Terahertz diagnostic tool for sub-relativistic electron beams

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Why use terahertz radiation for electron beam diagnostic?

Advantages of THz Technology

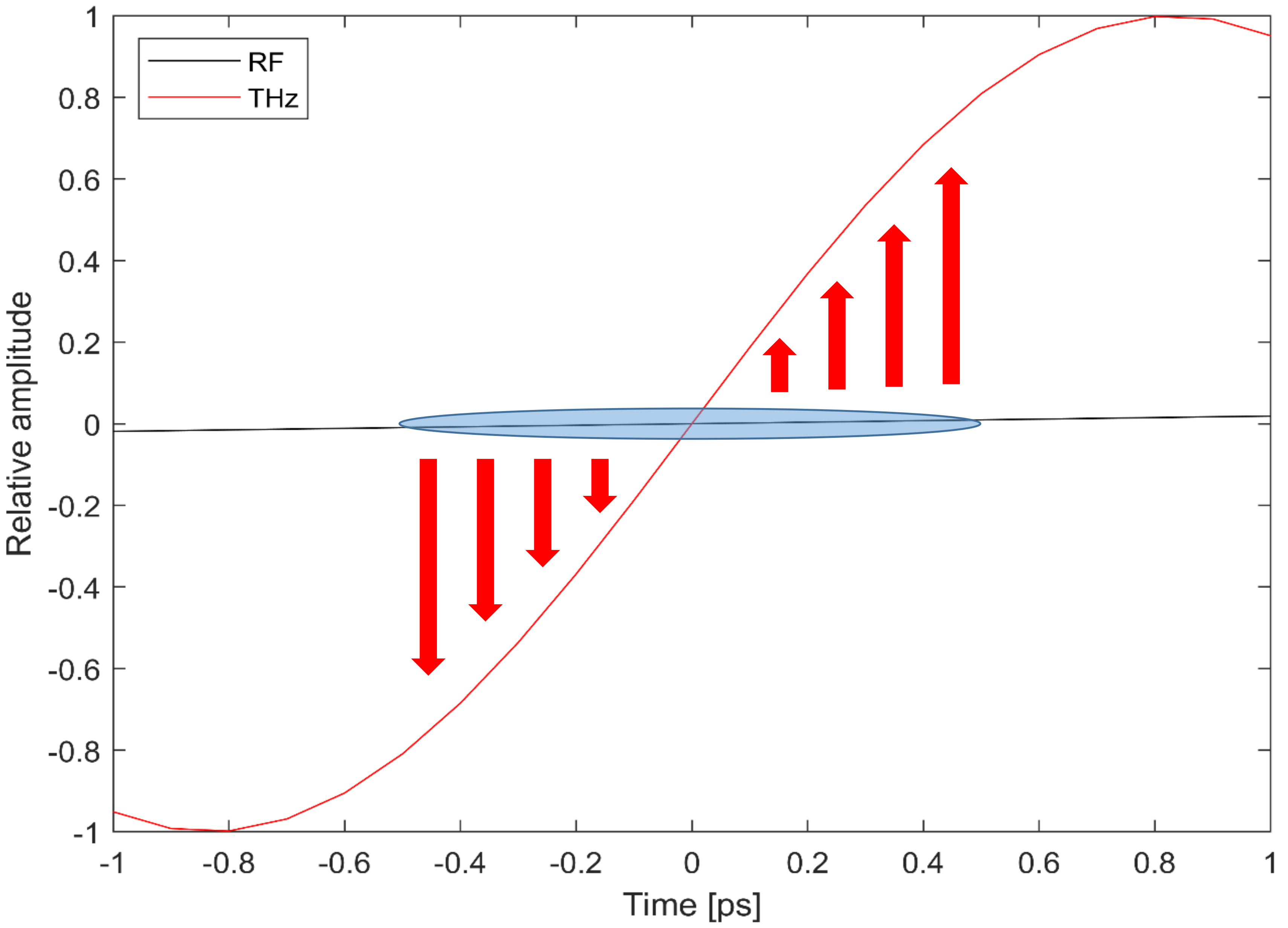
- Oscillation period well-matched to typical bunch duration allowing for fs resolution electron bunch diagnostics
- Inherent timing synchronisation and reduced timing system complexity
- High field strengths possible (100 MV/m to >GV/m)

Radio Frequency Limitations

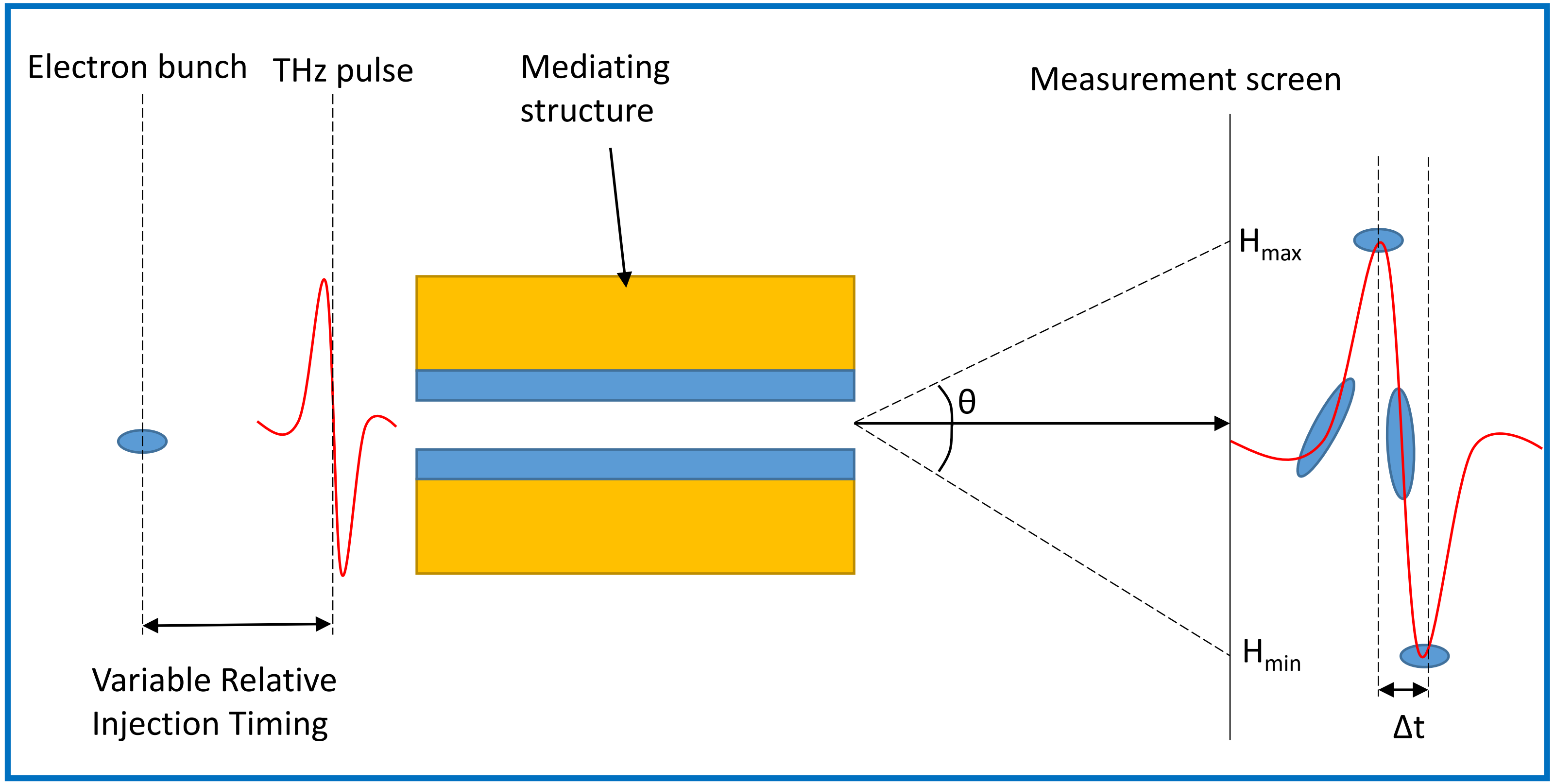
- Complicated timing systems
- Hard to achieve fs bunch diagnostics

