11th MT Annual Meeting
GSI, Darmstadt, Germany, 03. - 05. Nov 2025

Bundesministerium für Forschung, Technologie und Raumfahrt
Grant no.: 05K22RO1 and 05K22RD1

Development of Ultra-broadband Direct THz Detectors based on Schottky diodes and AlGaAs/GaAs FETs for Longitudinal Beam Diagnostics

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[2]*High Frequency Technology, THM Friedberg*
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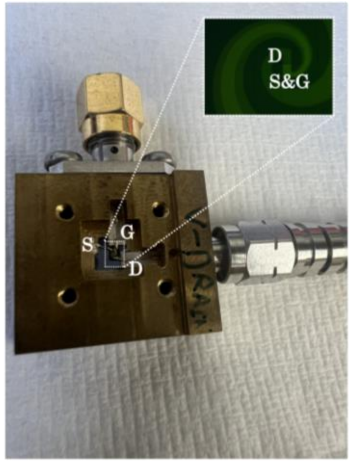

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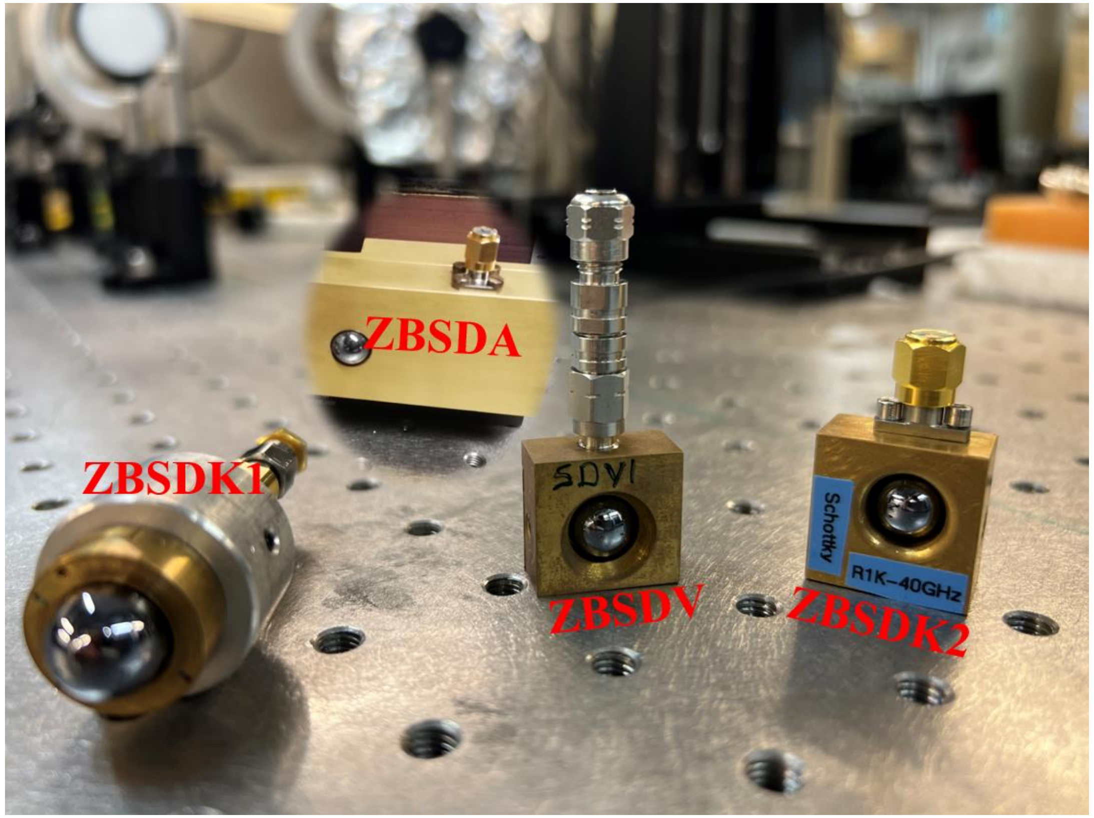
- Ultra-broadband THz detectors
- Longitudinal electron bunch diagnostics
- Summary & outlook



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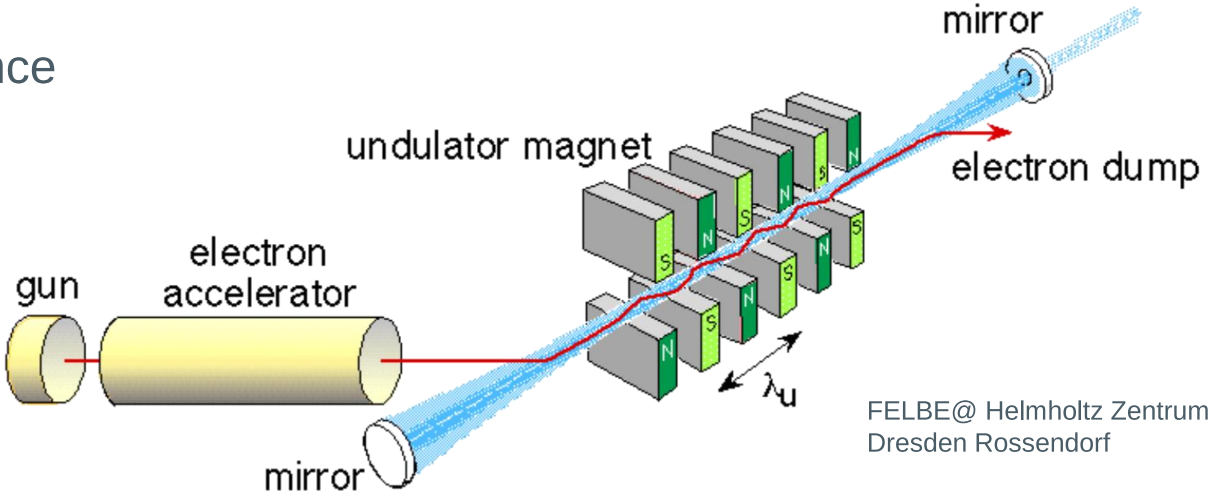
Motivation: THz Detectors for Longitudinal Diagnostics

User time limited to a few shifts upon proposal acceptance

THz pump-probe measurements:

- Time between pulses ~ **77 ns**
- THz pulse width ~**10 ps**
  - ⇒ **>1000** samples needed



FELBE@ Helmholtz Zentrum Dresden Rossendorf

Fast measurement method and fast detector required for alignment purposes

Goals:

1.) Versatile detectors for saving user time during alignment

2.) Single shot detector with <10 ps temporal resolution for FEL beam characterization:

- Longitudinal non-invasive diagnostics of electron bunches
- Accelerator stability, control, and synchronization

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Motivation: Fast & Sensitive Direct THz Detectors

High power detectors → Thermal →

Suitable for ms scale pulses

Source: SLT Sensor- und Lasertechnik GmbH

Fast high power detectors → Photon drag →

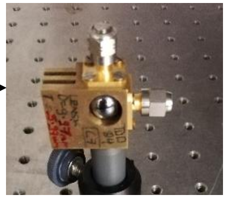
Suitable for less sensitive applications

Source: Hamamatsu photonics

Fast & sensitive detectors → Rectifying Schottky diodes THz detector →

Suitable for lower THz power, sensitive

Fast & sensitive detectors → Rectifying GaAs TeraFET THz detector →



Suitable for higher THz power, robust

THz Detectors Operational Frequency
- Intermediate Frequency (IF)
- THz Operational Frequency

Disclaimer: This covers selected aspects and is not exhaustive

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Ultra-Broadband Direct THz Detectors

