Karlsruher Institut für Technologie

TWEPP 2016 - Topical Workshop on Electronics for Particle Physics
Karlsruhe

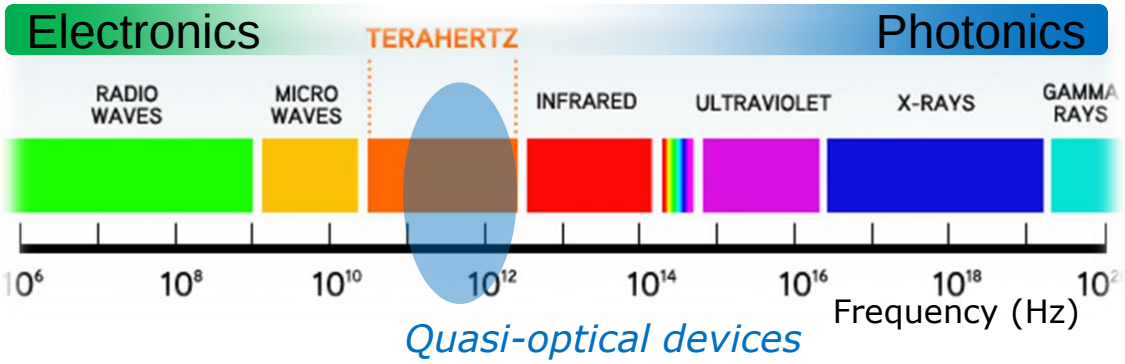
KAPTURE-2 – A picosecond sampling system for individual THz pulses with high repetition rate

TWEPP 2016, 26-30 September 2016. Karlsruhe Institute of Technology (KIT), Germany

M. Caselle, L.E. Ardila Perez, M. Balzer, M. Brosi, E. Bründermann, S. Chilingaryan, T. Dritschler, A. Kopmann, Juliane Raasch, L. Rota, J. Steinmann, M. Vogelgesang, A.-S. Müller, M. Siegel, M. Weber

KIT, Institut für Prozessdatenverarbeitung und Elektronik
M. Caselle

Terahertz – “new science”



Quasi-optical devices

The Terahertz region 200 GHz to 10 THz) between microwaves and the far infrared.

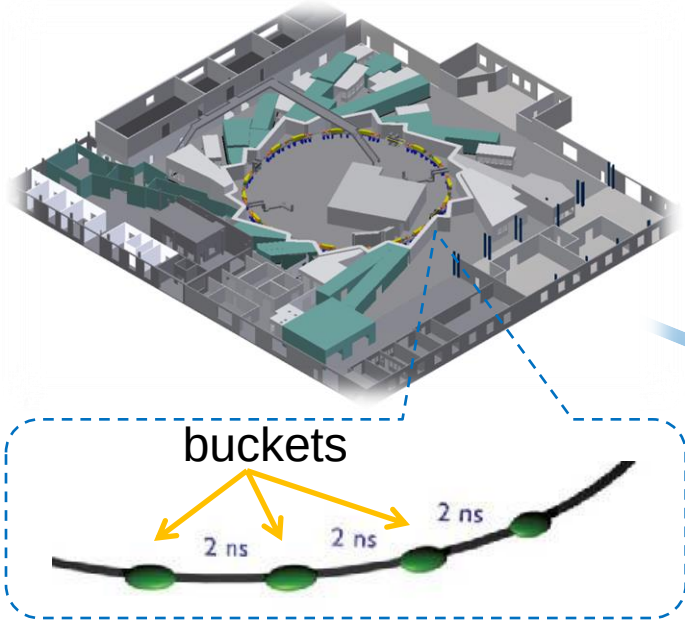
Range from 100 GHz -> 4 THz → *future application/devices.*

Outlook

- Coherent terahertz radiation source @ ANKA
- Terahertz sensor technology
- Readout electronics and picosecond pulse sampling “KAPTURE”
- Results and future work..
- Conclusions

Terahertz Coherent Synchrotron Radiation at ANKA

ANKA is the Synchrotron Radiation Facility at the Karlsruhe Institute of Technology (KIT)



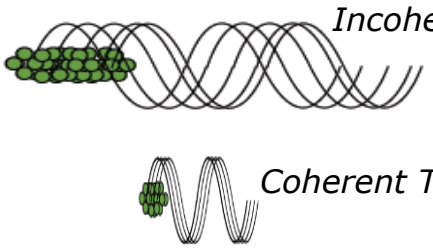
- RF-system: **500 MHz** (bunch spacing 2 ns)
- Harmonic number: **184**
- Bunch length (low alpha) : **few ps**

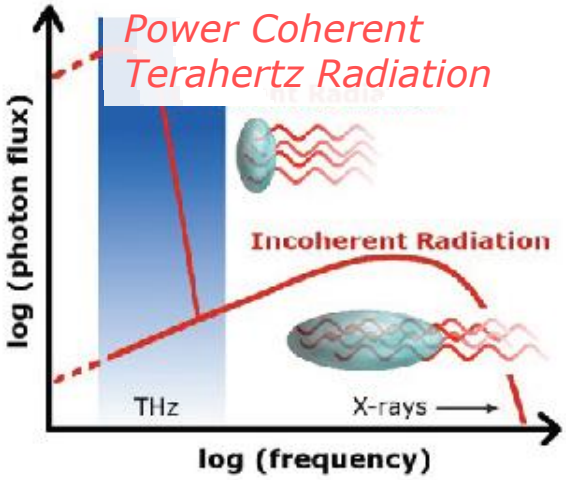
ANKA THZ GROUP

ANKA
Terahertz beamline

Two operation modes:

- *Normal mode*
- *Low alpha mode (compact mode)*





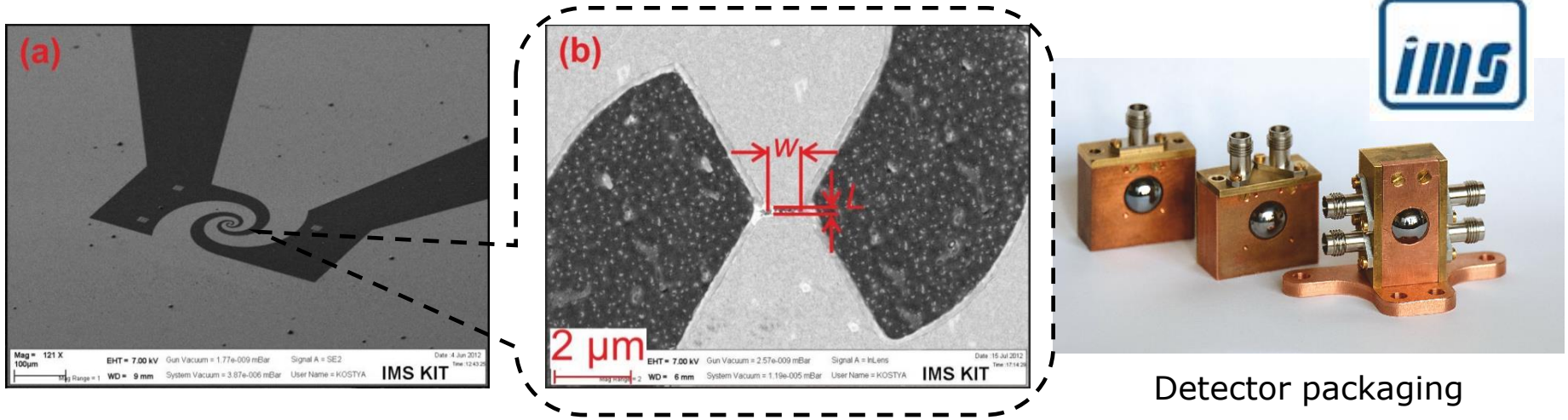
Reference:

A.-S. Müller, et al. "**Experimental Aspects of CSR in the ANKA Storage Ring**" ICFA Beam Dynamics Newsletter No. 57, 154–165 (2012).

A.-S. Müller, et al. "Observation of Coherent THz Radiation from the ANKA and MLS Storage Rings with a Hot Electron Bolometer". TU5RFP027 (2009)

Ultra-fast YBCO THz detectors

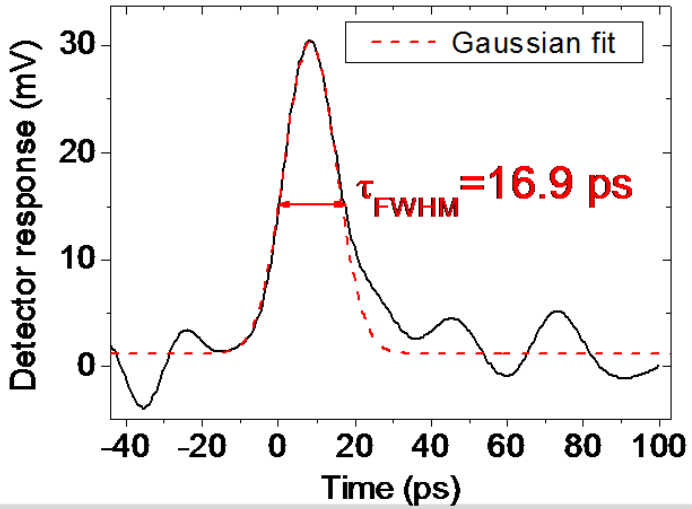
Multi-channel thin Yttrium Barium Copper Oxide (YBCO) superconductor film liquid-nitrogen-cooled detectors. Produced @ IMS-KIT



