Probe
- Straightened trajectory in entrance/exit periods with pulsed-wire measurements
 - Performed wire-scans off-axis
- Recently improved pulsed-wire sensitivity with new design
 - 50um slit to block excess laser
 - Si Amplified Detector
 - Oil dampers



Redesigned
laser-diode pair



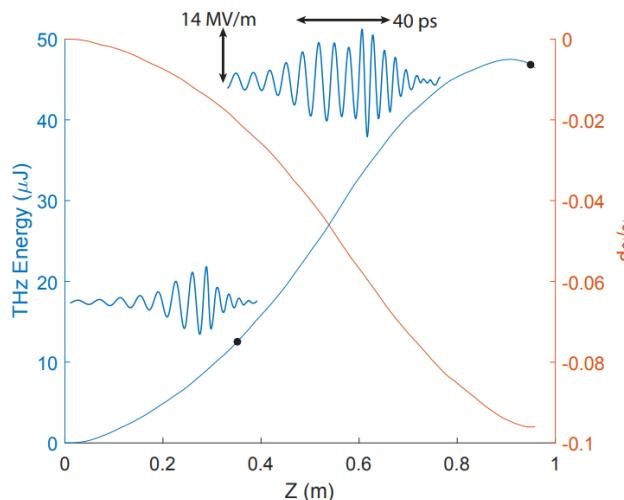
Pulsed-wire setup - 2020

Tapering Design

- FEL interaction simulated with GPTFEL, a custom element extension for GPT code.
 - Frequency domain
 - Simulates free space and waveguide modes
- Utilize GPT functionality
 - Space charge (Long. and transverse)
 - CSR calculations
 - Interface with photoinjector/beam transport
 - **Start-to-end with single code**
- Design Tapering
 - No effect from higher order modes
 - Decelerate resonant electrons >20%

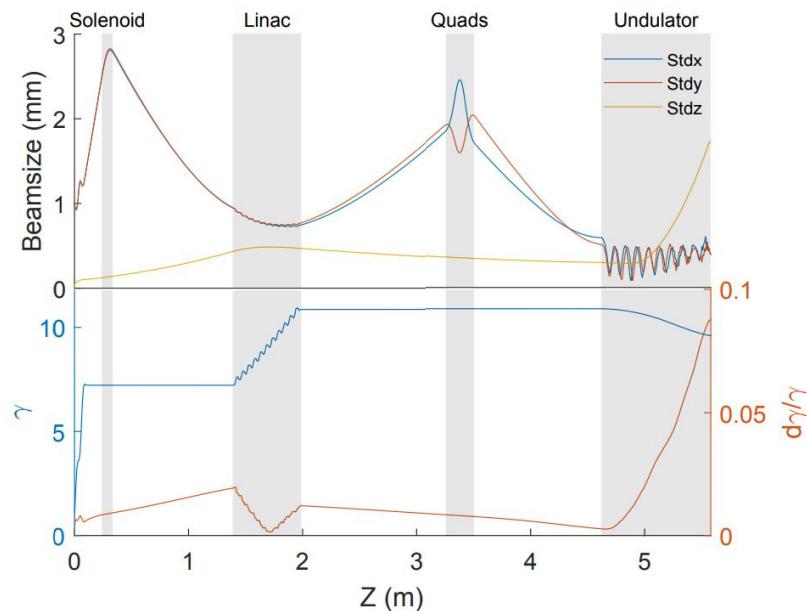
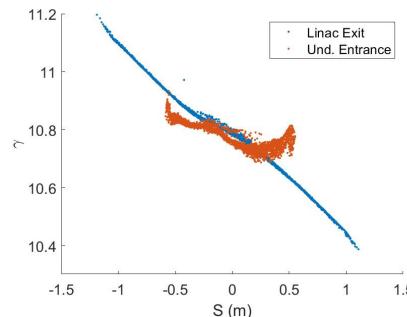
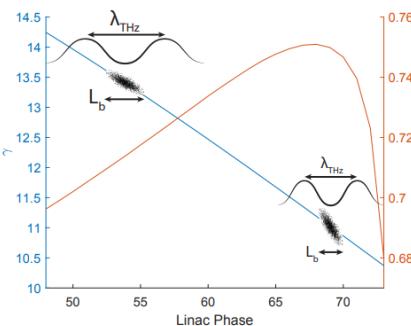
Self-consistent numerical approach to track particles in free electron laser interaction with electromagnetic field modes
A. Fisher, P. Musumeci, and S. B. Van der Geer
Phys. Rev. Accel. Beams **23**, 110702 – Published 12 November 2020