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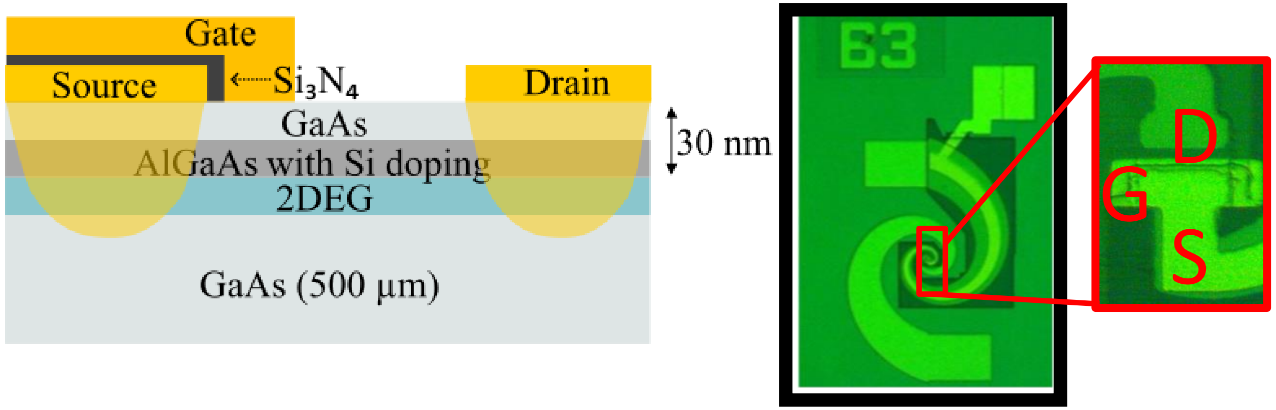
Ultra-Broadband Direct THz Detectors: TeraFETs

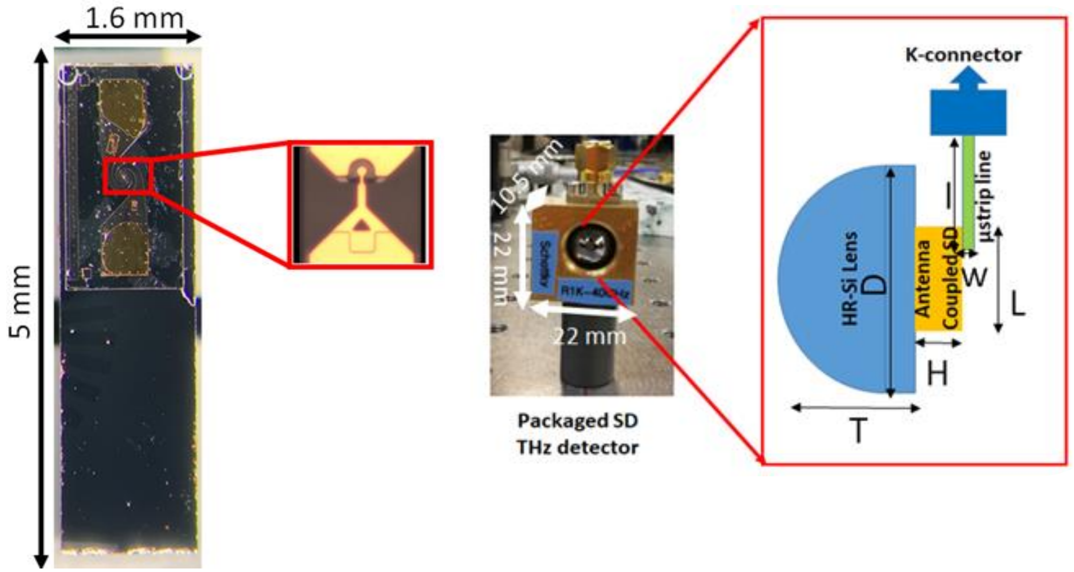
- Direct THz detectors:
  - ZBSDs: Zero-bias Schottky Diode-based
  - TeraFETs: GaAs high electron mobility transistor-based ($\mu_e = 5990\ cm^2/Vs$)

Developed TeraFETs Sample



R. Yadav, et. al, *Optics Exp.*, 32, 43407-43416 (2024)

Developed ZBSD Sample



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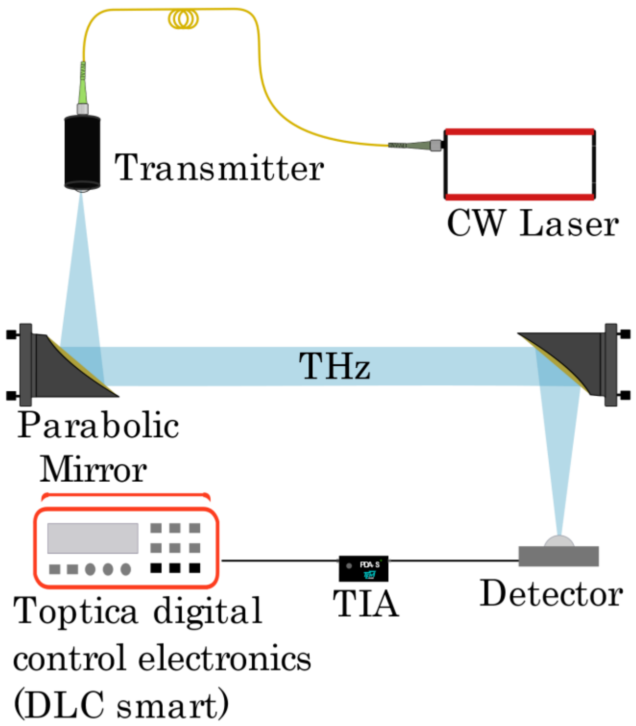
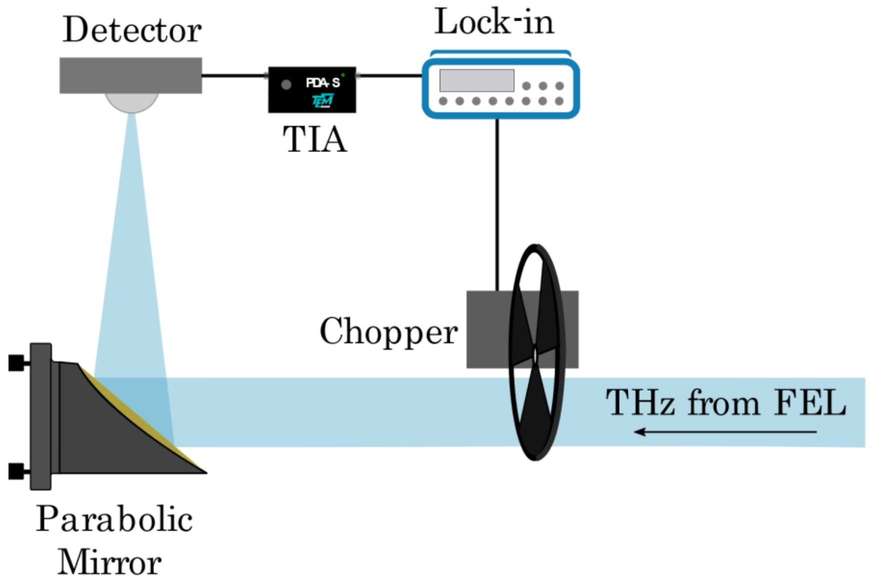
Ultra-Broadband Direct THz Detectors: Experimental Setup

