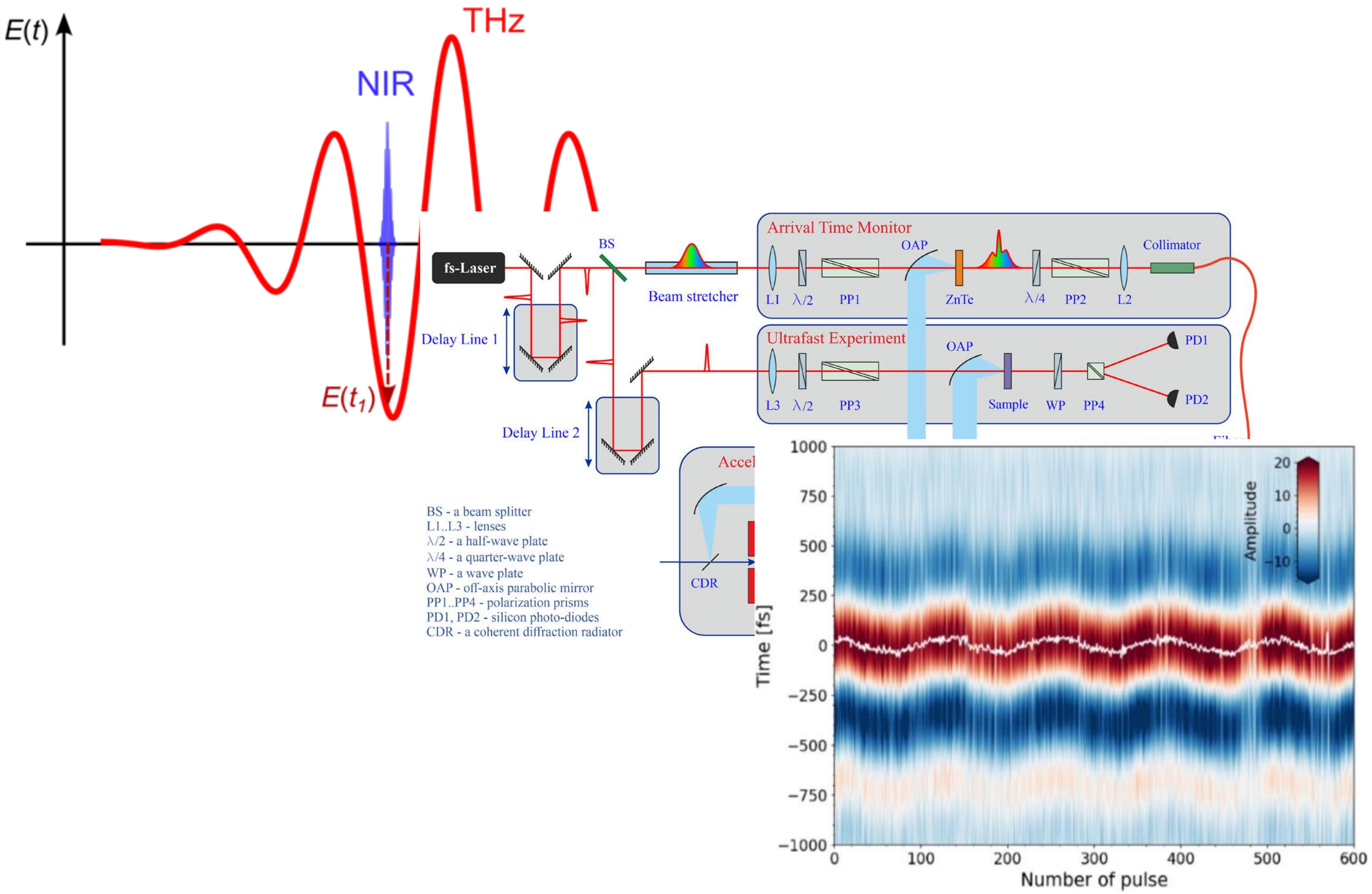
Sub-Cycle Terahertz Diagnostics

Jan-Christoph Deinert · TELBE THz facility · Institute of Radiation Physics

Outline

- Introduction THz detection

- Coherent Detection
  - Electro-optic sampling
  - (Single-shot) Spectral decoding
  - EO sampling-based diagnostics
  - Phase-resolved FEL



TELBE at HZDR

ELBE center (back) and high-magnetic field lab.

Sebastian Maehrlein
Department leader (since June 2024)

Jan-C. Deinert
TELBE, Young investigator group

Igor Ilyakov
Beamline Scientist, THz-driven dynamics

Alexey Ponomaryov
Sample environments and computational analysis

Thales de Oliveira
SNOM and infrared

Sergey Kovalev
Beamline scientist, team leader (until 09/2023 now at TU Dortmund)

Acknowledgements and collaborations

ELBE

Andreas Wagner
Ulf Lehnert
André Arnold
Michael Kuntzsch

Collaborations

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF — FELBE: O. Pashkin, S. Winnerl, M. Klopf

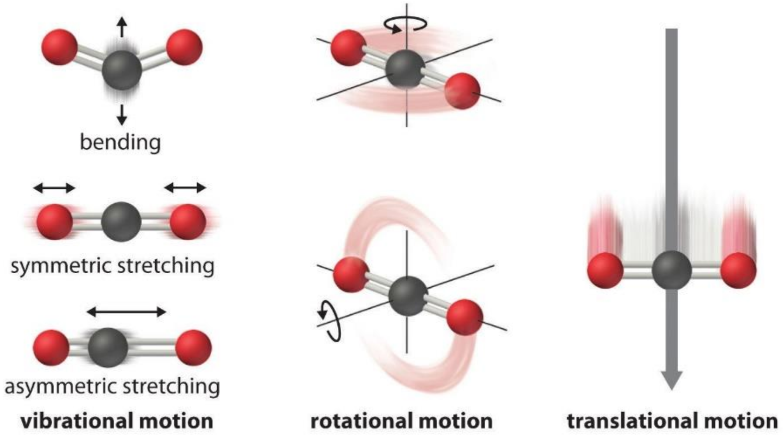
FERMI @elettra — A. Perucchi, L. Foglia

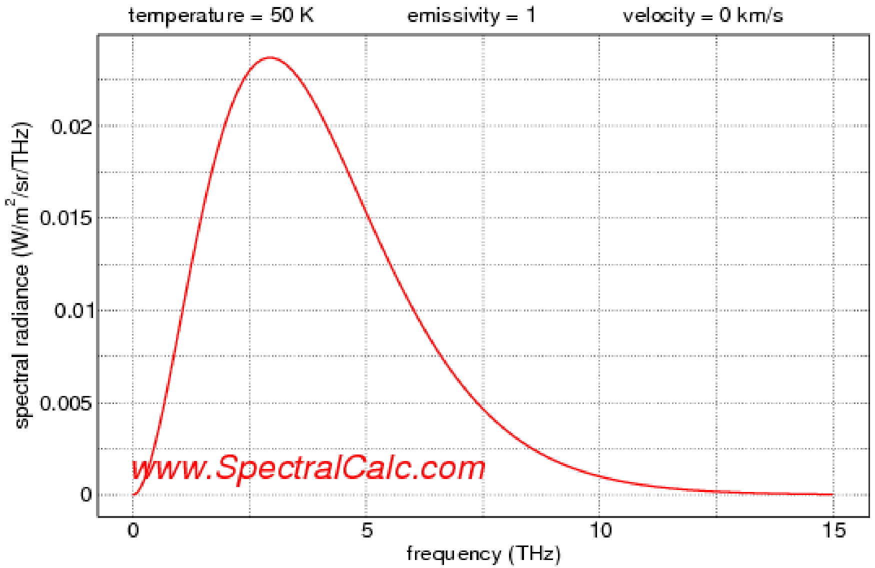
European XFEL — A. Scherz, R. Carley

Bundesministerium für Bildung und Forschung
DFG Deutsche Forschungsgemeinschaft German Research Foundation
STAATSMINISTERIUM FÜR WISSENSCHAFT KULTUR UND TOURISMUS | Freistaat SACHSEN
CALIPSOplus
PHYSICS OF LIFE
EUCALL
DRESDEN concept

THz basic properties

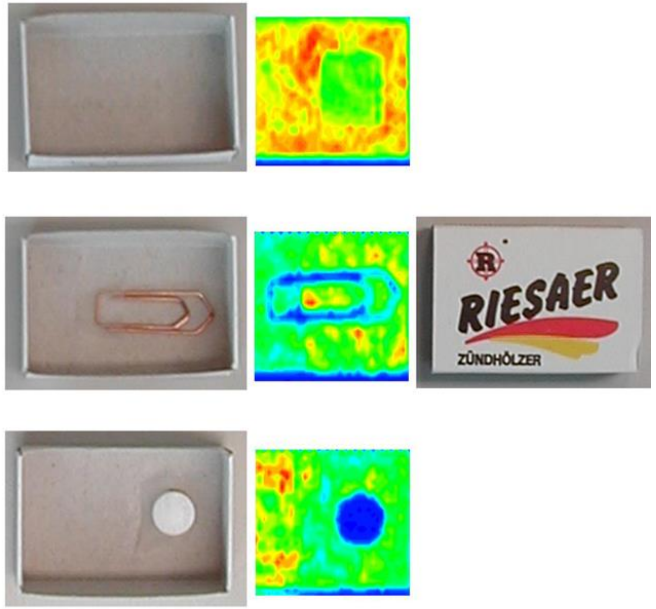
- Molecular rotations, lattice vibrations → thermal radiation
- Black body: emission maximum at 50 K → 3 THz





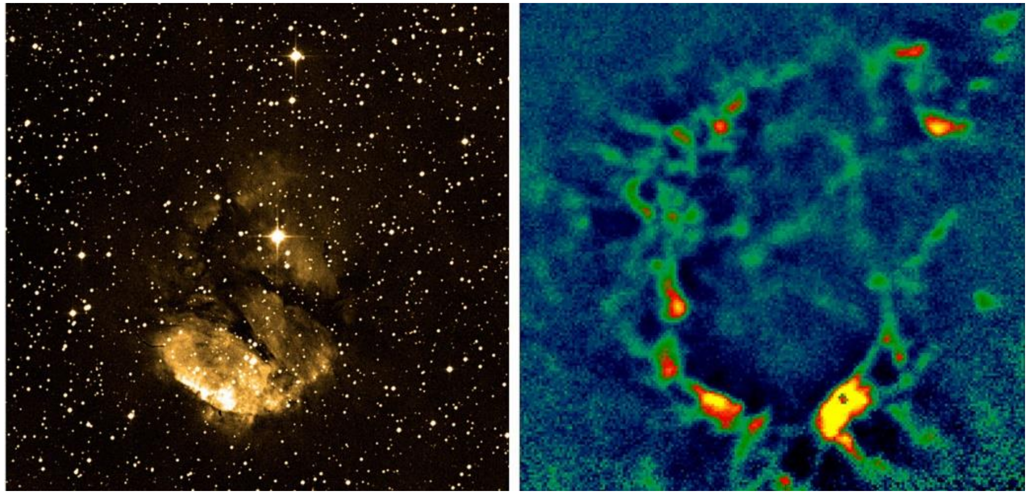
Ubiquitous incoherent THz background.
Strong absorption by water molecules.

Applications of continuous wave THz radiation



- THz transmitted through plastic, fabrics, not metals
- Characteristic absorption spectra depending on material.
- Non ionizing.

→ **Security applications**



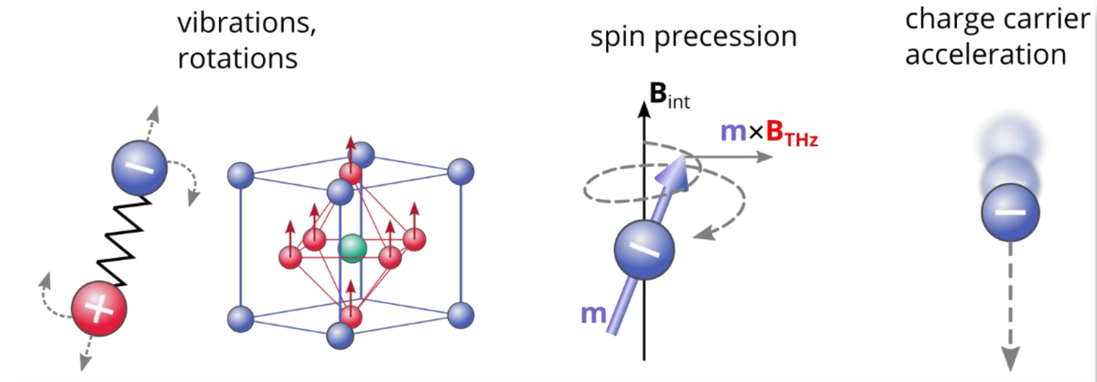
Astronomy:

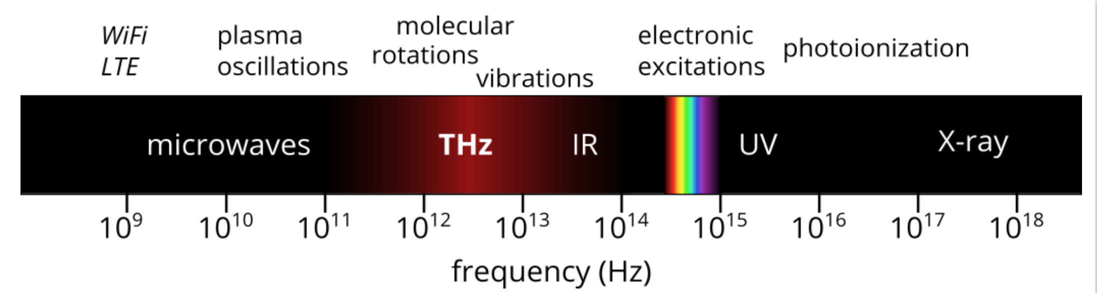
- Gas clouds as nucleus for start formation:
  → THz signatures ($T \approx$ -250°C)

Via: https://www.weltderphysik.de/gebiet/teilchen/licht/elektromagnetisches-spektrum/terahertz-wellen