GPTFEL



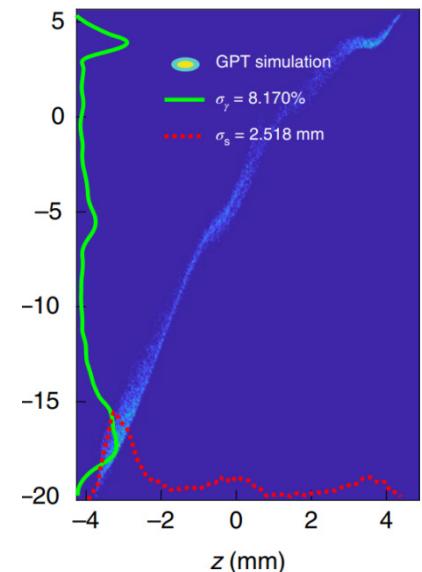
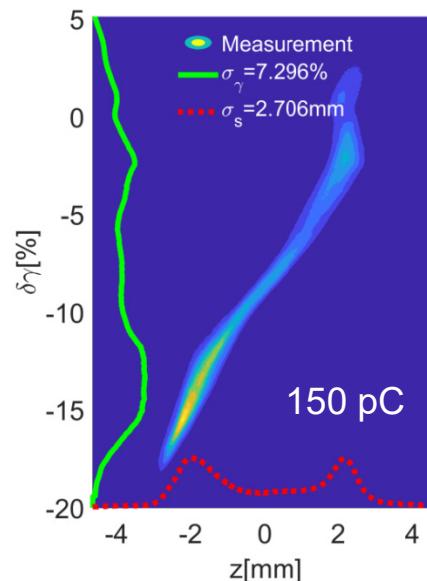
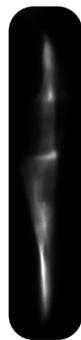
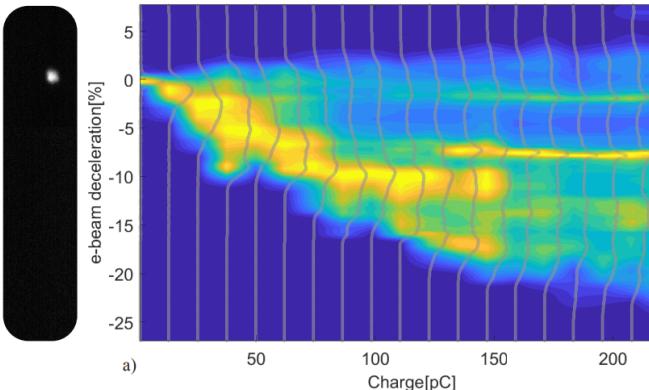
Seeding the Interaction

- Accelerate and compress with linac
 - Limited by maximum accelerating gradient
 - Bunching factor varies little with energy
- Match beam into undulator with quad triplet
 - Strong space charge
 - Minimum separation limited by beamline real-estate



