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THz Detection Techniques Overview

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IBIC2020

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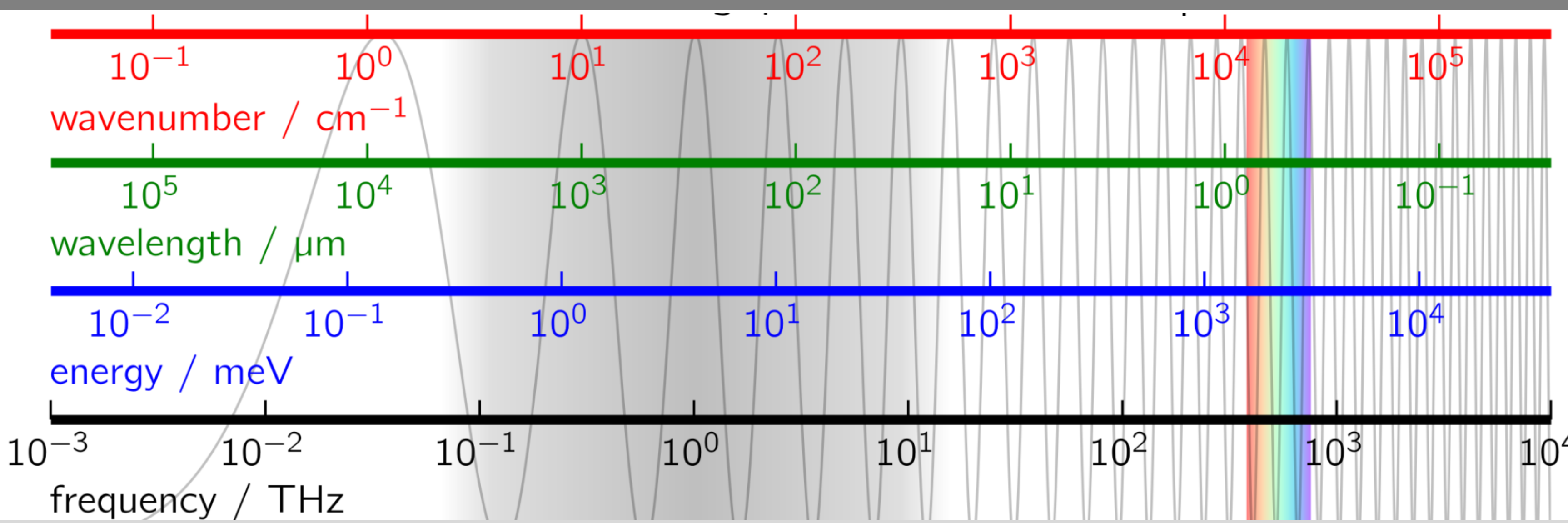

Overview

- Introduction
- Thermal Detectors
- Direct Detection Devices
- Hetherodyne Detection
- Sampling Detection
- Summary

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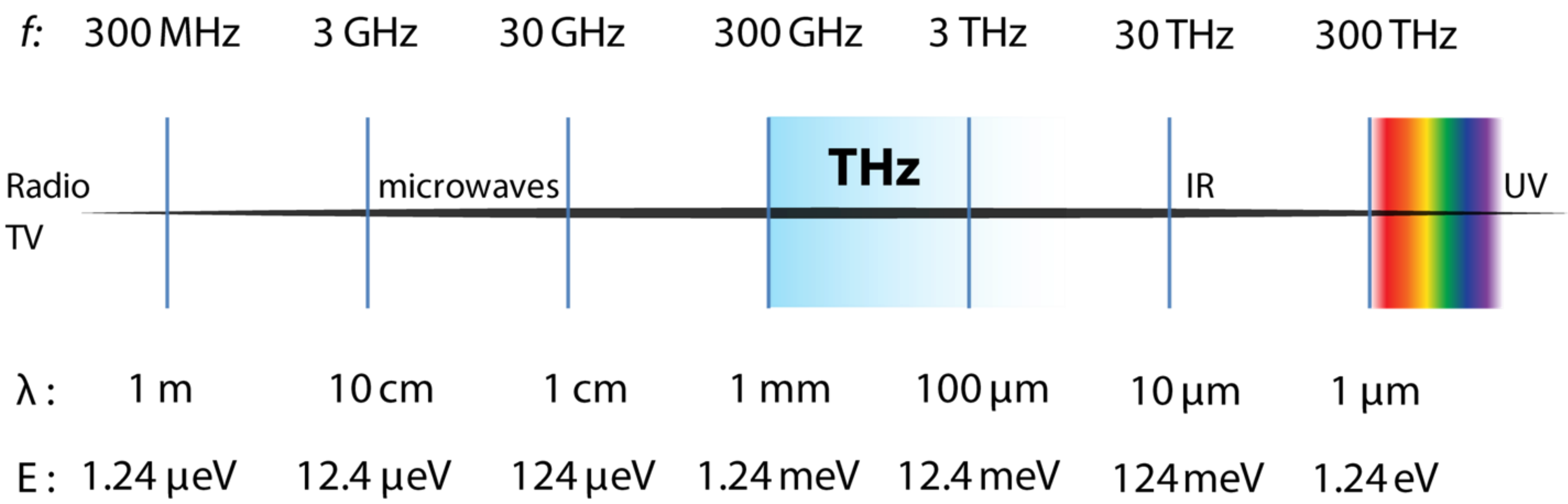
Introduction – THz spectrum

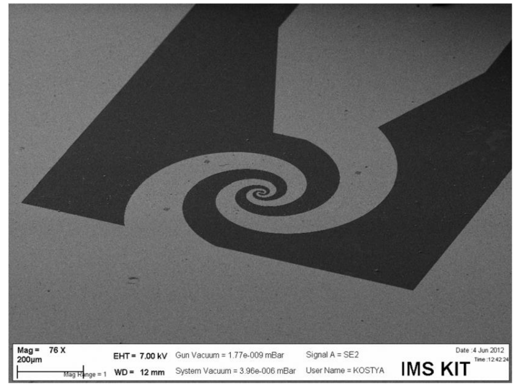


- Many natural molecular dynamics happen in the THz range → 👍 molecular sensing, 👎 absorbed by atmospheric gases and water
- Non ionizing radiation → 👍 safety 👎 ambient thermal noise can be an issue ($k_B T$ (300K) ~ THz!)

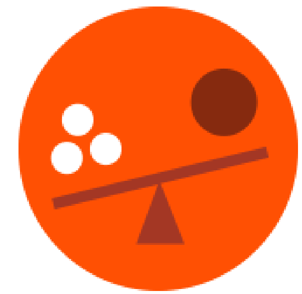
- Pass through many dielectrics, reflected by metals → imaging

THz Diagnostics - Overview of Sys. Req.