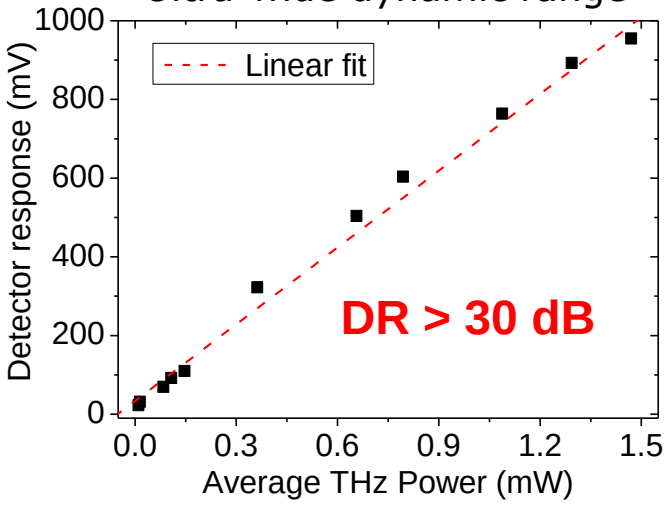
Detector packaging

P. Thoma et al., *Applied Physics Letters*, 101, 142601, 2012
P. Probst et al., *Physical Review B*, 85, 174511, 2012

Picosecond time resolution



Ultra-wide dynamic range



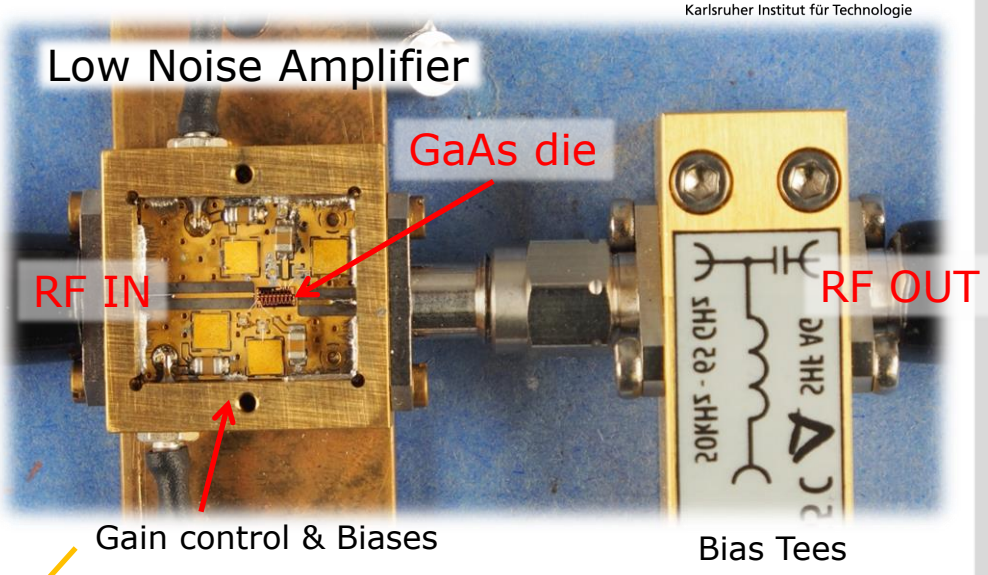
Front-end – Low Noise Amplifier

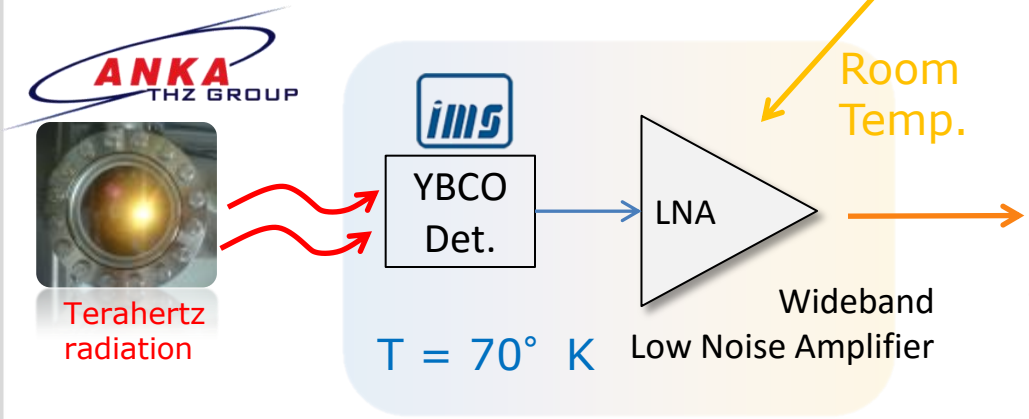
Detector:

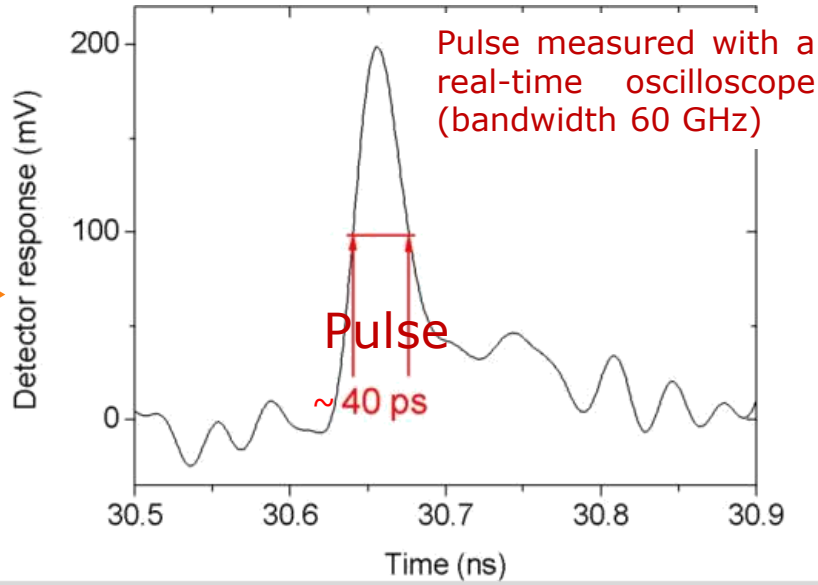
- Output impedance 50 Ω
- Picosecond time accuracy
- Connection by wideband RF cable

Front-end:

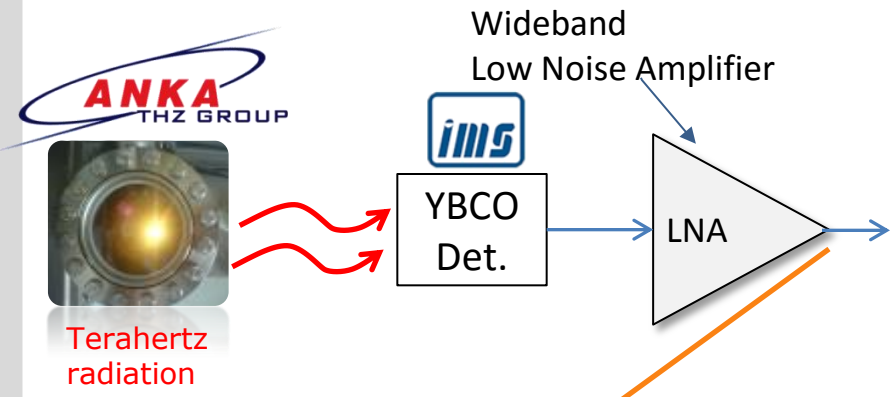
- Low Noise Amplifier (DC-50 GHz) based on GaAs HEMT device
- Limited number of channels
- Higher repetition rate hundreds MHz/ GHz

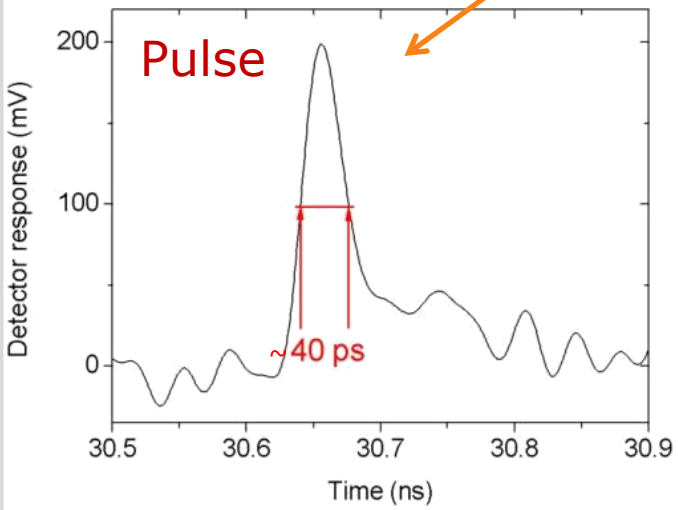






Requirements



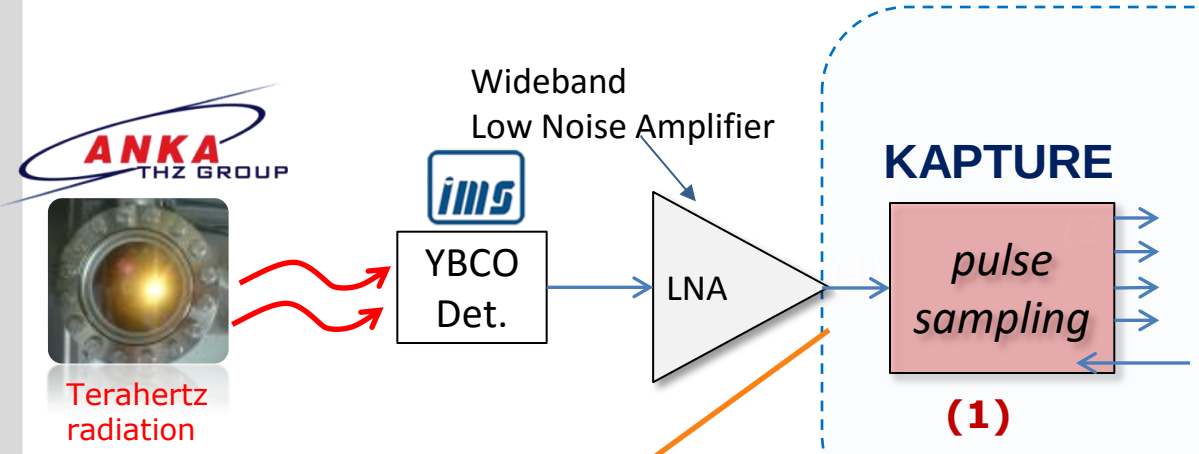


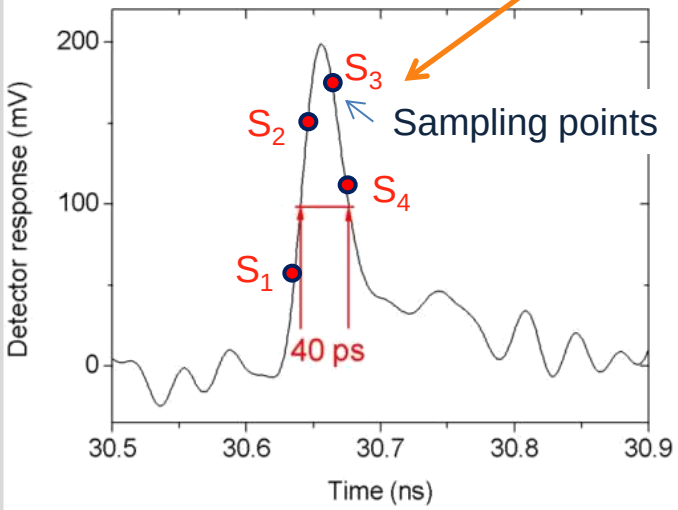
Requirements:

- Acquire each pulse →pulse repetition rate of 500 MHz
- For each pulse → measure amplitude and peaking time respectively with "mV" "picosecond" accuracy

Ultrafast THz readout system (I)

KAPTURE system





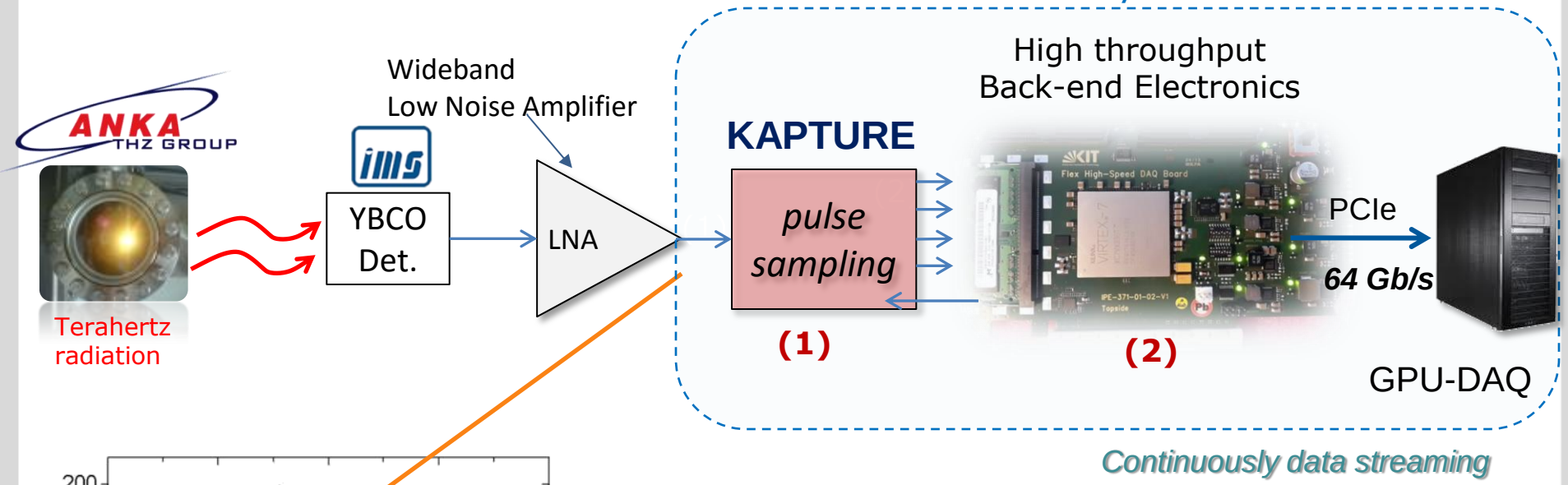
1. Sampling: each pulse sampled with 4 samples by **KAPTURE** board, minimum sampling time of 3 ps.