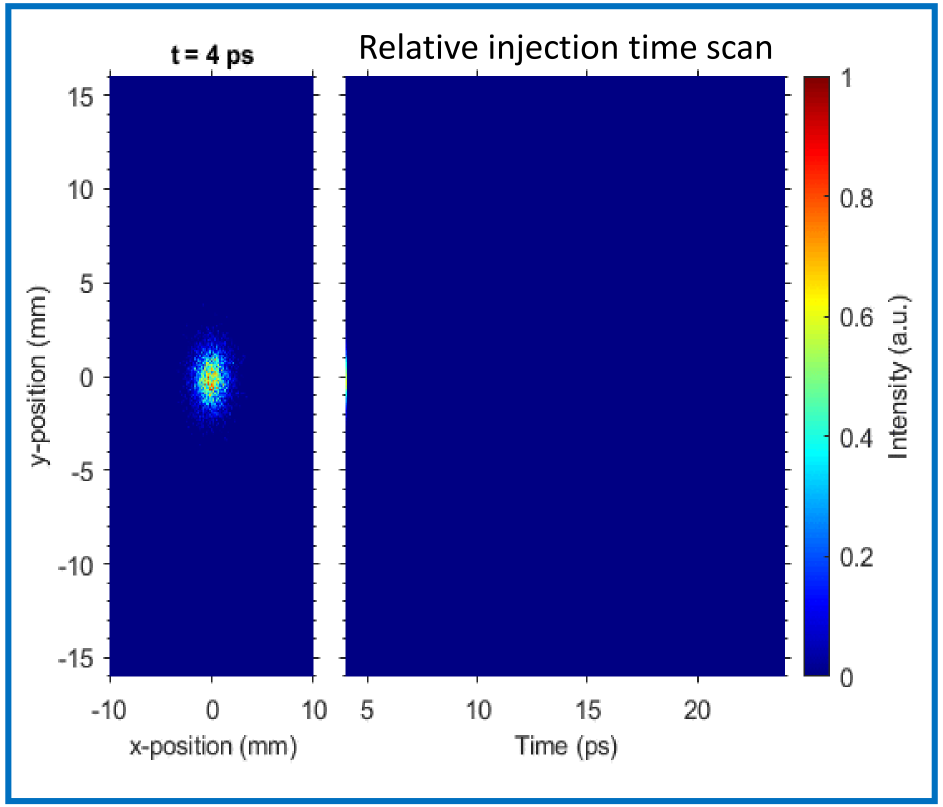
Diagnostics Uses

- Streaking to transfer longitudinal bunch information into measurable transverse change for ultrashort bunches

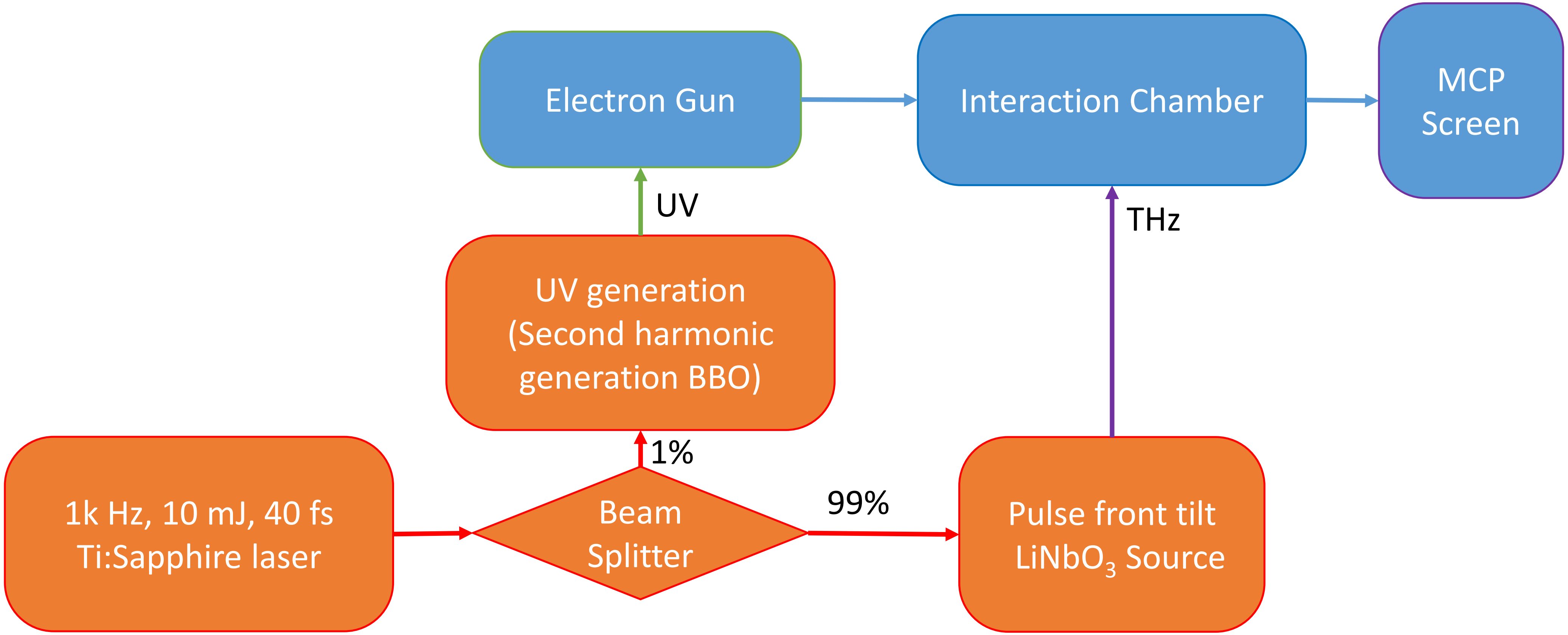


Ultrafast Electron Diagnostics: Terahertz Deflectograms





100 keV Sub-Relativistic Experimental Test Bed



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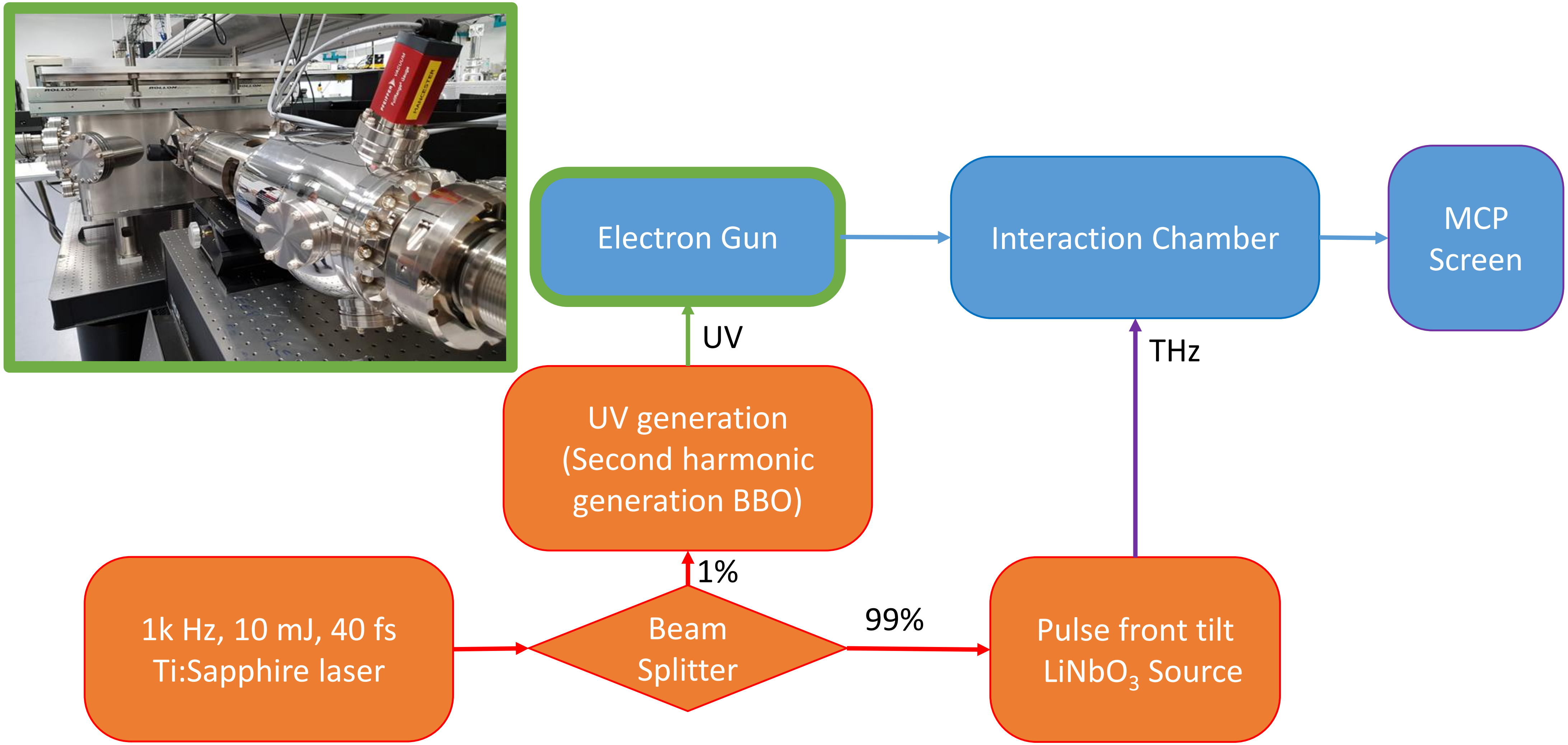