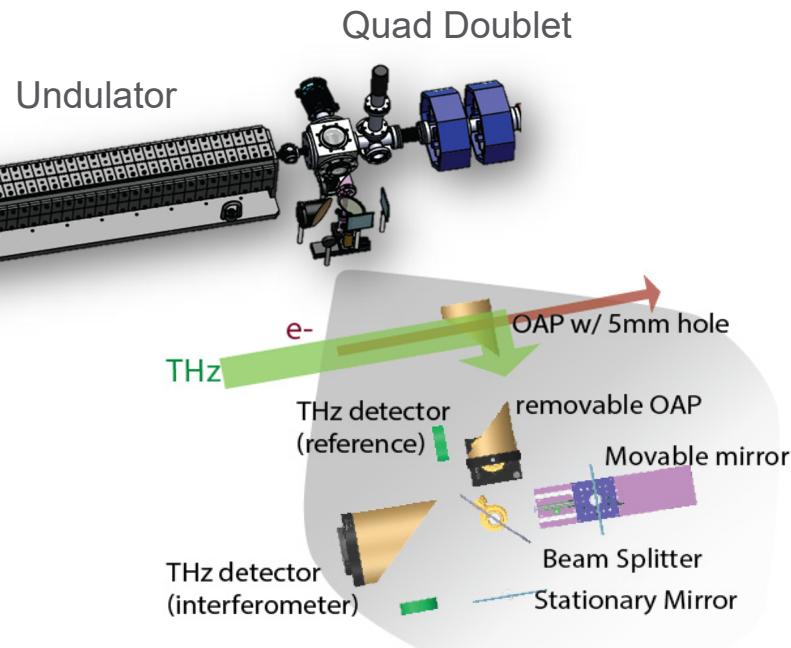
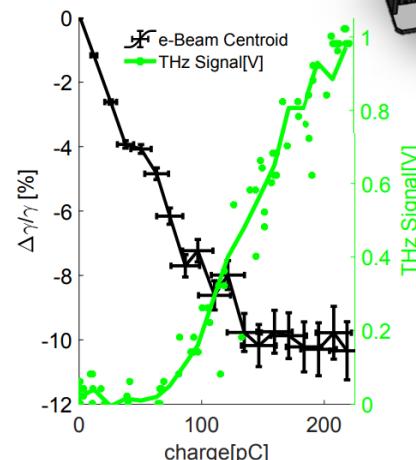
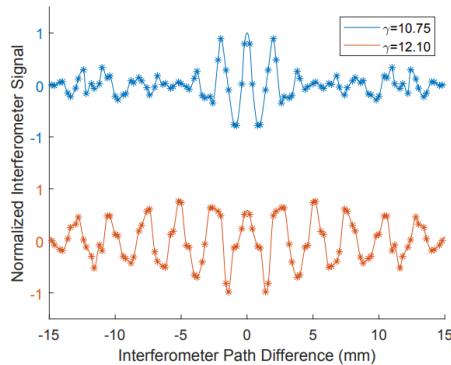
Spectrometer Measurements

- Establish FEL interaction
 - Charge scan showing maximum 10% efficiency
 - Energy undulations
- Streaking with deflector
 - Single LPS ponderomotive bucket
- Limited Charge Transmission



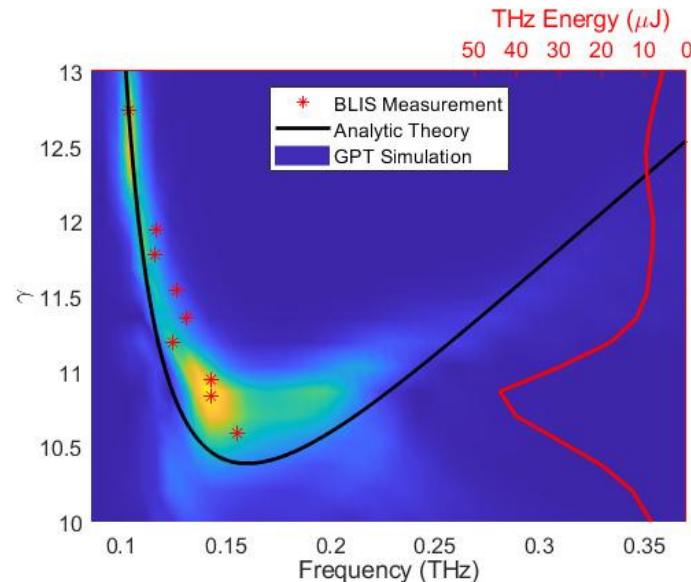
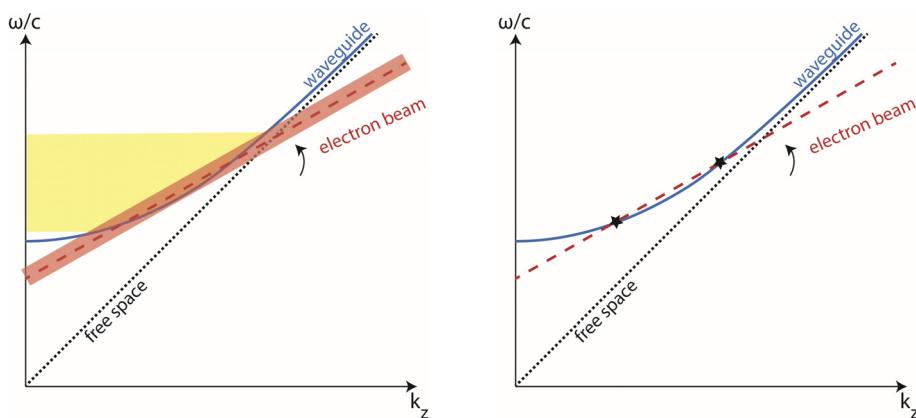
THz Diagnostics