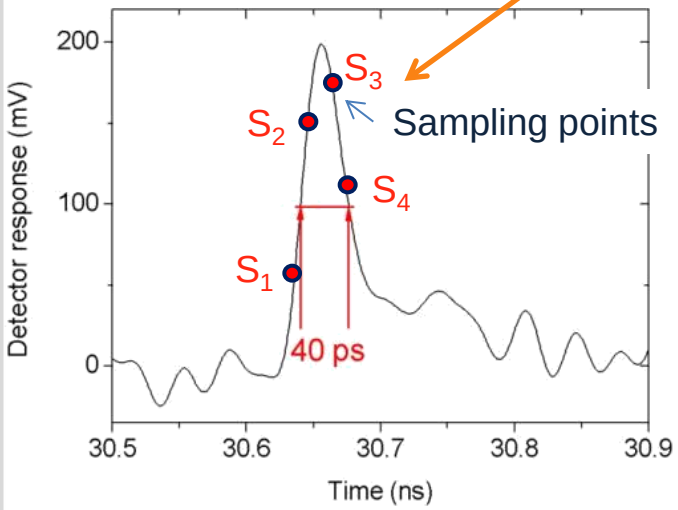
M. Caselle, et al. *Ultra-fast Data Acquisition System for Coherent Synchrotron Radiation Based on Superconducting Terahertz Detectors.* 10/06/2013.

Pulse with repetition rate 500 MHz

Ultrafast THz readout system (II)

KAPTURE system





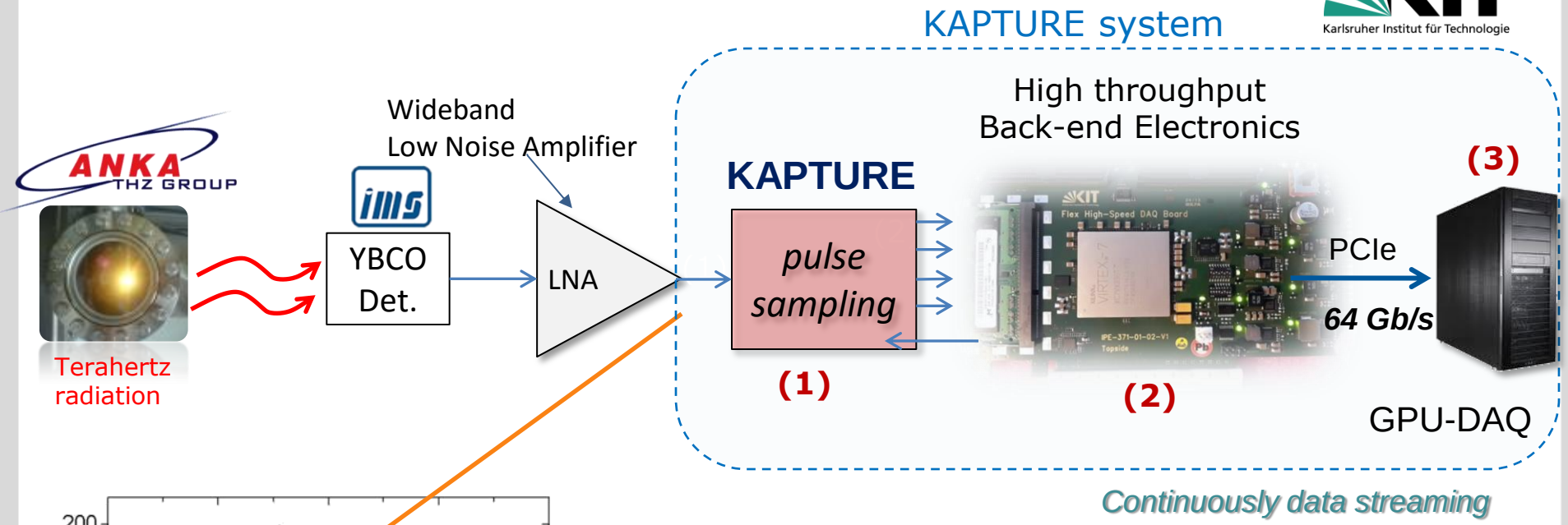
Pulse with repetition rate 500 MHz

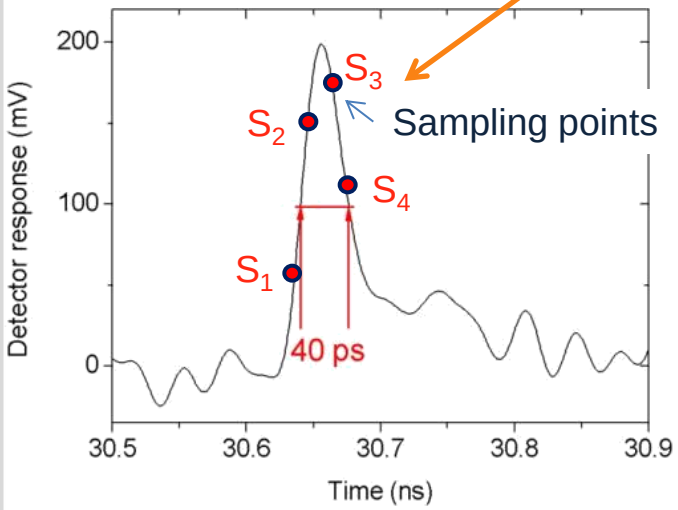
1. Sampling: each pulse sampled with 4 samples by **KAPTURE** system , minimum sampling time of 3 ps.

2. Data transfer: digital samples transferred to high-end GPU (Graphics Processing Units) by a *DMA-> DirectGPU* technology

Poster pos. M4

Ultrafast THz readout system (III)





Pulse with repetition rate 500 MHz

1. Sampling: each pulse sampled with 4 samples by **KAPTURE** system , minimum sampling time of 3 ps.

2. Data transfer: digital samples transferred to high-end GPU (Graphics Processing Units) by a *DMA-> GPUDirect* technology

Poster pos. M4

3. Real-time GPU data processing: pulses reconstruct, amplitude and peaking time respectively with "mV" "picosecond" accuracy are evaluated

Ultrafast THz readout system (III)

KAPTURE system

Wideband
Low Noise Amplifier

High throughput
Back-end Electronics

Terahertz radiation

YBCO Det.

LNA

KAPTURE

pulse sampling

(1)

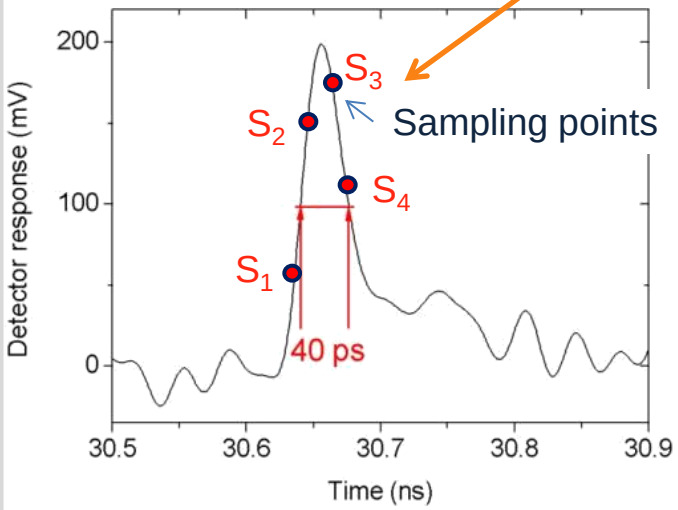
(2)

PCIe

64 Gb/s

(3)

GPU-DAQ



Pulse with repetition rate 500 MHz

KAPTURE system

Ultrafast THz readout system (III)

KAPTURE system

Wideband
Low Noise Amplifier

Terahertz radiation

YBCO Det.

LNA

KAPTURE

pulse sampling

(1)

High throughput
Back-end Electronics

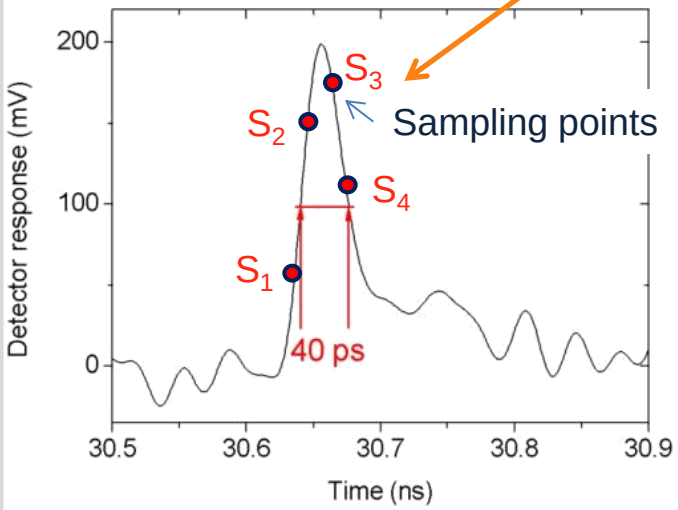
(2)

PCIe

64 Gb/s

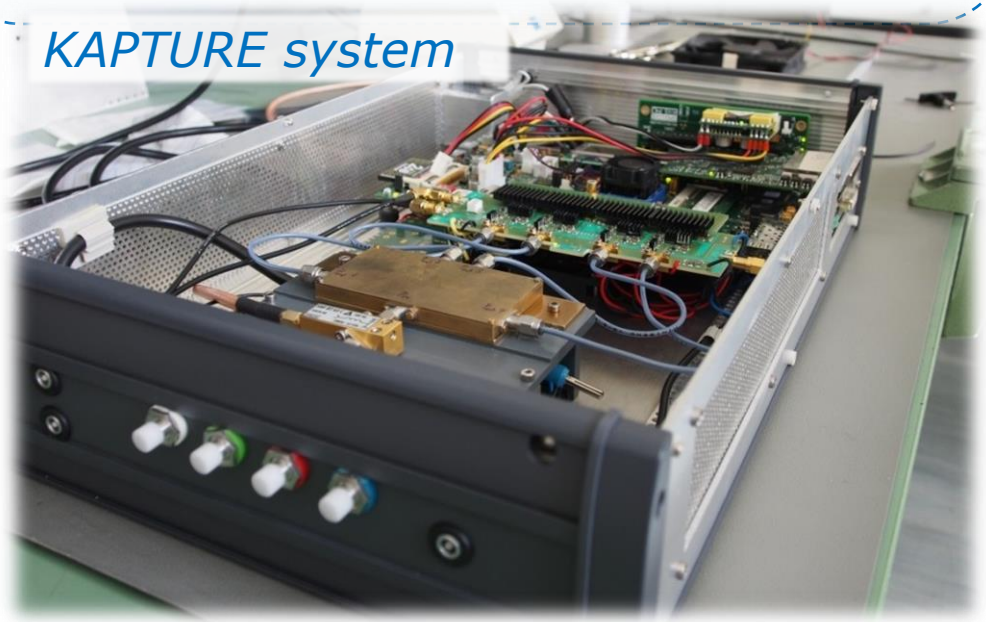
(3)