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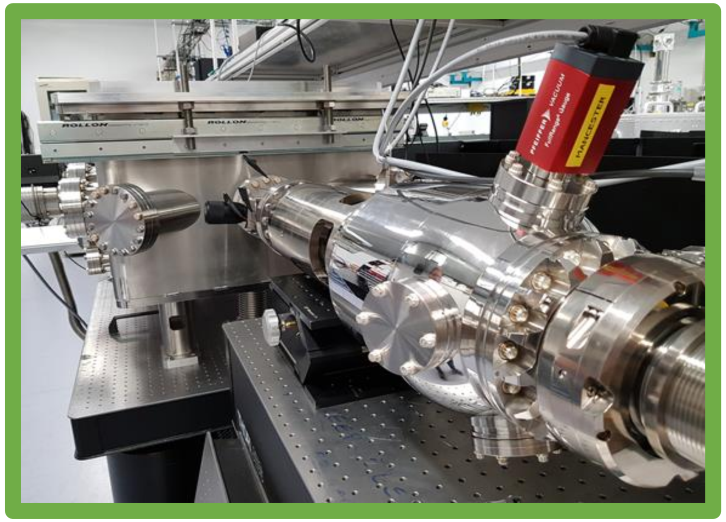


Electron Gun → Interaction Chamber → MCP Screen

UV

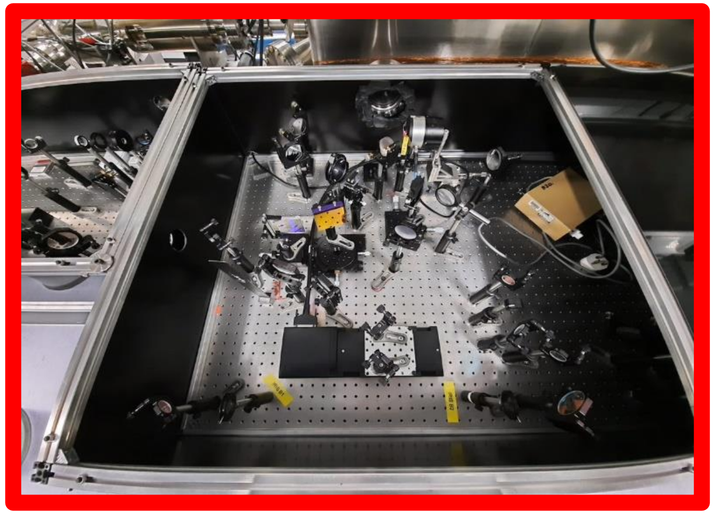
THz

UV generation (Second harmonic generation BBO)

1%

99%

1k Hz, 10 mJ, 40 fs Ti:Sapphire laser → Beam Splitter → Pulse front tilt $LiNbO_3$ Source



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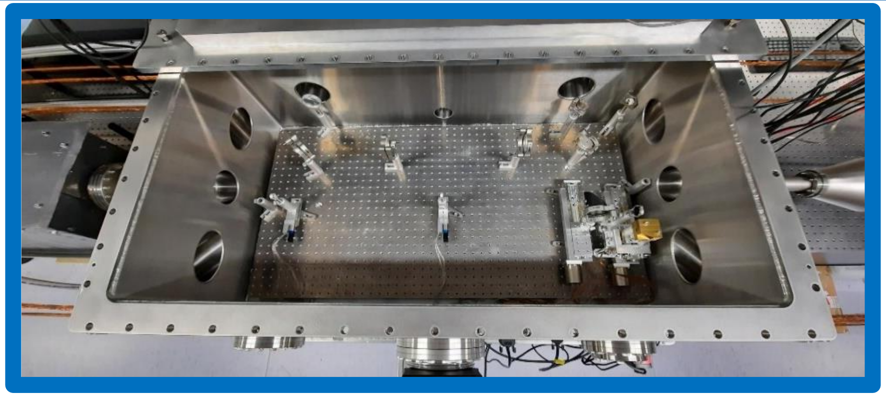