Toptica CW THz table-top system



Measurement at FELBE*

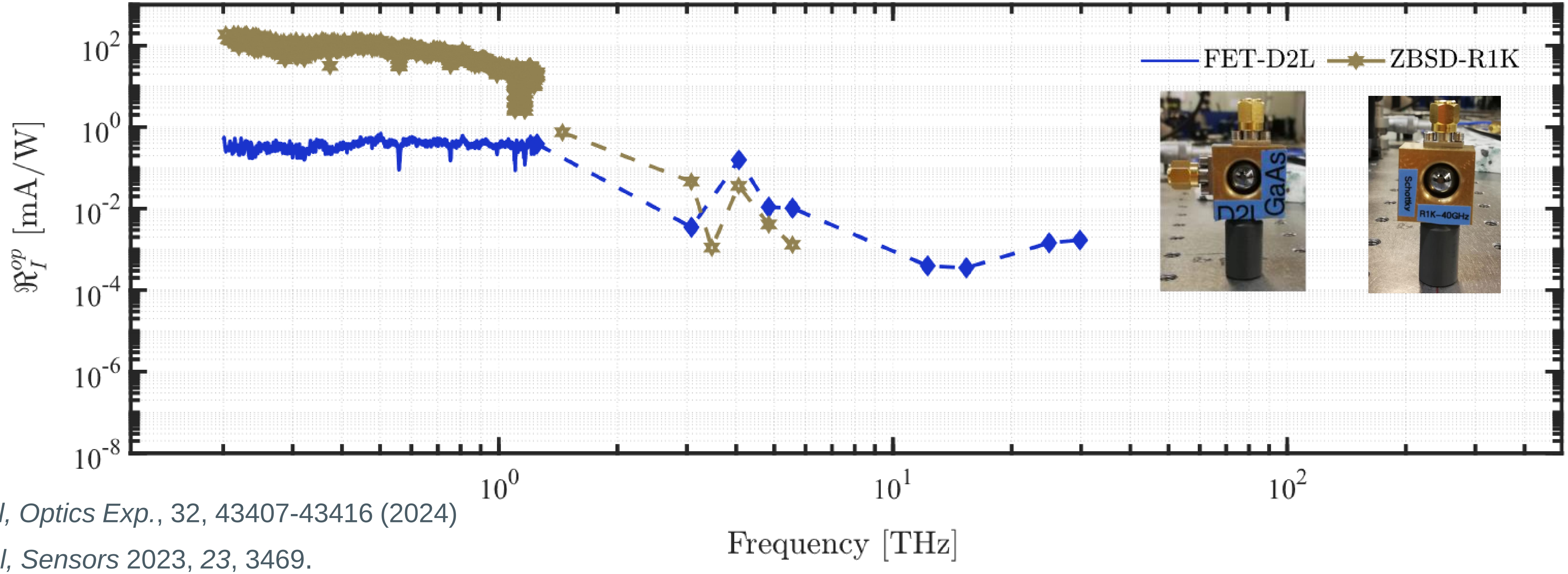


*FELBE : Free electron laser facility @ HZDR, Dresden, Germany

R. Yadav, et. al, Optics Exp., 32, 43407-43416 (2024)

Ultra-Broadband Direct THz Detectors: THz Bandwidth

- Ultra-broadband THz detectors:
  - ZBSD-R1K from **0.05 to 5.75 THz** with maximum responsivity of **100 mA/W** from **0.2 to 0.6 THz**
  - FET-D2L from **0.05 to 29.8 THz** with maximum responsivity of **0.59 mA/W** at **0.5 THz**



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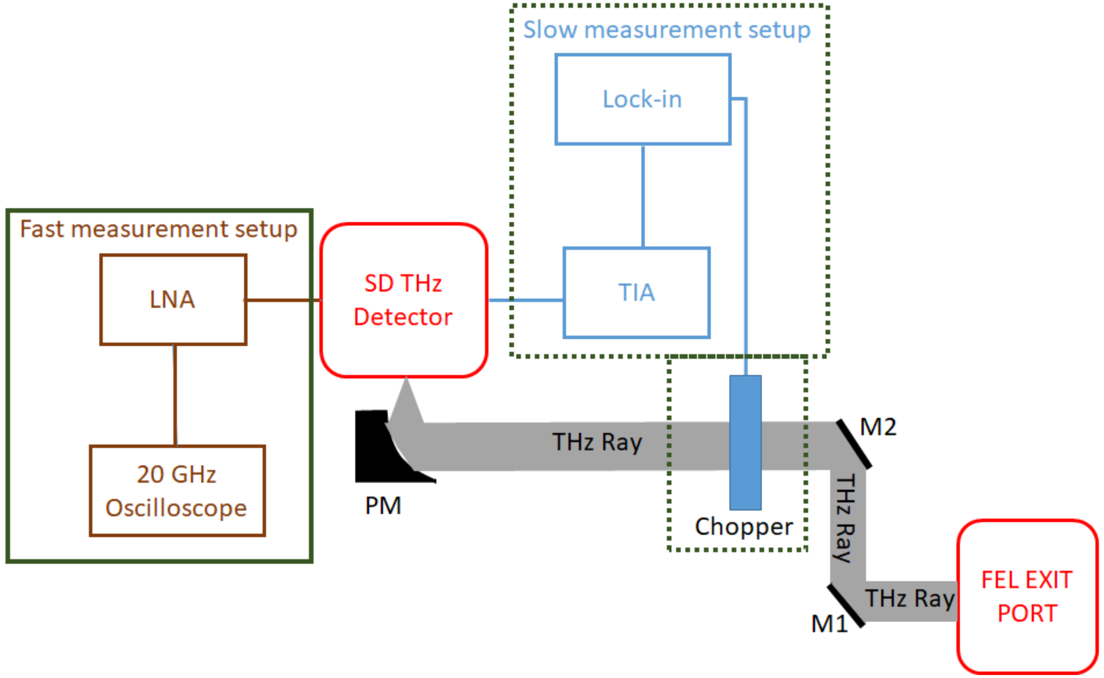
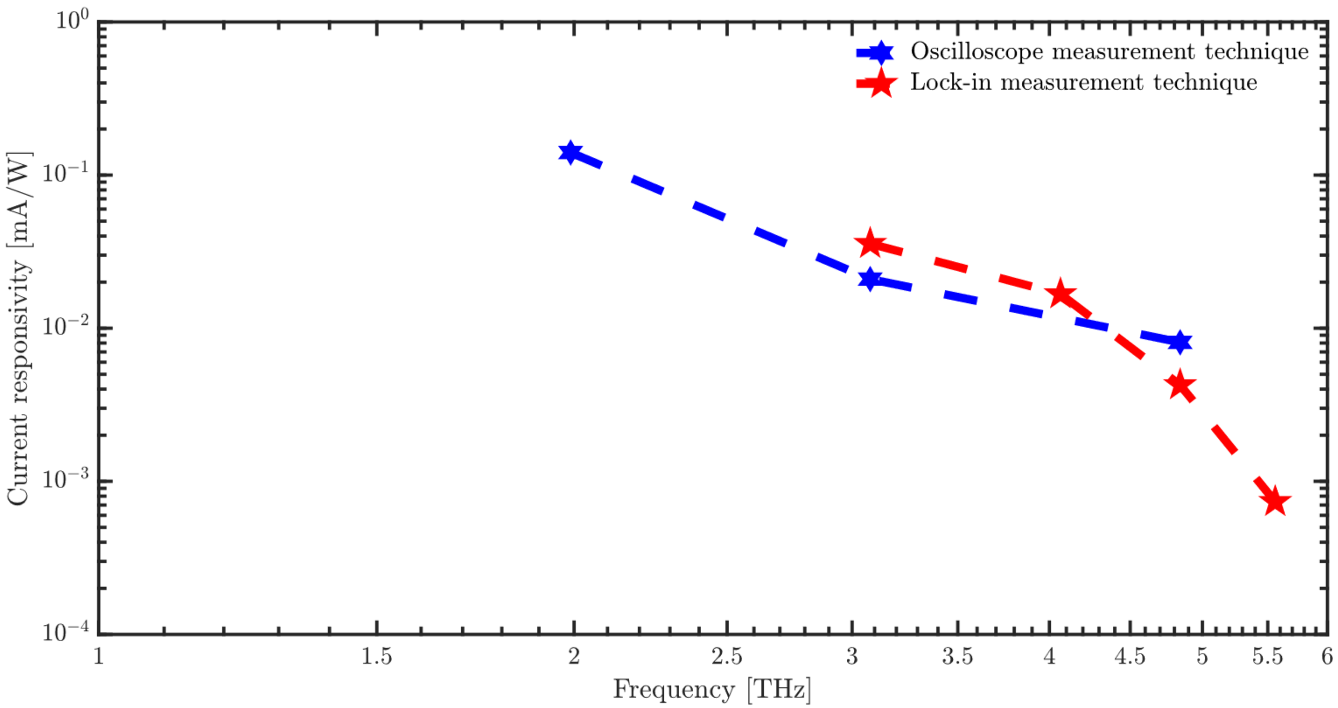
Ultra-Broadband Direct THz Detectors: THz Bandwidth