GPU-DAQ

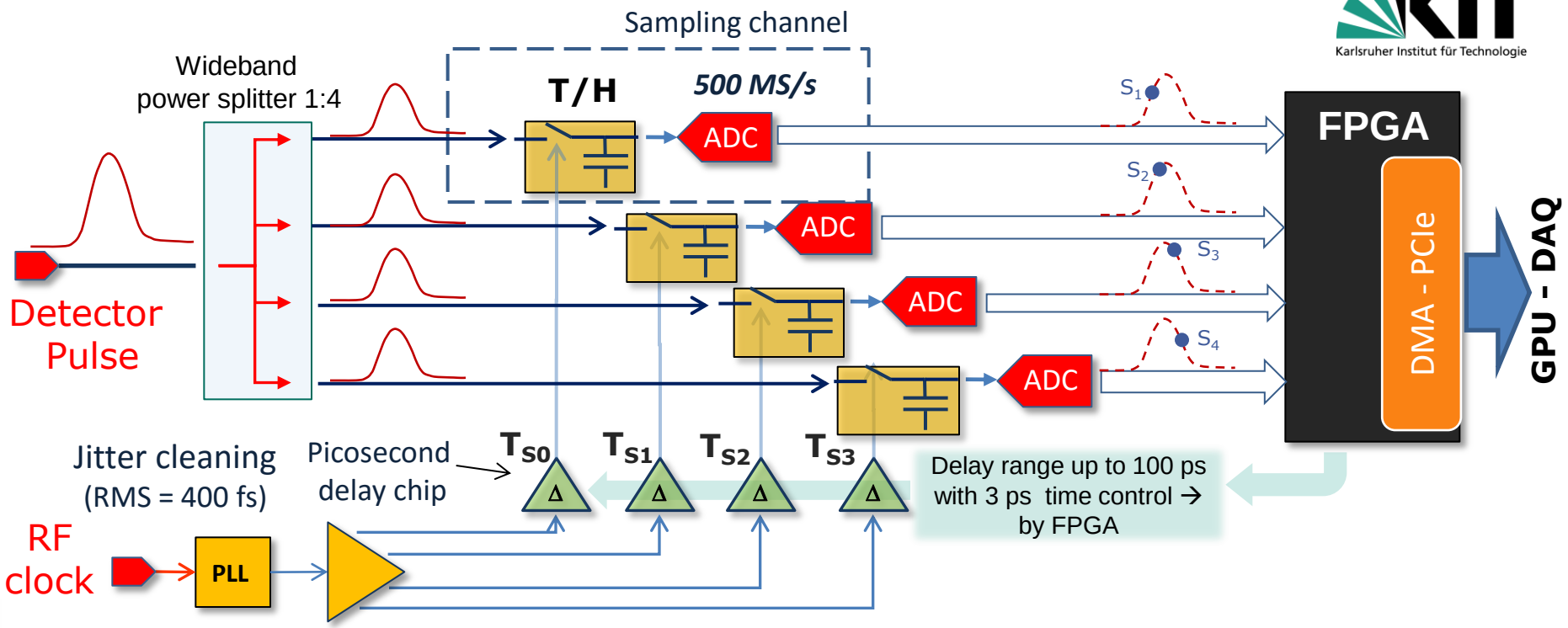


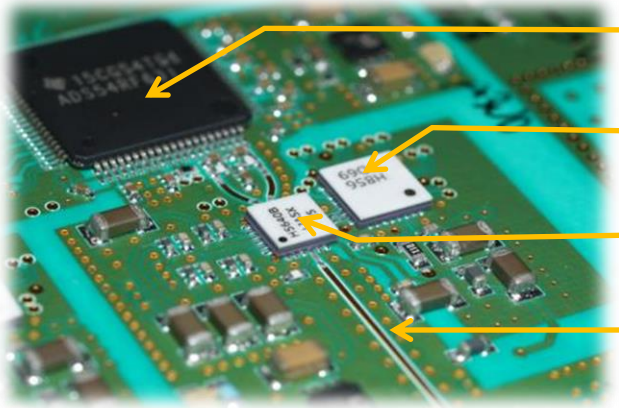
Pulse with repetition rate 500 MHz

KAPTURE system



KArlsruhe Pulse Taking Ultra-fast Readout Electronic





Fast ADC

Picosecond delay chip

DC-18 GHz Track-and-Hold

Wideband transmission line

M. Caselle, et al. *A Picosecond Sampling Electronic ``KAPTURE'' for Terahertz Synchrotron Radiation.* 01/06/2015
http://accelconf.web.cern.ch/AccelConf/IBIC2014/papers/moczb1.pdf

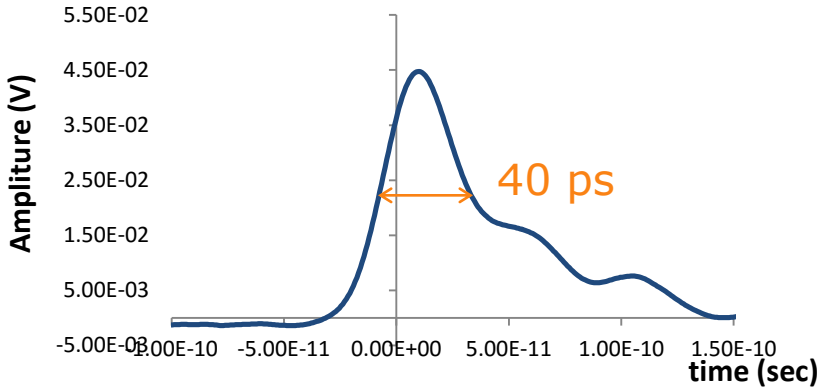
12 layers of RF/Microwave ROGER 4003C

Picosecond time accordion traces

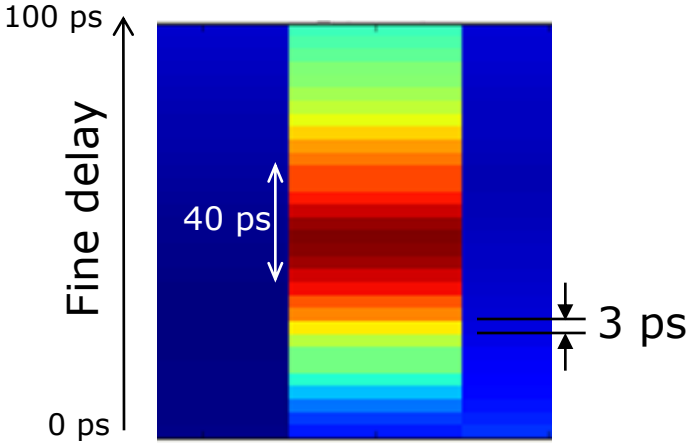
KAPTURE vers. 1 - Time characterization

YBCO detector pulse acquired by KAPTURE → "equiv. time sampling mode"

Pulse measured by real-time oscilloscope (bandwidth 60 GHz)

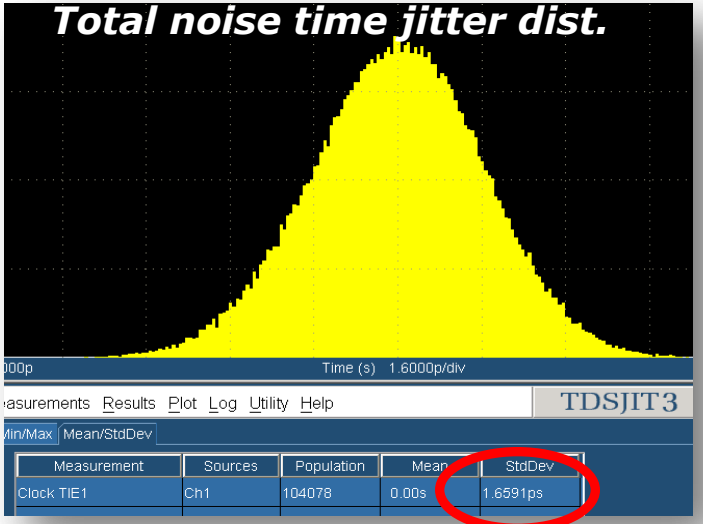


Pulse measured by KAPTURE equivalent time sampling @ 3 ps



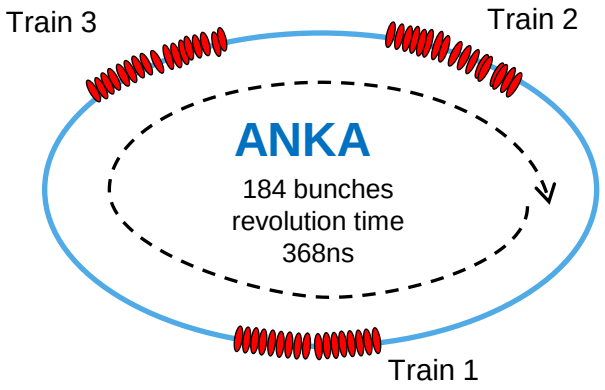
KAPTURE, electrical characteristics:

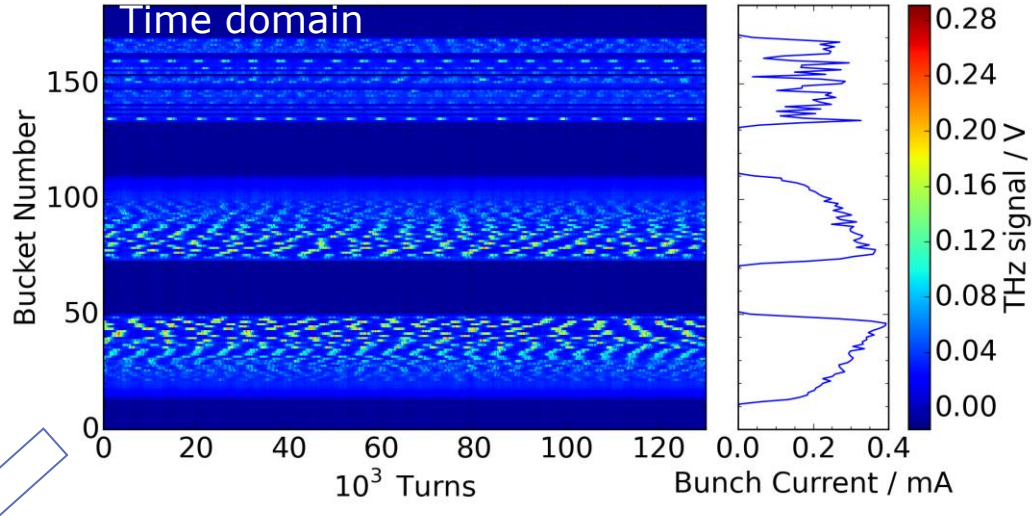
Dynamic range	**± 800 mV**
Trigger rate	**500 MHz**
Minimum sampling time	**3 ps**
Total RMS time jitter	**< 1.7 ps**
Noise RMS	**< 2 mV**

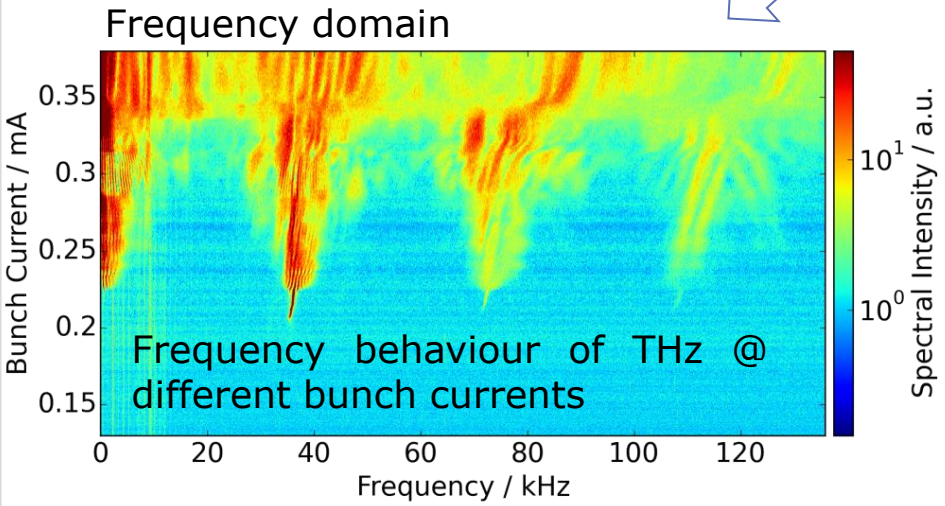


Experimental results - THz Bursting thresholds

To study the fluctuations of coherent terahertz radiation → caused by the micro-bunching instability (bursting).