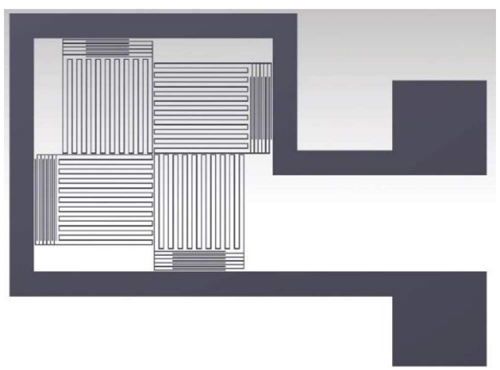
Dynamic range
(e.g. Heterodyne ~ 100 dB)



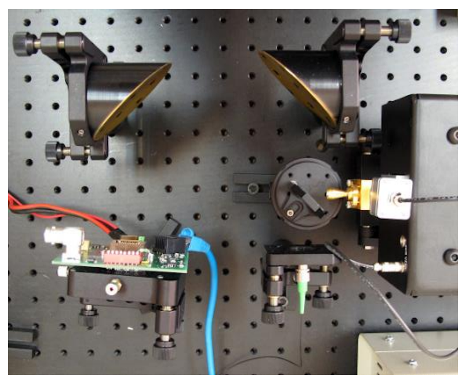
Speed
(e.g. IMS YBCO, < 10 ps)



TRADE-OFFS
No perfect device

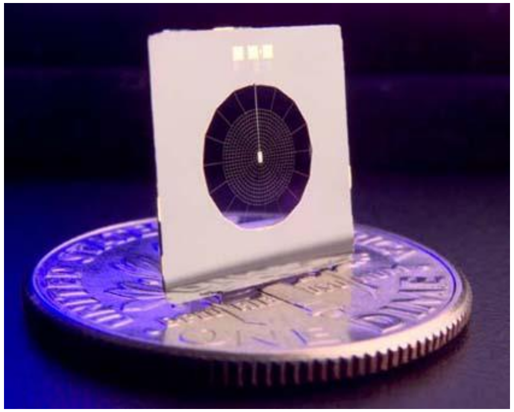


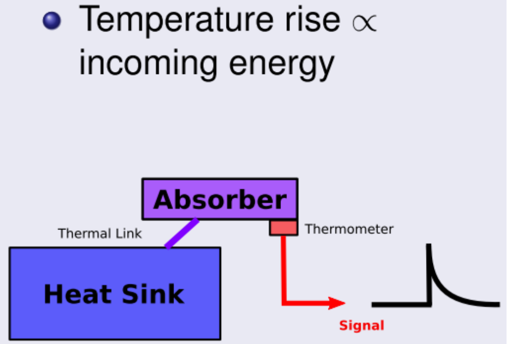
High Sensitivity
(e.g. KID, ~ 10^{-19} W)



Bandwidth
(e.g. EO sampling,100 GHz → 37 THz)

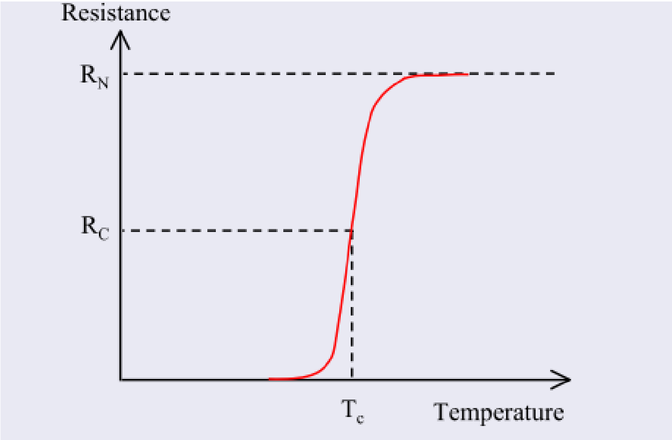
Thermal Detector – Bolometer

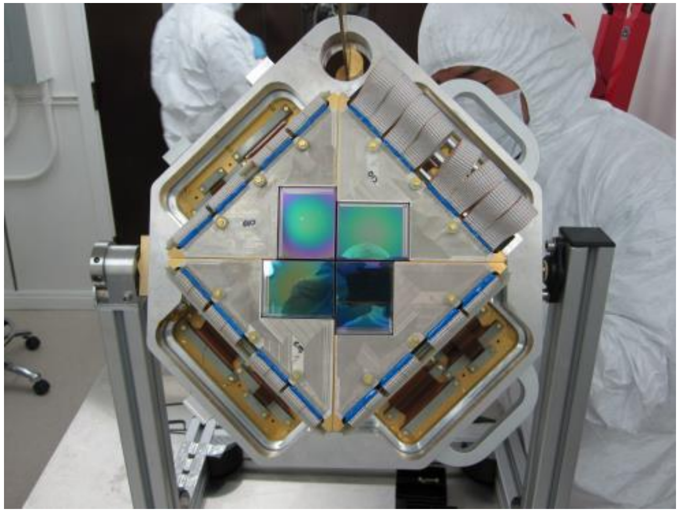




- Absorber + thermal reservoir + thermal connection
- Absorbed power P = G *ΔT, ΔT given by resistive thermometer
- Faster than pyros and Golay cells (~ 10 µs)
- Lowest noise room temperature detector (NEP: ~ 10^{-12} W/$Hz^{1/2}$)
- Widely used in large arrays in thermal cameras and in astrophysics (MAMBO2, SHARC II, SCUBA, P-Artemis…)

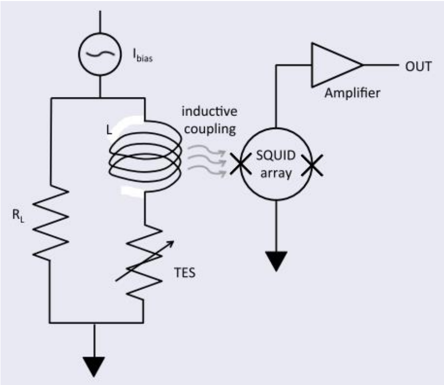
Thermal Detector – Transition Edge Sensor



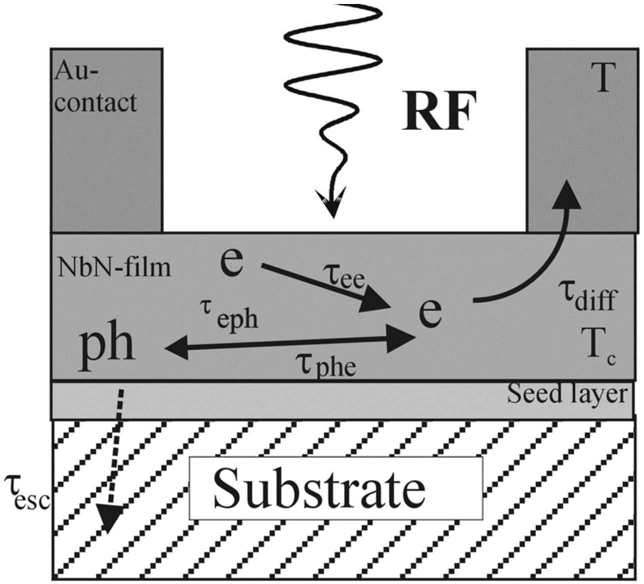


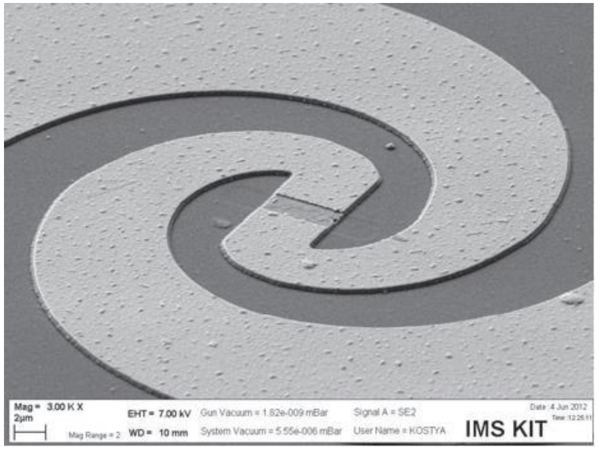
SCUBA2

- Cryogenic version of bolometers
- Absorber is held at the superconducting transition temperature → strong T-R response → high det. eff. (~ 98 %)
- SQUID multiplexing + voltage bias → *dR/dT < 0* → negative electrothermal feedback → stability (low noise)
- Extremely sensitive: NEP: ~ 10^{-19} W/Hz$^{1/2}$ @ 10^{-15} W (background load dependent)
- Slow response ~ µs
- Expensive (50 mK!)



