XFEL Accelerator R&D Status Report
RP-421: THz Generation at PITZ

Continuing R&D of accelerator-based THz source for pump-probe experiments at the European XFEL

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Scope of the R&D activity

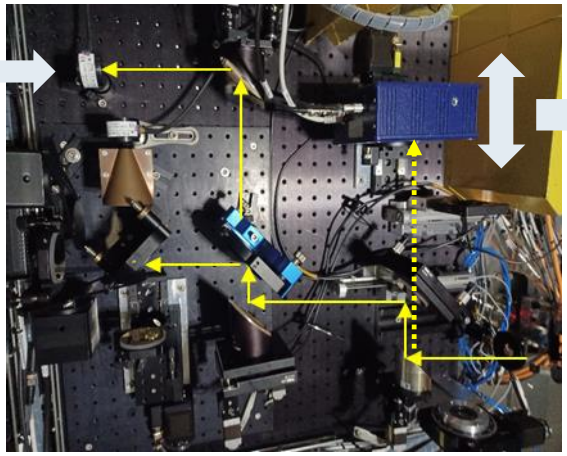
- THz@PITZ is R&D towards an accelerator-based THz source for pump-probe experiments at the European XFEL. After successful demonstration of 3THz generation at PITZ, this follow-up proposal targets the following goals:
  - Experimental verification of remaining key challenges that will influence the conceptual layout
    - Demonstrating continuous **tunability** (1-5 THz) of the undulator source, understanding and improving seeding options for better radiation stability, and engaging the bunch compressor for different modes of operation. A key tool to achieve this is to use and tune the now available advanced photo-cathode laser pulse shaping (6 weeks beam time).
    - Demonstrate **broadband** THz radiation generated through coherent transition or diffraction radiation (CTR/CDR) using compressed or modulated electron bunches (2 weeks beam time).
    - Demonstrate that the **high electric field strength** (>1-2 MV/cm) can be reached (6 weeks beam time).
  - Conceptual **layout** of a photoinjector-based facility optimized as a tunable, high-power THz source for pump probe experiments at the European XFEL
- Start Q3/2025

Achievements in 2025: July-August

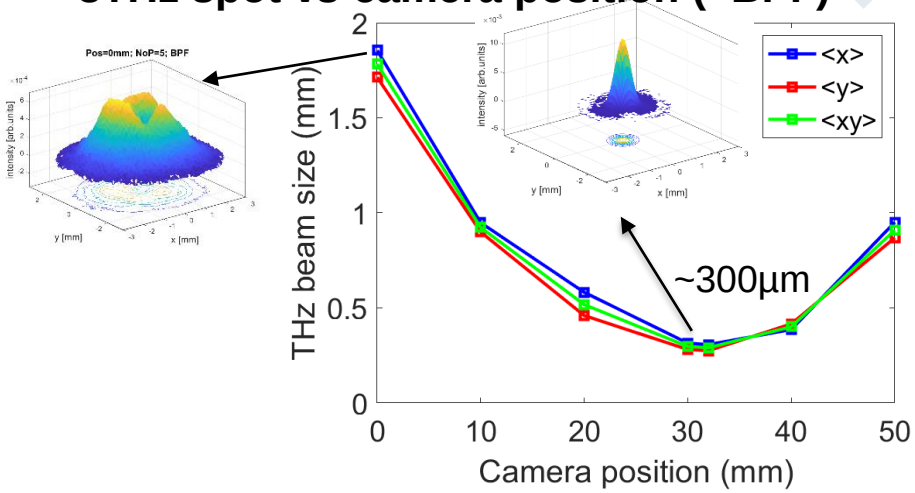
- 2 Postdocs employed:
  - Dr. Namra Aftab (THz diagnostics, simulations, experiments planning)
  - Dr. Siriwan Pakluea (EOS design, advanced THz diagnostics)
- Standard THz diagnostics setup:
  - TD3 refurbished to upgrade Michelson interferometer (+reference signal)
  - TD1 (after BC) - redesigned
- 2 Run blocks (22 shifts in week 28 + 6 shifts in week 35)
  - Restored 3THz lasing, transverse distribution with THz camera
  - Upgraded Michelson Interferometer commissioning
  - First 5THz light generated
- First EOS design considerations – using available laser systems at PITZ
- Supplementary simulations for THz generation at PITZ:
  - 5THz proof-of-principle experiment
  - Waveguide and wakefield effect estimation
  - Bunch compressor (BC) case studies: THz FEL and superradiance