M. Brosi, M.Caselle et al. *Fast Mapping of Terahertz Bursting Threshold and Characteristic at Synchrotron Light Source.* 02/05/2016,

J.L. Steinmann, M. Caselle, et al. *Influence of Filling Pattern Structure on Synchrotron Radiation Spectrum at ANKA.* 03/06/2016,

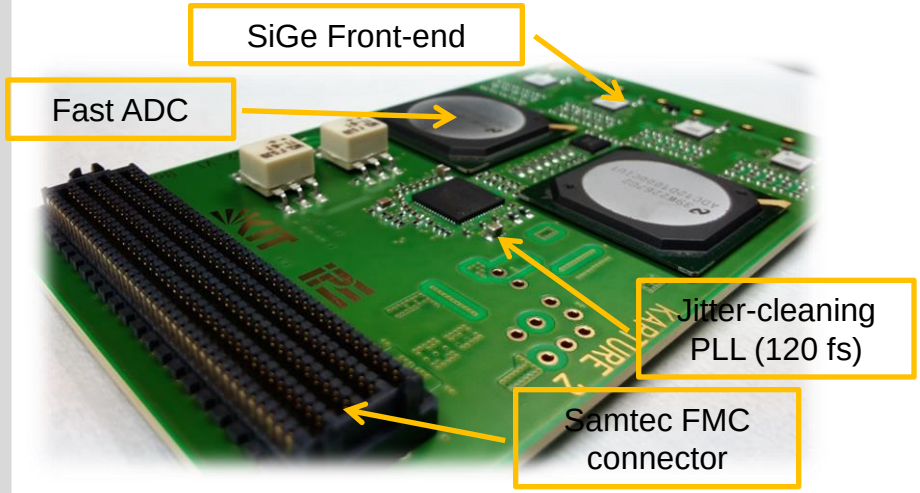
M. Brosi, M. Caselle, et al. *Online Studies of THz-radiation in the Bursting Regime at ANKA.* 04/07/2015

J.L. Steinmann, M. Caselle, et al. *Non-interferometric Spectral Analysis of Synchrotron Radiation in the THz regime at ANKA.* 04/07/2015

A.-S. Müller, M. Caselle, et al. *Studies of Bunch-bunch Interactions in the ANKA Storage Ring with Coherent Synchrotron Radiation using an Ultra-fast Terahertz Detection System.* 10/06/2013

KAPTURE: confirmed excellent agreement between theory and experimental data

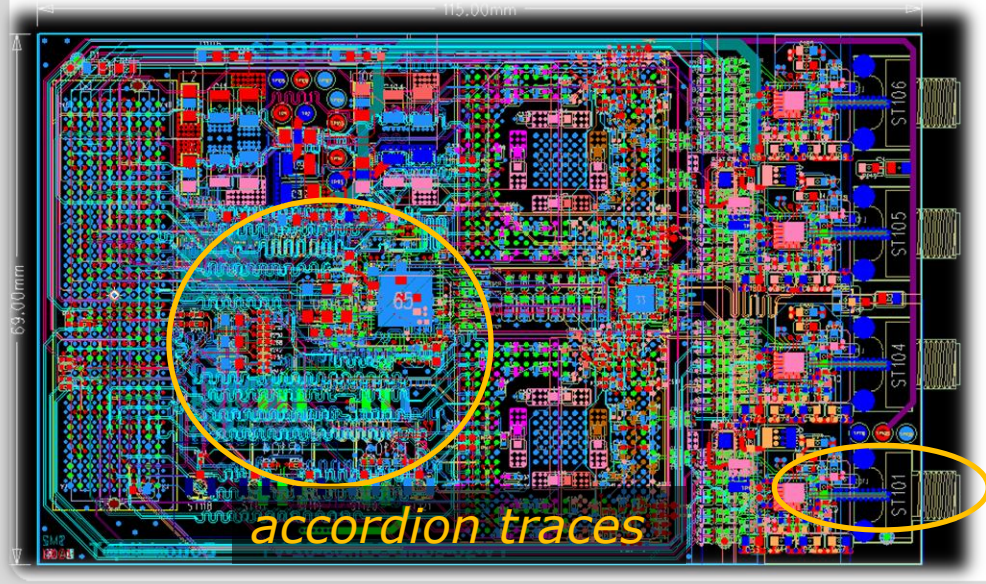
KAPTURE v. 2 – Overview



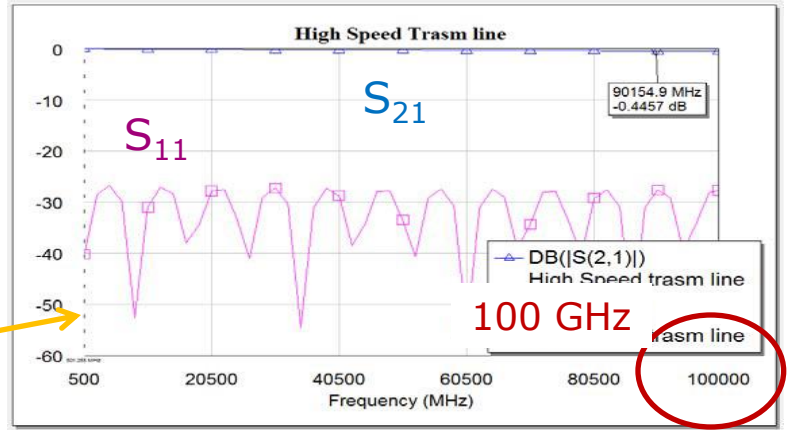
- Analog input bandwidth: DC – 60 GHz
- Single channel mode: continuous 4 x 1.8 GS/s = 7.2 GS/s @ 12 bit waveform sampling
- 16 layers of RF/Microwave ROGER 4003C
- Mechanically/electrically compatible with FMC / µTCA system

Supported by the German Federal Ministry of Education and Research *BMBF* (Grant No. 05K16VKA)

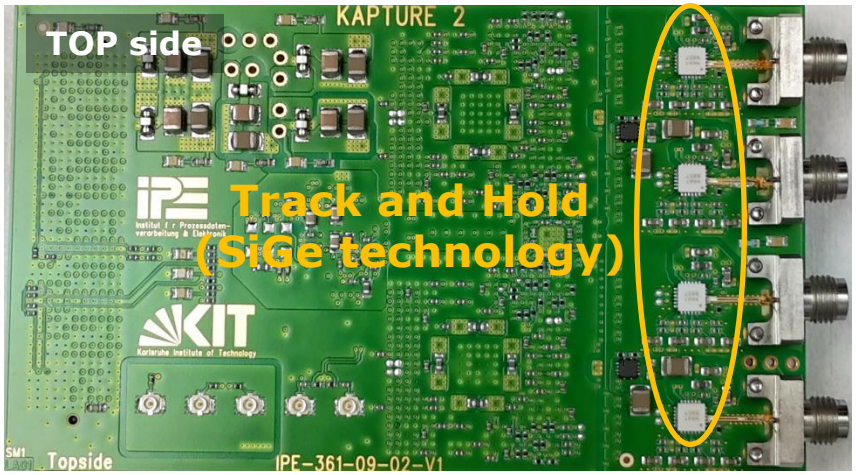
Produced 2016, currently under test

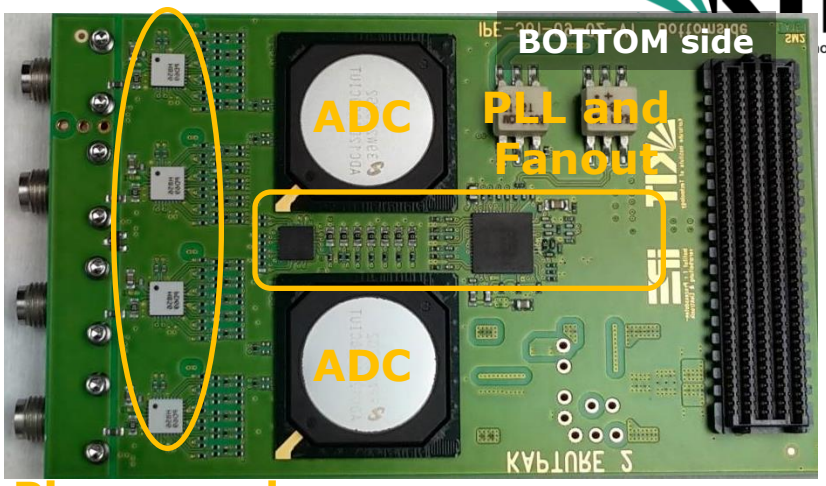


Low-noise PCB design, wideband transmission lines, accordion traces for length matching, etc.



KAPTURE v. 2 – Picosecond sampling architecture





Picosecond delay chip

Wideband power splitter 1:4

T/H

1.8 GS/s Dual ADC

Fast ADC

S_1 & S_2

Fast ADC

S_3 & S_4

FPGA

DMA - PCIe

GPU - DAQ

Detector pulse

T_{S0} T_{S1} T_{S2} T_{S3}

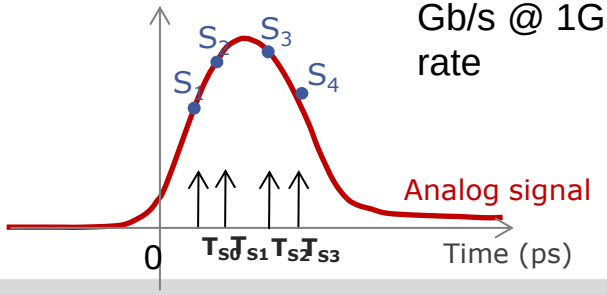
PLL jitter clearing
(RMS = 120 fs)