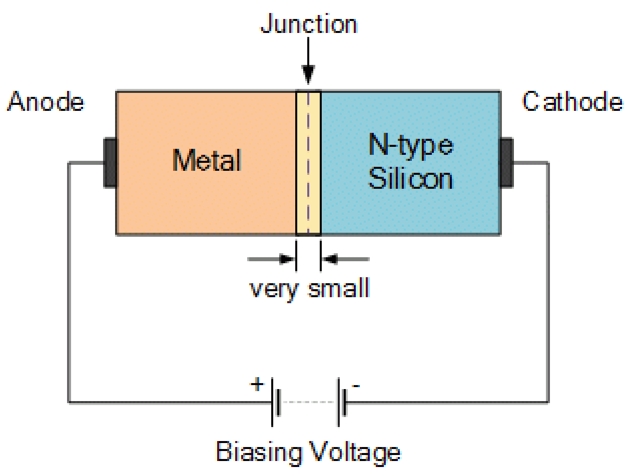
Thermal Detector – Hot Electron bolometer





- Weak e^- - ph coupling at thermal equilibrium
- Radiation breaks the coupling → hot electrons
- Heat capacity = electrons
- Thermal conductance = e^- - ph relax. time
- Resp. time: ~ 10 ps
- NEP: 10^{-18} W/Hz$^{1/2}$

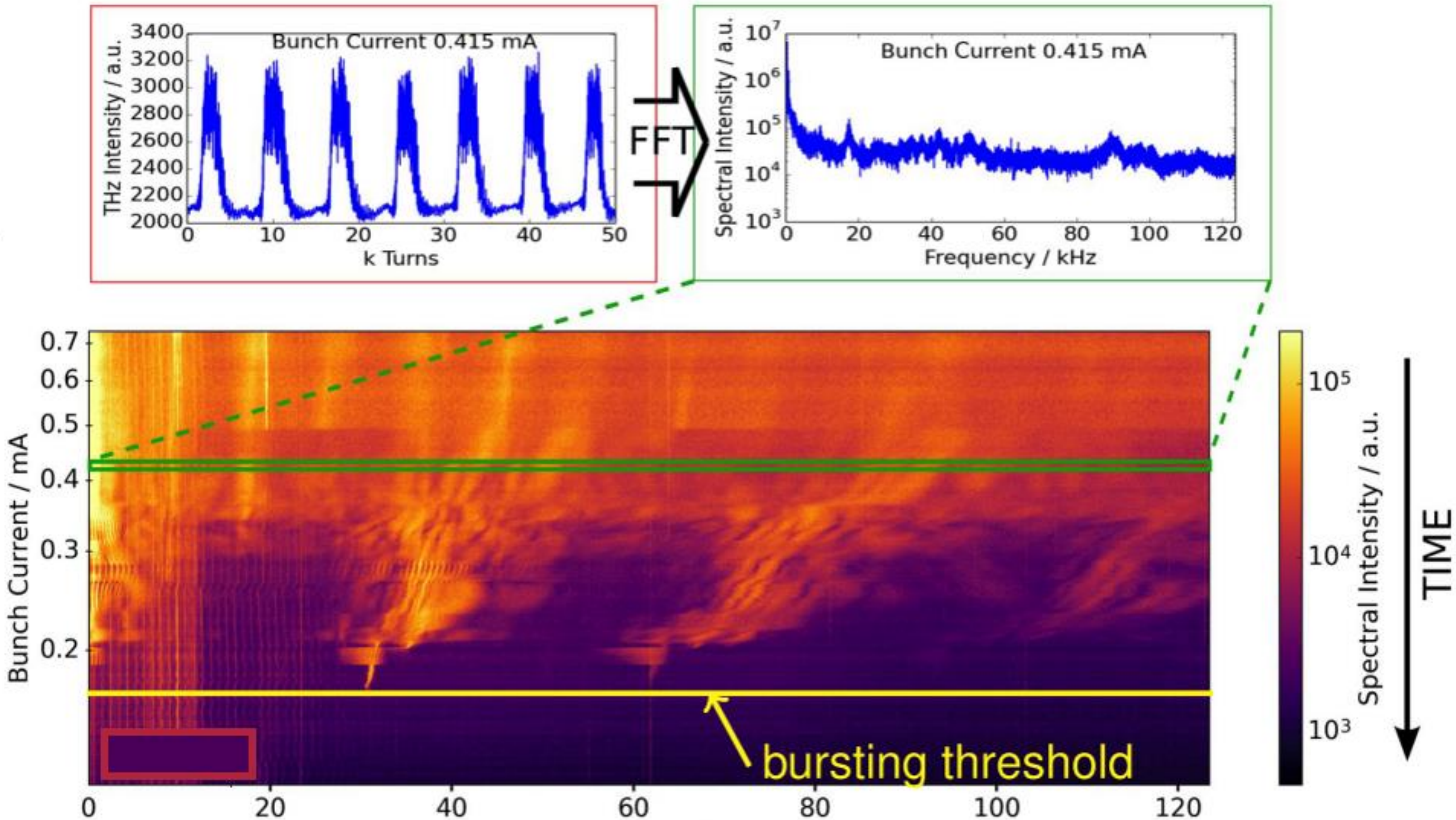
Direct Detection – Schottky Diode



- Schottky Barrier Diodes are formed by the junction of metal with a semiconductor
- Very low forward voltage drop (but very high reverse leakage current)
- Majority carrier semiconductor device → very fast switching action (< 10 ps)
- Room temperature operation
- Can be operated bias free → low noise (10^{-12} W/Hz$^{1/2}$)
- Ultra-Wideband: can be as wide as 50 GHz → 5 THz

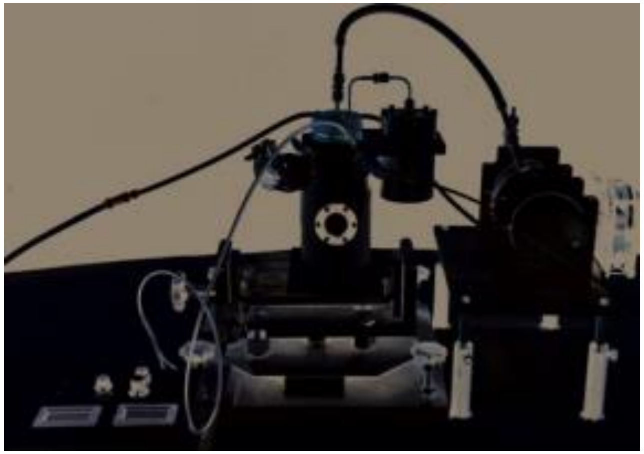
Direct Detection – Schottky Diode

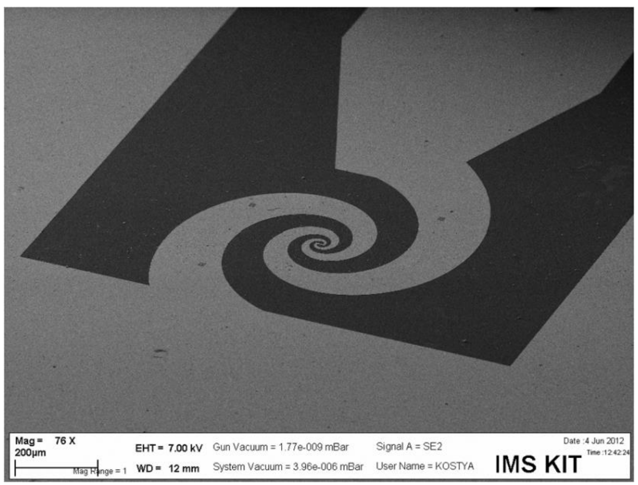
- Application: microbunching measurement @ KIT – IBPT
- Required time resolution: 2 ns