Achievements in 2025: THz diagnostics

Upgrade of THz diagnostics Station (TD3)
- adding reference signal

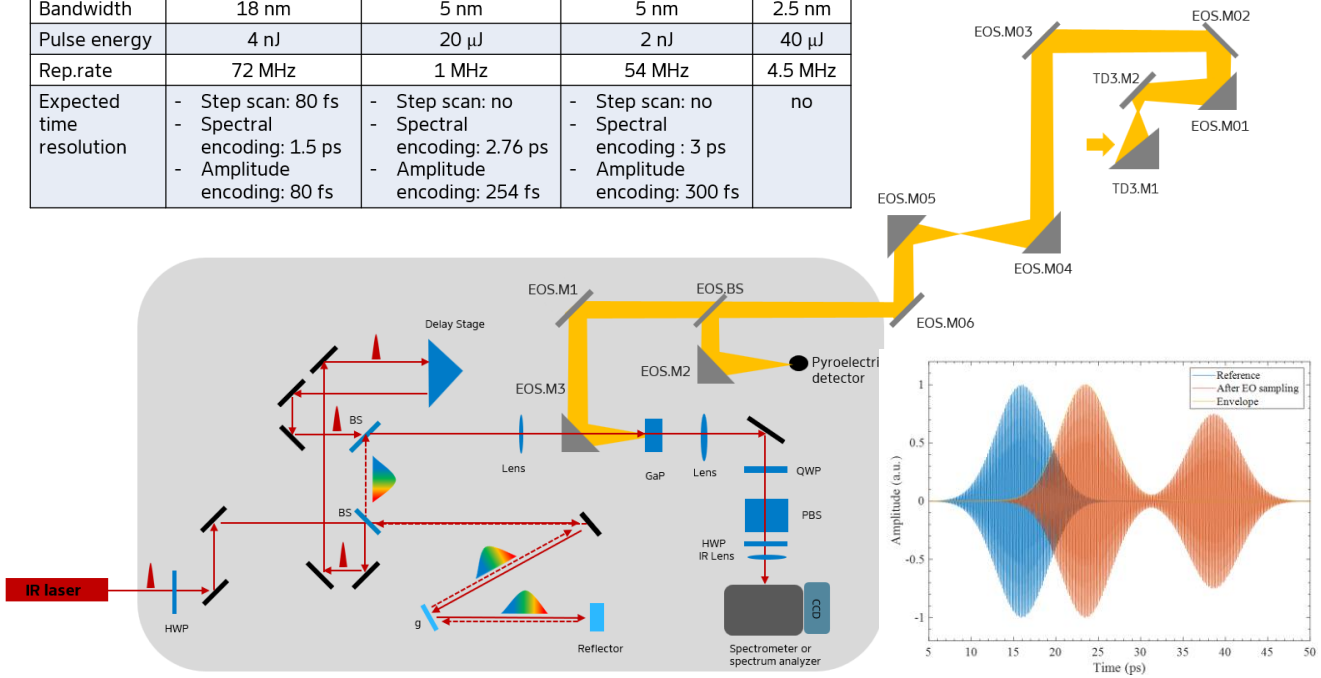


3THz spot vs camera position (+BPF)



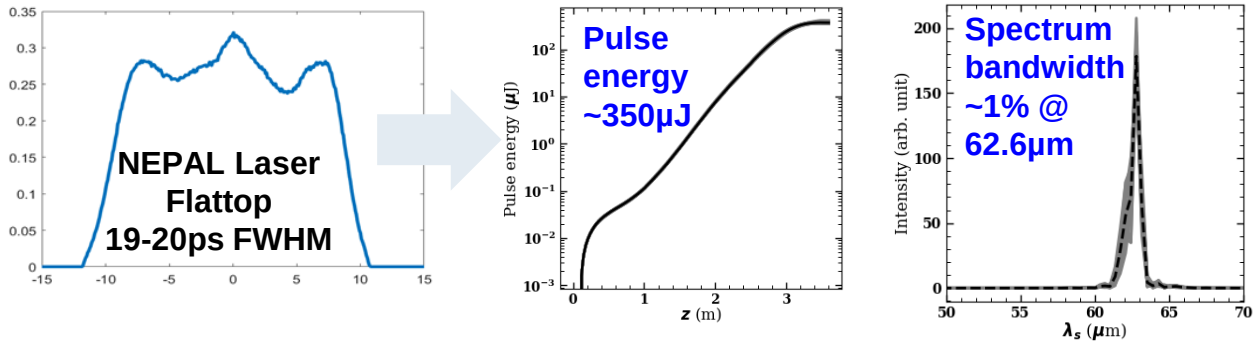
Design Considerations for Electro-Optic Sampling (EOS) at THz FEL at PITZ - Amplitude encoding spectra interferometry: Temporal profile measurement