- THz Diagnostics
 - Able to measure total energy and spectrum
- Energy measurement consistent with spectrometer data
- THz losses



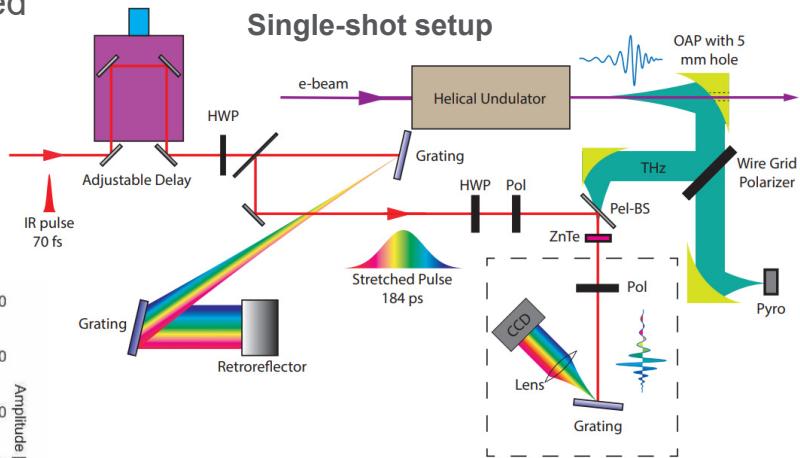
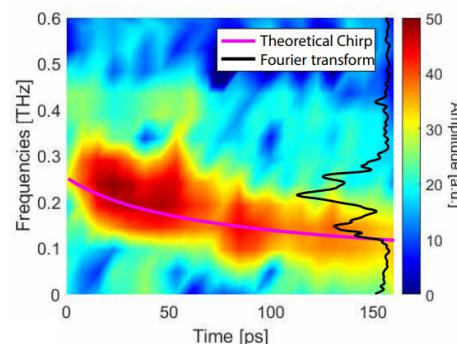
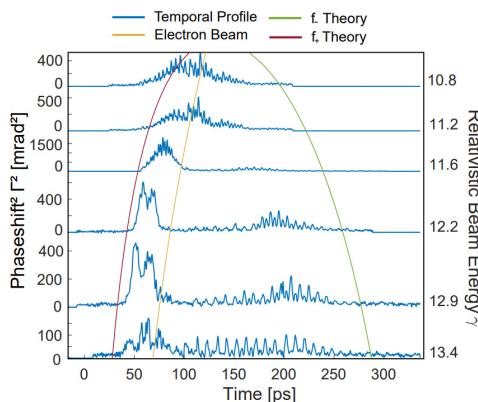
Energy Resonance

- As energy **increases**, frequency **decreases**
- Energy detuning
 - Energy spread and transverse emittance



Electro-optic Sampling (EOS)