M. Brosi et al., PhysRevAccelBeams.19.110701

Direct Detection – YBaCuO thin film detector





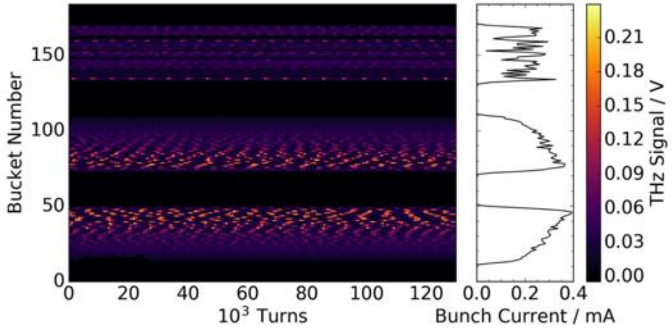
- 30 nm YBaCuO thin films detector
- Detection mechanism: non-bolometric, vortex assisted @ THz (Phys.RevB 85, 174511 (2012))
- High temp. superconductor → LN_2 cryo
- Ultrawide band 30 GHz → 2.5 THz
- Response time < 15 ps → CSR pulse real time evo

Thoma, P.; Raasch, J.; et al.; IEEE Trans. Appl. Supercond., vol.23, no.3, June 2013

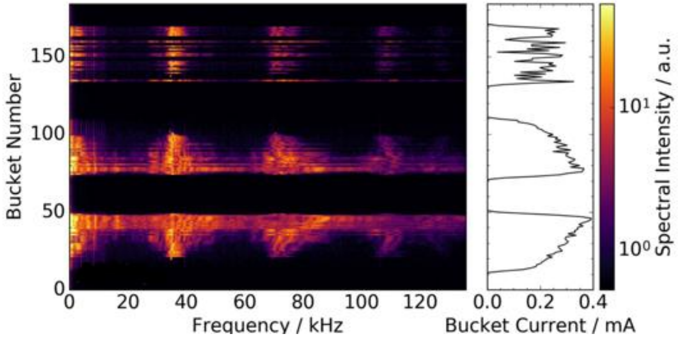
Direct Detection – Readout system example

KAPTURE: **KA**rlsruhe **P**ulse **T**aking **U**ltra-**F**ast **R**eadout **E**lectronics

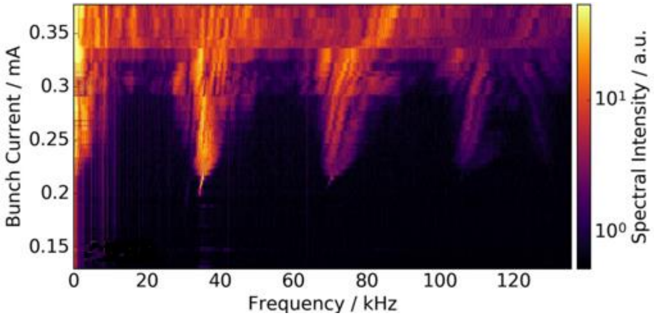
- YBCO, HEB, Schottky compatible
- Continuous acquisition
- Real time eval. Via GPUs



Spectrogram



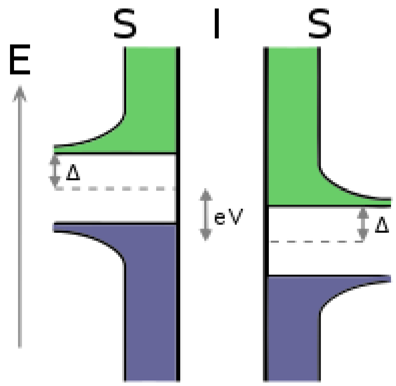
Bunch signal FFT

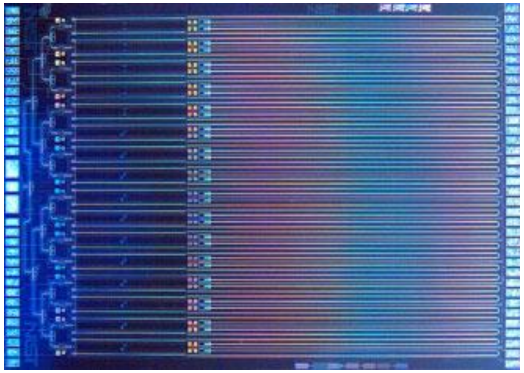


Sorting (bunch current)

M. Caselle, et al. An ultra-fast data acquisition system for coherent synchrotron radiation with terahertz detectors, JInst 9 C01024

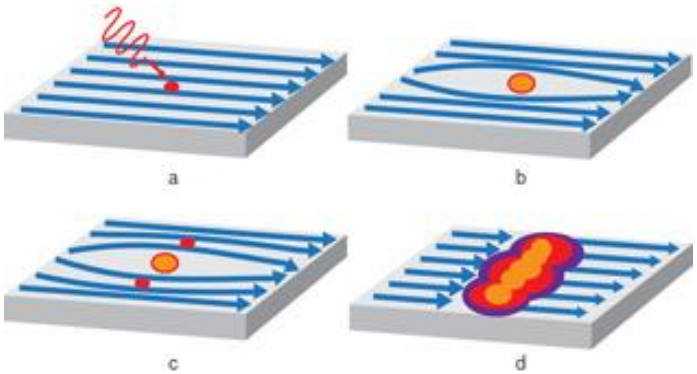
Direct Detection – Superconducting Tunnel Junction

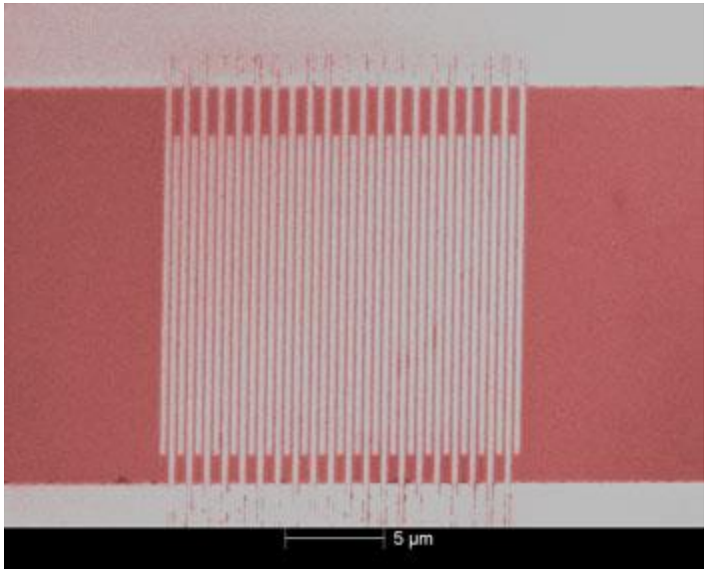




- Based on photon-assisted quantum tunneling of charge carriers through the insulating barrier
- Charge carriers: supercarriers (Cooper) and quasiparticles (electrons)
- The junction is voltage biased
- Incoming photons break down Cooper pairs, generating excess quasi particles → detectable tunnel current
- NEP: 10^{-18} W/Hz$^{1/2}$ @ 1 THz Ariyoshi et al. Appl. Phys. Lett.95, 193504
- Broadband (0.7 – 2.4 THz)