Low-energy modes in THz regime

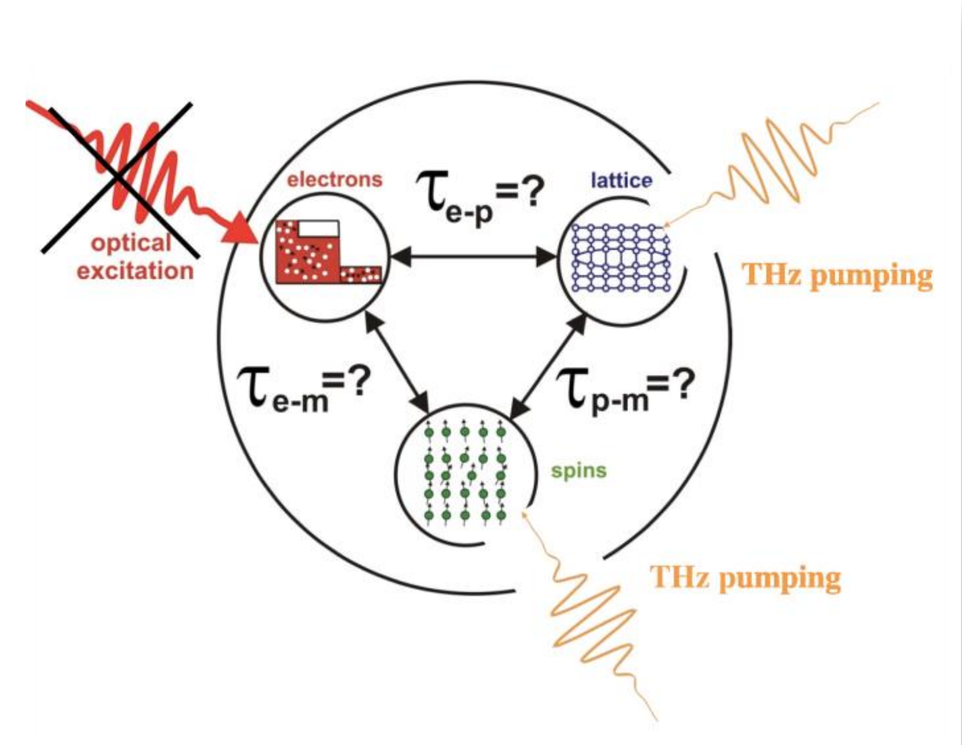
Terahertz frequencies (1 THz ≙ 4.1 meV) correspond to lowest energy motions / quanta





THz drive:

- Direct electronic transitions avoided.
- Coherent **selective excitation** of relevant modes



Courtesy of I. Radu, MBI Berlin

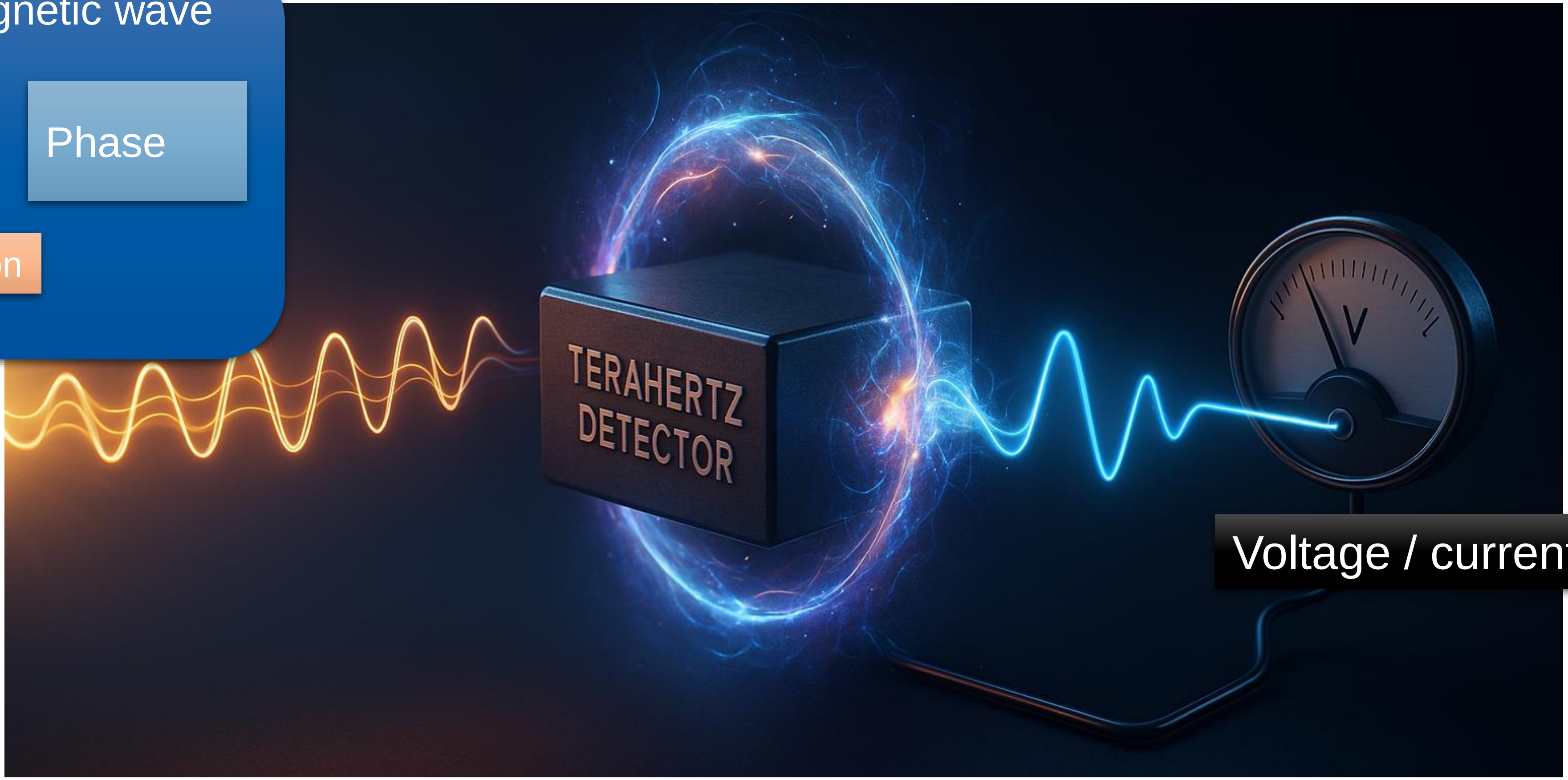
Terahertz detection

Introduction

“Convert an incoming signal into a convenient form for observation and analysis.”

Electromagnetic wave

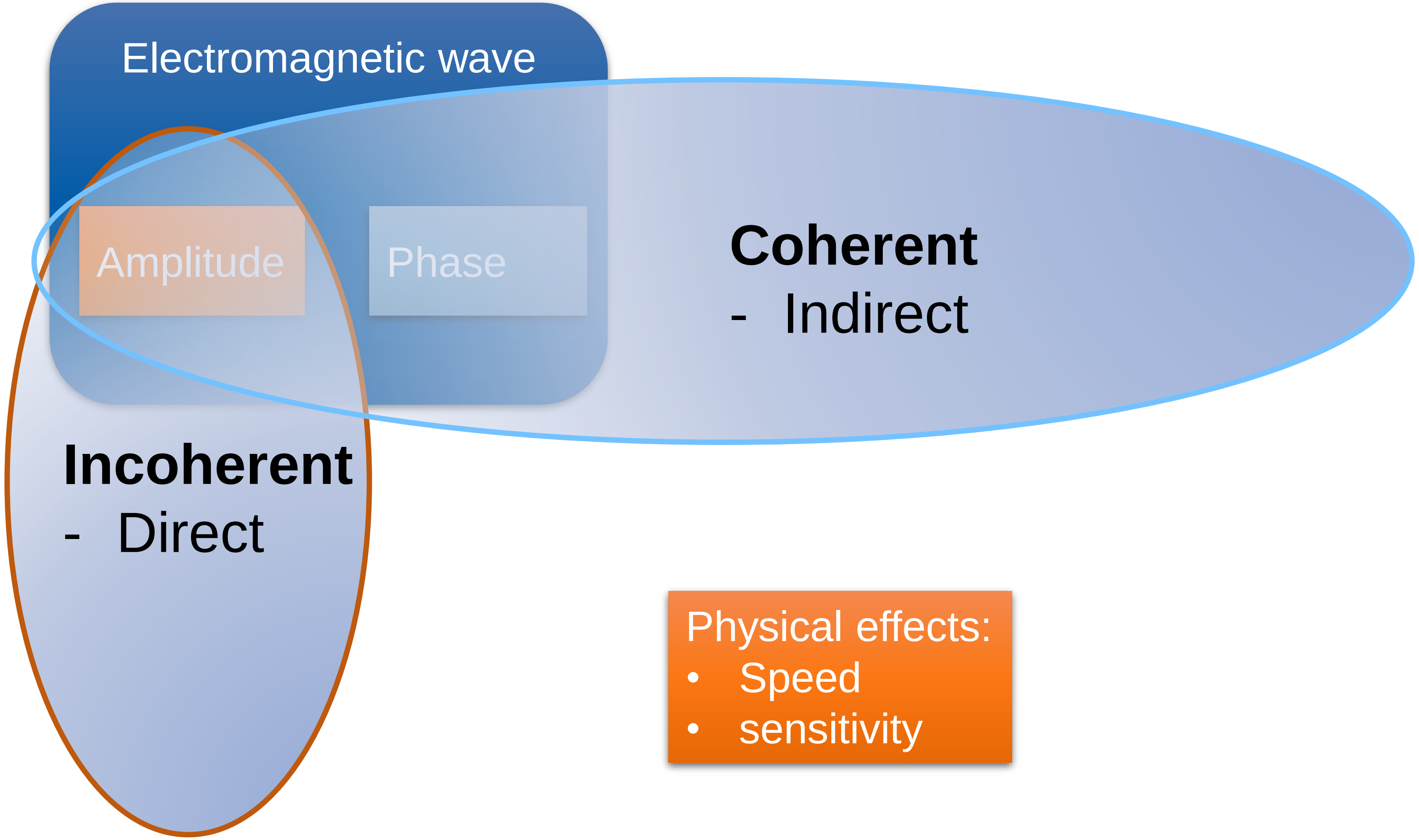
- Amplitude
- Phase
- polarization



Voltage / current signal

Terahertz detection

Introduction



Physical effects:

- Speed
- sensitivity

Terahertz detection

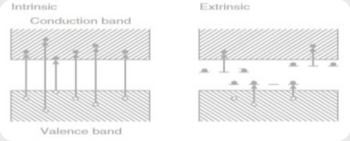
Introduction

Thermal detectors

- Radiation → Heat
- Pyroelectric
Golay cell
Bolometer
- Typically slow
- Wide spectral range

Photodetectors

- Electronic excitations → resistance change



- Semiconductors Ge:Ga, n-InSb, GaAs
- Strong cooling required

Rectifiers

- Schottky diodes
- Delicate and unreliable
- Promising recent developments.

Mixers

- Heterodyne detection
- Noise suppression and bandwidth selectivity
- Applications with several types of detectors

Time-domain spectroscopy

- Electro-optic sampling
- Requires ultrashort pulsed lasers
- Ambient conditions
- Full characterization of amplitude and phase

E. Bründermann et al., “Terahertz Techniques”, Springer Series in Optical Sciences 151 (2012).

Electro-optic sampling

Full characterization of electric-field waveform in amplitude and phase

Pockels effect (linear **electro-optic effect**)

EO tensor

$$\Delta n = n_0^3 \cdot r_{\mathrm{eff}} \cdot E(t)$$

- Nearly instantaneous local modulation Δn of the refractive index by electric field $E(t)$.

- Only in non-centrosymmetric media: zincblende type (ZnTe, GaP, ...), $\mathrm{LiNbO_3}$, ...

Advantages:
- Sensitivity
- Dynamic range
- Temporal resolution

Electro-optic sampling

Typical detection scheme

1. THz test wave *E*(*t*) induces transient birefringence in EO crystal.
2. NIR gate pulse samples *E*(*t*) in EO crystal.

Slightly **elliptical** polarization of gate pulse after EO crystal with phase

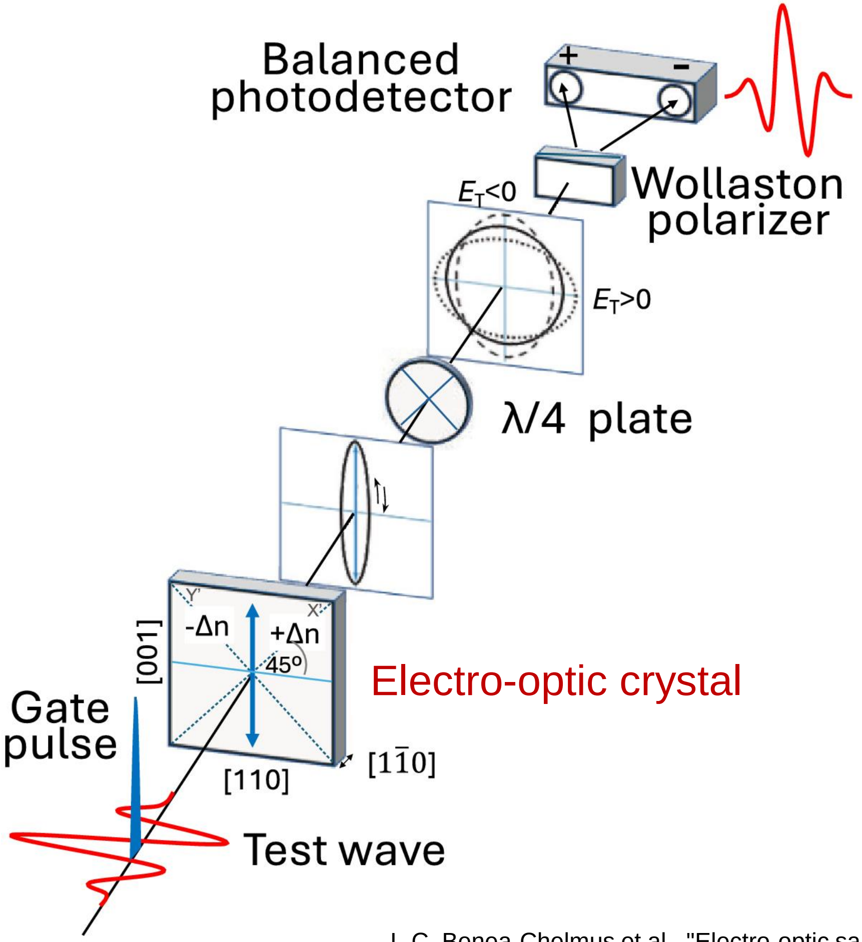
$$\theta = \frac{\omega l}{c} \Delta n.$$

${}^{\lambda}/_{4}$ wave plate set to **circular** polarization for $\theta = 0$.