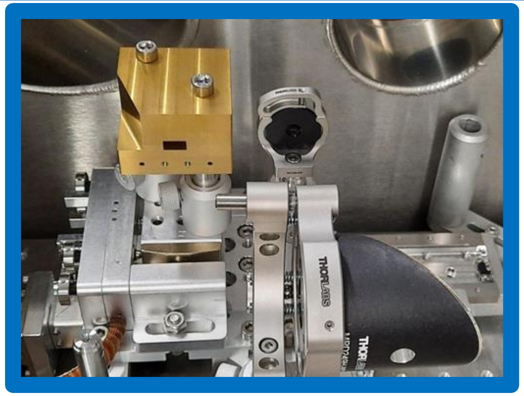

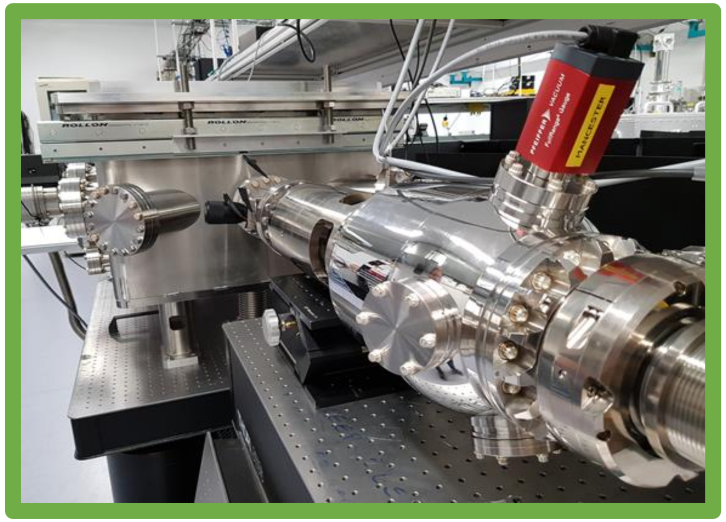

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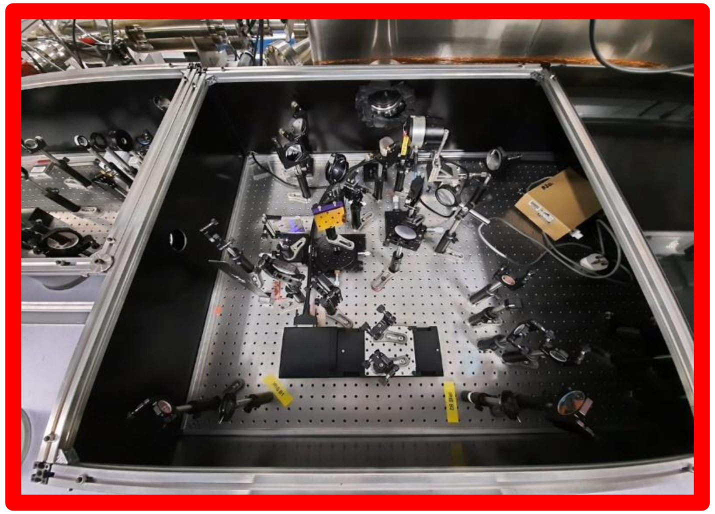
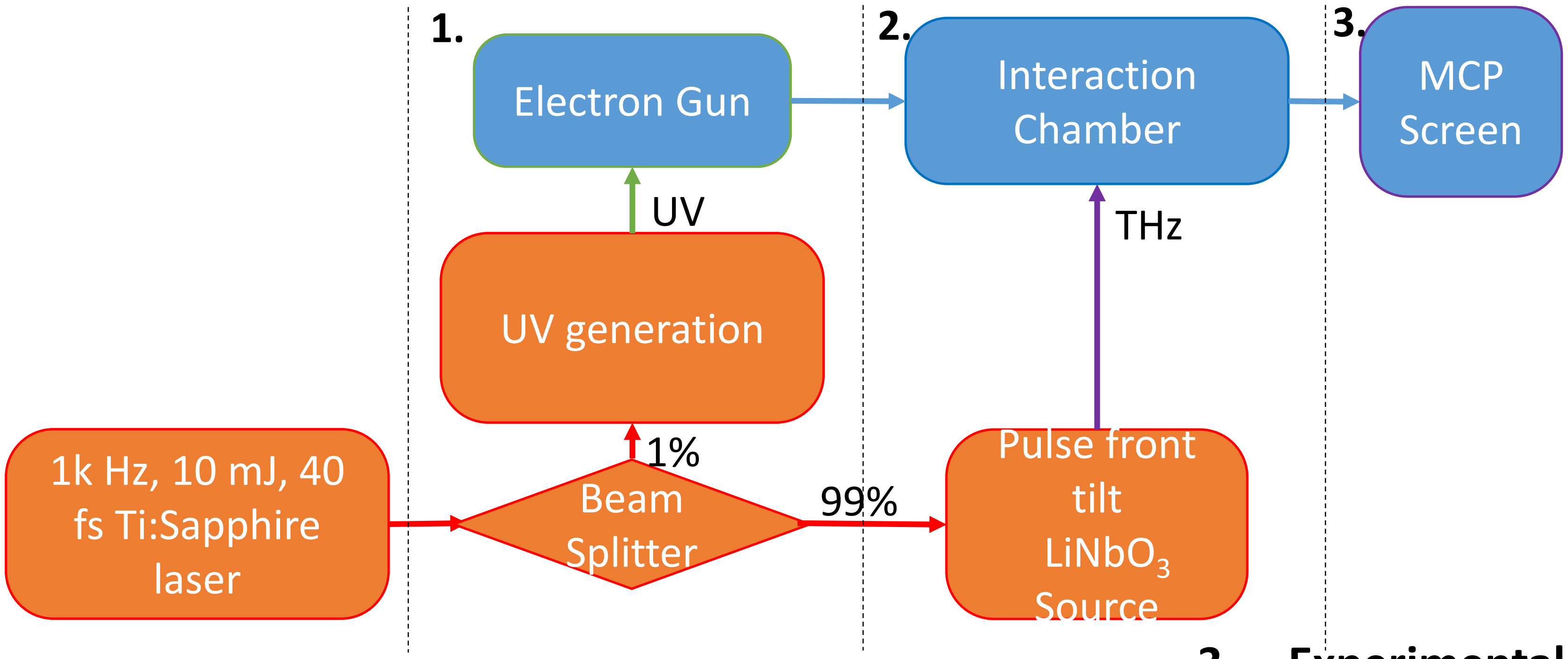
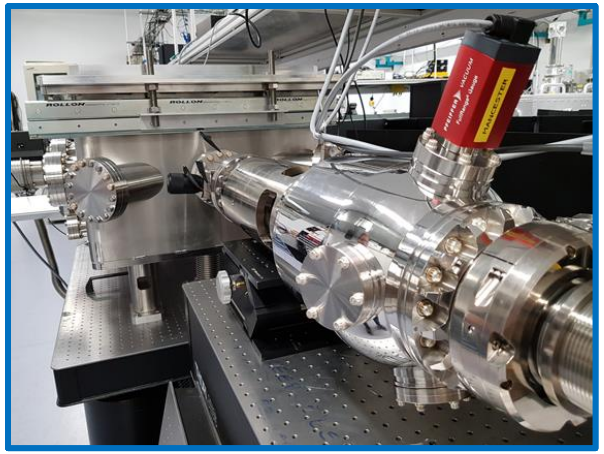