Direct Detection – Superconducting Nanowire Single Photon Detector

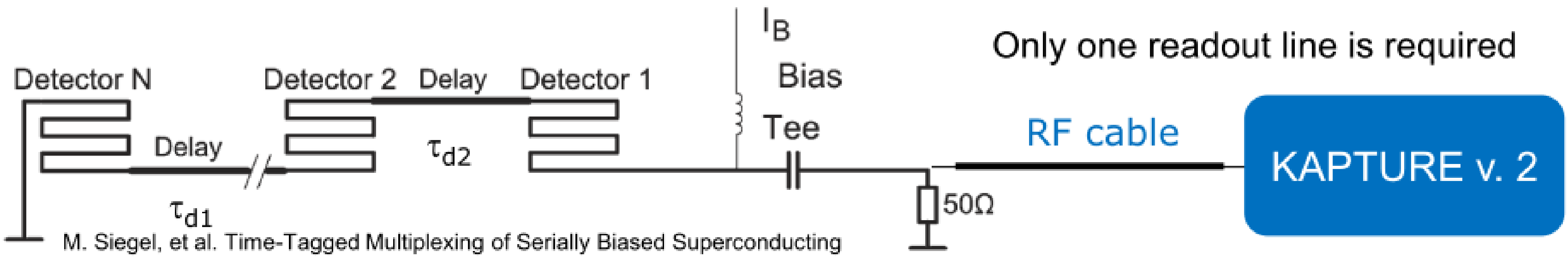




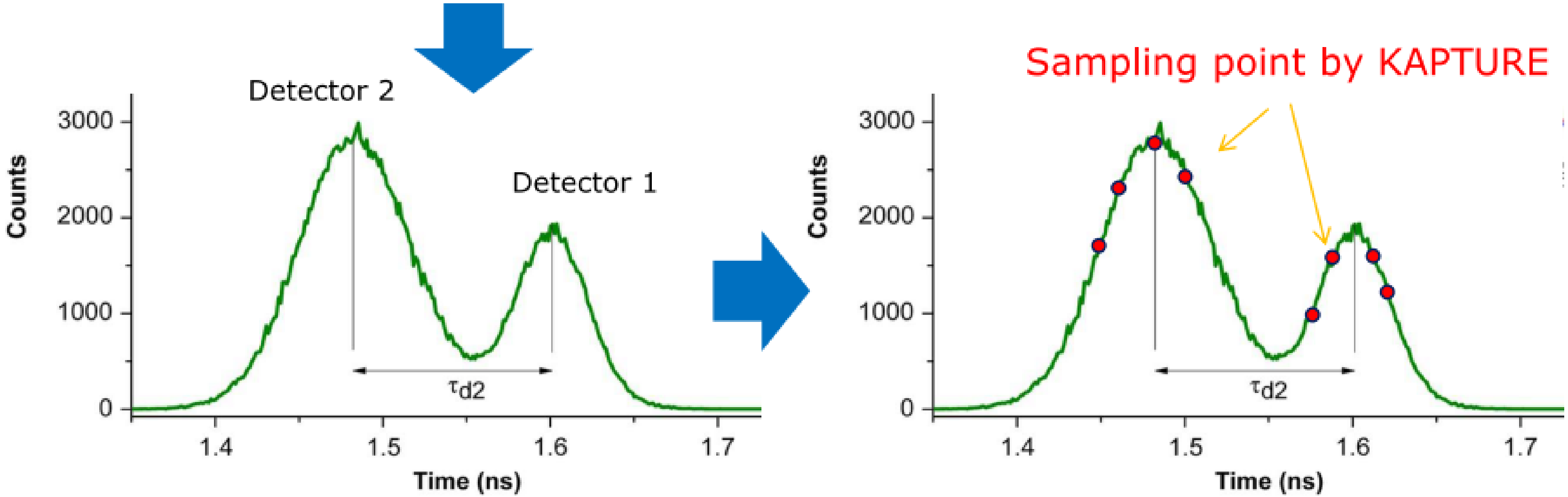
- Biasing current close to superconducting critical current
- Photons incident on the nanowire generate quasi particle
- Quasi particles lower critical current locally → local resistance hotspots
- Typical nanowire dimensions: 5nm thickness, 100 nm width
- Very high detection efficiency (> 90%)
- Extremely sensible (NEP: ~ $5*10^{-21}$ $W/Hz^{1/2}$)
- Resp. time < 20 ps

Direct Detection – Superconducting Nanowire Single Photon Detector

Multipixel THz SNSP Detectors – Ongoing investigation @ KIT IMS & IBPT!

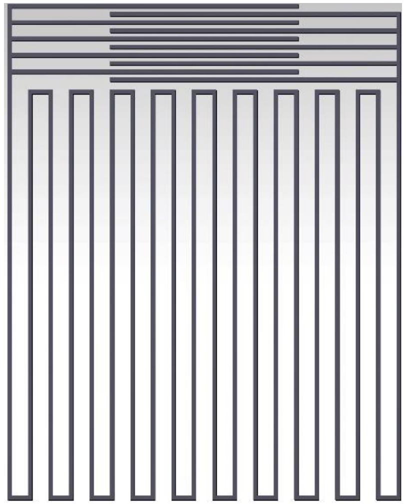


M. Siegel, et al. Time-Tagged Multiplexing of Serially Biased Superconducting Nanowire Single-Photon Detectors. IEEE DOI: 10.1109/TASC.2013.2245935

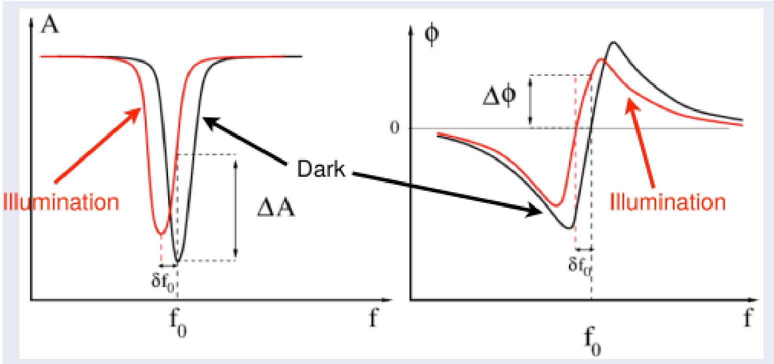


Designed to sample two ultra fast pulses with very short time distance. Time distance settable by FPGA from 25 ps to 400 ps with incremental step of 25 ps.

Direct Detection – Kinetic Inductance Detector



- Meandered Line: L
- Interdigital Capacitor: C

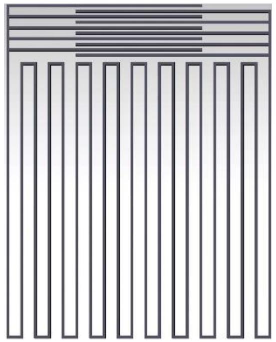


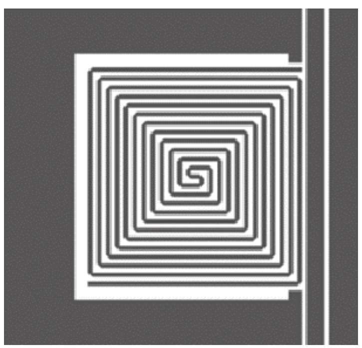
L_K

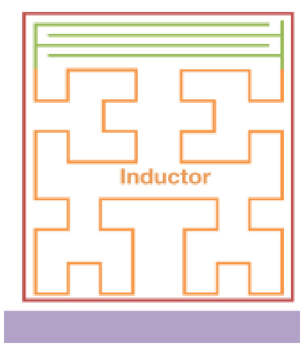
$$\sigma = \frac{ne^2\tau}{m(1+i\omega\tau)} = \frac{ne^2\tau}{m(1+\omega^2\tau^2)} - i\frac{ne^2\omega\tau^2}{m(1+\omega^2\tau^2)}$$