Separation of vertical and horizontal components by Wollaston polarizer and detection by balanced photodetector:

$$\frac{\Delta I}{I} = \frac{I_{\text{vert}} - I_{\text{horiz}}}{I_{\text{vert}} + I_{\text{horiz}}} = \sin 2\theta \approx 2\theta = \frac{\omega l}{c} n_0^3 \cdot r_{\text{eff}} \cdot E(t)$$

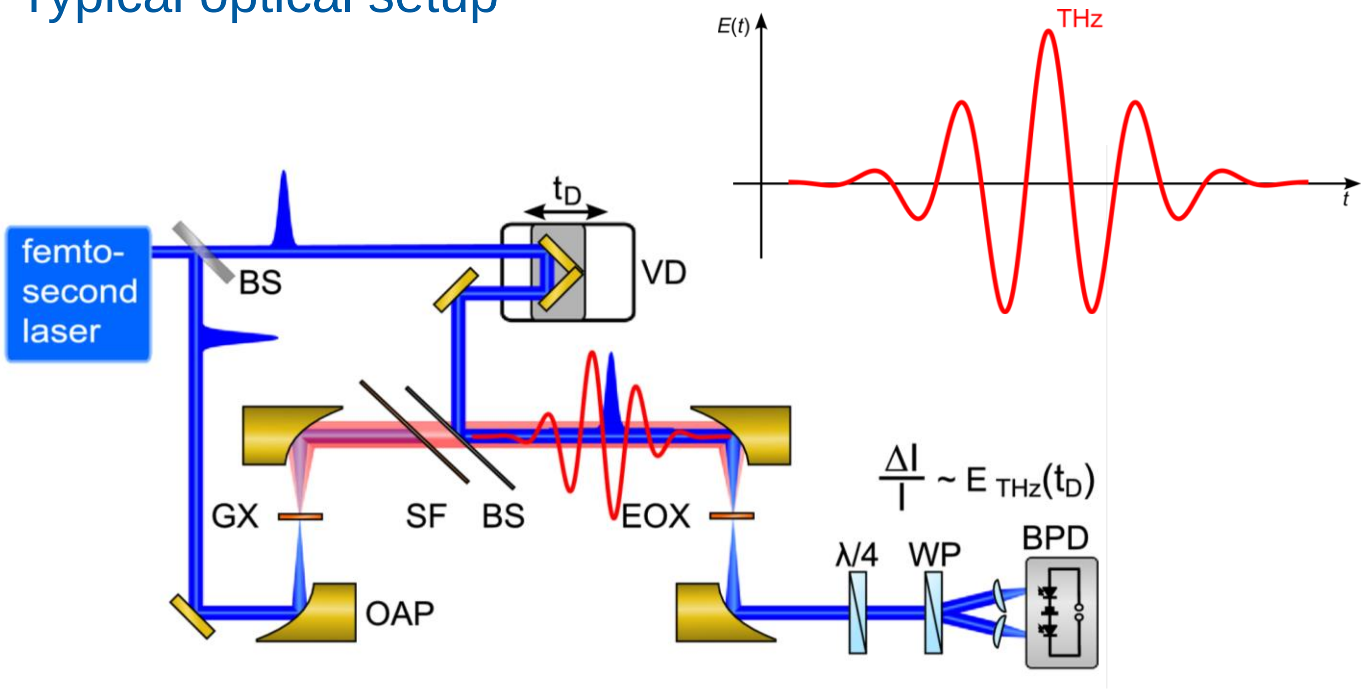
Linear relation

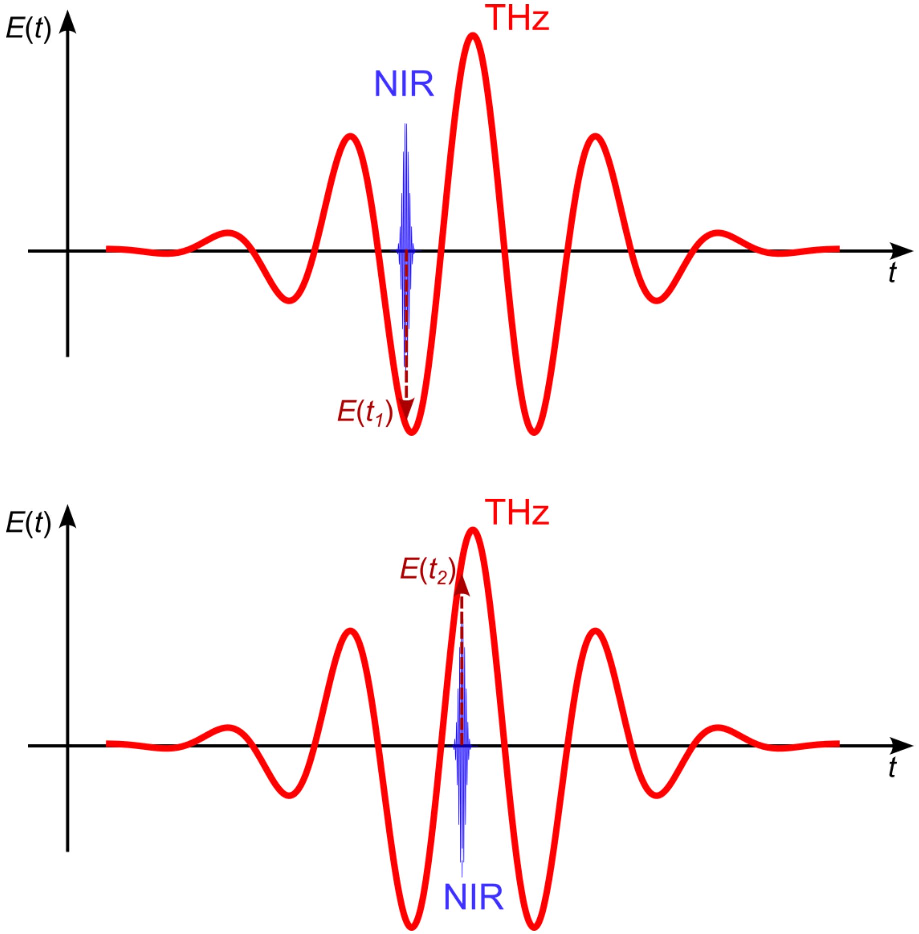


I.-C. Benea-Chelmus et al., "Electro-optic sampling of classical and quantum light," Optica **12**, 546-563 (2025)

Electro-optic sampling

Typical optical setup





- Sampling pulse shorter than half cycle of THz pulse.
- Variable time delay for tracing THz field over many single pulses.

I.-C. Benea-Chelmus et al., "Electro-optic sampling of classical and quantum light," Optica **12**, 546-563 (2025)

2D Electro-optic sampling

Characterization of amplitude, phase and **polarization state** of arbitrary THz waveforms

EOS schemes can be extended to measure complex polarization states.

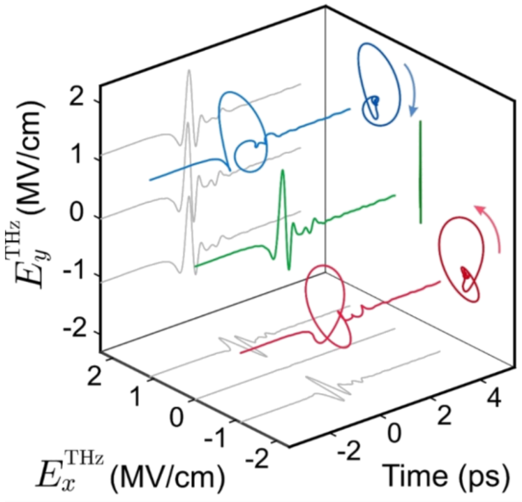
THz helicity shaping
as important prerequisite for
- Coherent control of chiral quasparticles
- Chiral or helical nonlinear phononics.

α-Quartz as EO material for high field (> 100 kV/cm) applications:
- Linear
- Low-cost
- High dynamic range
- High damage threshold.

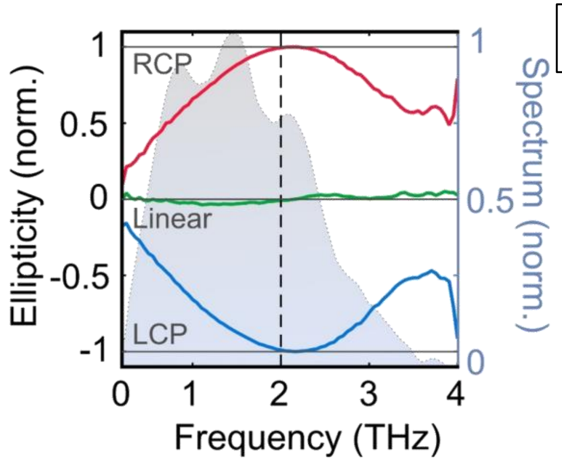
Symmetry allows full vectorial EOS just by measuring two probe poalrizations, e.g. $\vartheta = 0°$ and $\vartheta = 45°$.

M. Frenzel et al., "Quartz as an accurate high-field low-cost THz helicity detector," Optica **11**, 362-370 (2024)

Time domain

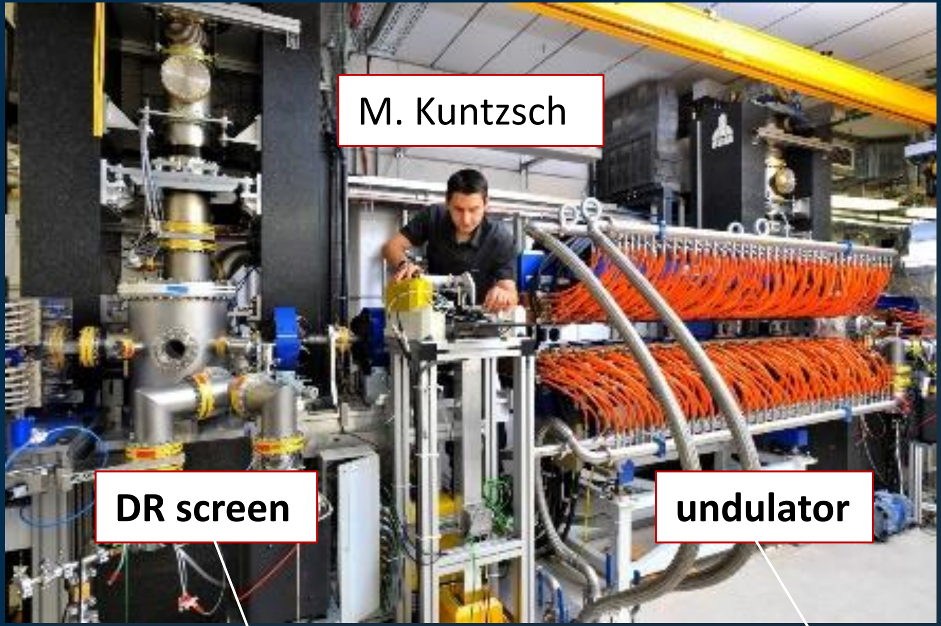


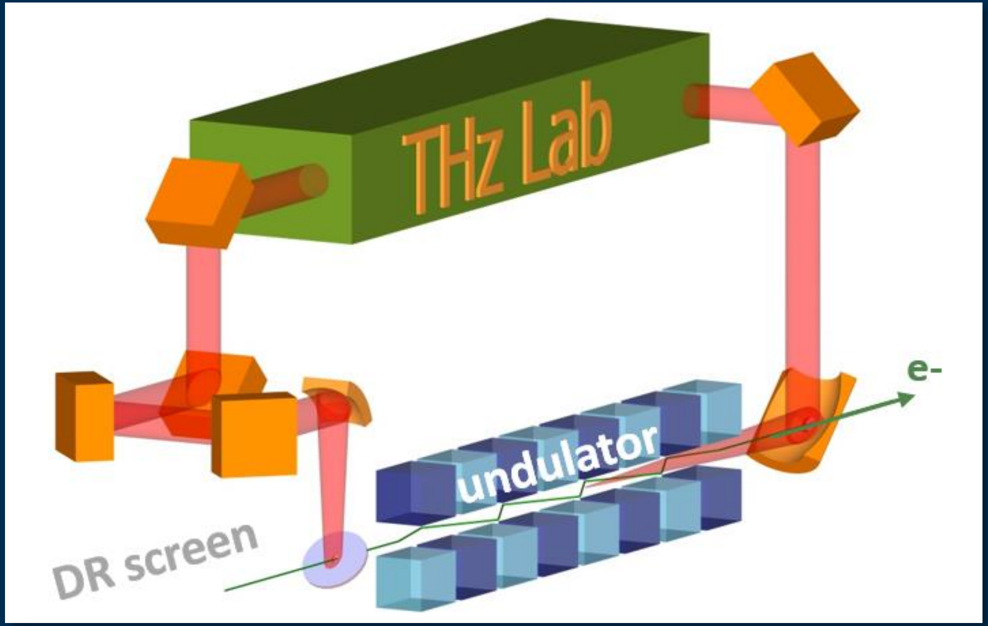
Frequency domain



EOS at accelerator facilities

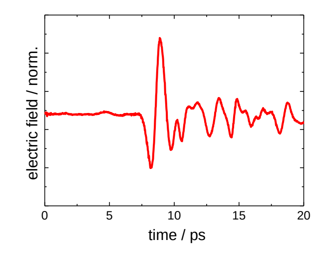
TELBE at HZDR

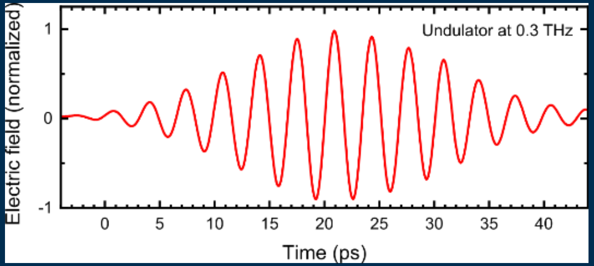




broadband

narrowband





EO sampling and jitter

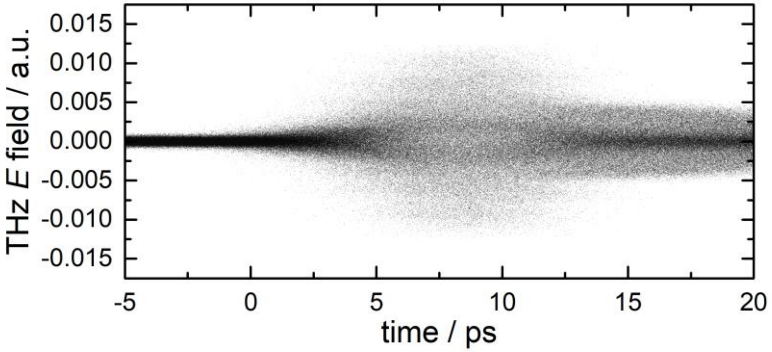
Combination of different types of light sources