Fast measurements (on sub-ns scale)	Slow measurements (on ms scale)
Oscilloscope	Lock-in amplifier with chopper
Not temperature dependent	Temperature dependent (Bolometric effects)
Use for THz pulse detection and synchronization	Use to investigate detectors working principle and developments

Slow and fast measurement comparison



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High-speed Direct THz detectors

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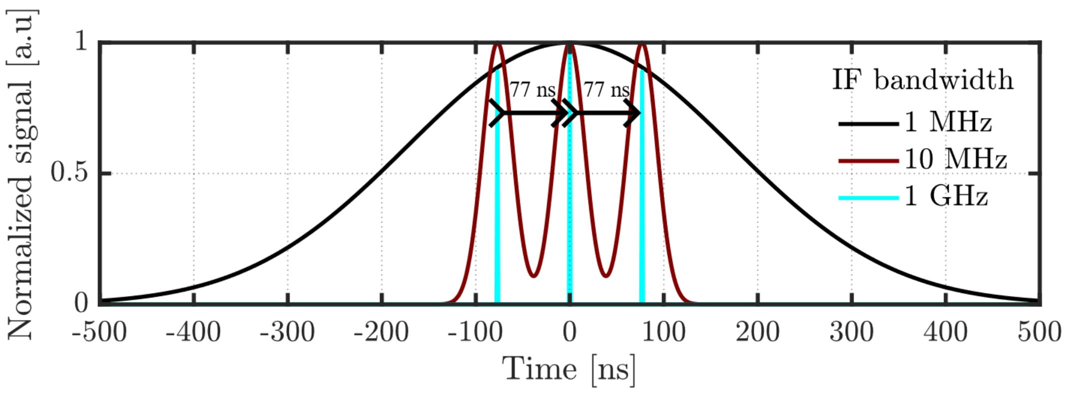
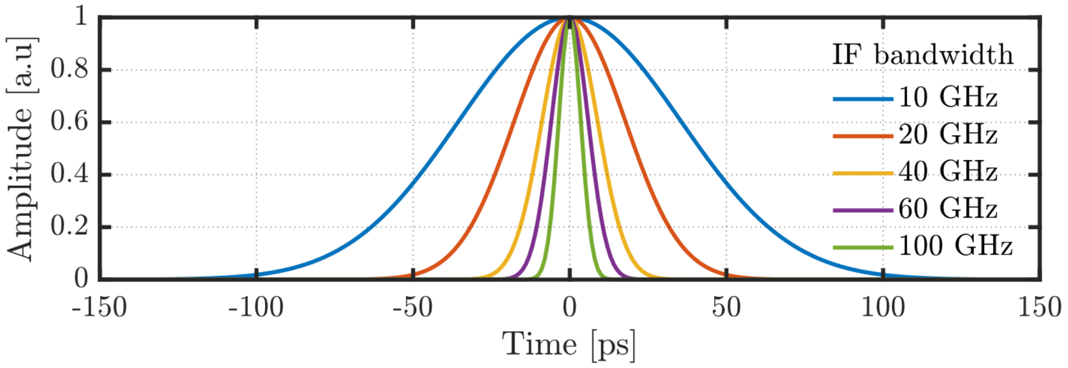
High-speed THz Detectors Requirement: IF Bandwidth

- High repetition rate in the range of a few tens of MHz
- Resolving individual pulses with ultra-wide IF/ video bandwidth
- Extreme-range beam diagnostics in the frequency and time domains
- Detectors capable of Single-shot measurements with high repetition rate beams

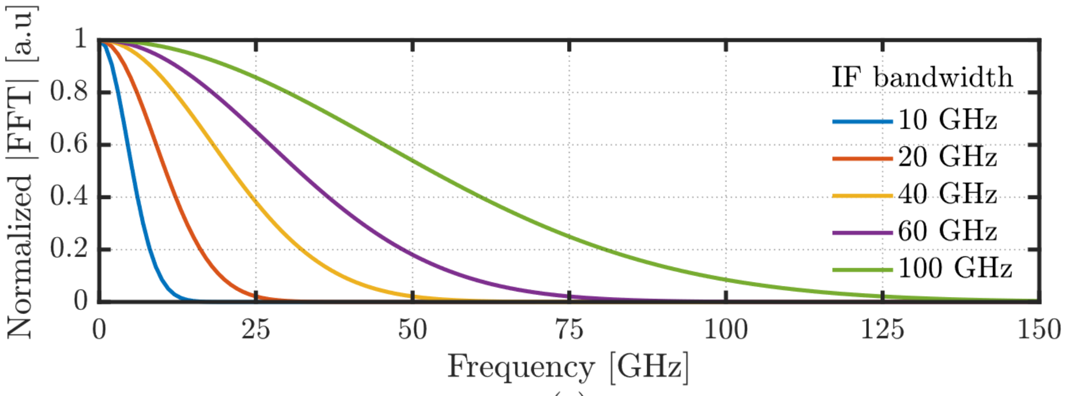
THz Pulses Repetition Rate Simulation



(a)



(b)



(c)

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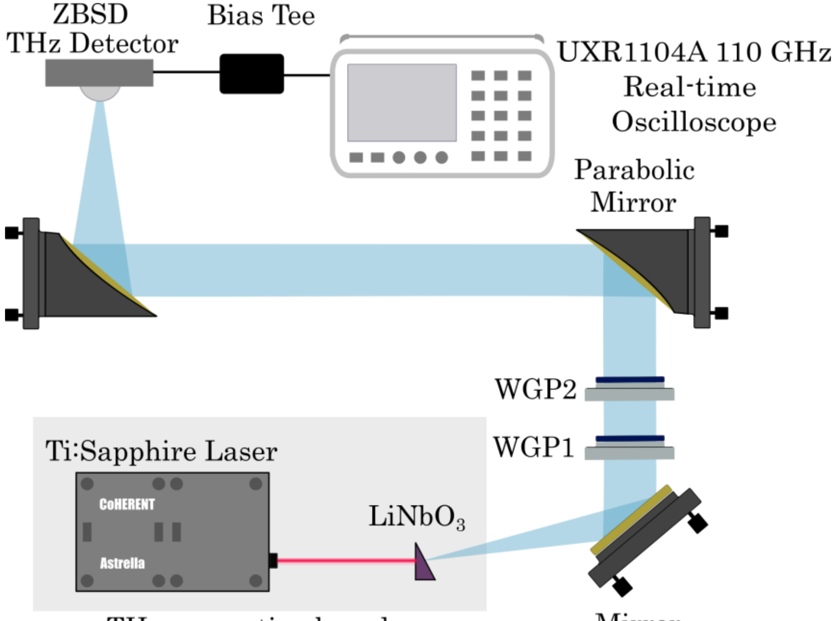
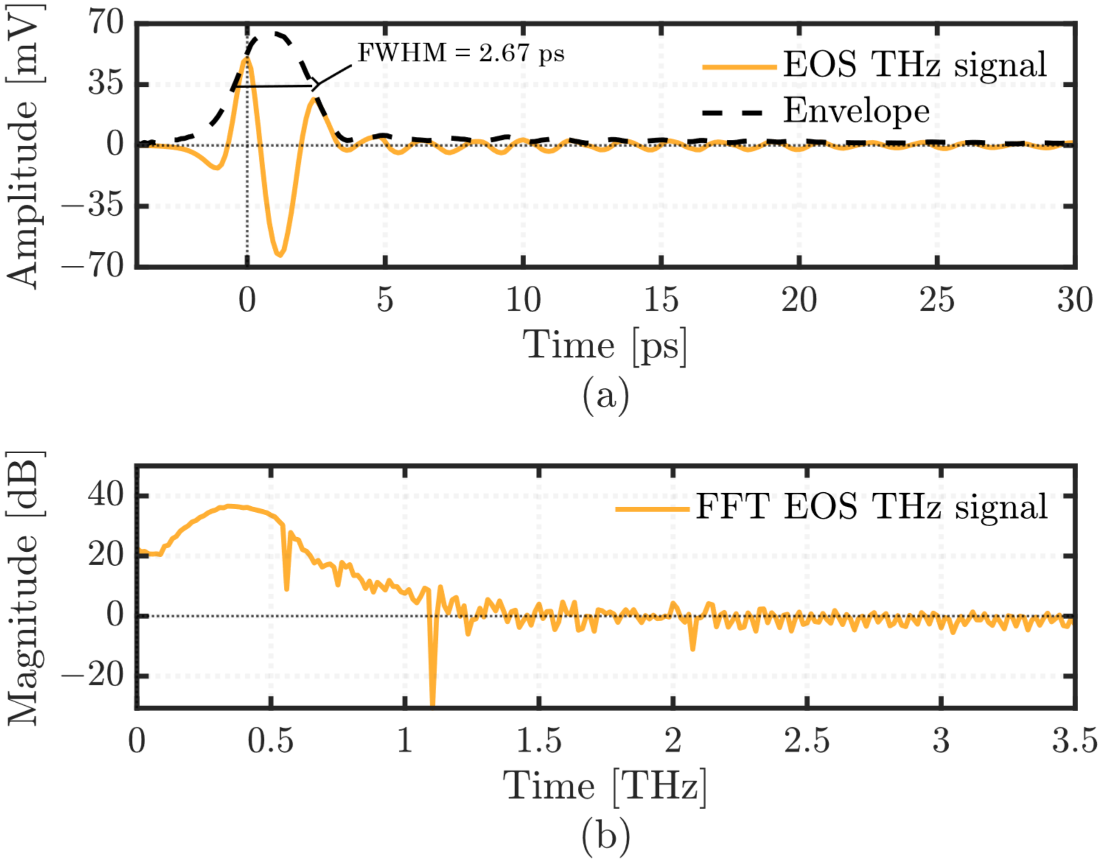
High-speed THz Detectors: Experimental Setup