- Appreciable ONLY in superconductors
- $L_K \sim 1/n_C$
- Photons → Cooper pairs breakage → excess quasiparticles → L_K increases upon photon absorption
- Incoming photons are detected through a change in the resonant frequency and phase of the circuit (S_{21} parameter)

Direct Detection – Kinetic Inductance Detector



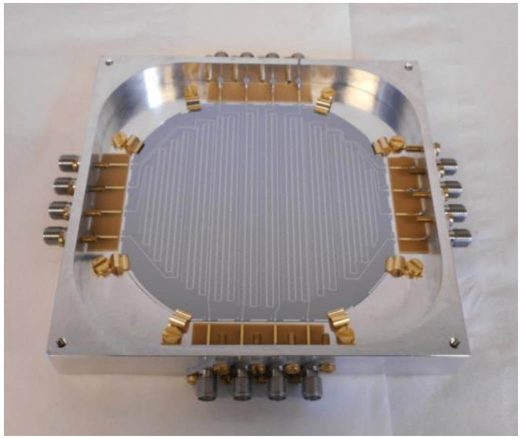




- Many possible configurations (ex: grid, spiral, Hilbert inductor) → polarization sensitiveness, lumped elements (no antenna)
- Ease of fabrication: single layer deposition, planar geometry, MS/CPW, photolithography
- Very high number of pixels (>1000) feasable with simple read out
- Extreme sensitivity possible (record NEP 3.8 * 10^{-19} W/Hz$^{1/2}$)
- Energy res. ~ 100 meV (theoretical GR limit ~ 10 meV)
- Rise time ~ 50 ps (intrinsic ~ 10 ps)
- High degree of tunability: bandwidth from RF GHz to X rays

Direct Detection – Kinetic Inductance Detector

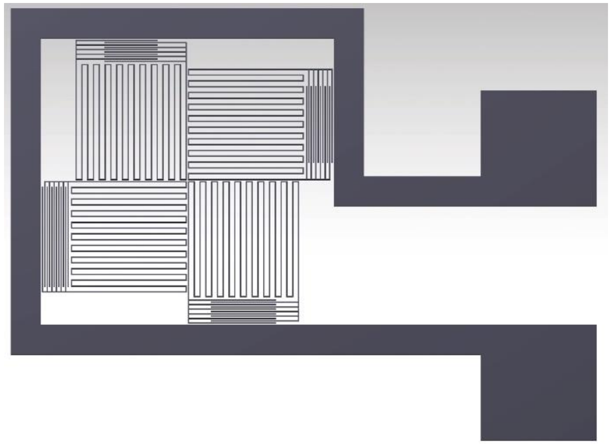
Astrophysics Application – NIKA2



R.Adam et al., A&A 609, A115 (2018)

- Dual band camera (150 / 260 GHz) for IRAM's 30 m radiotelescope
- 2900 detectors over three monolithic arrays
- Al thin film over HRSi
- 150 mK operating temperature

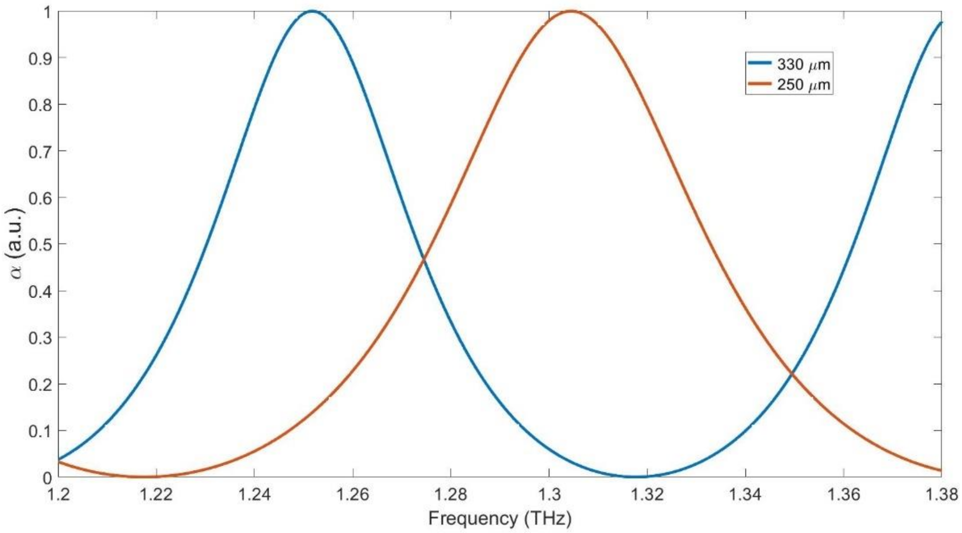
Fusion Plasma Diagnostics – Polarimeter



F.Mazzocchi et al., Fus.EngDes 130, May 2018

- 4 pixel, polarization sensitive array
- NbN 15 nm thin film, Si/Sapphire/ Diamond substrates
- 1.3 THz detection frequency
- 4.2 K operating temperature

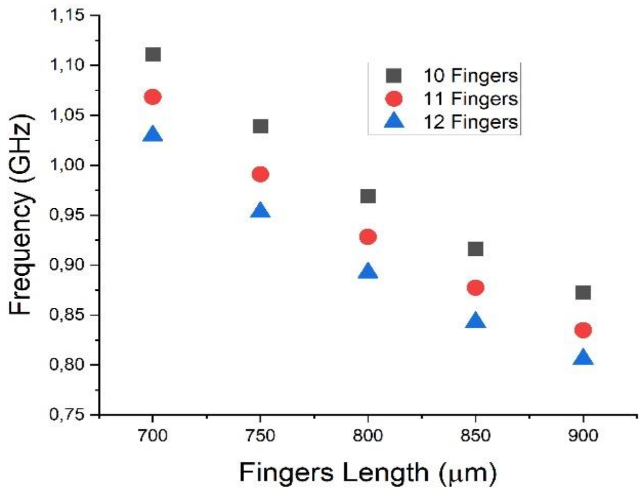
KID – Characteristics and Tuning



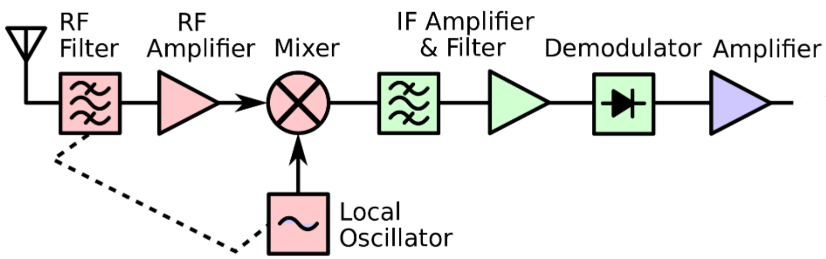
- Radiation coupling: substrate + thin film impedance
- Backshort → substrate thick. → spectral response
- Interdigital capacitor finger length → resonators tuning