THz
from accelerator-based source

+

800 nm probe
from table-top laser

Timing and intensity jitter



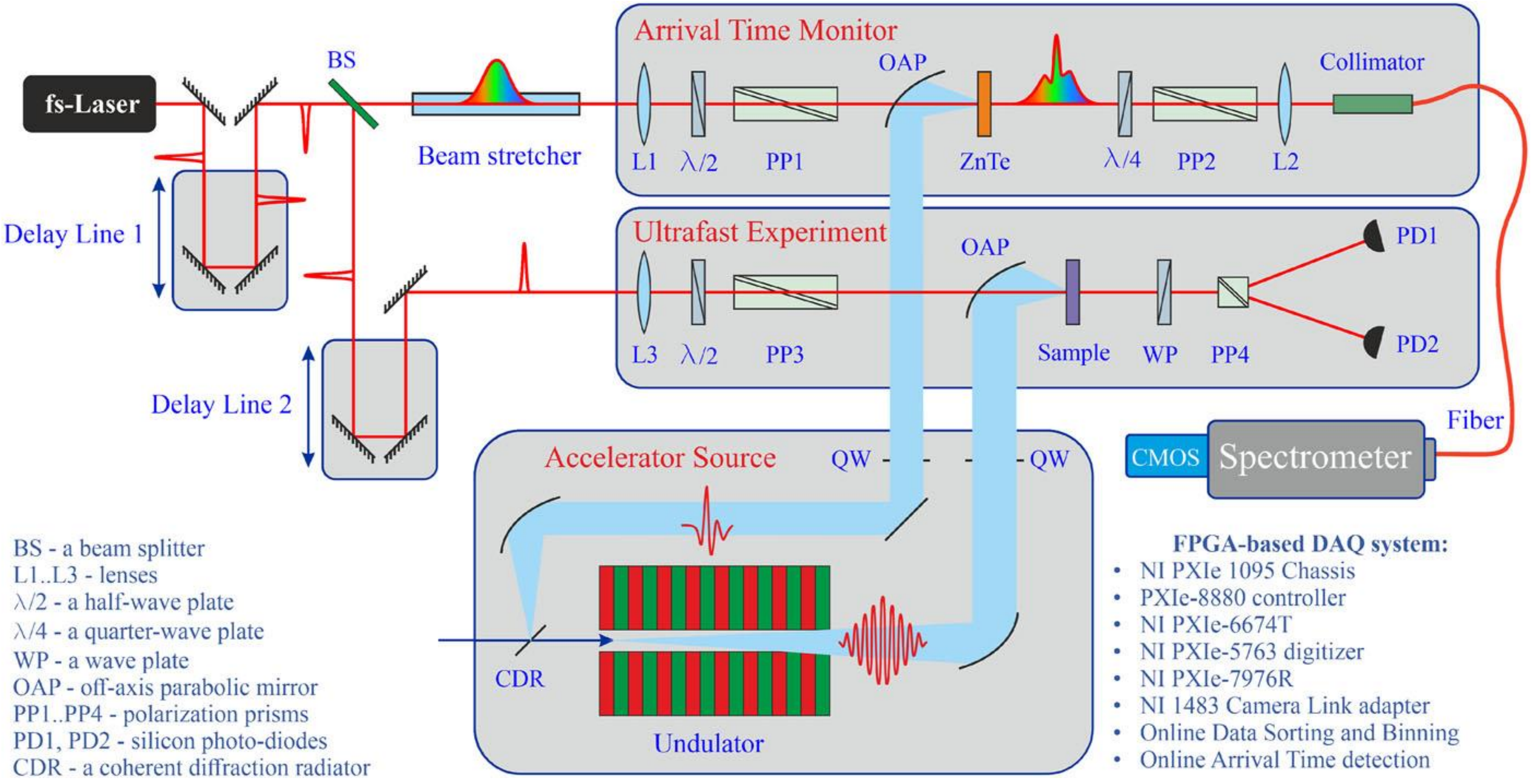
< 100 fs RMS jitter at TELBE

Sufficient for signals below 1.5 THz, above:
Spectral decoding and *post mortem* data sorting

S. Kovalev et al., *Struct. Dyn.* **4**, 024301 (2017),
B. Green et al., *Scientific Reports* **6**, 22256 (2016).

Spectral decoding

Single-shot EO sampling



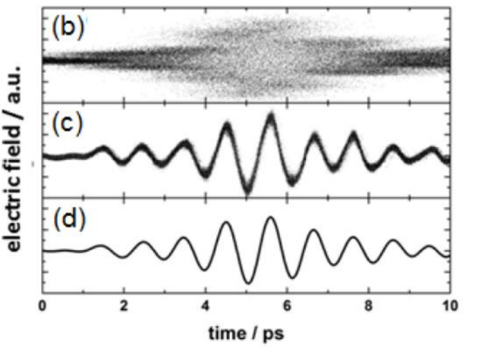
BS - a beam splitter
L1..L3 - lenses
λ/2 - a half-wave plate
λ/4 - a quarter-wave plate
WP - a wave plate
OAP - off-axis parabolic mirror
PP1..PP4 - polarization prisms
PD1, PD2 - silicon photo-diodes
CDR - a coherent diffraction radiator

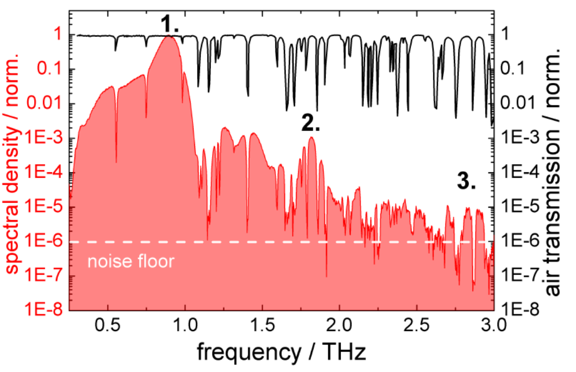
FPGA-based DAQ system:

- NI PXIe 1095 Chassis
- PXIe-8880 controller
- NI PXIe-6674T
- NI PXIe-5763 digitizer
- NI PXIe-7976R
- NI 1483 Camera Link adapter
- Online Data Sorting and Binning
- Online Arrival Time detection

A. Ponomaryov et al., *Rev. Sci. Instrum.* **95**, 103008 (2024)

THz-based bunch diagnostics

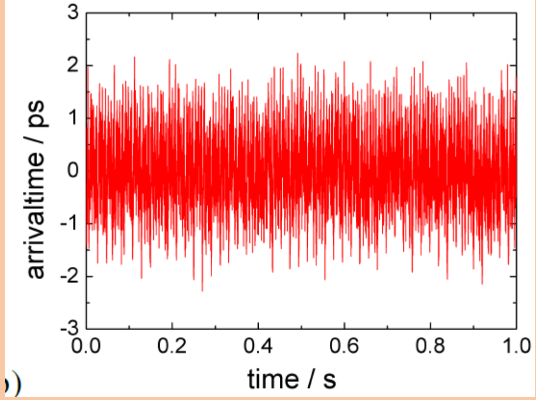


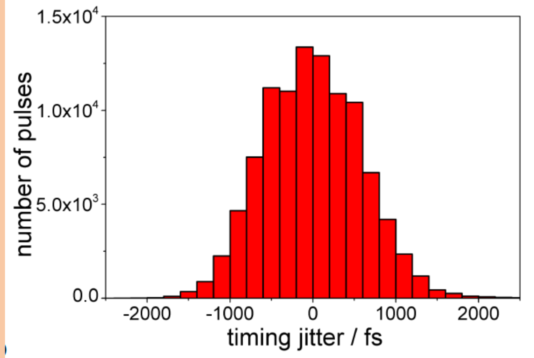


FFT shows:

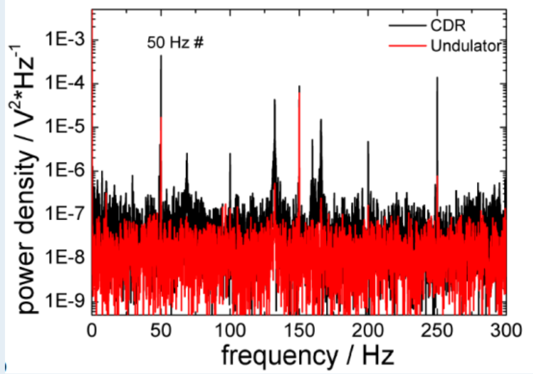
- Dynamic range
- Harmonics from the undulator.
- Water absorption in lab.

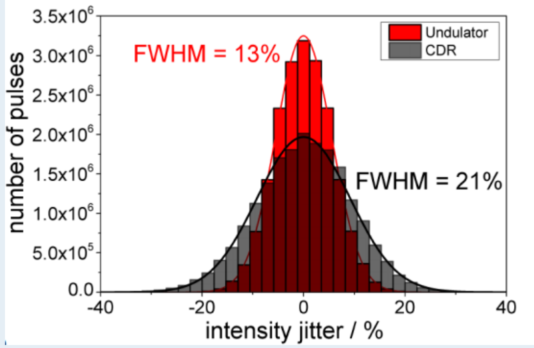
Arrival time





Intensity





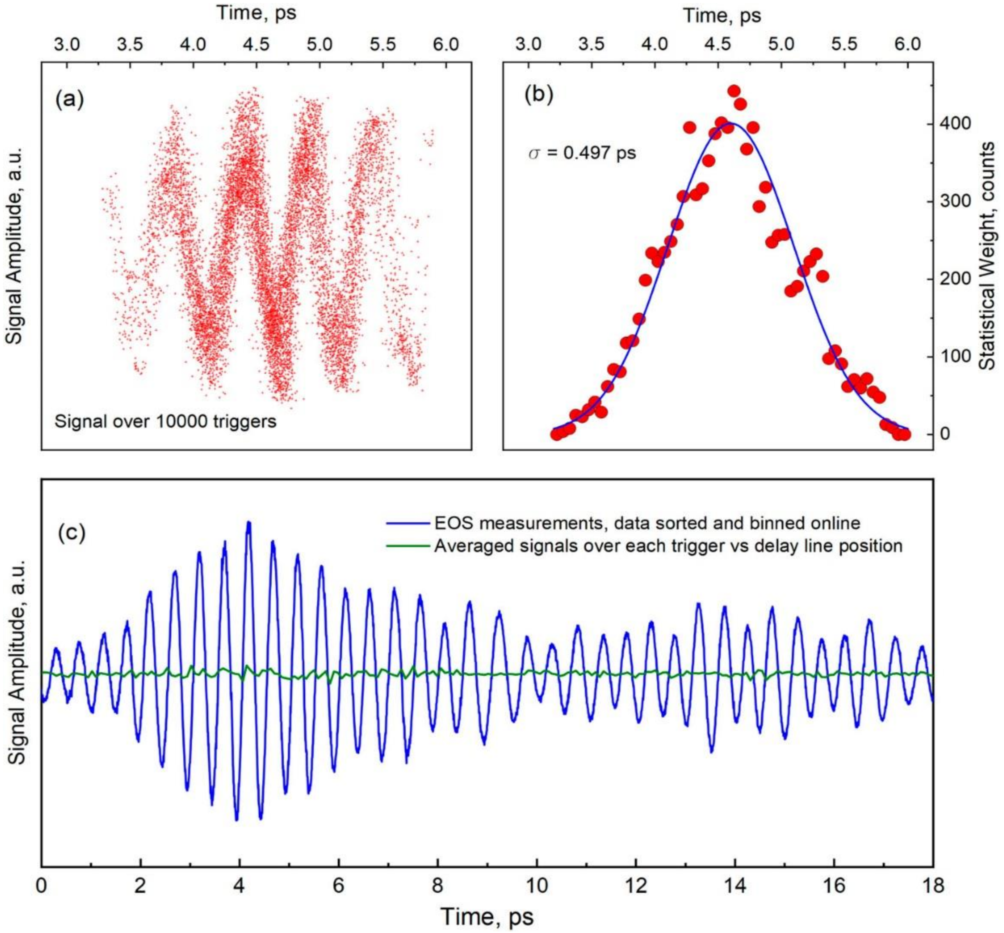
B. Green, *Superradiant Terahertz Sources and their Applications*, PhD thesis, KIT 2017.

Spectral decoding

Single-shot EO sampling on the fly

FPGA-based online data analysis

- Record, distribute and analyze 50000 datasets per second.
- Immediate data visualization to user.
- Detection bandwidth increased to > 10 THz.

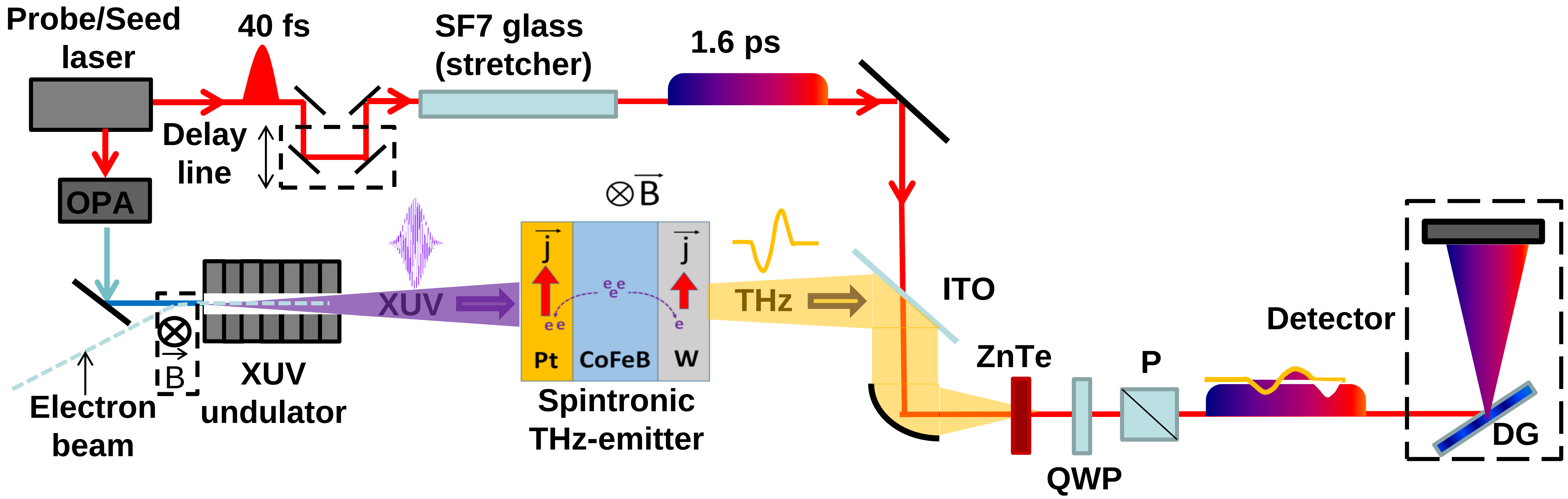


Demonstration of FPGA performance on dataset with 500 fs RMS jitter. Clear EOS trace of 2.1 THz signal achieved.

A. Ponomaryov et al., *Rev. Sci. Instrum.* **95**, 103008 (2024)

THz diagnostics for XFELs

THz fingerprints of XUV generation revealed in sigle-shot EOS

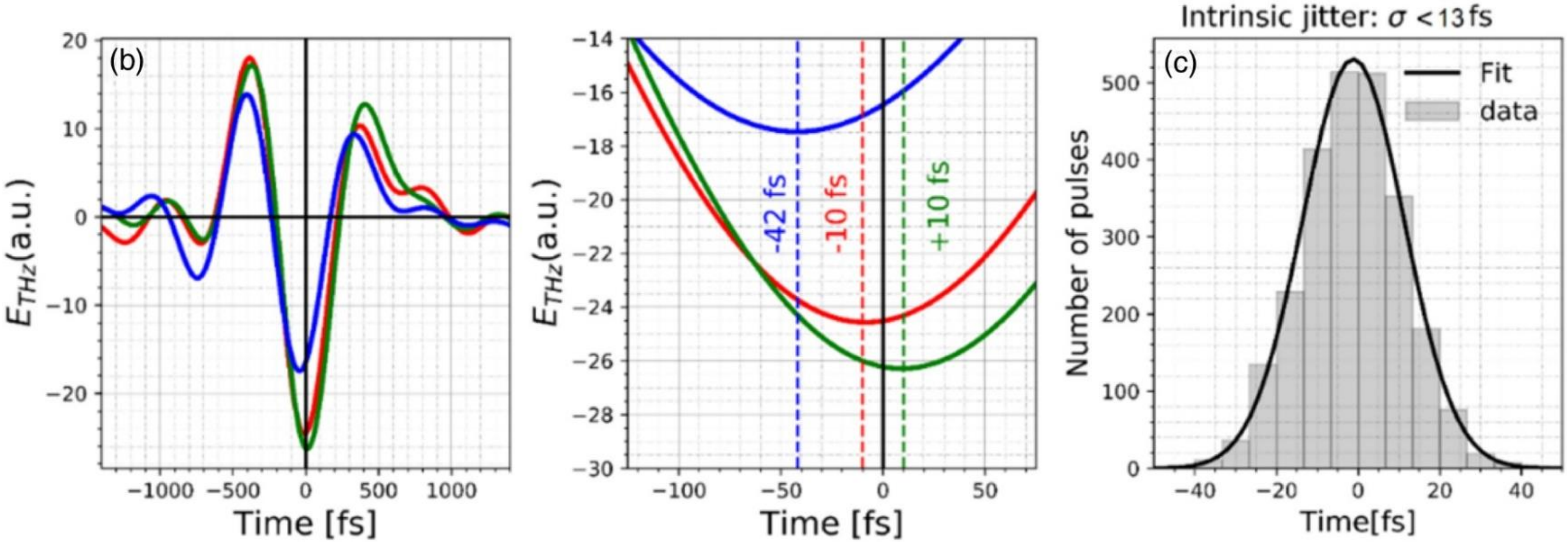


- First demonstration at Fermi seeded XFEL.
- THz emission based on spintronic emitter.