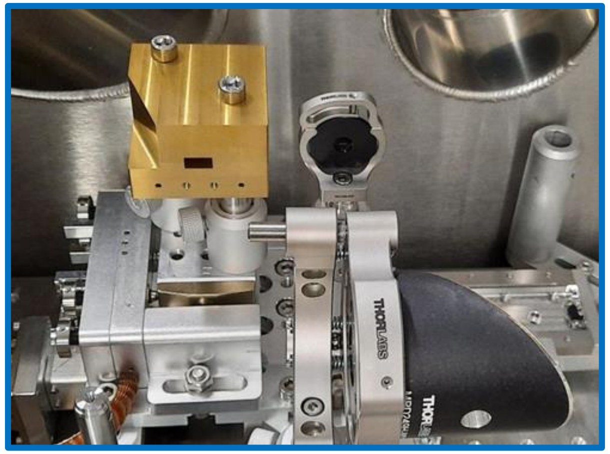
100 keV Simulation Development



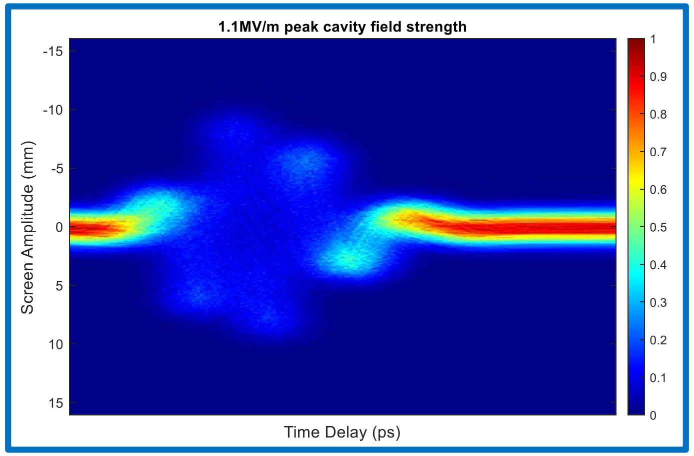
1. Electron gun modelling

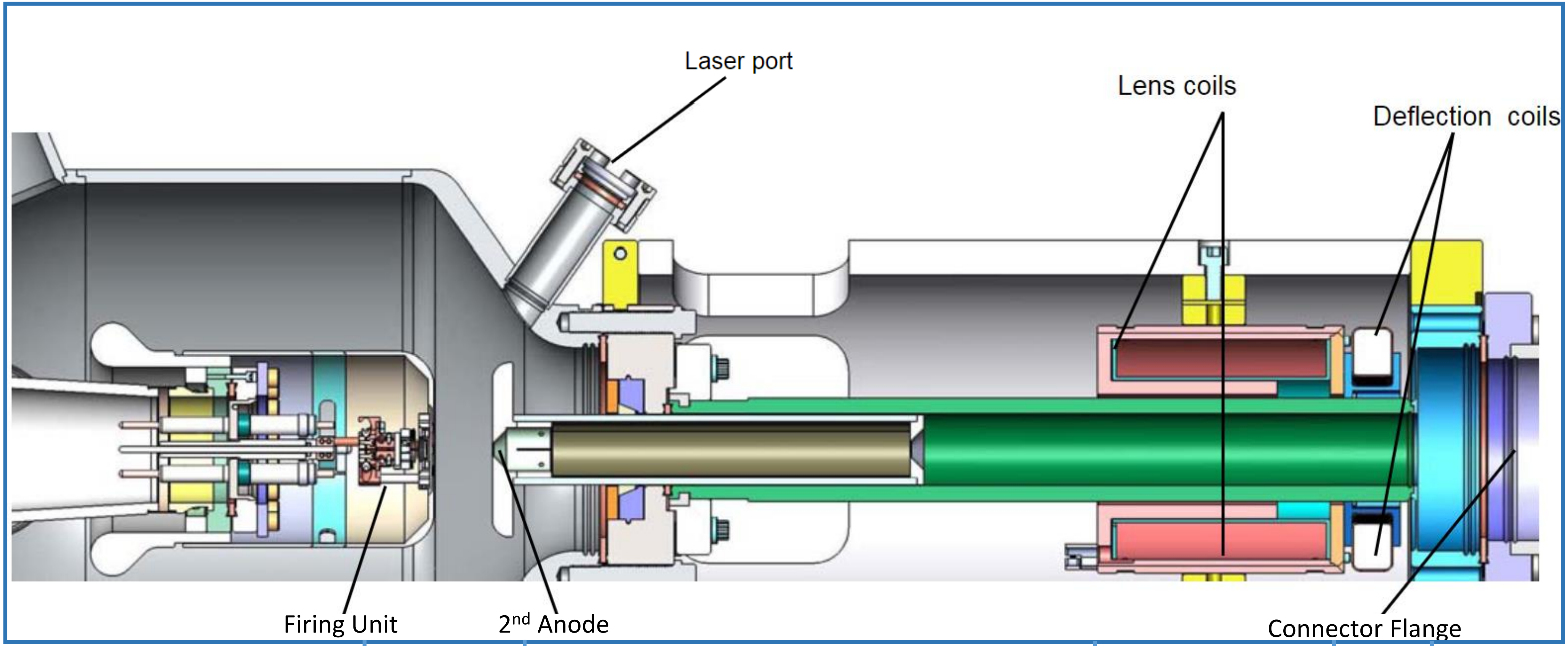


2. Waveguide field simulations



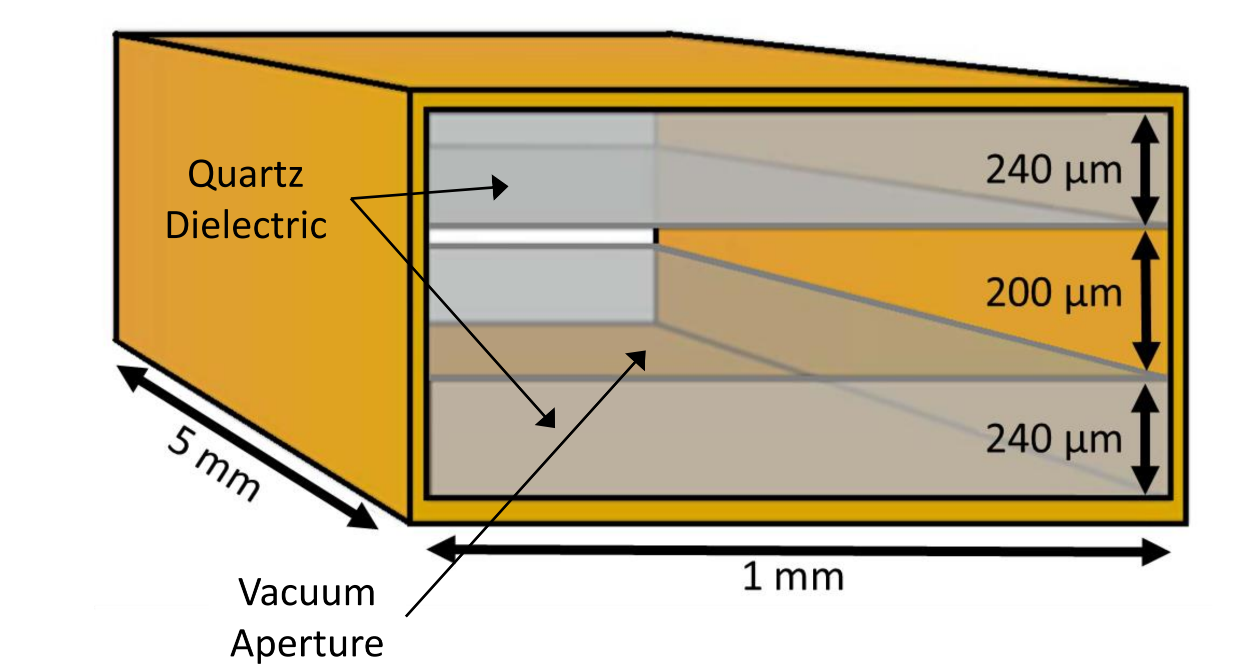
3. Experimental and Simulation Results

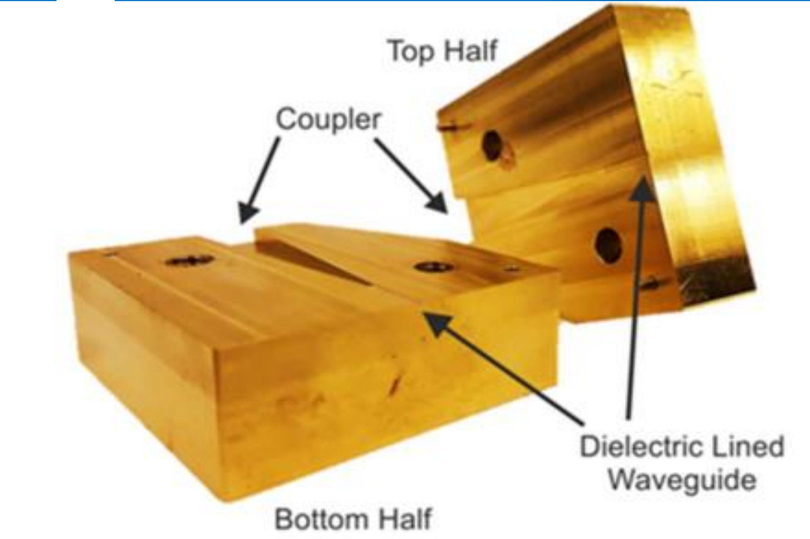




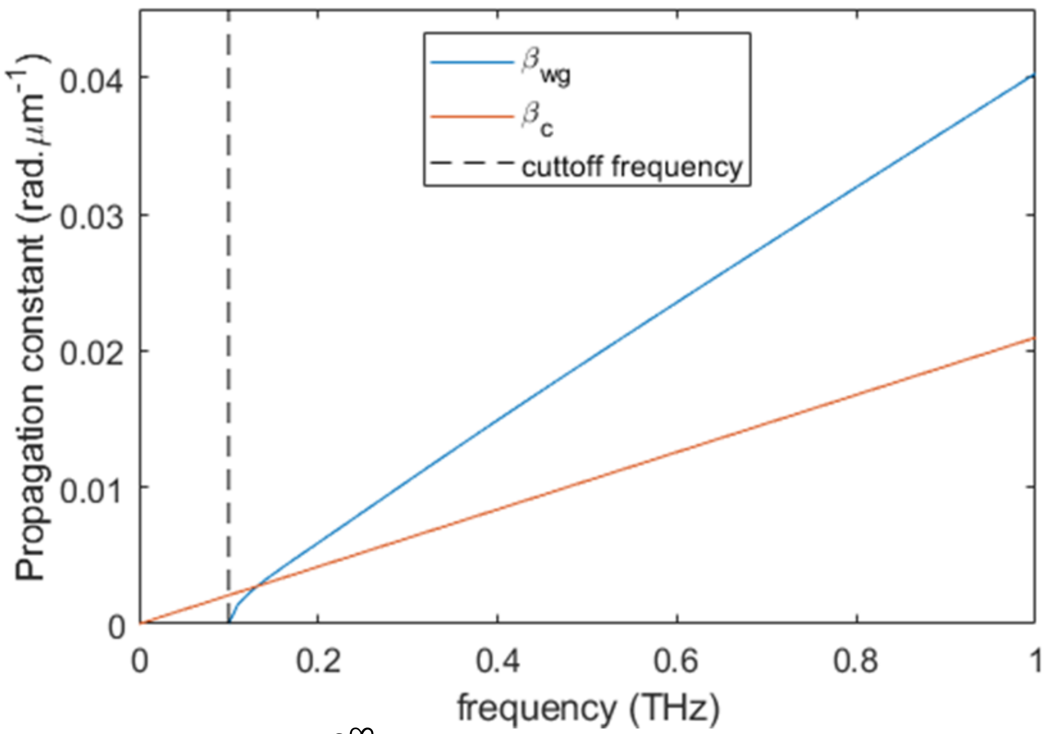
Early gun region | Drift region | **Focusing region** | steering