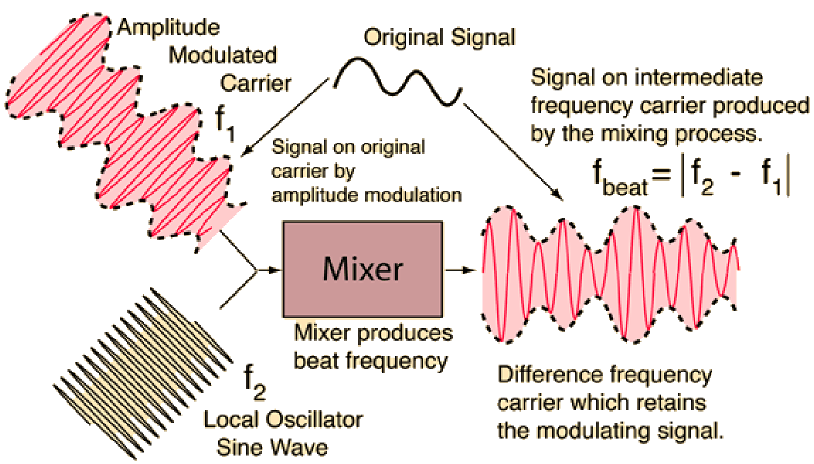
$$\alpha = 1 - \left|\frac{Z_0 - Z_{Eff}}{Z_0 + Z_{Eff}}\right|^2 \qquad Z_{Eff} = \frac{1}{\frac{1}{Z_{KID}} + \frac{1}{Z_{Sub}}}$$

$$Z_{KID} = \frac{\rho_{NbN} s}{d_{NbN}\, w} \qquad Z_{Sub} = j\, Z_{Sub} \tan(\beta l),$$

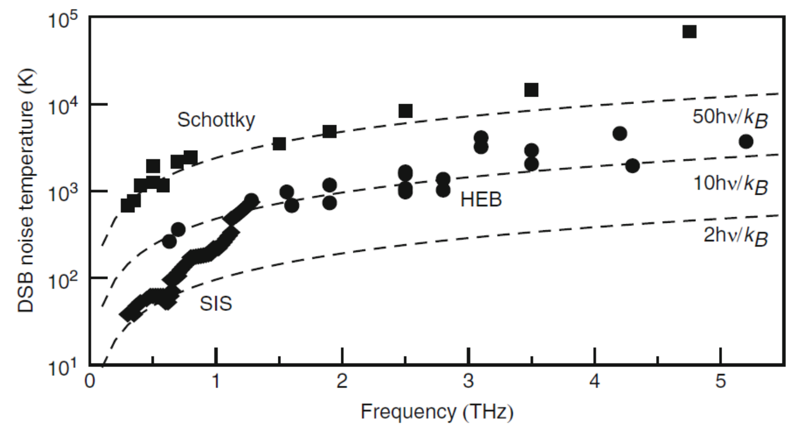


Hetherodyne Detection



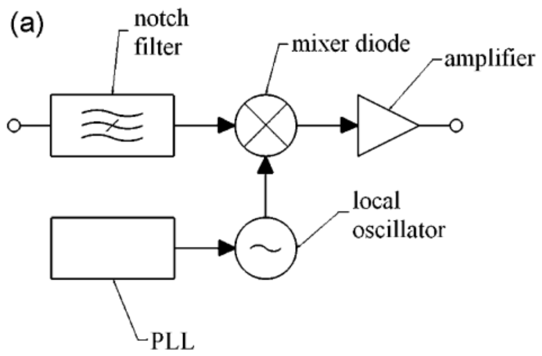


- Detection techniques based on mixing the incoming THz signal with LO signal
- Mixer: non linear component, producing the beat IF
- THz LO: Multipliers (→ 2 THz), QCLs (> 2 THz)
- THz Mixer: Schottky (RT), HEB, STJ (Cryo)

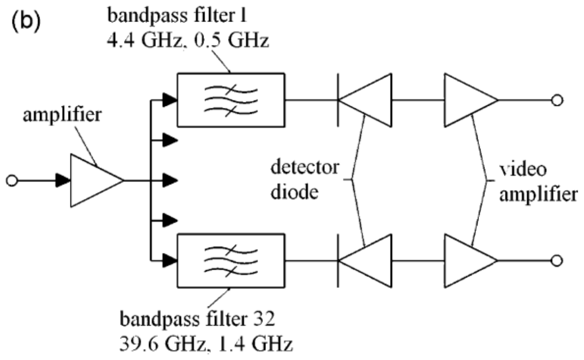


E. Bründermann, H.W. Hübers, M.F. Kimmit, Terhertz Techniques, Springer

Heterodyne Detection – W7X ECE 32ch radiometer

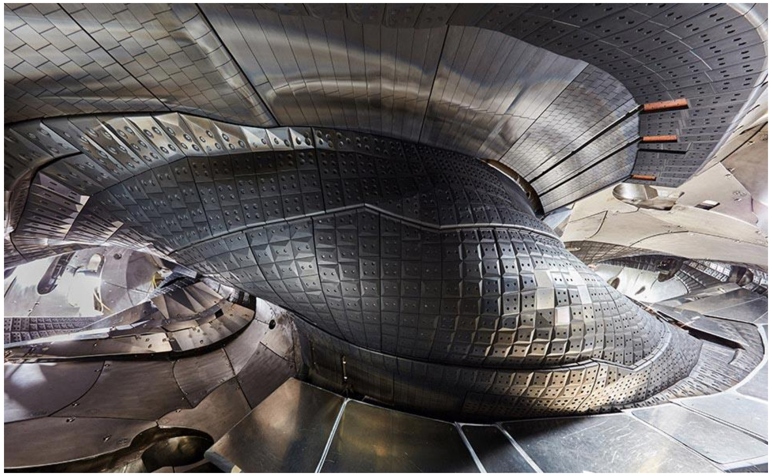


Front end



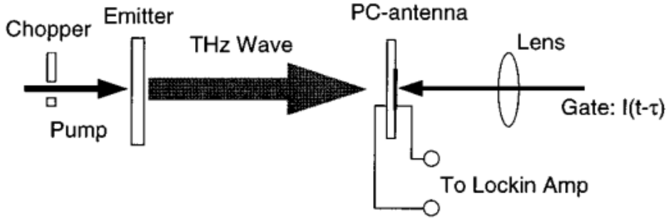
IF stage

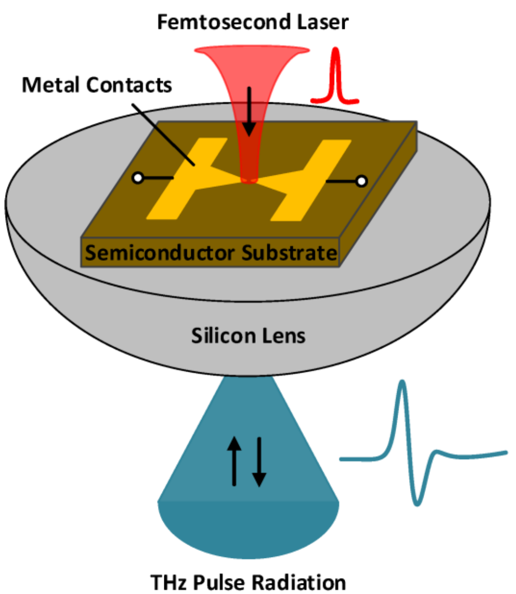
S.Schmuck et al., Fus.EngDes. 84 (2009) 1739 - 1743



- Electron Cyclotron Emission diagnostic → plasma electron temperature profile
- Detects second harmonic of electron gyromotion fundamental mode at 70 GHz
- Notch filters at 140 GHz (ECRH) to avoid detector overload
- 126 – 160 GHz range, downconverted to 4 – 40 GHz

Sampling detection – Auston switch





- Auston switch: gated photoconductive antenna (semiconductor bridged gap)
- Femtosecond pulse laser increases the conductivity of the antenna, excites charge carriers
- Incoming THz radiation induces a measurable photocurrent
- Response time depends on antenna structure and photocarriers lifetime (~ 300 fs for InGaAs emitter)
- Antenna parameters also limit the bandwidth to typically 6 THz