Set by FPGA

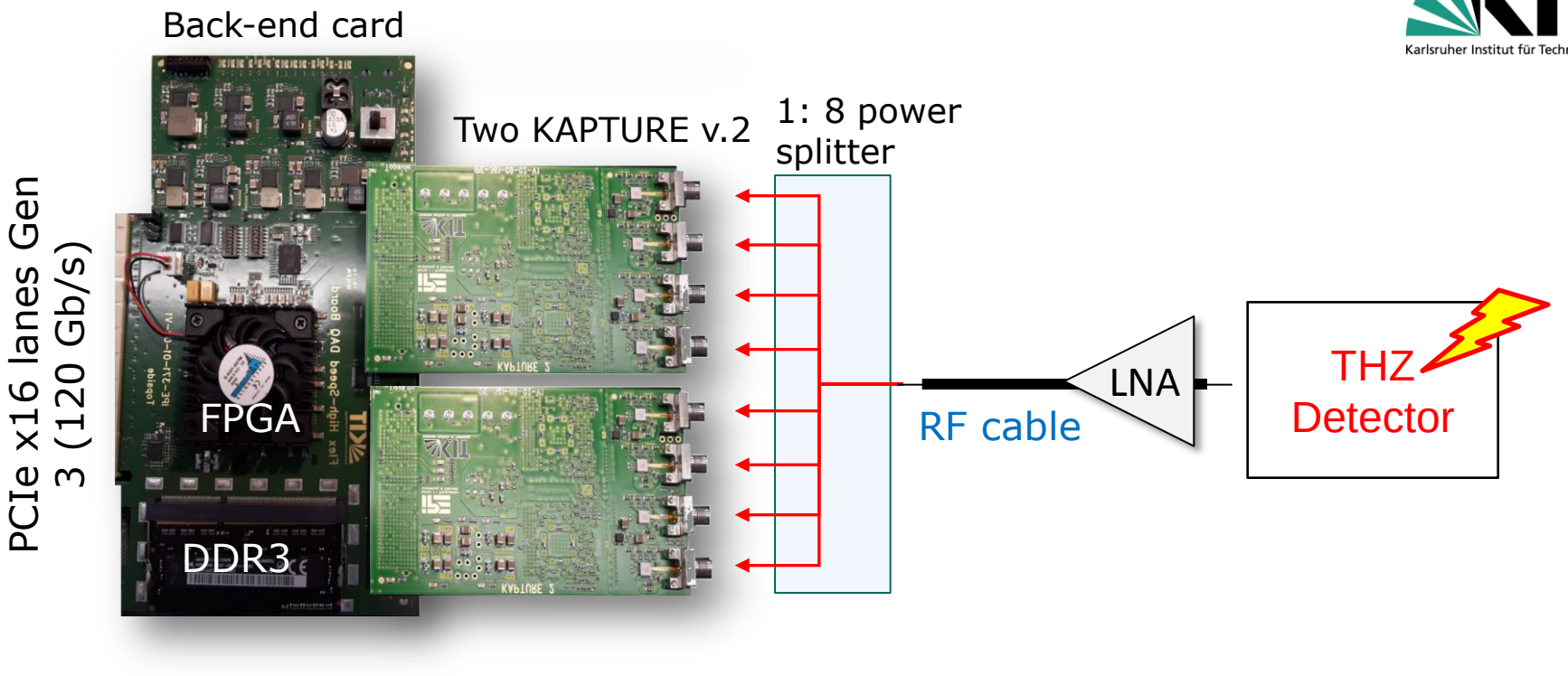
PLL

Fout

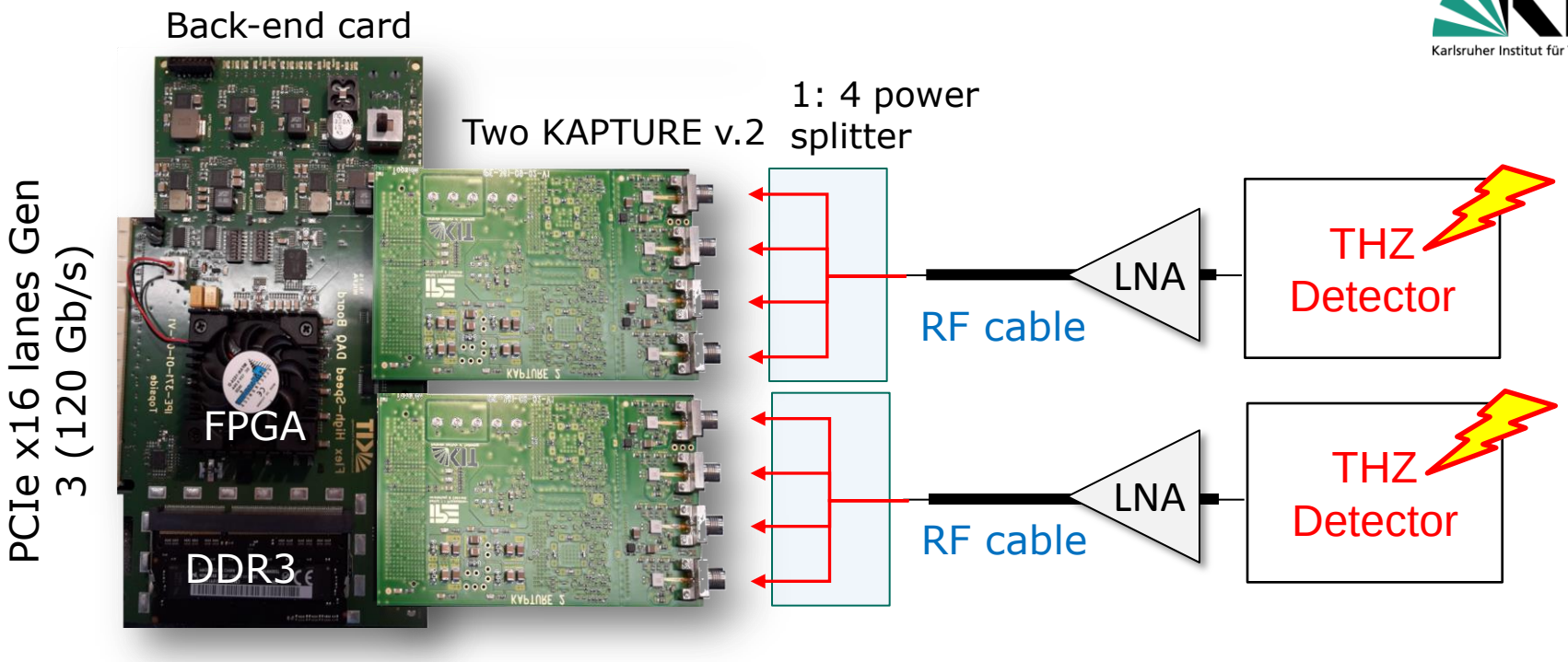
Data rate of 64 Gb/s @ 1GHz pulse rate



KAPTURE v. 2 – Operation mode (I)

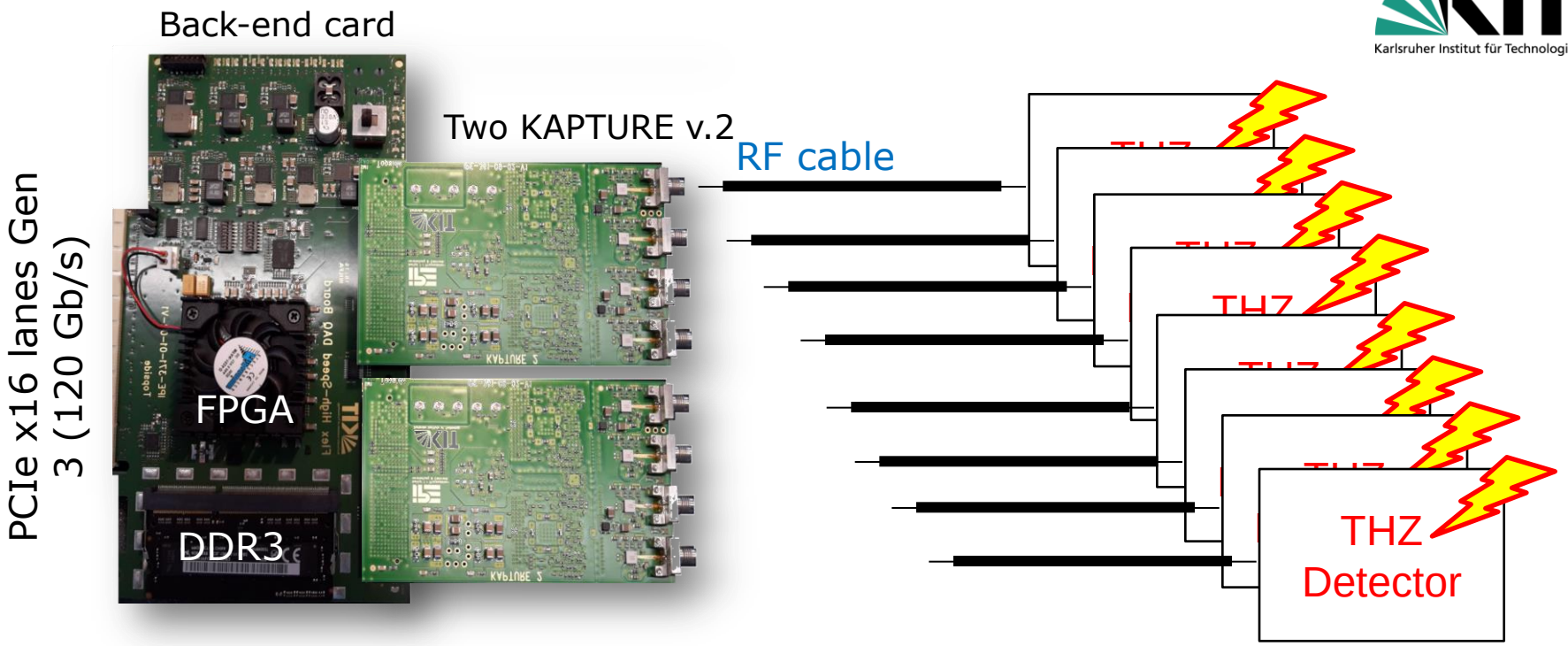


KAPTURE v. 2 – Operation mode (II)



- # 1 THz Detector → up to 8 samples per pulse @ max. pulse rate of 1.8 GHz
- # 2 THz Detectors → up to 4 samples per pulse @ max. pulse rate of 1.8 GHz

KAPTURE v. 2 – Operation mode (II)



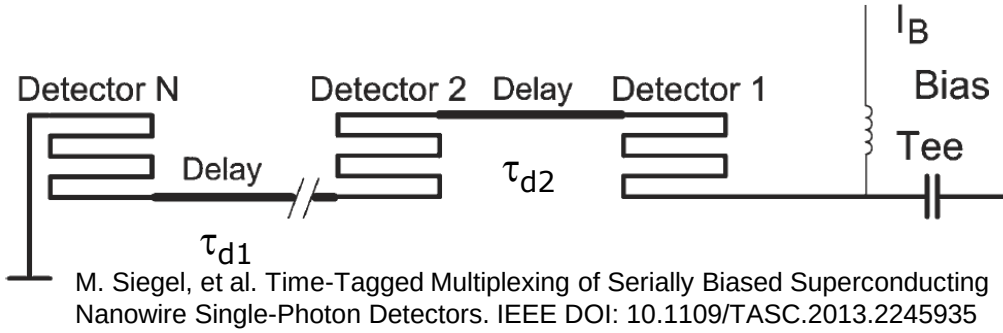
- # 1 THz Detector → up to 8 samples per pulse @ max. pulse rate of 1.8 GHz
- # 2 THz Detectors → up to 4 samples per pulse @ max. pulse rate of 1.8 GHz

.....