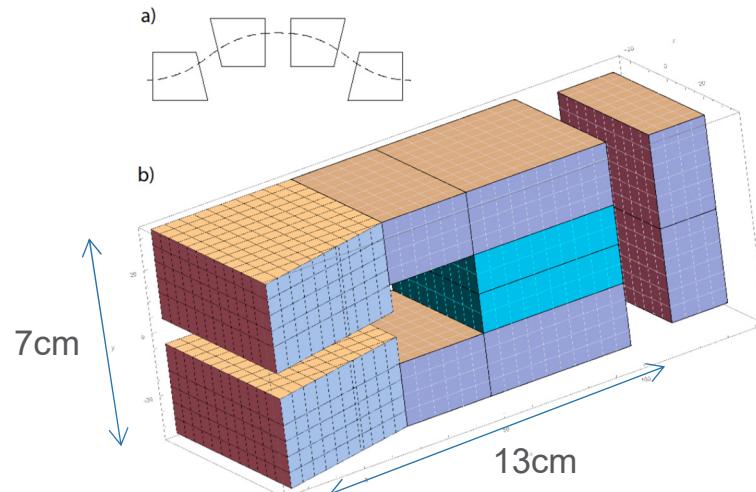
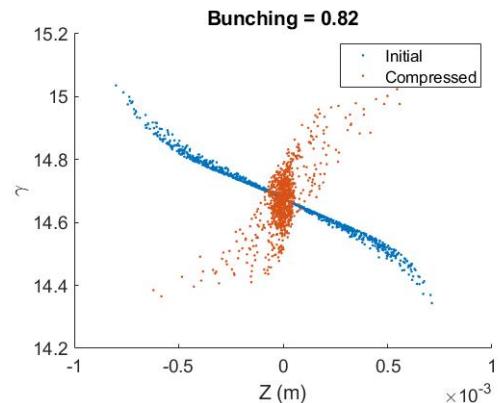
- Utilizes crystal birefringence induced by an applied electric field.
- Measure pulse in time domain
 - Multi-shot with short IR pulse
 - Single-shot with stretched IR pulse



Looking forward: Targeting Higher Frequencies

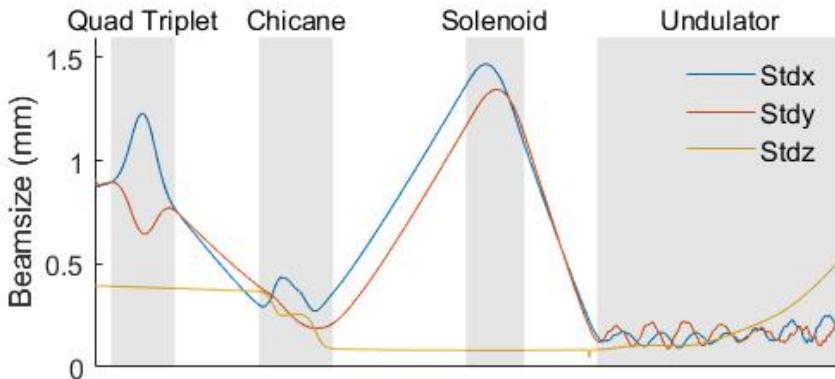
- Experiment to target 330 GHz
 - Less charge required
 - Beam closer to axis
- Beam compression with permanent magnet chicane
 - Strong transverse beam focusing
 - Iron shunt to adjust peak field

Chicane Parameters	
Gap	8 mm
Field	270 mT
θ_{bend}	30 deg.
R_{56}	0.05 m
Drifts	3 cm
Total Length	29 cm



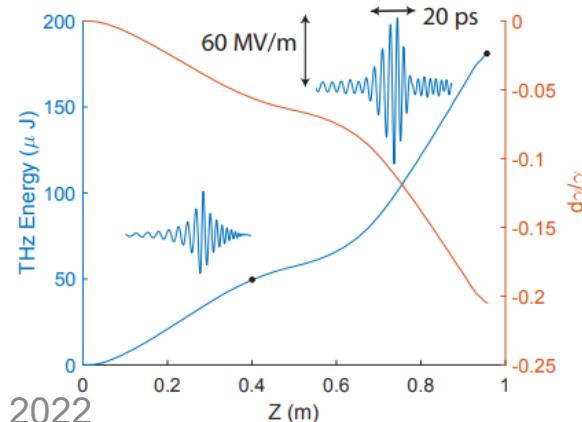
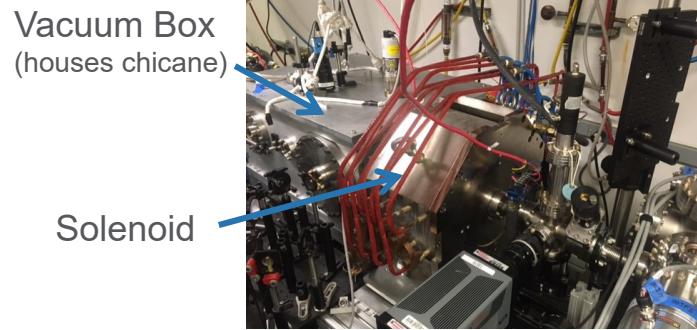
Looking forward: Beam Transport