Sampling Detection – Electro Optical

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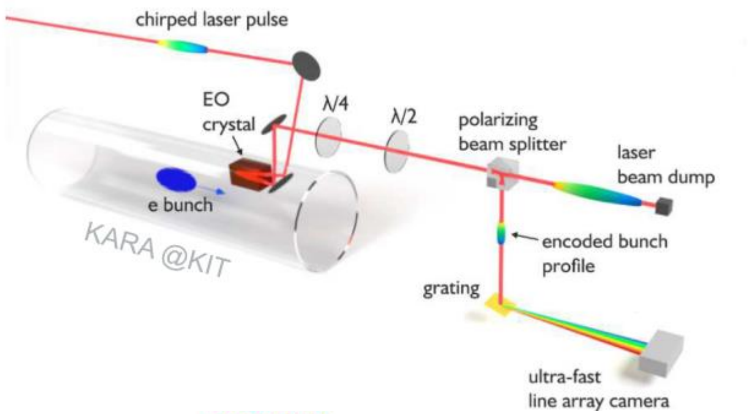

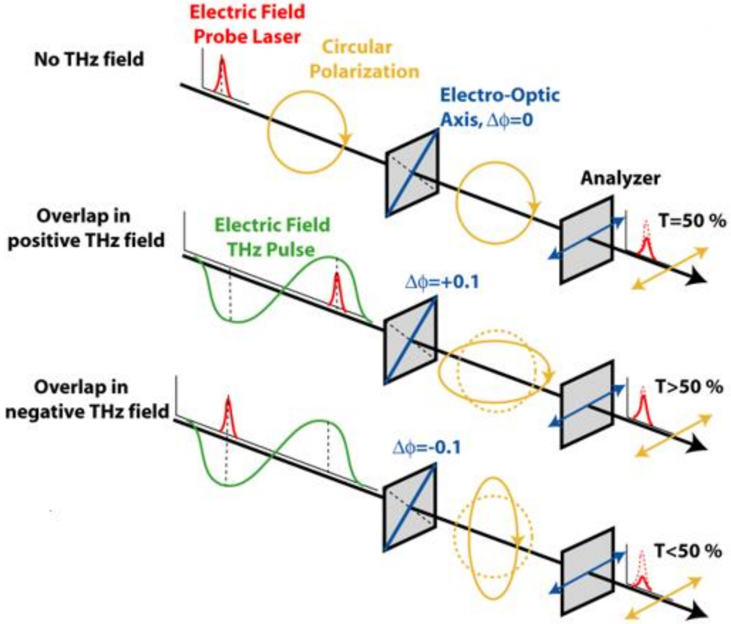

- Pockels effect: EO crystal (for example, ZnTe) birefringency **Q** bias voltage
- The THz signal works as modulation signal for the crystal birefringency
- Polarization status of an ultrafast (fs) probe beam is modulated by the THz radiation
- WP separates P and S components of the encoded bunch profile
- Balanced detector P-S **Q** THz ampl.
- Huge bandwidth: 100 GHz – 37 THz

S. Funkner, G. Niehues, M. J. Nasse, E. Bründermann, M. Caselle, B. Kehrer, L. Rota, P. Schönfeldt, M. Schuh, B. Steffen, J. L. Steinmann, M. Weber, A.-S. Müller arXiv preprint, arXiv:1912.01323

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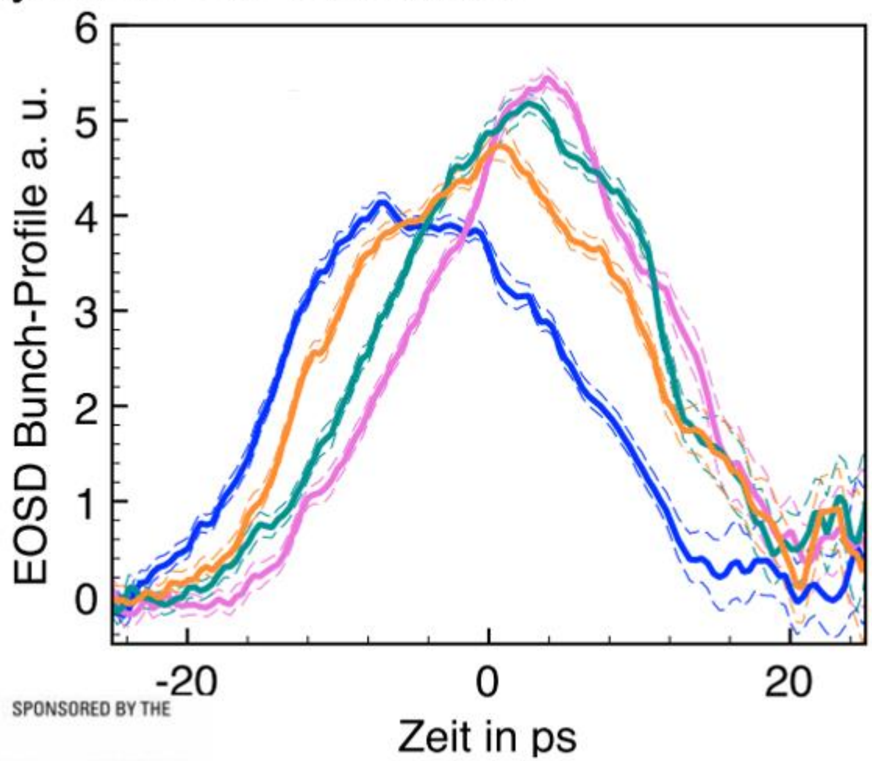
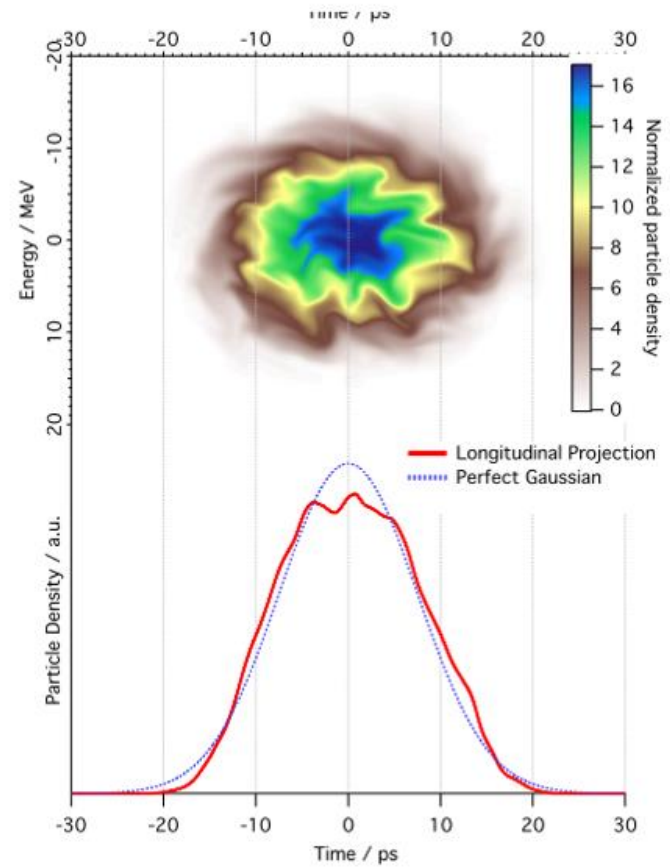
Sampling Detection – EO @ KARA

- Single-shot EOSD measurements show dynamic sub-structures



N. Hiller, et al., IBIC 2014, MOPD17

simulated phase space



courtesy J. Steinmann, P. Schönfeldt

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Summary

- Large variety of detectors and techniques exist or are under development in THz detection:
  - Thermal
  - Direct
  - Heterodyne
  - Sampling

- Direct detection techniques generally offer very good performances (sensitivity, speed, etc.) with the advantage of being realatively simple

- Innovative devices like YBaCuO and KID are being developed as low-cost simple solutions with very good perspective

THANK YOU!

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