Waveguide Simulation: Waveguide Features





V. Georgiadis, et al. Appl. Phys. Lett. **118**, 144102 (2021)



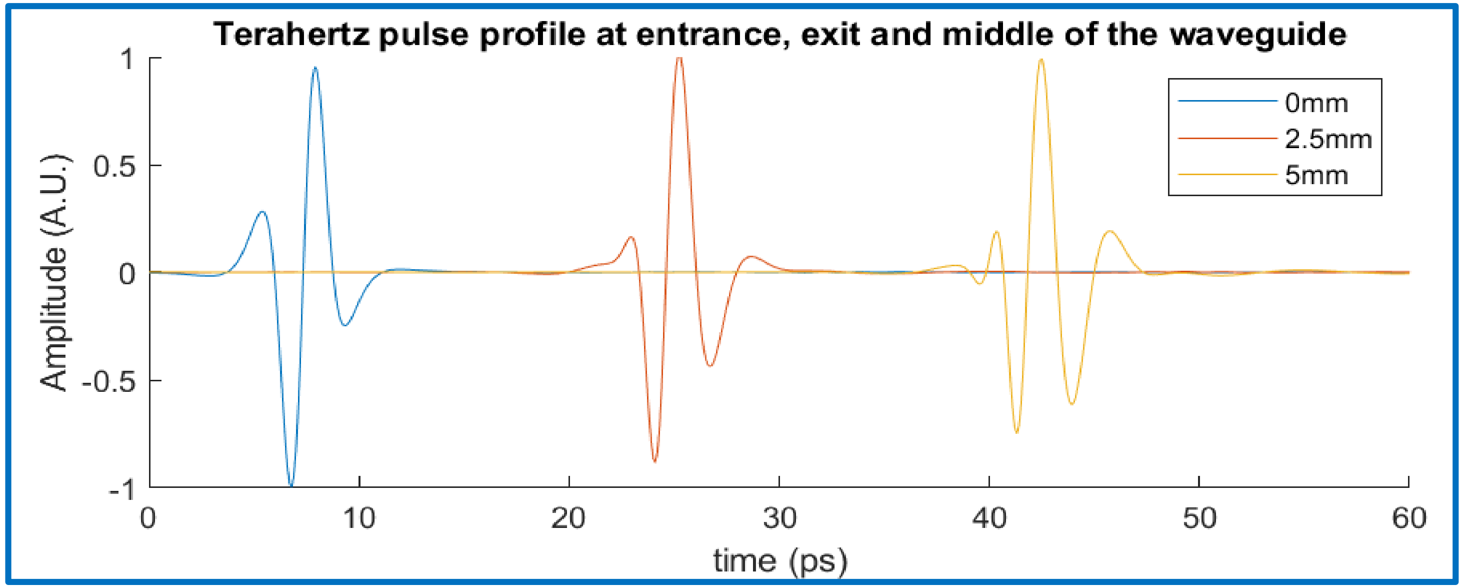
$$\tilde{E}(t) = \int_{\omega_c}^{\infty} \tilde{A}(\omega) exp\,[i\beta(\omega)z]\exp[-i\omega t]d\omega$$

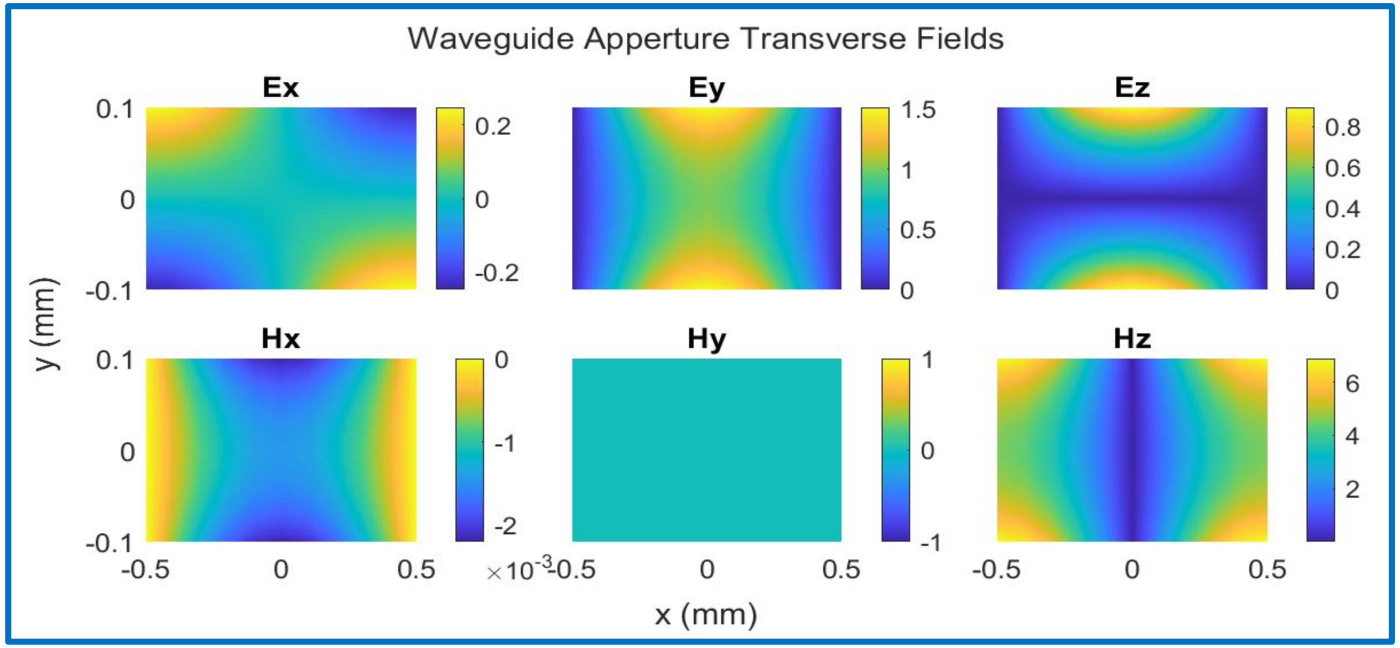
- 44 mm coupler used to transport TE_{10} mode THz pulse to waveguide
- LSM_{01} mode waveguide structure is designed to match THz phase velocities with 100 keV electrons (0.548c) at frequency 0.47 THz
- Dispersion calculate for individual frequencies according to the LSM_{01} mode equations with boundaries defined by the waveguide dimensions

Waveguide Simulation: Field Map Construction

$$\tilde{E}(t) = \int_{\omega_c}^{\infty} \tilde{A}(\omega) exp\,[i\beta(\omega)z]\exp[-i\omega t]d\omega$$

- Phase advance calculate for individual frequencies according to the LSM_{01} mode propagation constants
- Normalised longitudinal pulse profile calculated and recorded for each waveguide step in z