- Added solenoid to beamline
 - Can match strongly divergent beam from chicane into undulator
 - Symmetrize beam with quad triplet



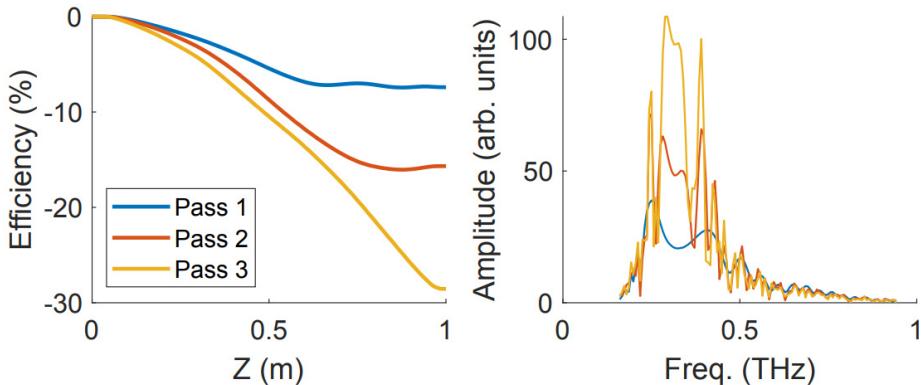
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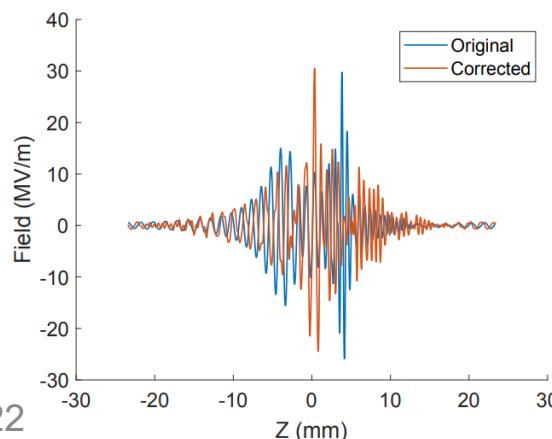
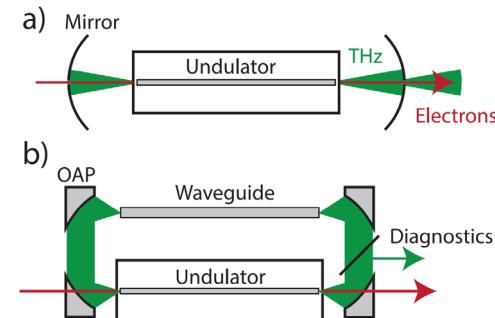
Looking forward: Recirculation

- Seed successive passes with produced THz
 - Extend frequency range of waveguide FEL
- Method for dispersion correction
 - Increase peak field



afisher000@g.ucla.edu

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Summary

- Achieve large efficiency with waveguide “zero-slipage” and strong undulator tapering
- Start to end with single code
- Experiment results show high (10%) efficiency as well as frequency branching and energy detuning
- Follow up experiment at 330 GHz with improved beam transport and compression.



Cover Artwork: Youna Park

Thank you for your attention!

- RadiaBeam Technologies
- Work supported by NSF grant PHY-1734215 and DOE grants DE-SC0009914 and DE-SC0021190
- Undulator construction funded by SBIR/STTR DE-SC0017102 and DE-SC0018559