- # Up to 8 THz Detectors → 1 samples per pulse (peaking time) @ max. pulse rate of 1.8 GHz

Multi-pixel THz readout scheme

Time-Tagged Multiplexing of Serially Biased Superconducting Nanowire Single-Photon Detectors

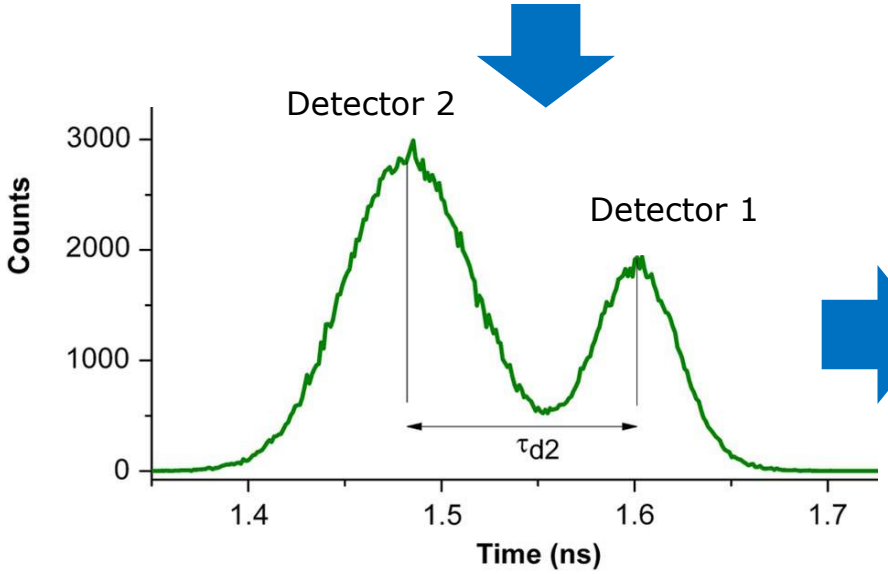


Only one readout line is required

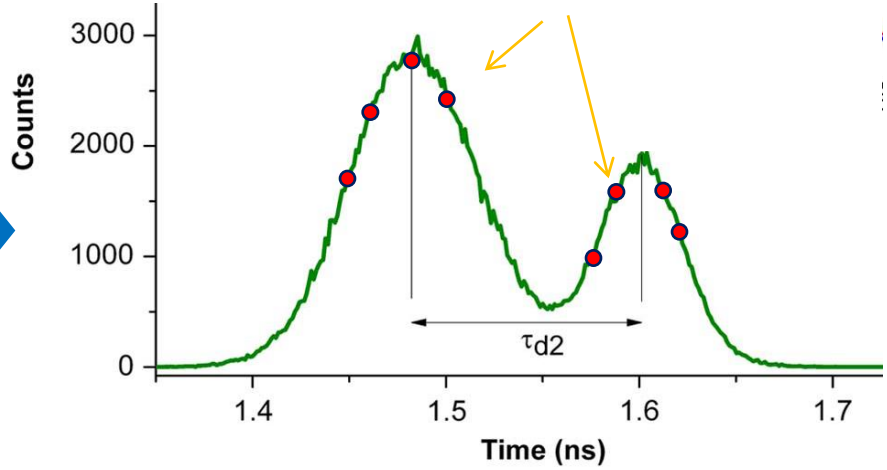
RF cable

KAPTURE v. 2

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

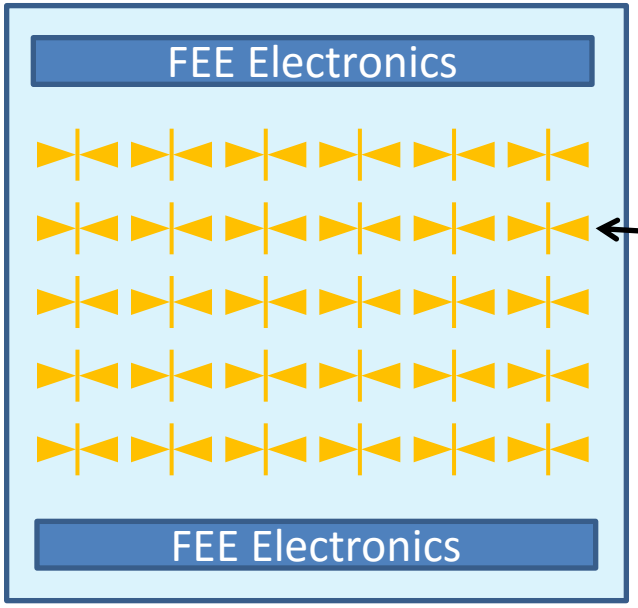


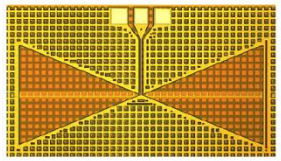
Sampling point by KAPTURE



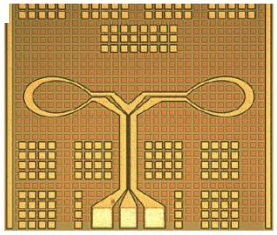
Designed to sample two ultra fast pulses with very short time distance. Time distance settable by FPGA from 25 ps to 400 ps with incremental step of 25 ps.

Matrix of THz Pixel detector – Future Perspective

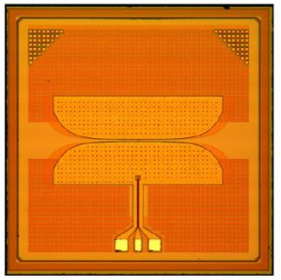




(a) Bow-tie antenna

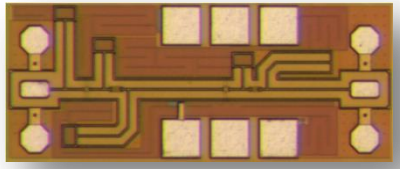


(b) Half-cloverleaf

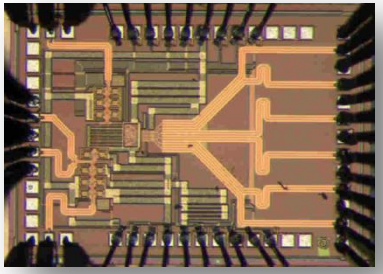


(c) Vivaldi Antenna

Novel GHz/THz room temperature sensors technologies are explored by *Technische Universität Dresden* based on 0.13 µm SiGe IHP (Germany)



First prototype of 200 GHz LNA

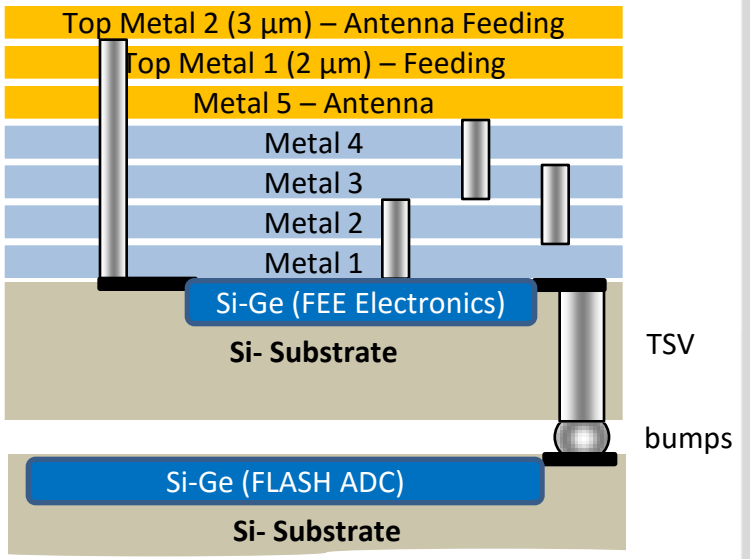


Test of the prototype of the 24 GS/s Fast ADC

Wideband on-chip GHz antenna device

Front-End Electronics based on LNA and fast Track-and-Hold (peak detector configuration)

FAST ADC (4 bits @ 24 GS/s)



Conclusions

- ✓ KAPTURE system acknowledged as an important diagnostic tool for the study of Coherent Synchrotron Radiation @ THz range → international accelerator machine community

- ✓ High performance back-end readout card combined with PCIe-DMA firmware based on "DirectGPU" technology, key component for a continuous data acquisition and real-time data processing up to 6.5 GB/s. ***→ Poster pos. M4***

- ✓ New KAPTURE version produced and currently under test → to improve the accuracy of THz pulse measurements → up to 8 samples points for each pulse.

- ✓ Large communities are interested → integrated "GHz-Pixel" matrix detector. Wide range of potential applications:
  - ✓ New generation of imaging & spectroscopy based on THz radiation → medical, biologic and pharmaceutical, industry, etc.
  - ✓ New physics → Beam monitoring of synchrotron and free electron laser machines, astrophysics → new generation of THz radio telescope
  - ✓ New generation of wireless devices

Picosecond Sampling Electronics for Terahertz Synchrotron Radiation
M. Caselle et. al. 28/04/2015 http://accelconf.web.cern.ch/AccelConf/PCaPAC2014/talks/fpo002_talk.pdf

A Picosecond Sampling Electronic ``KAPTURE'' for Terahertz Synchrotron Radiation
M. Caselle, et al. 01/06/2015 http://accelconf.web.cern.ch/AccelConf/IBIC2014/papers/moczb1.pdf

Studies of Bursting CSR in Multi-bunch Operation at the ANKA Storage Ring
V. Judin, M. Caselle, et al. 29/01/2015 http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/mopro063.pdf

Commissioning of an Ultra-fast Data Acquisition System for Coherent Synchrotron Radiation Detection
M. Caselle, et al. 29/01/2015 http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/thpme113.pdf

Computing Infrastructure for Online Monitoring and Control of High-throughput DAQ Electronics
S.A. Chilingaryan, M. Caselle, et al. 28/04/2015 http://accelconf.web.cern.ch/AccelConf/PCaPAC2014/papers/wco201.pdf

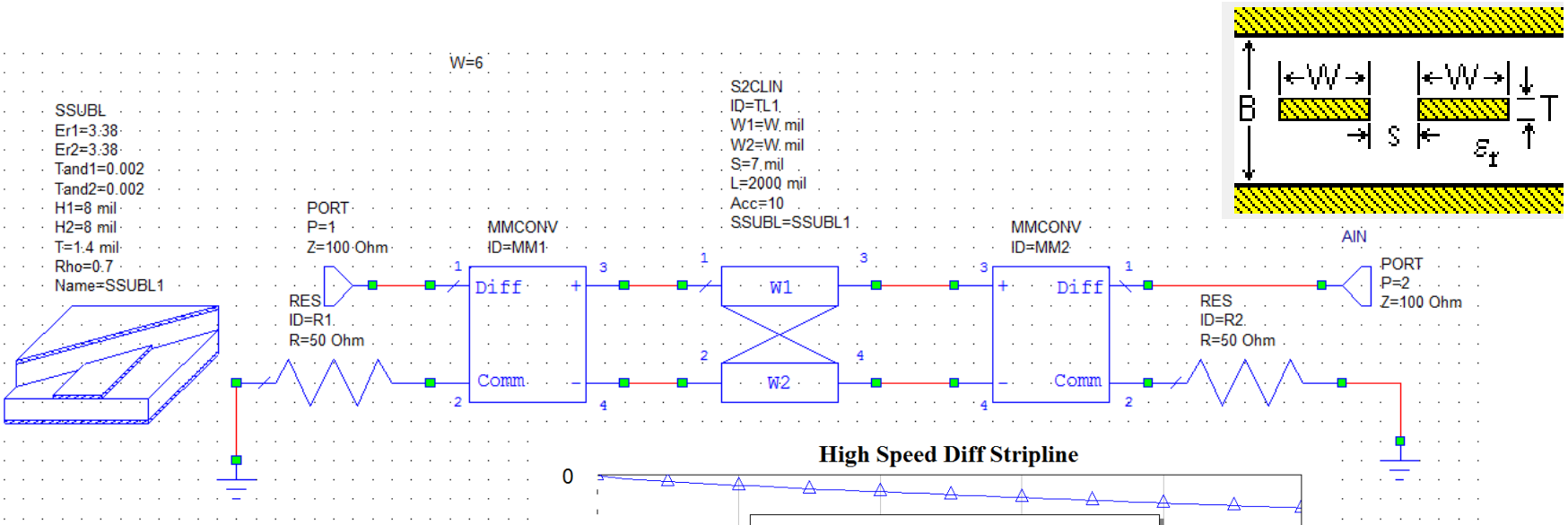
Picosecond Sampling Electronics for Terahertz Synchrotron Radiation
M. Caselle, et al. 06/01/2015 http://accelconf.web.cern.ch/AccelConf/PCaPAC2014/papers/fpo002.pdf