- Transverse THz field distribution calculated from the LSM_{01} mode field equations
- All points normalised relative to on design axis Ey field
- Cartesian EM Field components stored as a 3D grid for each time step and scaled by a maximum field amplitude at the waveguide entrance

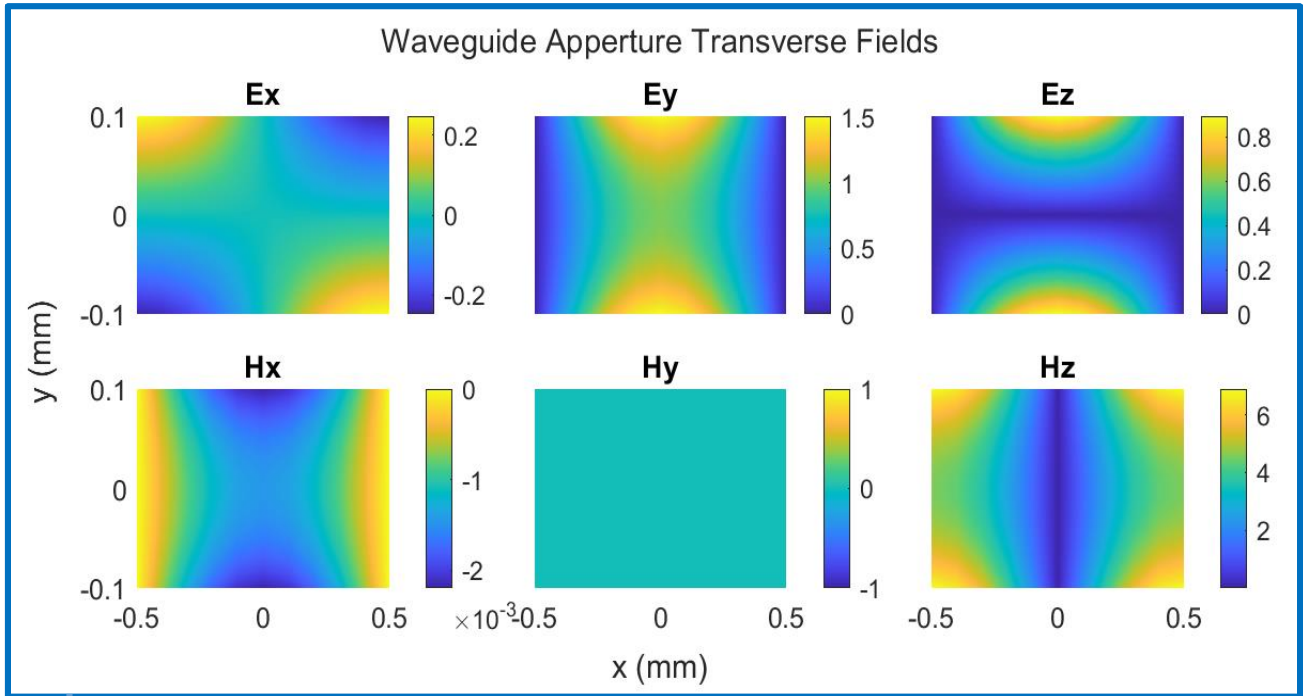
Simulation Results

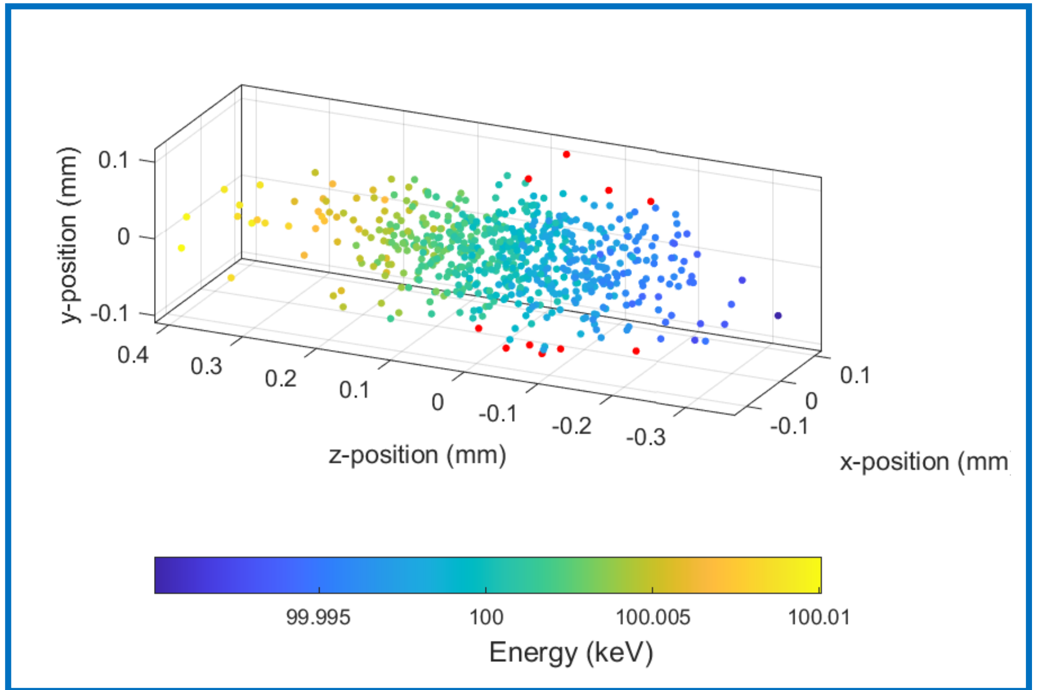
Terahertz parameters in waveguide

- 0.33 THz central frequency
- 0.5 THz bandwidth ($1/e^2$)
- 1.1 MV/m induced peak field within the cavity

Bunch Parameters at a waveguide focus :

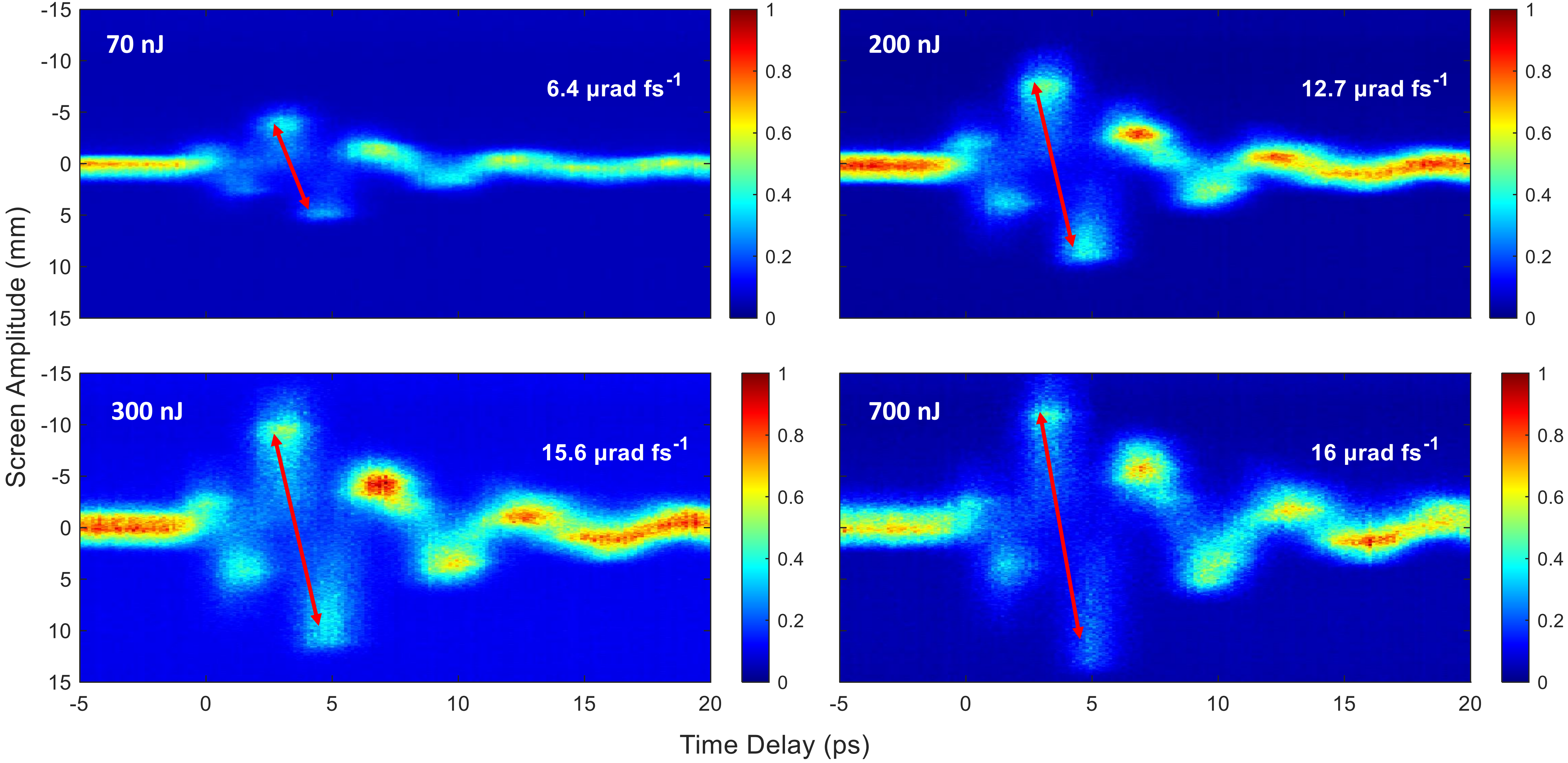
- 0.1 fC charge
- 240 µm transverse diameter ($1/e^2$)
- 1.2 mrad divergence (RMS)
- 1.9 ps bunch duration (FWHM)