I. Ilyakov, et al., Terahertz-wave decoding of femtosecond extreme-ultraviolet light pulses, Optica **9***, 545-550 (2022)*

THz diagnostics for XFELs

THz fingerprints of XUV generation revealed in sigle-shot EOS

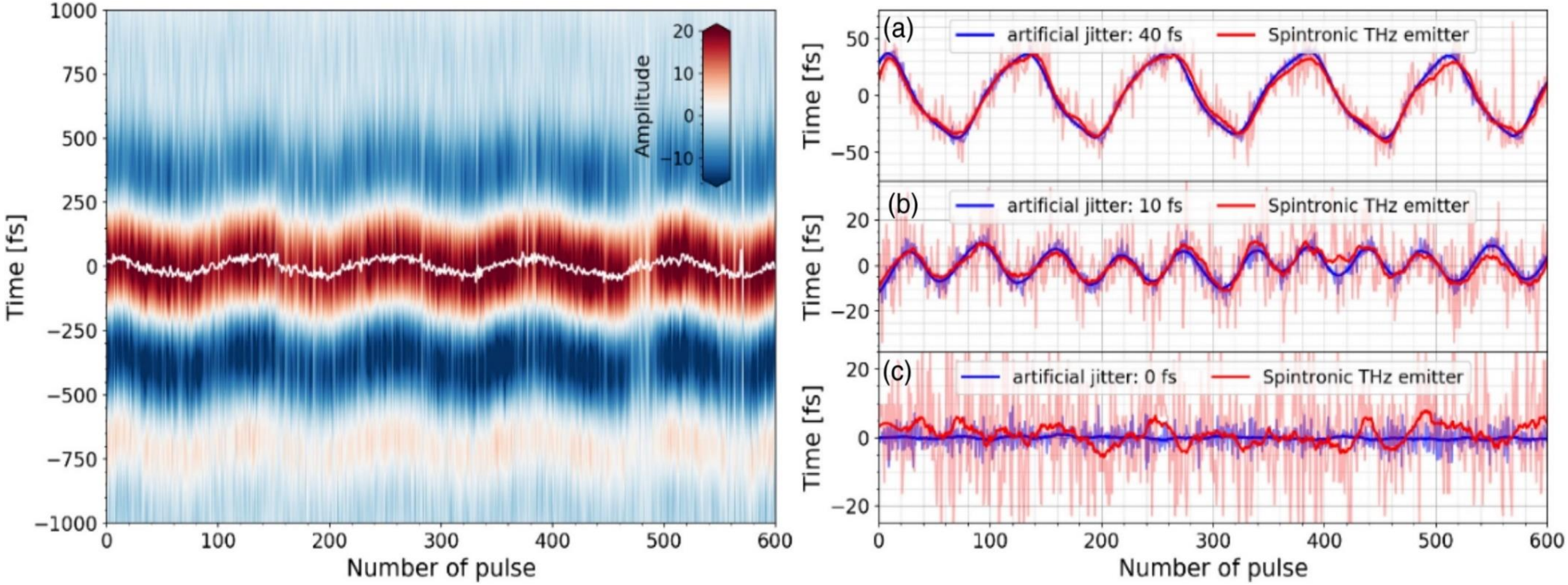


Characterization of arrival times.

I. Ilyakov, et al., Terahertz-wave decoding of femtosecond extreme-ultraviolet light pulses, Optica **9***, 545-550 (2022)*

THz diagnostics for XFELs

THz fingerprints of XUV generation revealed in sigle-shot EOS

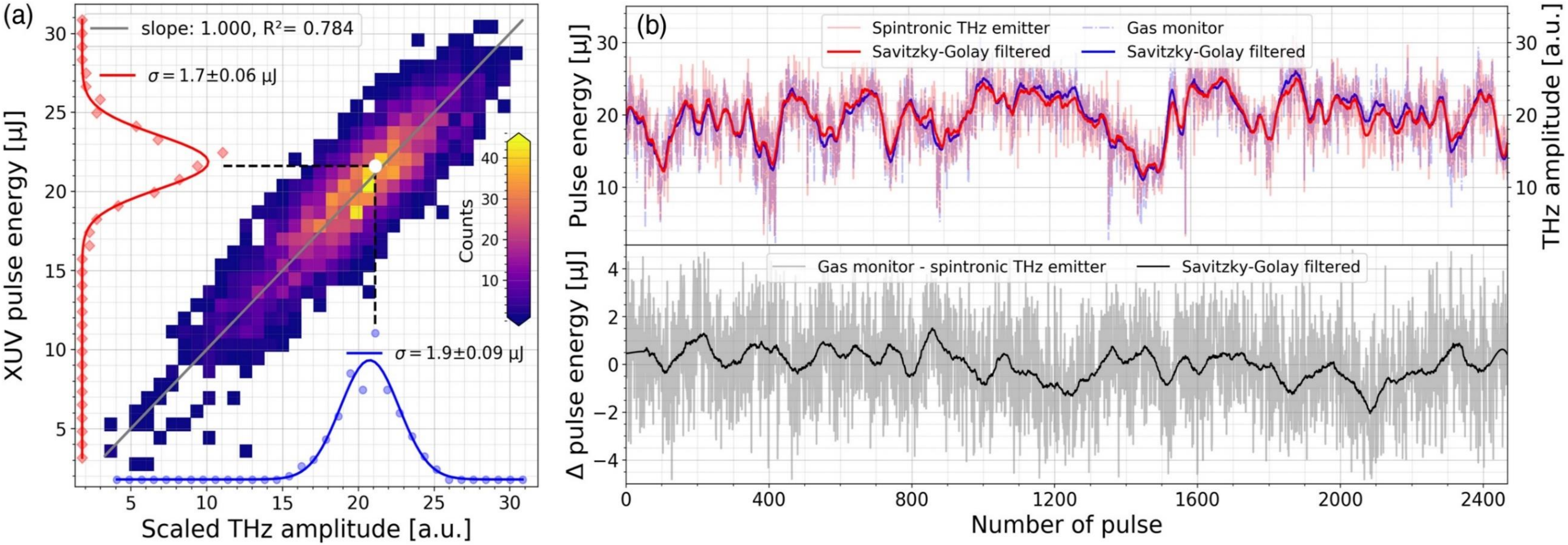


Long-term timing jitter analysis, comparison with artificially added jitter.

I. Ilyakov, et al., Terahertz-wave decoding of femtosecond extreme-ultraviolet light pulses, Optica **9**, *545-550 (2022)*

THz diagnostics for XFELs

THz fingerprints of XUV generation revealed in sigle-shot EOS



Linear correlation between XUV pulse energy and THz amplitude.

I. Ilyakov, et al., Terahertz-wave decoding of femtosecond extreme-ultraviolet light pulses, Optica **9**, *545-550 (2022)*

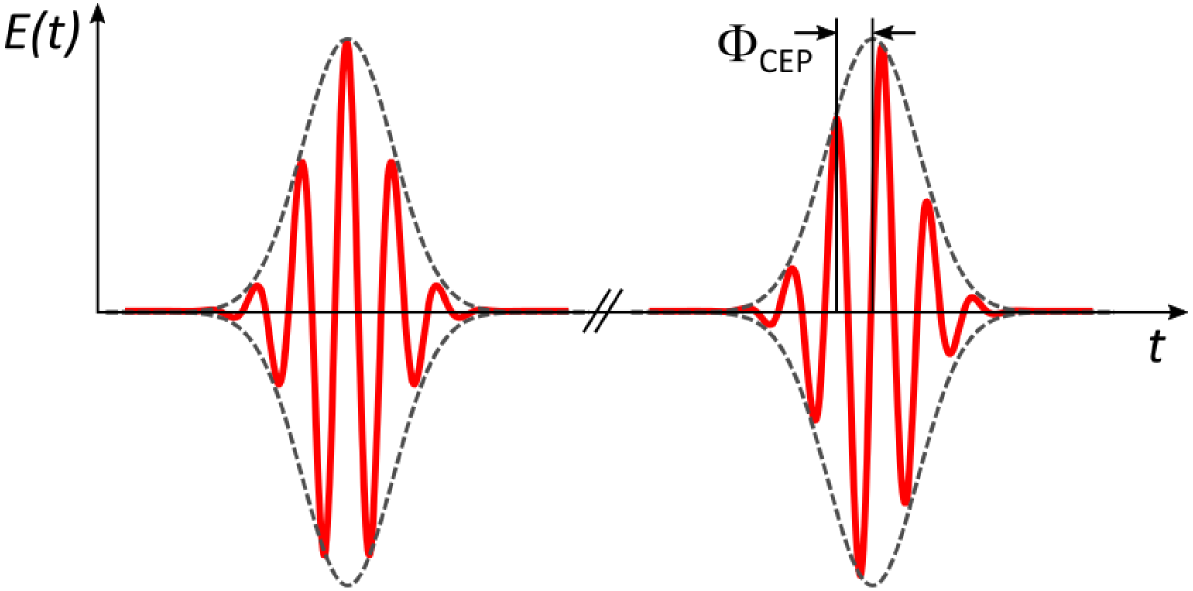
Carrier-envelope phase stability

Necessary for EOS?

EO sampling is typically stroboscopic.
→ Measurement over many pulses.

What if the CEP phase Φ_{CEP} is unstable?

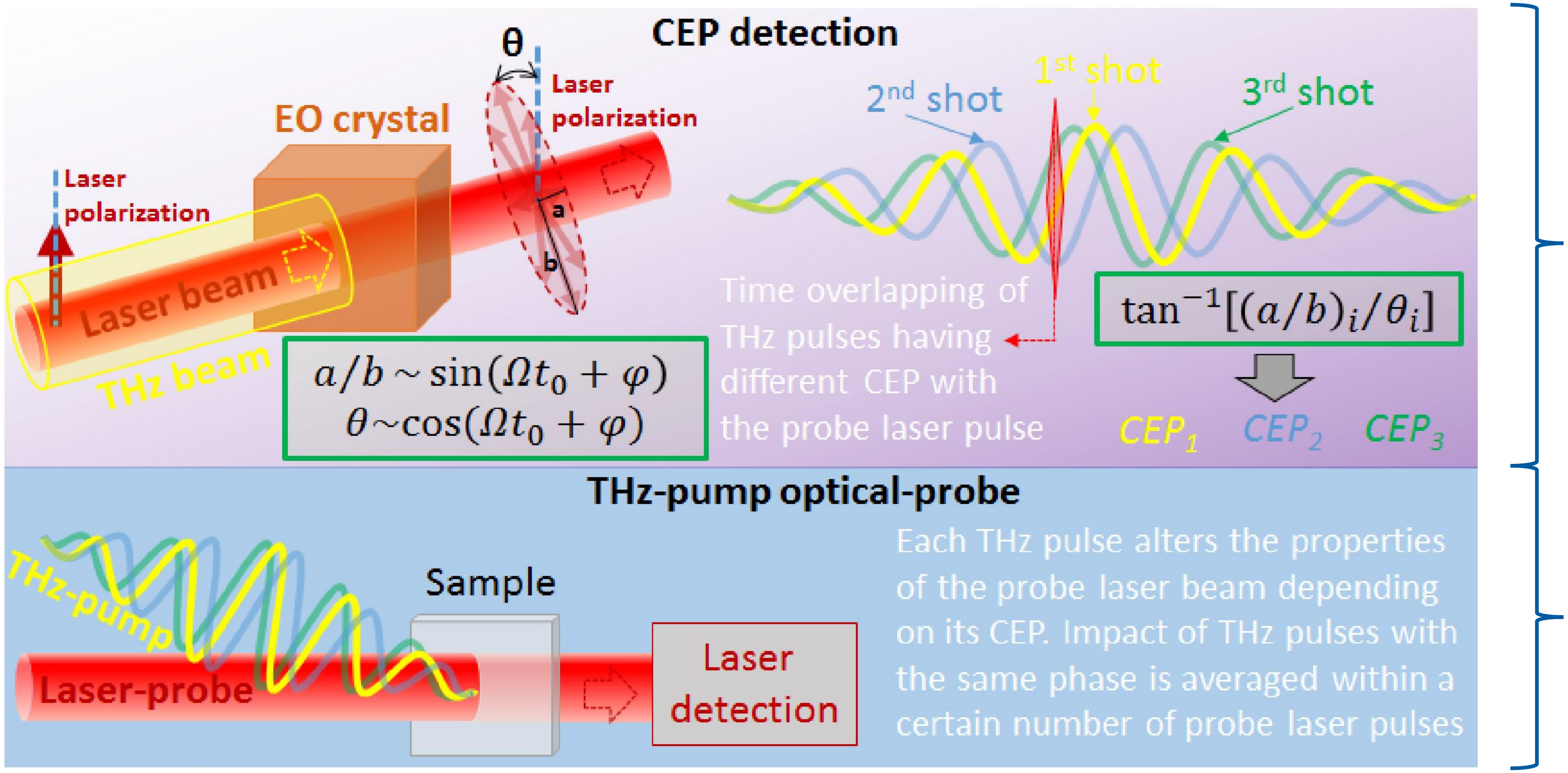
→ Typical case for IR FELs!
→ Any field-resolved signal will average out to zero.



How to measure phase-resolved sub-cycle dynamics at IR-FELs?

Phase-resolved detection at an IR-FEL

The THz CEP monitor



Ω: THz carrier frequency
φ: CEP

Simultaneous measurement of a/b, θ

CEP given by ratio ${}^{a/b}/_{\theta}$ between ellipticity and rotation.