Parameter	PHAROS		NEPAL-P	
	OSC	PA	OSC	PA
Wavelength	1030 nm	1030 nm	1030 nm	1030 nm
Pulse length	80 fs	254 fs	300 fs	1 ps
Bandwidth	18 nm	5 nm	5 nm	2.5 nm
Pulse energy	4 nJ	20 µJ	2 nJ	40 µJ
Rep.rate	72 MHz	1 MHz	54 MHz	4.5 MHz
Expected time resolution	- Step scan: 80 fs - Spectral encoding: 1.5 ps - Amplitude encoding: 80 fs	- Step scan: no - Spectral encoding: 2.76 ps - Amplitude encoding: 254 fs	- Step scan: no - Spectral encoding : 3 ps - Amplitude encoding: 300 fs	no

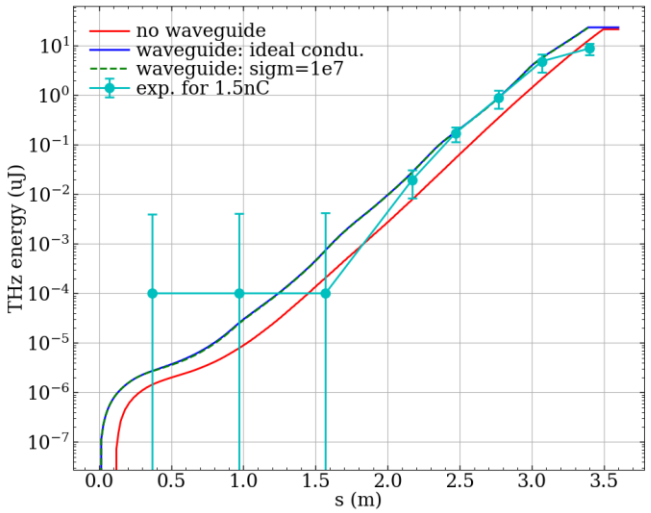


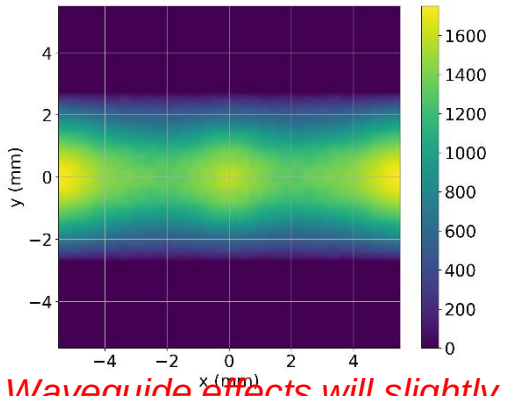
Achievements in 2025: Supplementary simulations for THz generation at PITZ