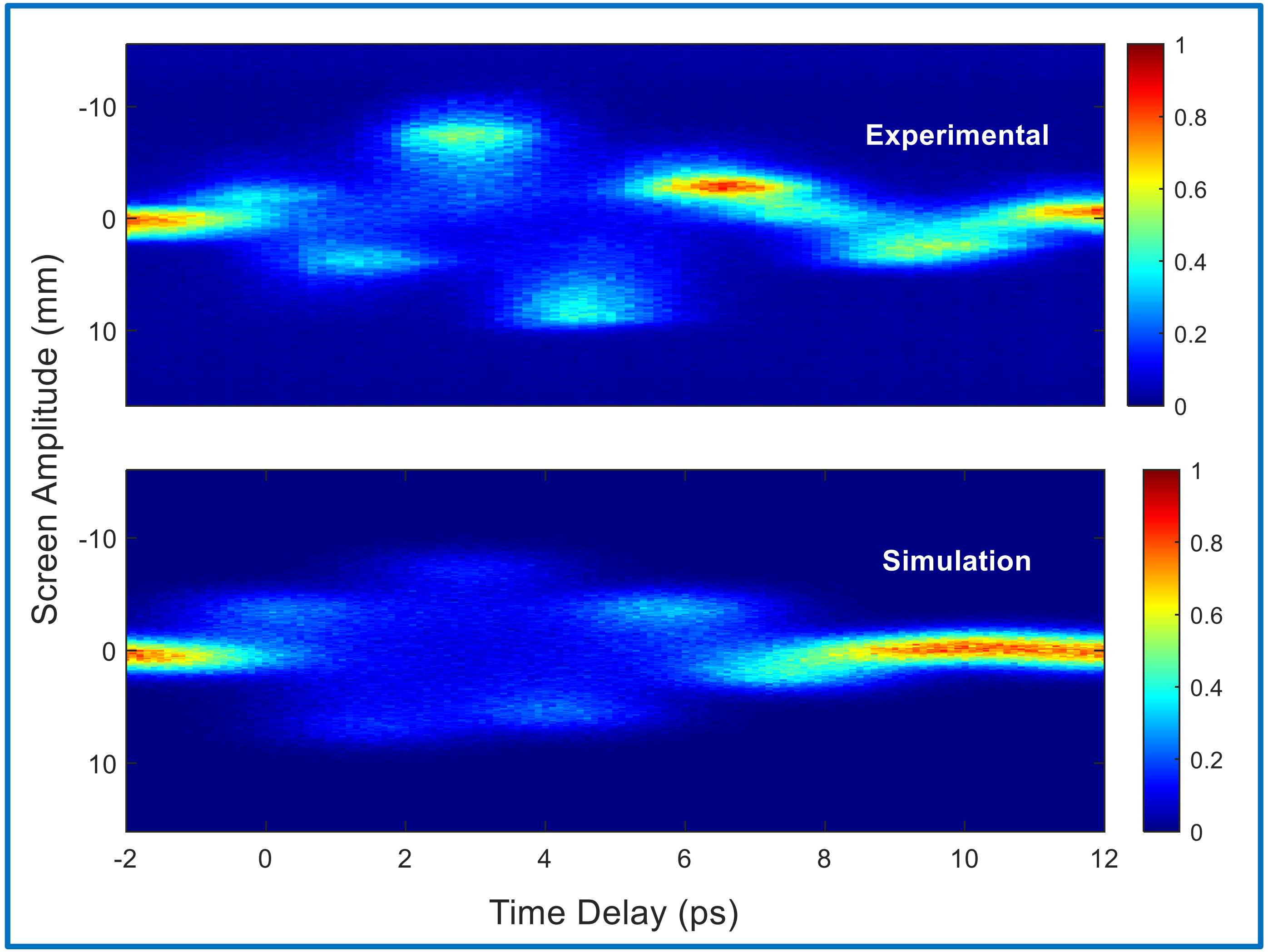


- Electrons stepped through generated field grid using Runge-Kutta 4th order in MATLAB simulation
- Electron bunches for each relative injection time transported to MCP screen by GPT simulation
- Y projections used to reconstruct final deflectogram

Experimental Results

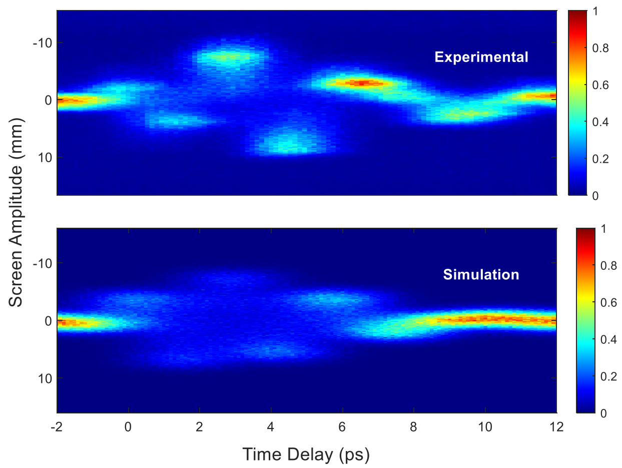


Comparison



- 200 nJ case corresponds well to the 1.1 MV/m peak field simulation which agrees with calculated field estimates
- 240 µm transverse diameter ($1/e^2$) shows good match to lab results indicating a good charge match as primarily driven by space charge broadening vs solenoid focusing
- Divergence features show match to trends in experimental data with minimal clipping when matched to a 200nJ THz pulse energy
- Width of key peaks in lab measurements allows the bunch length to be determined as 1.9 ps FWHM as used in simulations
- Trailing oscillations in the lab measurement are attributed to coupler dispersion on the THz pulse – CST simulations to include coupler effects are currently in development

Conclusions



Where we are:

- Electron gun simulations developed
- THz field map constructed from idealised LSM_{01} equations and EO measured pulse
- Successful matching of simulations with experimental results to analyse key features of the longitudinal electron bunch phase space

What's next?

- Continued development of CST simulations to better understand the effect of coupler dispersion on the interaction
- Tomography based analysis using beam transfer maps derived from simulation
- Alternative PPLN THz sources for narrowband deflection fields
- THz based compression in our 100 keV experimental test bed