- Pulsed THz source, repetition rate = 1 kHz, kW-level
- Driving laser ~800 nm
- Read-out with a real-time high-speed oscilloscope
- Spectral pulse characterization with electro-optic sampling setup





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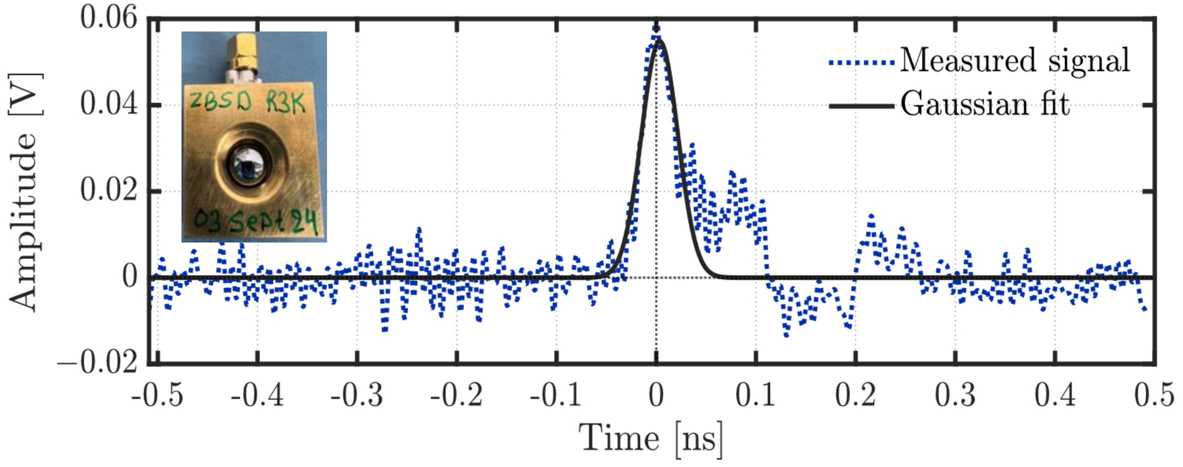
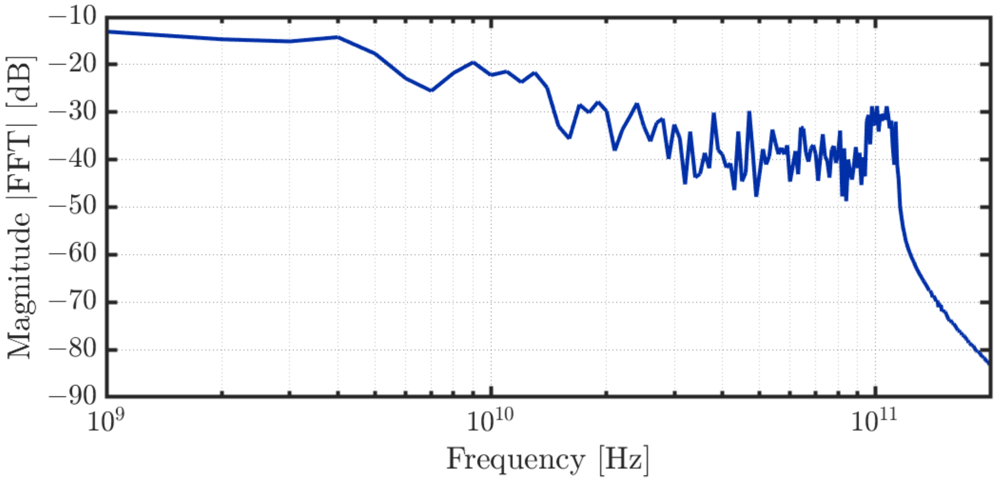
High-speed THz Detectors: Realization

Schottky diode-based THz Detector



- Measured rectified THz pulse at P_{av} = 8.26 µW ($P_{pk} = 4.37\ kW$)
- FWHM = 38.11 ps, $\tau_r = 22.9$ ps and $\tau_f = 45.04$ ps

Measured Signal FFT



- Extracted peak voltage responsivity:13.73 µV/W
- 1 to 5 GHz: flat response, followed by 20 dB/decade up to 30 GHz
- IF response+detector response+match/mismatch

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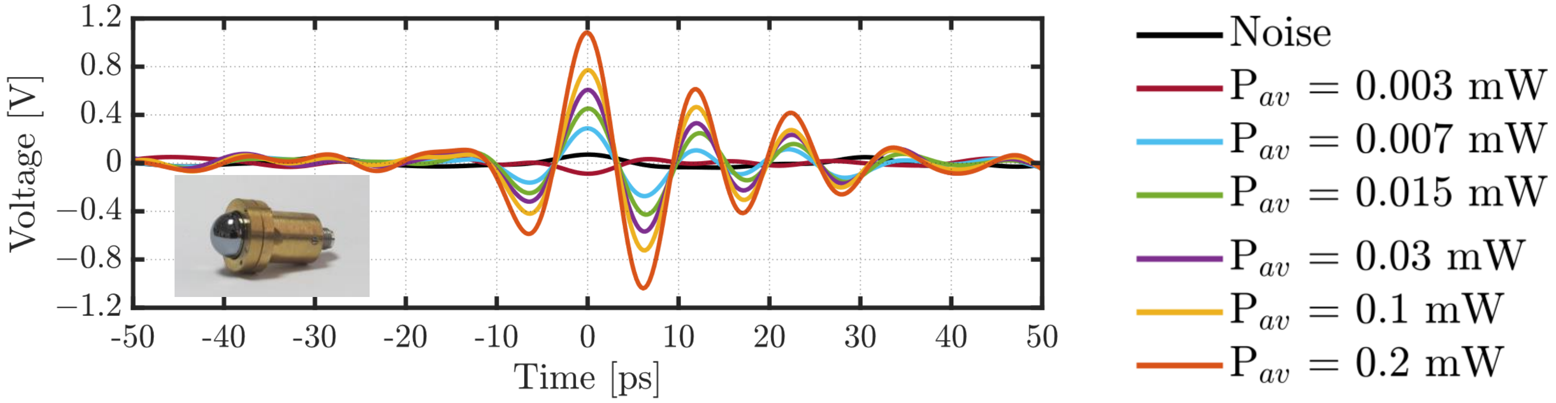
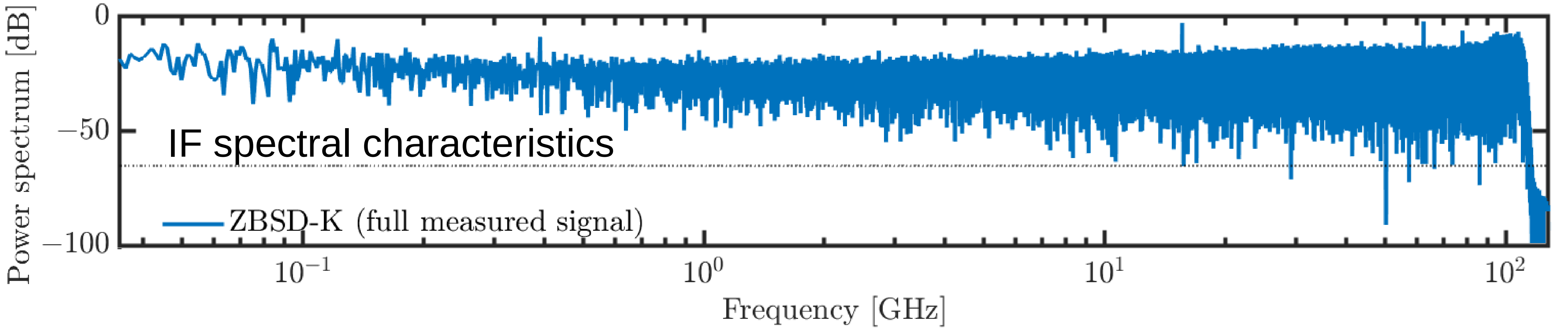
High-speed THz Detectors: Only IF Path Characteristics