5THz proof-of-principle experiment



Waveguide and wakefield effects

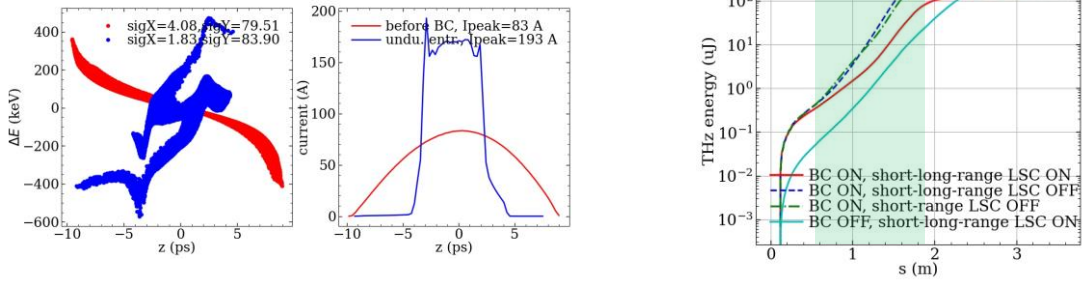


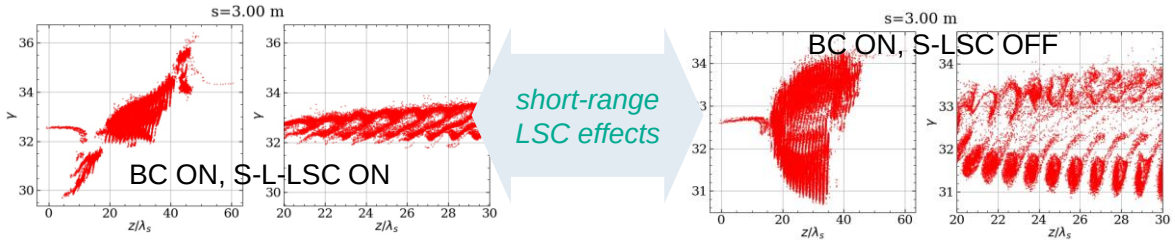


Waveguide effects will slightly enhance the FEL interaction; Ohmic loss could be ignored.

Bunch compressor (BC) case studies

THz FEL

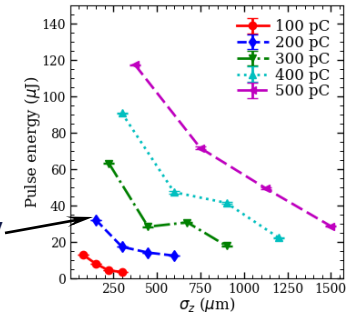




Superradiance

200 pC charge, 150 μm σ_z
electron bunch

4.1 ps FWHM, 30 μJ energy
THz pulse



Deviations from plan

- PITZ Timeline Update (2024–2025) → **Gun5** for XFEL is the **highest priority** !!!:
  - Gun5.2 in operation at PITZ (conditioning + characterization with e-beam) 14.01.2025- 31.08.2025 → XFEL Sept.2025
  - Gun5.3, now FALCO (single-side power coupler) → PITZ in October 2025+ *symmetric power coupler* (once ready), with conditioning and characterization planned to start at the **end of 2025**

- Up to now 28 shifts (67% of 42 shifts planned for 2025) – operation for THz generation

Timeline of this R&D activity

Proposed Date	Milestone Description	Updated Date
Q3/2025	Personnel assigned to THz@PITZ	Done
Q3/2026	Continuous tunability of the undulator source from 1 - 5 THz demonstrated	Started
Q4/2026	Initial structure (TOC) of the conceptual layout report defined	
Q2/2027	CTR/CDR broadband THz radiation demonstrated at PITZ	
Q4/2027	Initial layout of a THz source at XFEL is available	
Q2/2028	High electric fields of > 1-2 MV/cm demonstrated	
Q3/2028	Conceptual layout report completed	

Risks to R&D Project

- Gun5 operation at PITZ:
  - Gun5.2 is on the way to XFEL → only 1.3 week operation of 2 weeks planned for 2025
  - Gun5.3, after pre-conditioning at FALCO with a single-side power coupler, is expected to be delivered to PITZ (October 2025), will be equipped then with a symmetric power coupler, with conditioning and characterization planned to start in Fall/Winter 2025. → maybe no 1.7 week operation is possible in 2025

- Other risks:
  - Hardware failures (e.g., RF systems; three major technical failures already in 2025)
  - Conflicts with other tasks

Outlook / Summary

- XFEL Accelerator R&D activities RP-751: “THz Generation at PITZ” is started from Q3/2025:
  - 2 Postdocs employed:
  - Standard THz diagnostics setup – upgrade and commissioning
  - 2 Run blocks (28 shifts): 3THz recovered, THz radiation transverse distribution imaging, upgraded MIF commissioning and first 5THz light
  - First EOS design considerations – using available laser systems at PITZ
  - Supplementary simulations for THz generation at PITZ
  - Next steps: continue tunability + spectrum, pulse train flatness, CTR with BC, “ideal” facility layout
- **List of presentations/publications:**
  - M. Krasilnikov et al., “High Power Single Pass THz FEL in Operation at PITZ”, talk and paper (IEEE) at 50th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz2025)
  - N. Aftab “Overview of THz Diagnostics at PITZ”, talk and paper (IEEE) at 50th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz2025)
  - S. Pakluea “Design Considerations for Electro-Optic Sampling at THz FEL at PITZ”, poster at student workshop of IRMMW-THz2025