Pump-probe experiment

I. Ilyakov et al., "Field-resolved THz-pump laser-probe measurements with CEP-unstable THz light sources," *Opt. Express* **30**, 42141-42154 (2022)

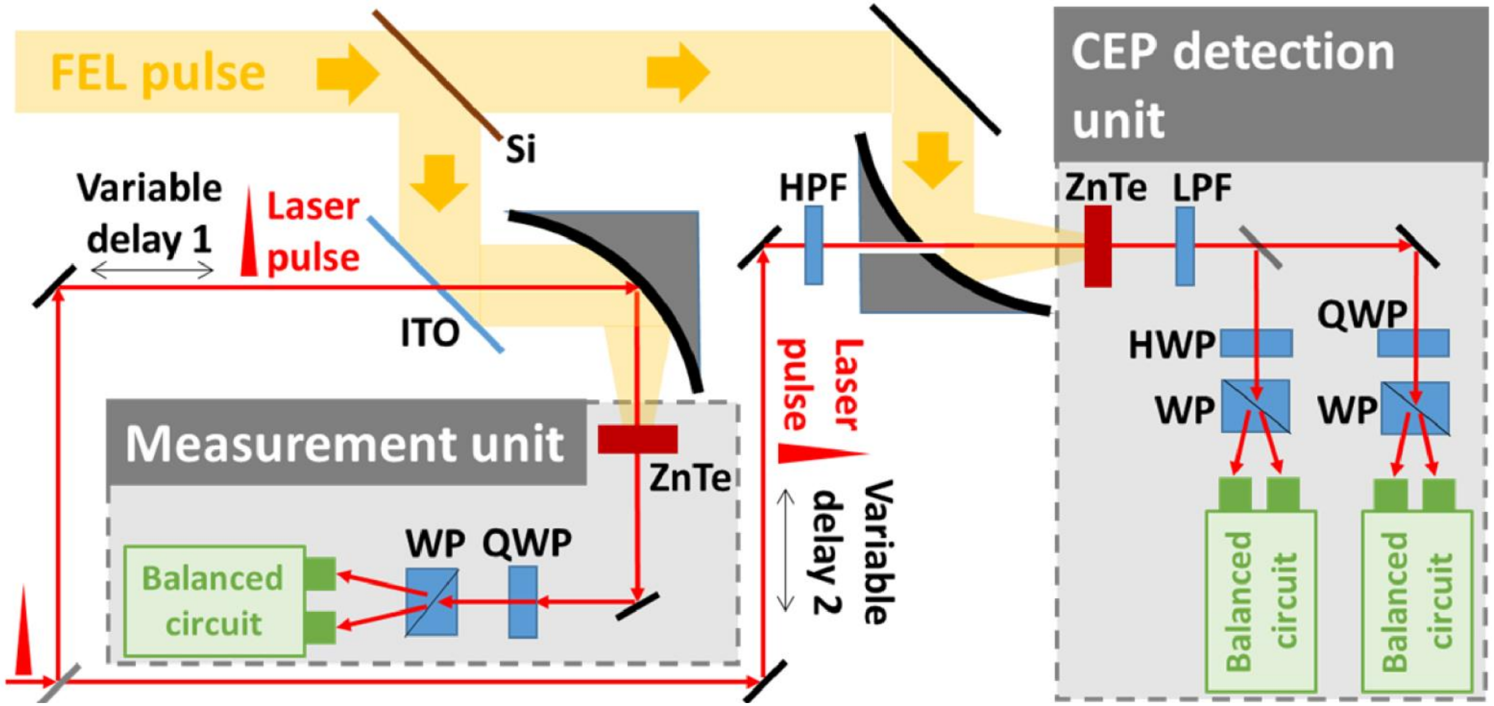
EO sampling at the FELBE FEL

Experimental scheme

Interaction in EO crystal causes
(i) phase $\Delta\varphi$ and
(ii) amplitude ΔA changes to probe laser.

Ratio between signals from (i) and (ii) determines CEP.

→ Measure both shifts simultaneously
→ Correlate with signal from measurement unit
→ Sort data accordingly.



I. Ilyakov et al., "Field-resolved THz-pump laser-probe measurements with CEP-unstable THz light sources," *Opt. Express* **30**, 42141 (2022)
I. Ilyakov et al., "Terahertz time-domain electro-optic measurements by femtosecond laser pulses with an edge-cut spectrum," *Opt. Lett*. **41**, 2998 (2016)

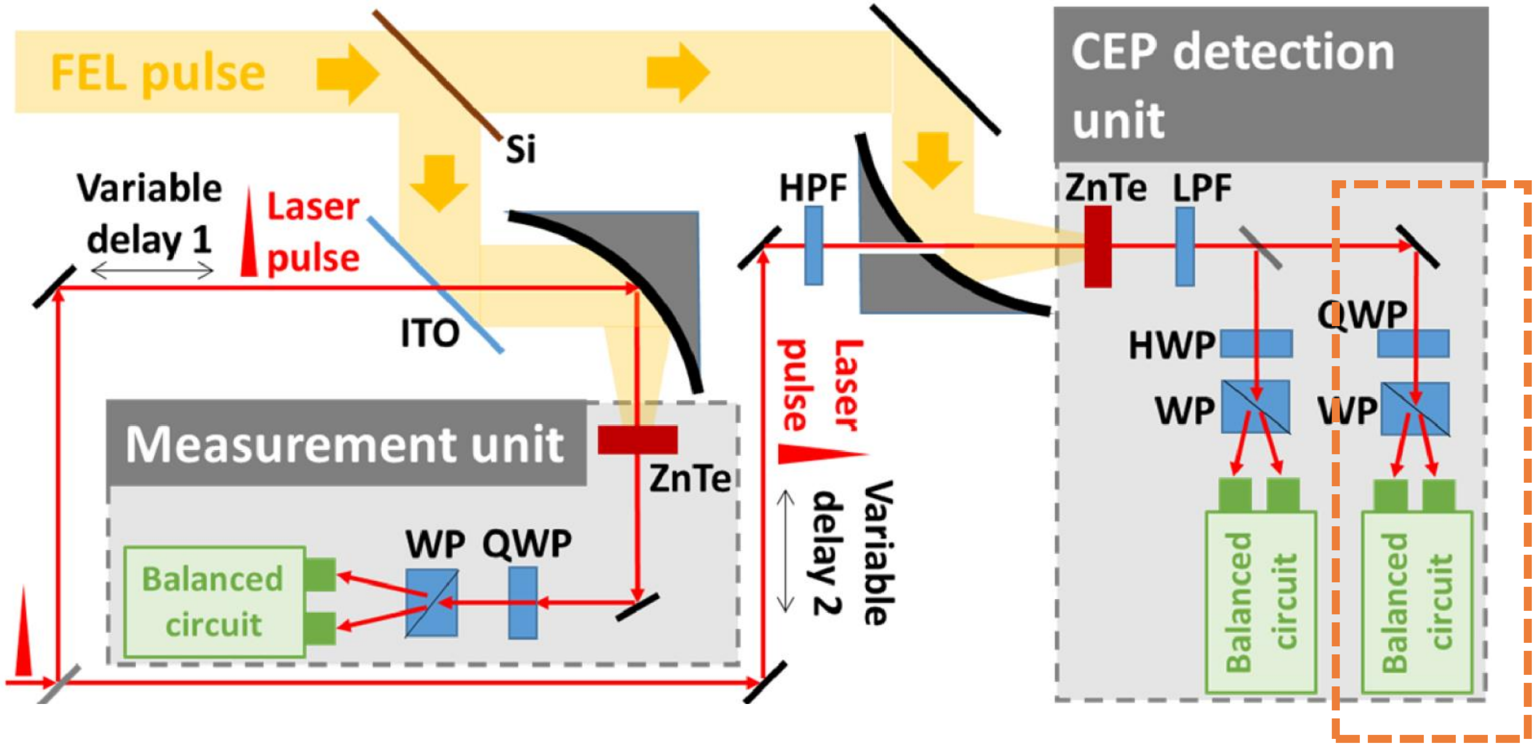
EO sampling at the FELBE FEL

Experimental scheme

(i) Measurement of the THz-induced phase change of orthogonal probe polarization components:

$$S_1 \sim E_\Omega = A_\Omega \sin(\Omega t_0 + \varphi_\Omega)$$

Bandpass filters increase sensitivity at high THz frequencies.



I. Ilyakov et al., "Field-resolved THz-pump laser-probe measurements with CEP-unstable THz light sources," *Opt. Express* **30**, 42141 (2022)
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EO sampling at the FELBE FEL

Experimental scheme

(ii) Measurement of the THz-induced Amplitude change of orthogonal probe polarization components (**rotation**):

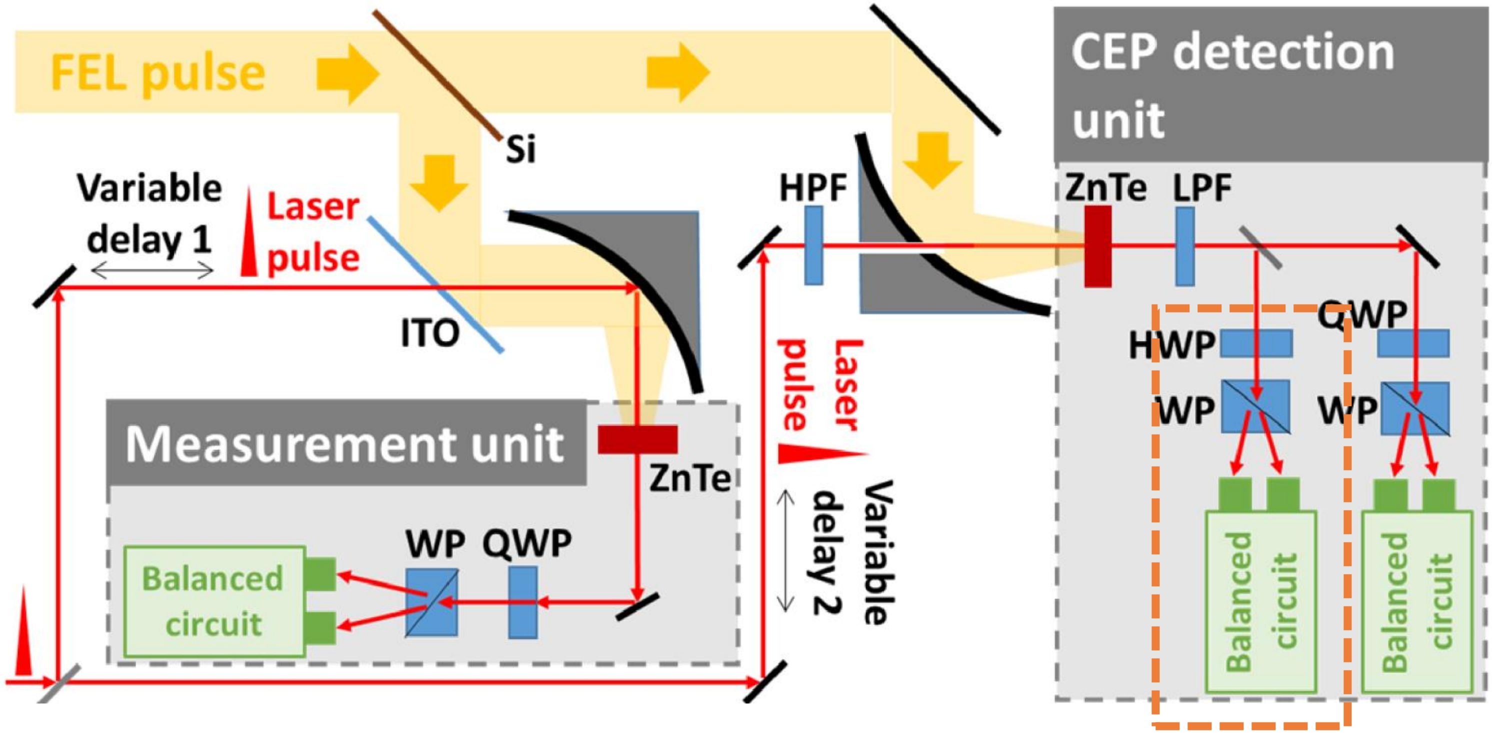
$$S_2 \sim A_\Omega \cos(\Omega t_0 + \varphi_\Omega)$$

Shifted by $^{\pi}/_{2}$ relative to S_1.

$$\alpha \cdot S_1/S_2 = \tan(\Omega t_0 + \varphi_\Omega)$$

CEP: $\varphi \equiv \Omega t_0 + \varphi_\Omega$

$$\Rightarrow \varphi = \tan^{-1}(\Omega t_0 + \varphi_\Omega)$$

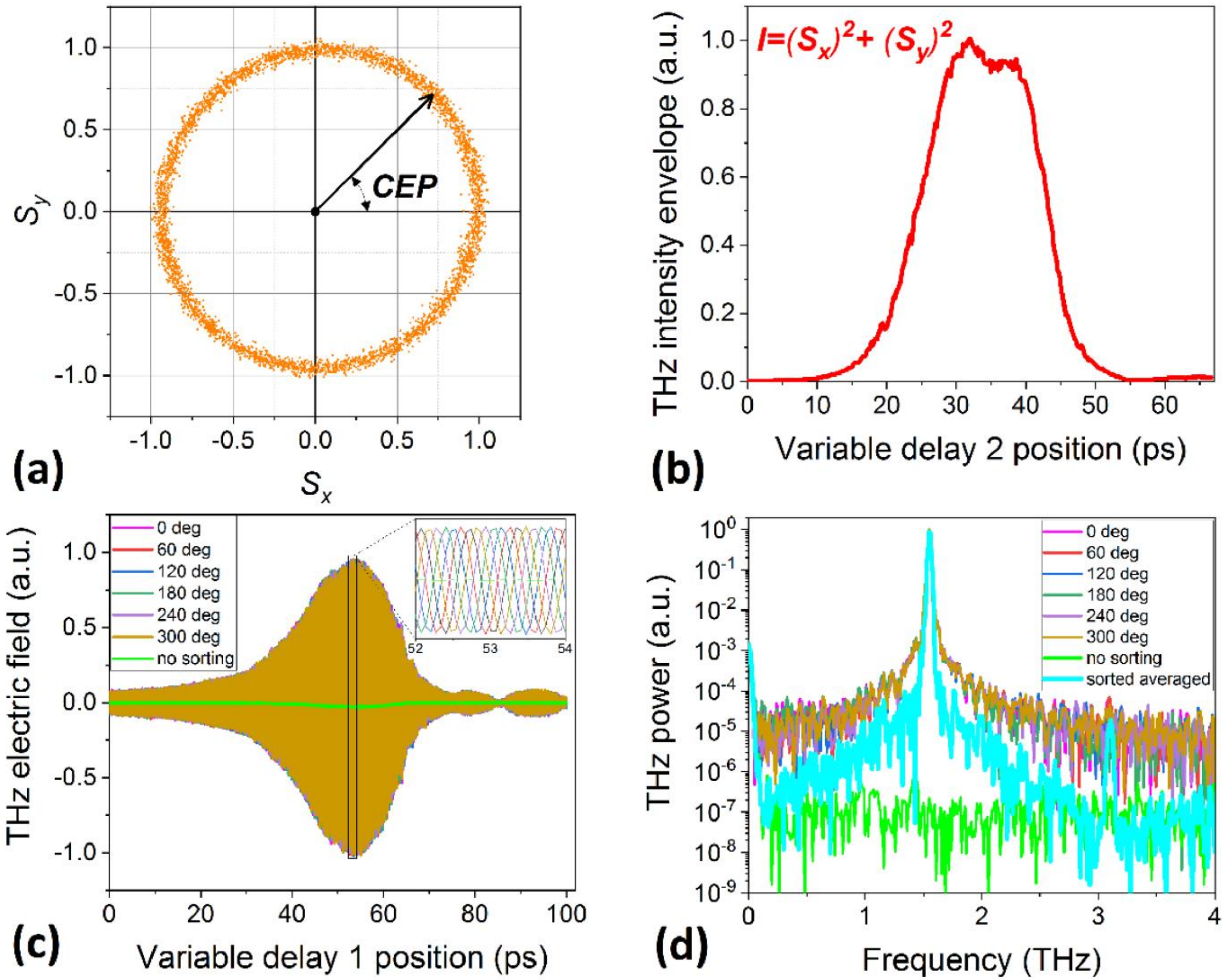


I. Ilyakov et al., "Field-resolved THz-pump laser-probe measurements with CEP-unstable THz light sources," *Opt. Express* **30**, 42141 (2022)
I. Ilyakov et al., "Terahertz time-domain electro-optic measurements by femtosecond laser pulses with an edge-cut spectrum," *Opt. Lett*. **41**, 2998 (2016)