Interesting observation with High power case (P_{pk}~MW- tens of MW)

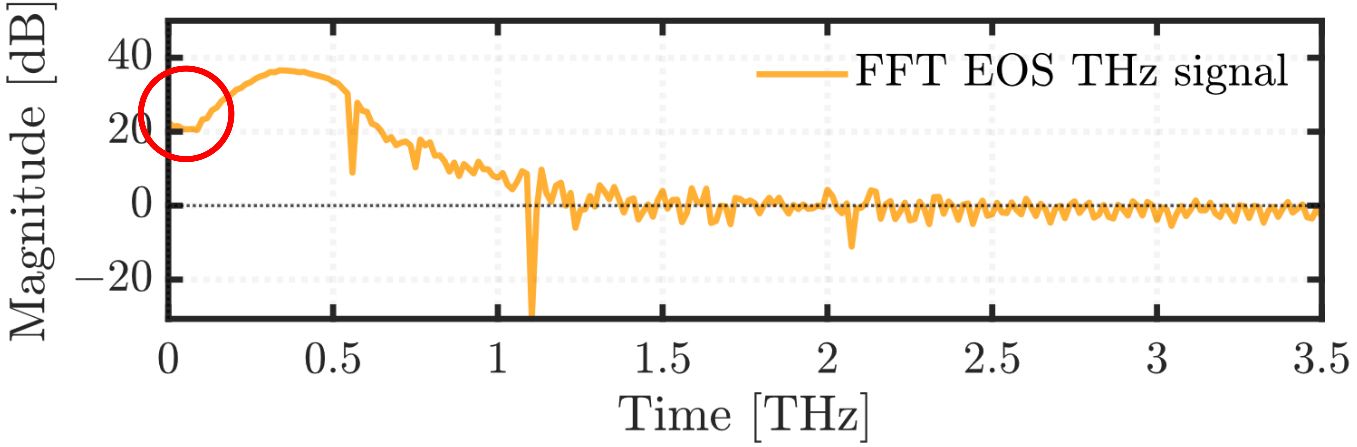


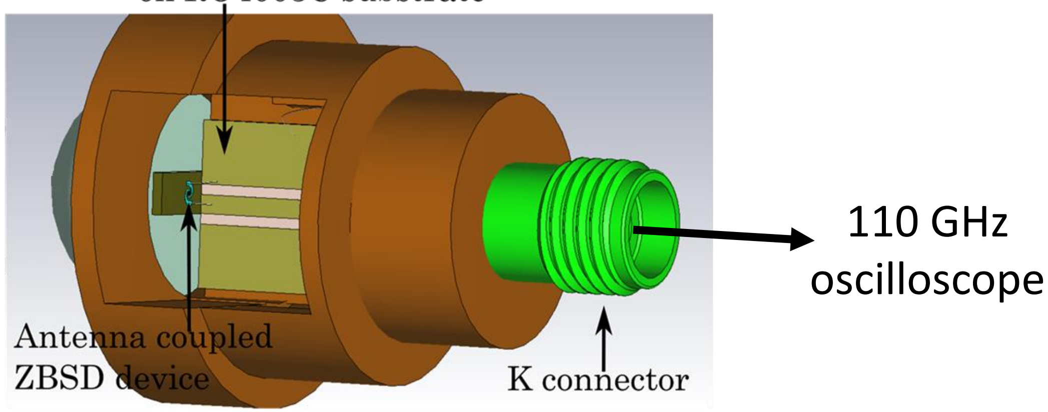
- Detected signal is larger than the built-in Schottky diode potential (unphysical!)

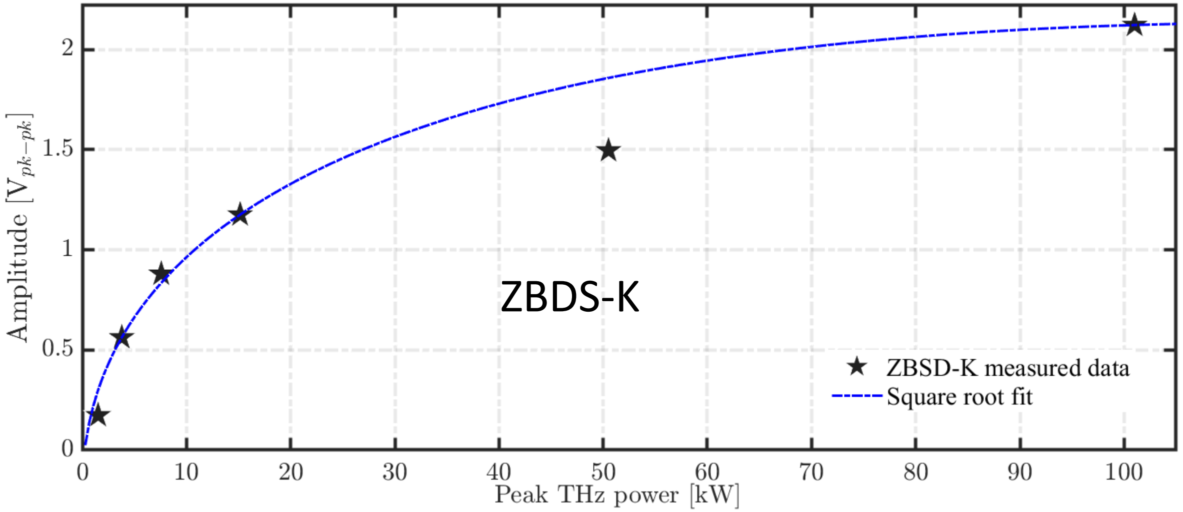
→ superposition of two detection processes?!



High-speed THz Detectors: Only IF Path Characteristics







- 110 GHz oscilloscope sees **directly** the THz components of the pulse **<110 GHz**
- $V_{out} \sim U_{THz} \sim \sqrt{P_{THz}}$
- Unsuited for detector characterization
- Still suited for characterizing the IF path w/o device

Longitudinal Electron Bunch Diagnostics

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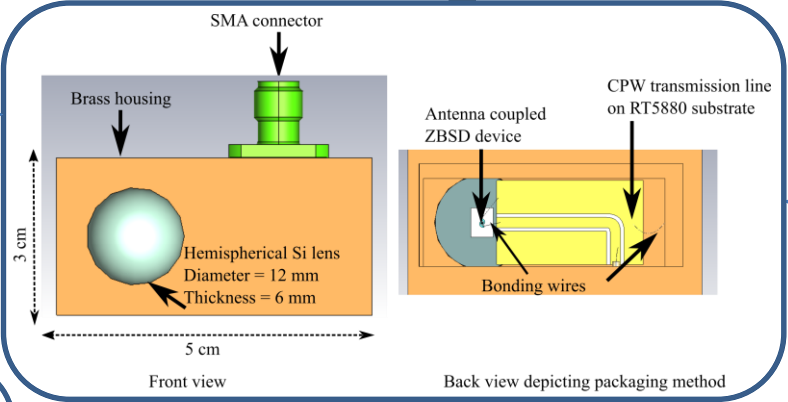
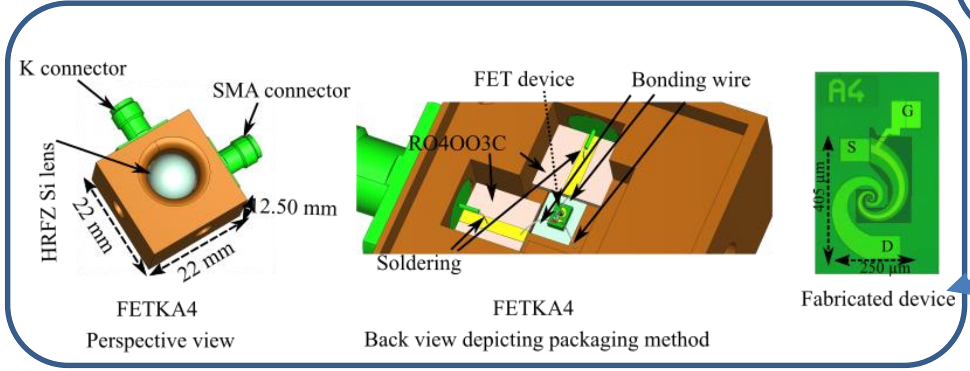
Longitudinal Electron Bunch Diagnostics: Bunch Charge

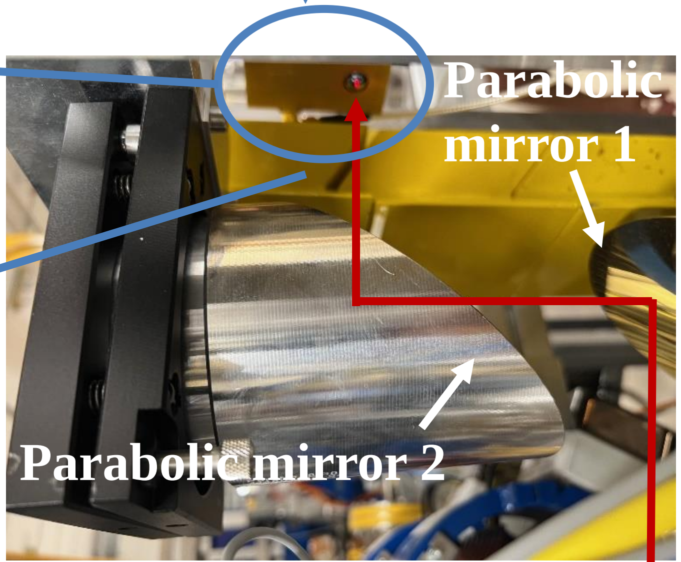
Zero-bias Schottky diode (ZBSDA)



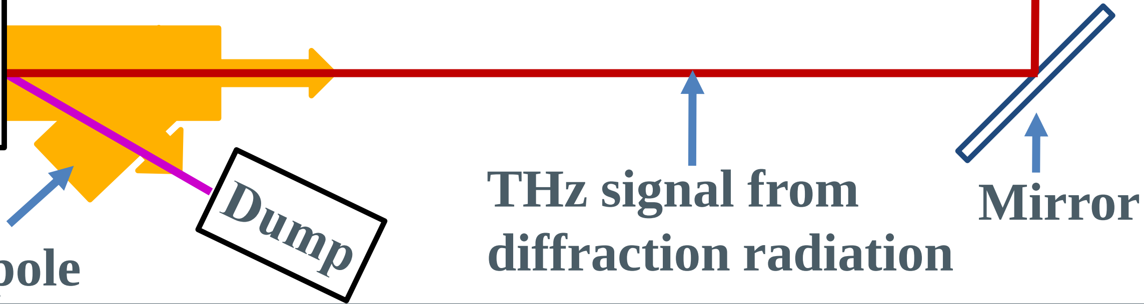
GaAs TeraFET (FETKA4)



THz Detector



Accelerator beamline at TELBE (U300), HZDR, Dresden



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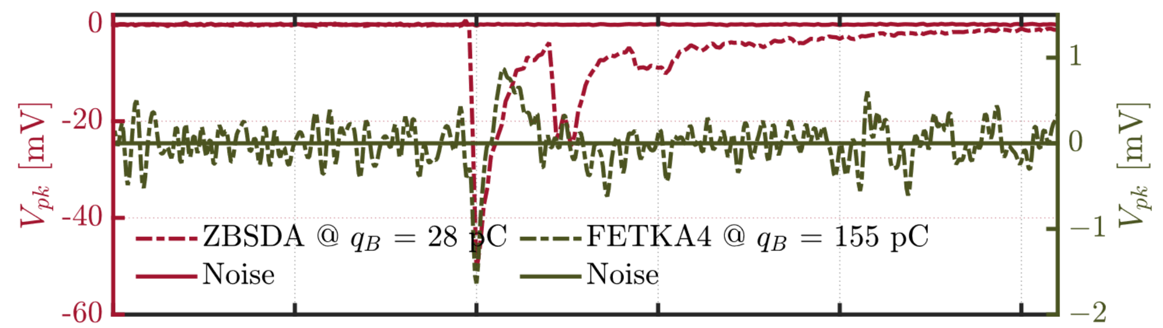
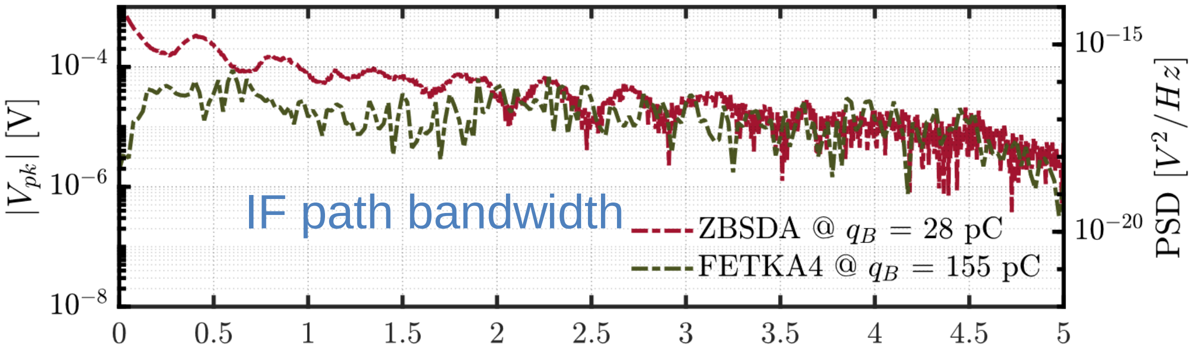
Longitudinal Electron Bunch Diagnostics: Bunch Charge