Phase-resolution at an IR-FEL

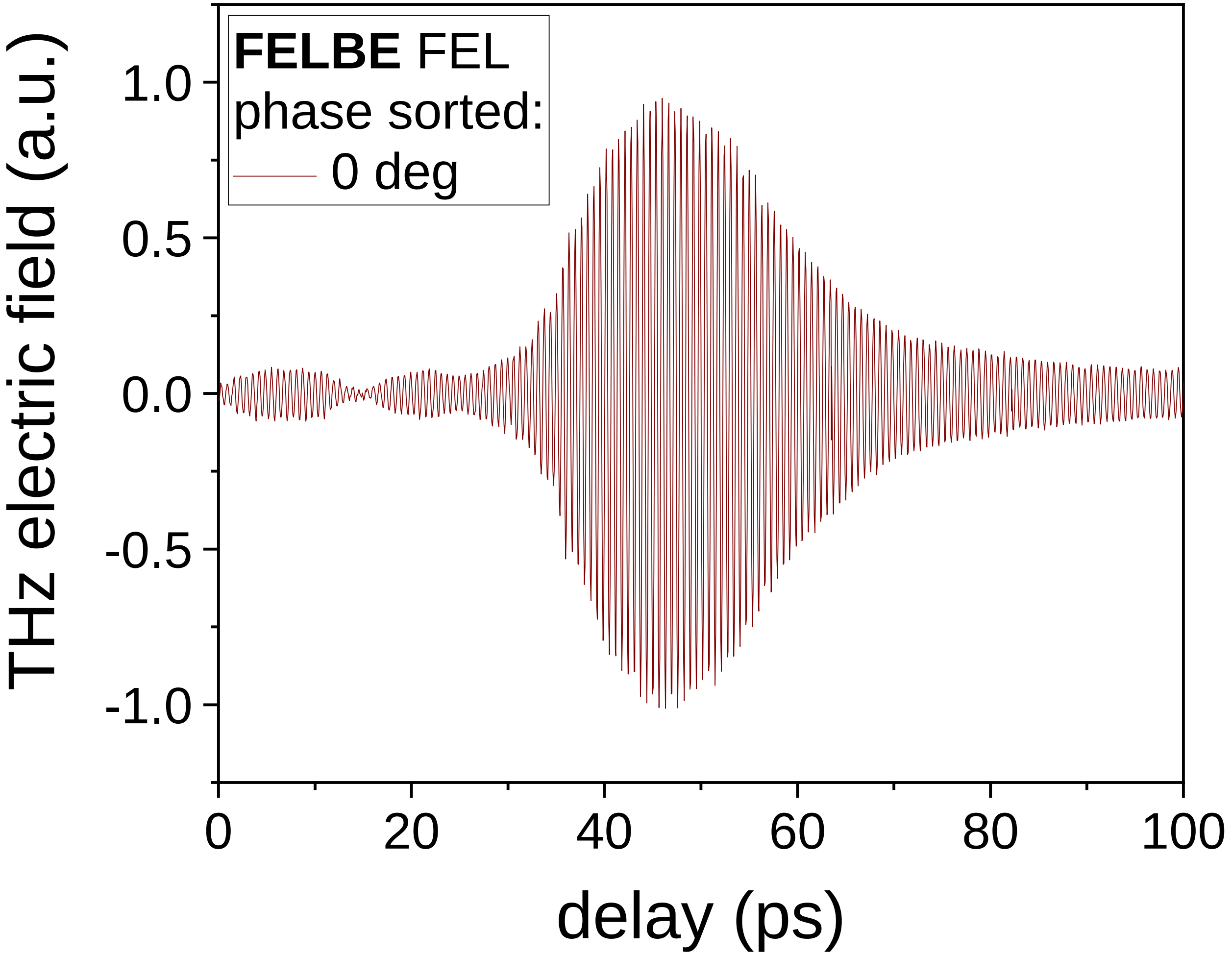
Enabling measurement of

a) CEP
b) Pulse intensity envelope
c) FEL field transients
d) Corresponding FFTs



I. Ilyakov et al., "Field-resolved THz-pump laser-probe measurements with CEP-unstable THz light sources," *Opt. Express* **30**, 42141 (2022)

Phase-resolution at an IR-FEL



Scheme enables measurement of sub-cycle field-driven dynamics at IR-FEL sources.

I. Ilyakov et al., "Field-resolved THz-pump laser-probe measurements with CEP-unstable THz light sources," *Opt. Express* **30**, 42141 (2022)

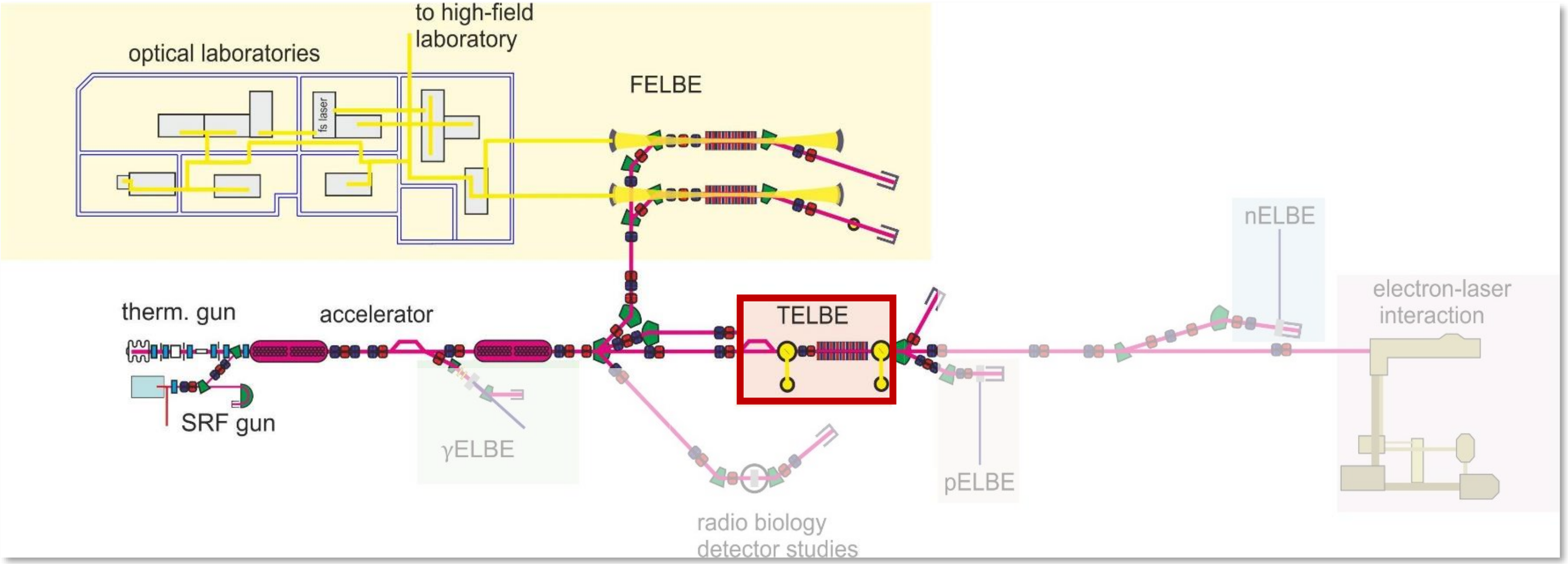
Thank you!

Light-sources for THz nonlinear optics

Required:

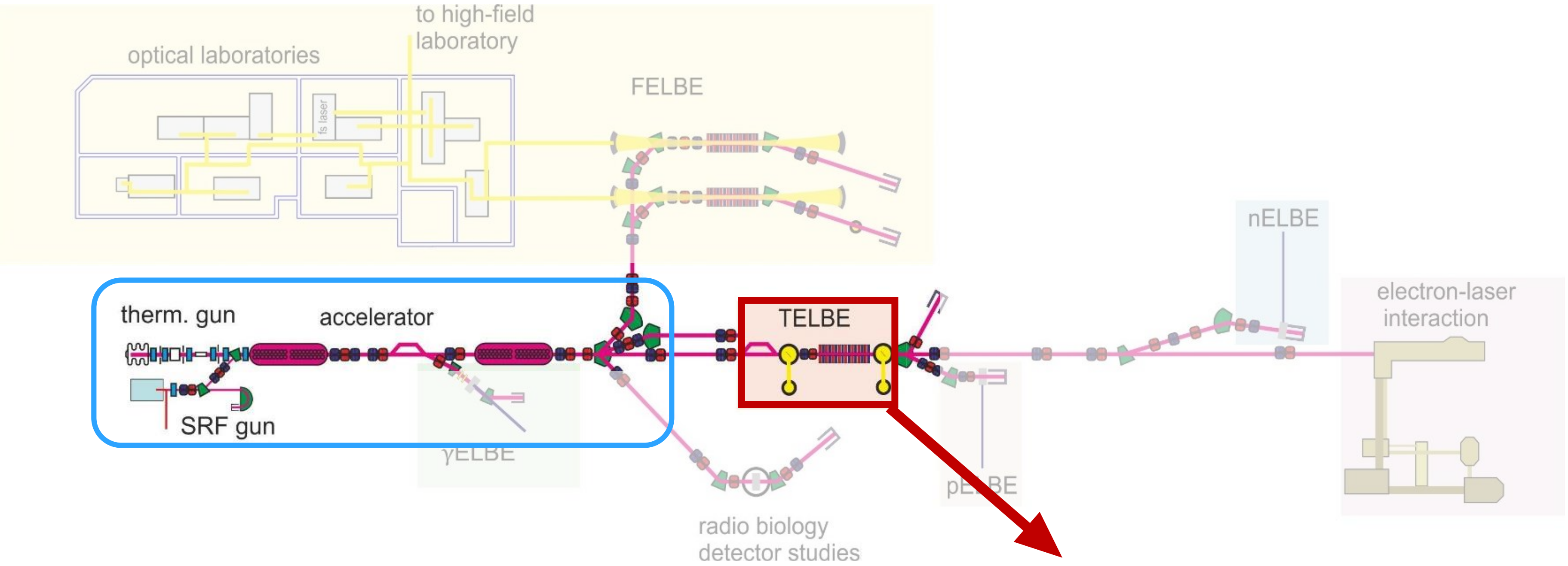
- High spectral density = High peak field + narrow bandwidth
- High repetition rate (>> 1 kHz)
- Frequency tunability
- Sub-cycle time resolution

Accelerator-based sources offer superior parameters



Schematic layout of the ELBE center at HZDR with IR/THz sources FELBE and TELBE

TELBE at HZDR: Linac-Based THz Sources



ELBE accelerator facility:

- Superconducting RF gun
  - Quasi-CW operation (up to 500 kHz)
  - 250 pC bunch charge
- 2 **linac** modules
  - Up to 40 MeV kinetic energy

TELBE

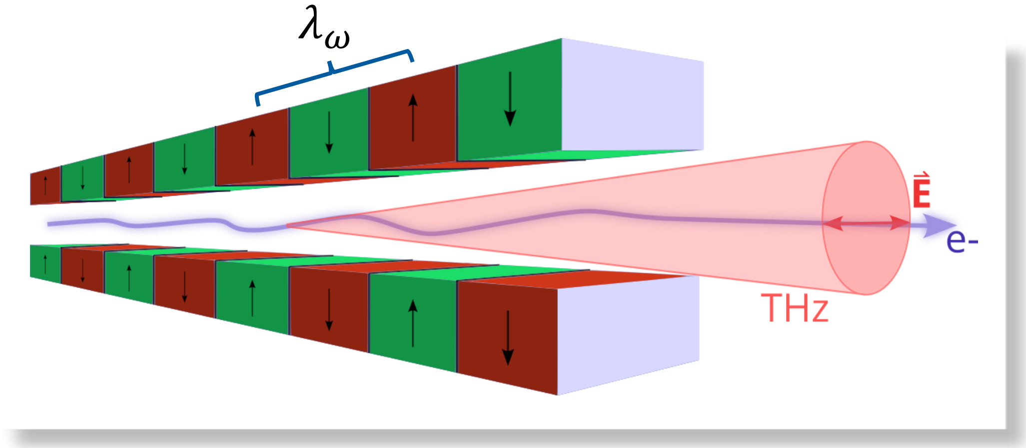
- Frequency tunable, 0.1 - 2.5 THz
- ~ 20% bandwidth
- µJ pulse energies
- CEP stable
- Few 10 fs timing accuracy

User operation **since 2016**

TELBE – Superradiant high-field THz sources

- THz radiation from sinusoidally accelerated electron bunch
- Emission frequency ν tunable by changing magnetic field *B*

$$\nu = \frac{c}{\lambda_\omega} \frac{2\gamma^2}{\left(1+\frac{1}{2}K^2\right)} \qquad \text{(undulator equation, } K \propto B\text{)}$$

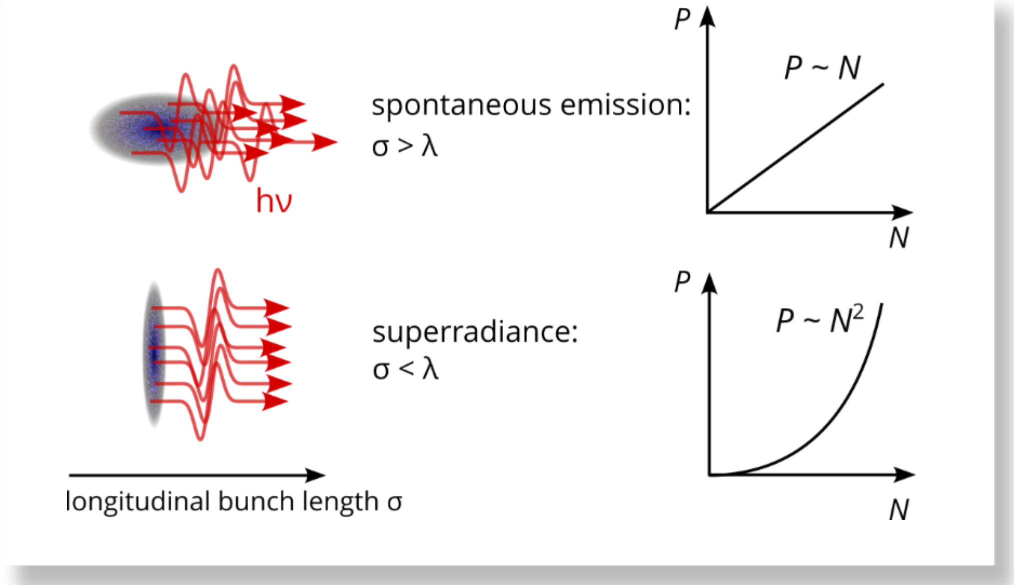


Superradiant emission:

Compression of the electron bunch length σ below emitted wavelength $\lambda = 300\ \mu\text{m} \triangleq 1\ \text{THz}$

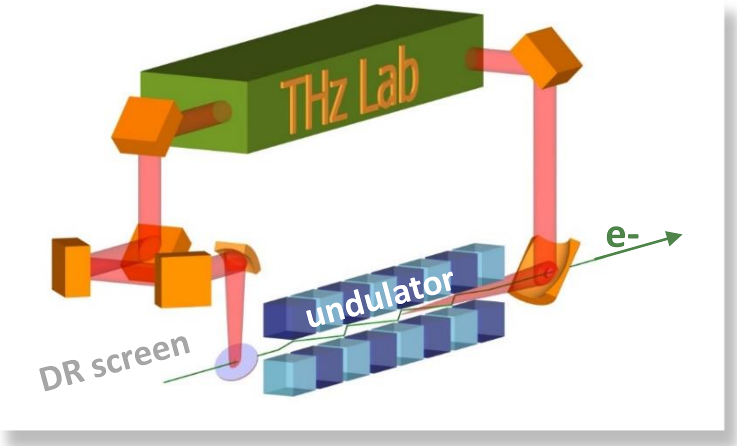
⇒ Emitted power $P \propto N^2$

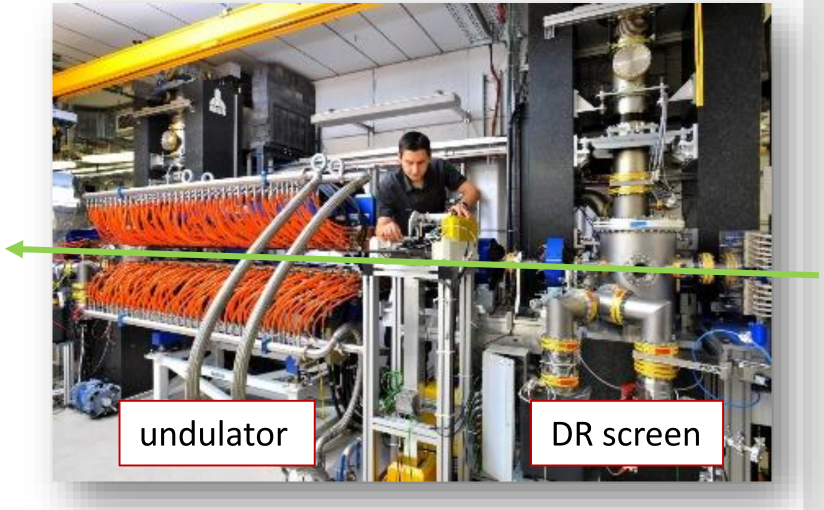
Bunch charge 250 pC ≙ $N \approx \mathbf{10^9}$ electrons



B. Green et al., *Sci. Rep.* **6**, 22256 (2016)
Deinert, J.-C., Kovalev, S. and Gensch, M., *Phys. Unserer Zeit* **54**, 12-17 (2023)

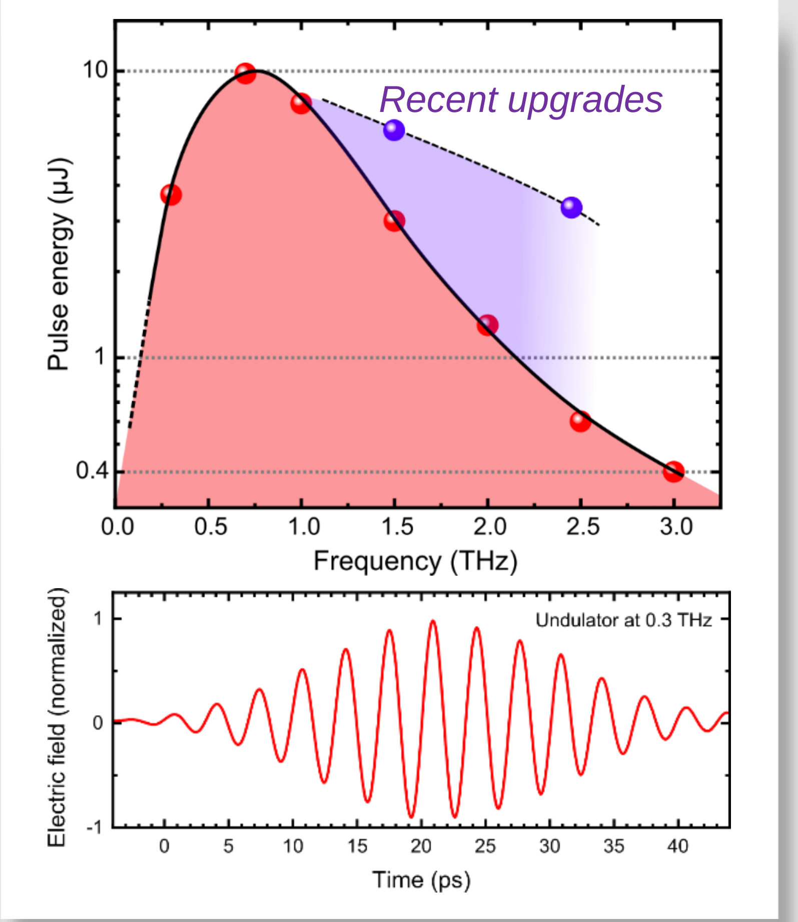
TELBE – Superradiant high-field THz sources



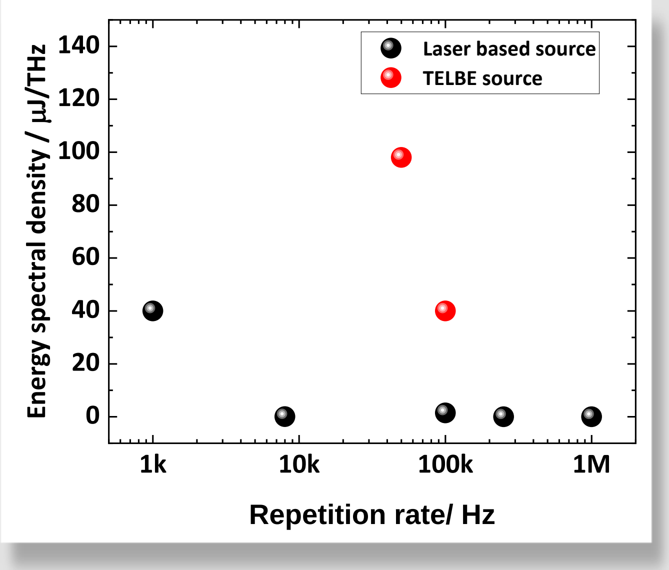


B. Green et al., *Sci. Rep.* **6**, 22256 (2016)

Superradiant undulator at TELBE



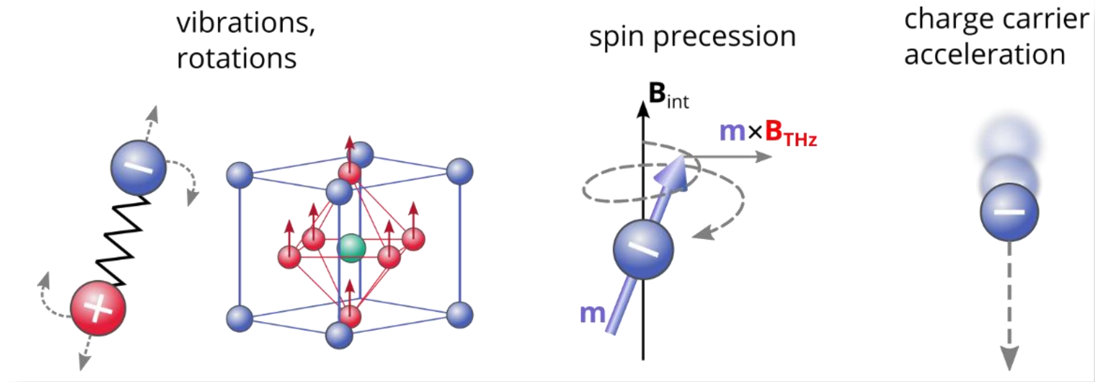
- E_{THz} few 100 kV/cm
- Superior spectral densities compared to laser-based sources

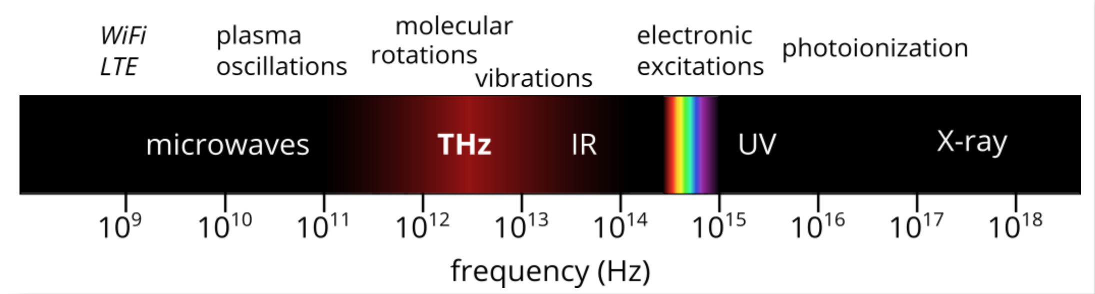


- Continuous improvements on THz intensity and timing stability

Nonlinearities in optical vs THz regime

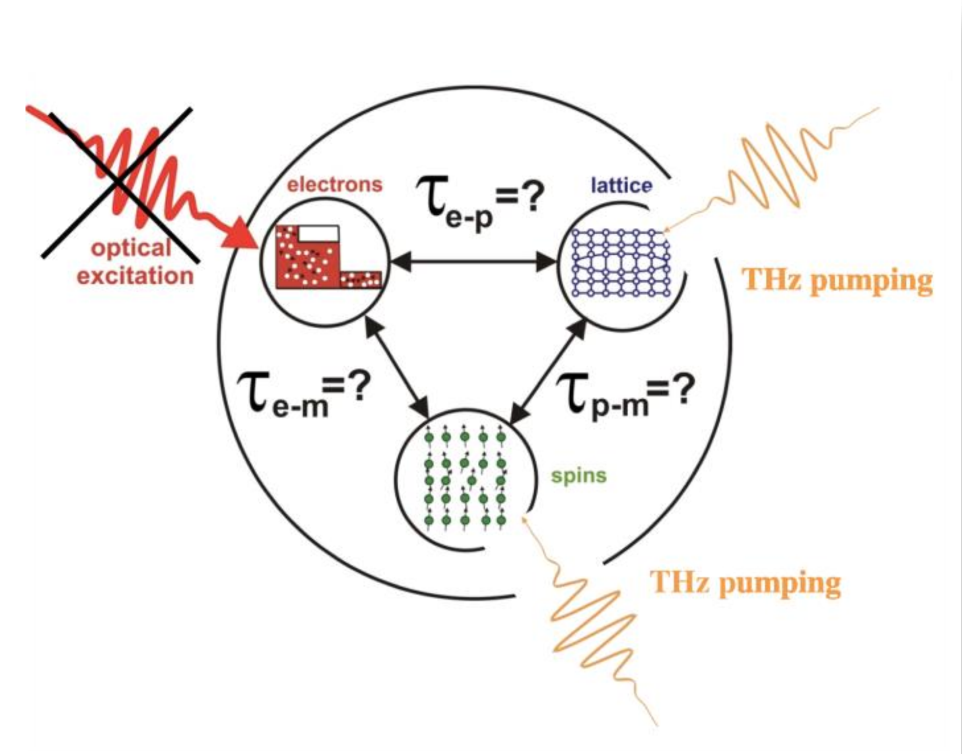
Terahertz frequencies ($1\ \mathrm{THz} \triangleq 4.1\ \mathrm{meV}$)
correspond to lowest energy motions / quanta





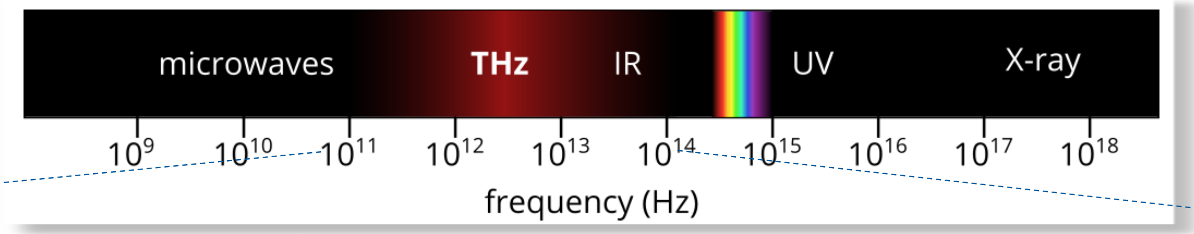
THz drive:

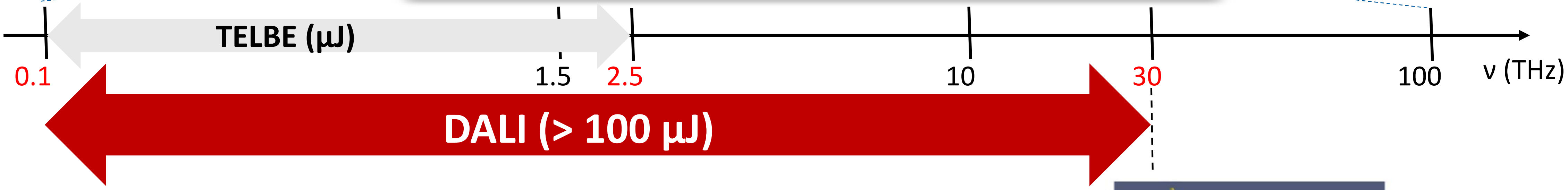
- Direct electronic transitions avoided.
- Coherent **selective excitation** of relevant modes



Courtesy of I. Radu, MBI Berlin

Fundamental (quasiparticle) excitations in THz regime



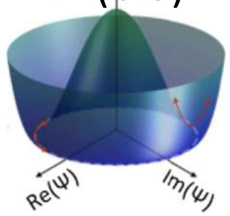


magnons

molecular
rotations

vibrations of large
(bio) molecules

pseudogaps in high
***T_c* superconductors**



superconducting
order parameter

charge currents
(lightwave electronics)

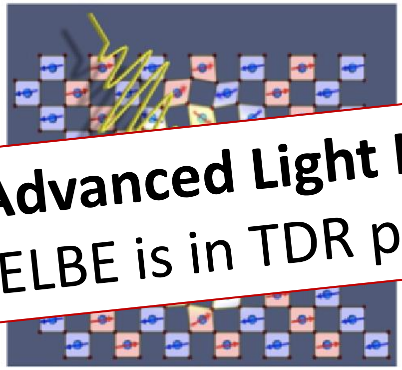
plasmons

phonons
(lattice vibrations)

molec
(finge

narrow-gap
semiconductors

intersubband
transitions



DALI (Dresden Advanced Light Infrastructure)
as successor to ELBE is in TDR phase.

- Large, tunable frequency range highly advantageous