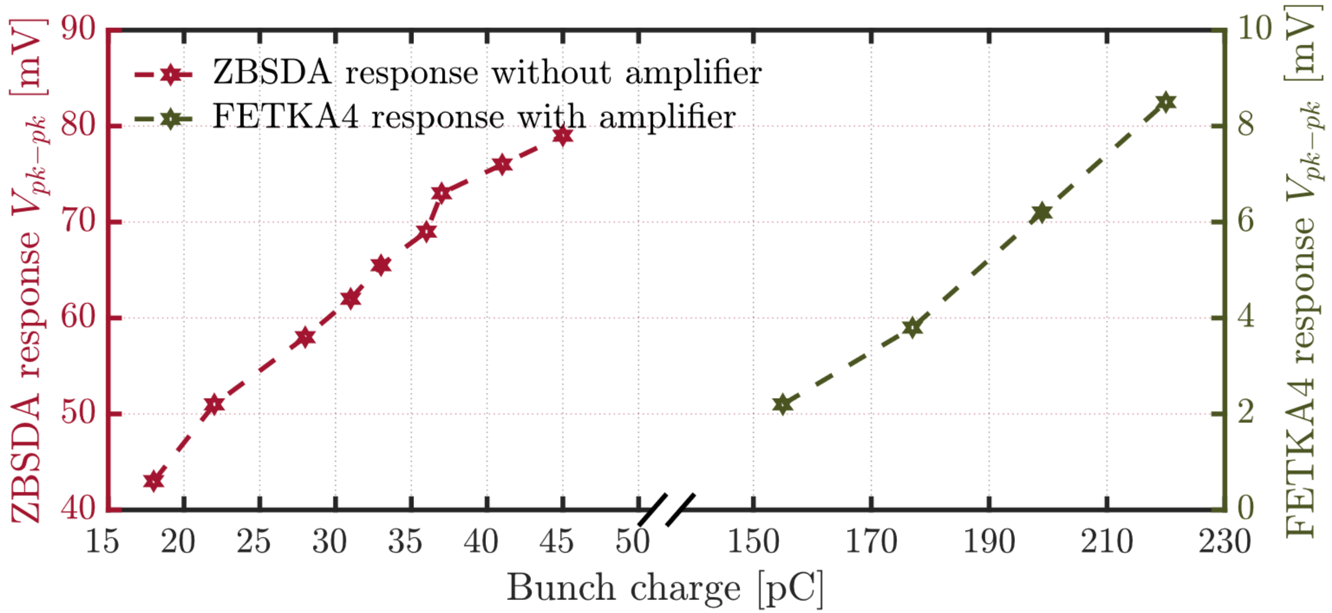


(a)



(b)

- Bunch charge sweep:
  ZBSDA: 18 to 45 pC, without amplifier
  FETKA4: 155 to 220 pC, with LNA amplifier (ZX60-P33ULN+)
- ZBSDA: 3 dB bandwidth of 0.47 GHz with 15 dB losses till 4 GHz
- FETKA4: Almost flat response up to 3.5 GHz



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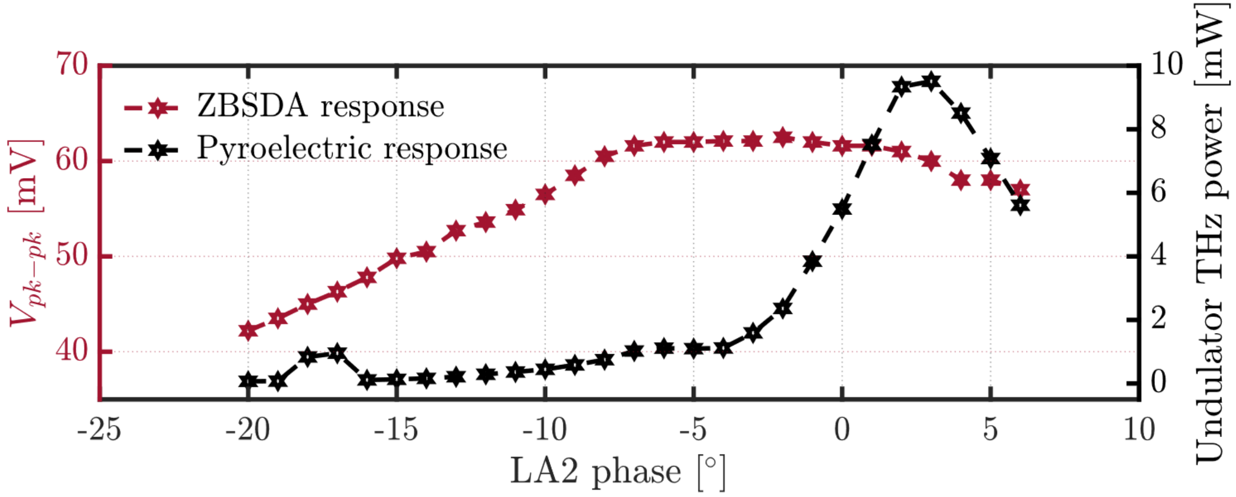
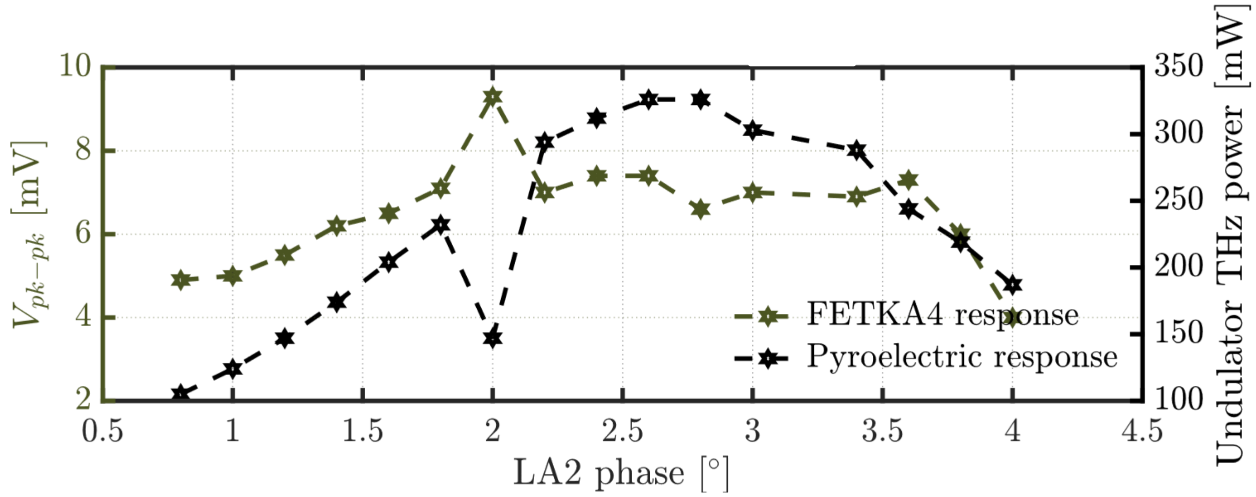
Longitudinal Electron Bunch Diagnostics: Bunch Compression

- Reference measurement: Ophir 3A-P-Thz thermal detector
- LA2: arbitrary offset phase, used to tune RF cavities, which induces the phase difference in the electron bunches
- ZBSDA: shows linear trend between -20° and -10° , where the thermal detector is almost insensitive
- FETKA4: shows a similar trend to the pyroelectric detector in the whole bunch compression range





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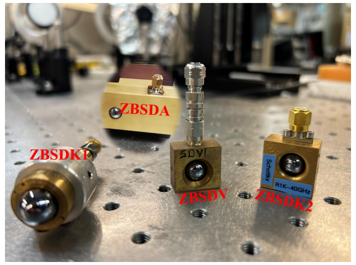
Summary and Outlook

Summary & Outlook

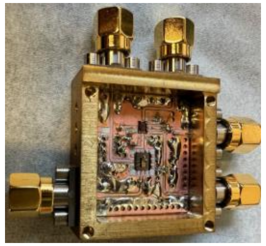
Summary

- Room-temperature operable, fast, compact and robust direct THz detectors
- Two types of detector technologies
- Ultra-broadband THz detectors from microwave to mid-infrared frequency range
- THz detectors capable of longitudinal diagnostics from single-digit pC to three-digit pC electron bunch charges



Outlook

- Higher 3 dB THz bandwidth
- Integration of the developed detectors with various post-detection electronics
- Thorough characterization of these detectors in the BCM process
- Detectors realization at various facilities



Thank you for your attention and questions are welcome

Team @ THM

Team @ TU Darmstadt

This work is supported by the German Federal Ministry of Education and Research (BMBF) under contract no. 05K22RO1 & 05K22RD1 and also by Hesse ministry of science and culture.