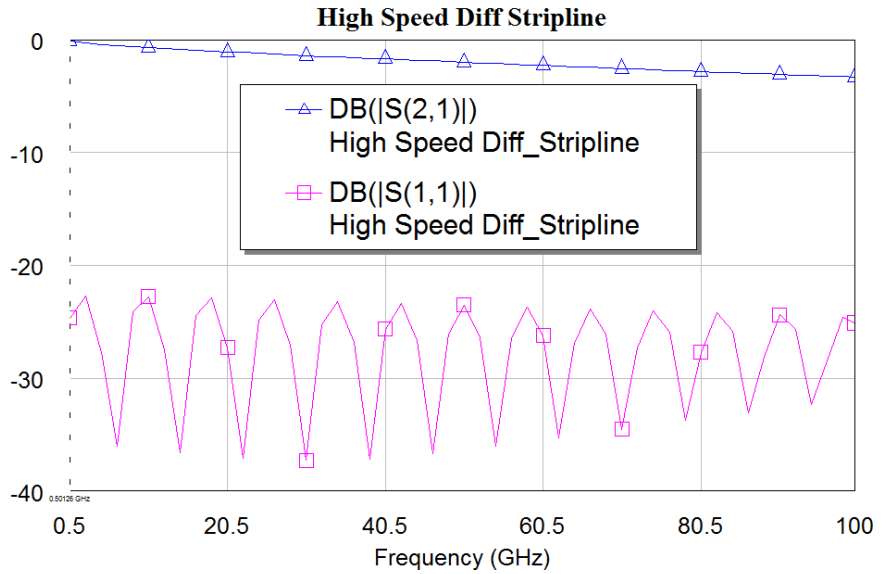
Ultra-fast Data Acquisition System for Coherent Synchrotron Radiation Based on Superconducting Terahertz Detectors
M. Caselle, et al. 10/06/2013 http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/weobb202.pdf

Backup slides

Differential Stripline (TL)

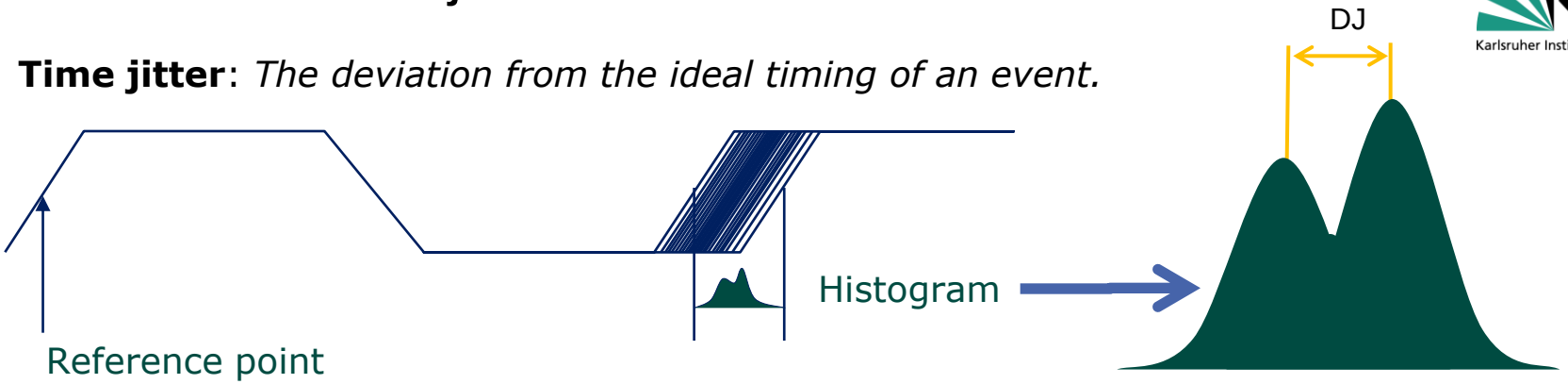
Digital signal, ADC clock distribution f=500MHz





FSP board : Time jitters measurements

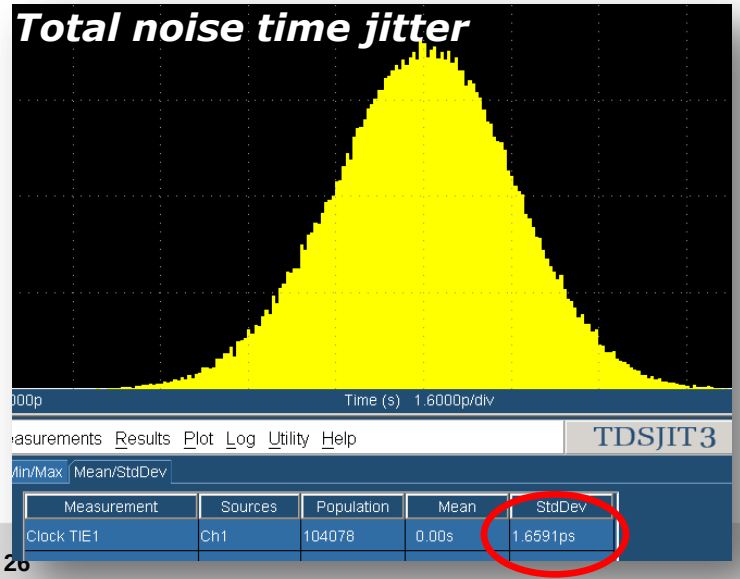
Time jitter: *The deviation from the ideal timing of an event.*



Jitter is composed of: both deterministic (DJ) and Gaussian (random) (RJ) content.

Cross talk, EMI radiation, noisy reference plane, Simultaneous Switching Outputs (SSO), etc.

Thermal and shot noise, etc.

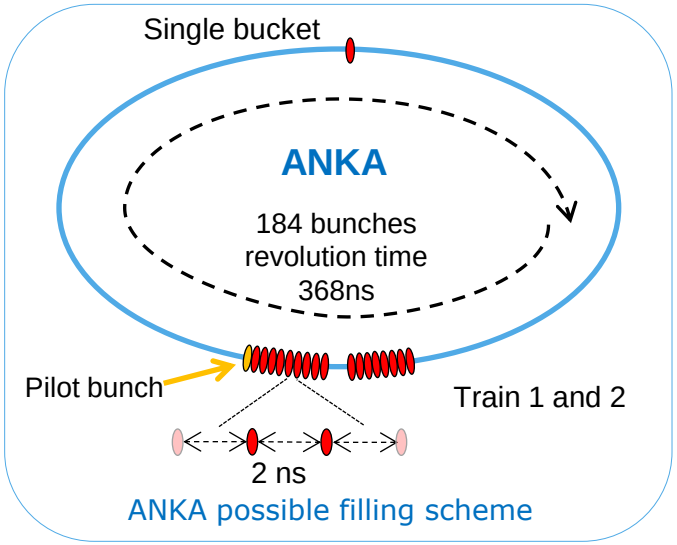


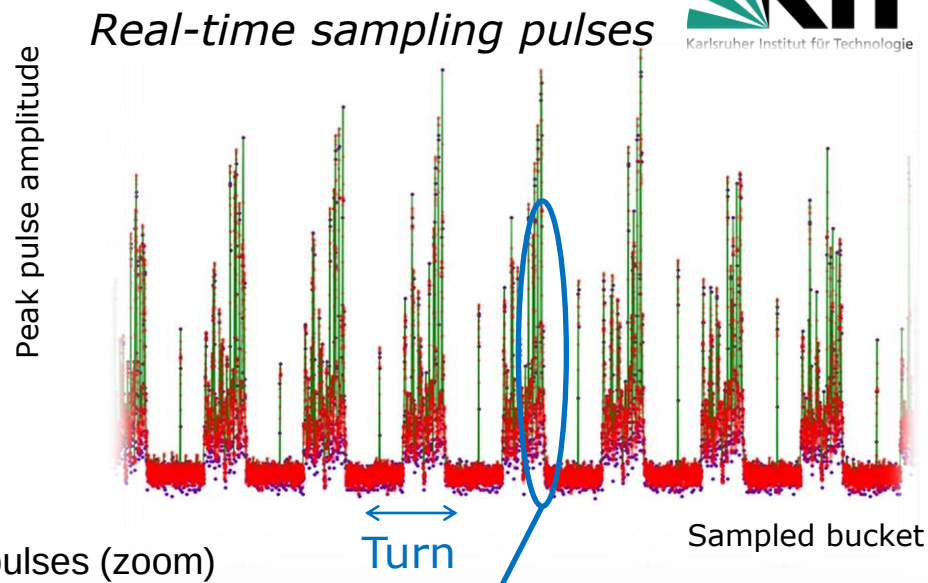
NO deterministic component → NO digital cross-talk in the analog circuitries, EMI or SSO, etc..

Total noise time jitter StdDev < 1.7 psec

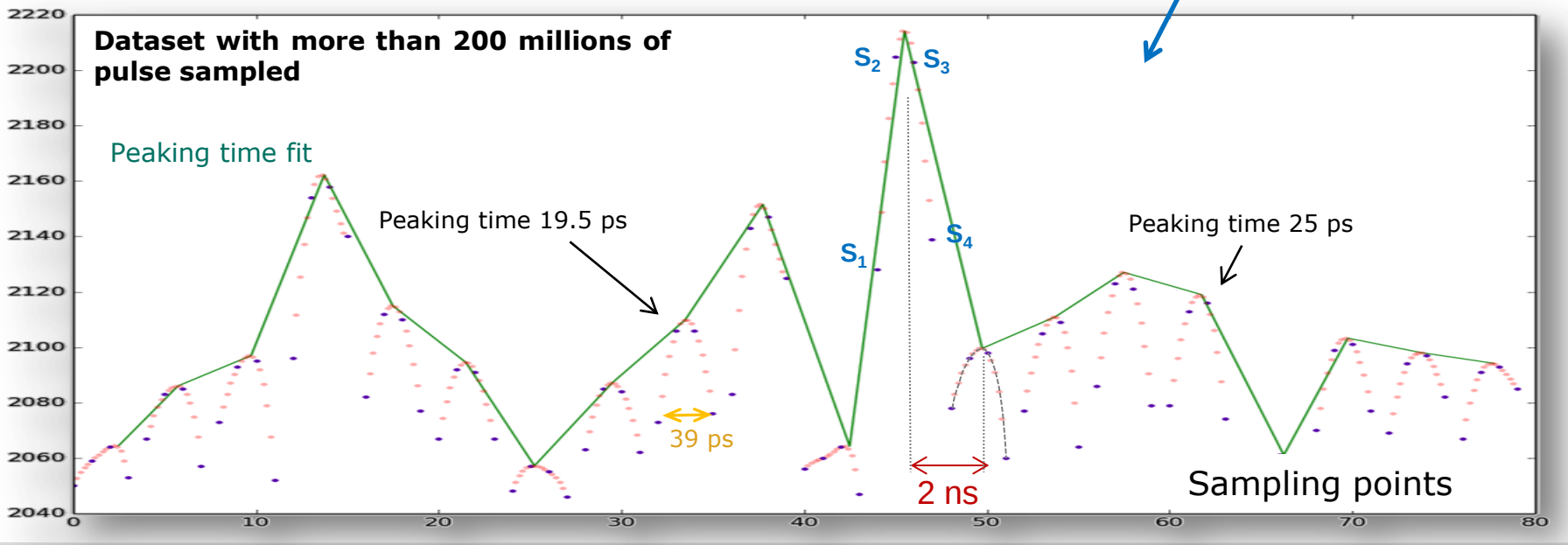
N.B. *The time resolution measured on the most advanced ASICs based on CFDs is of the order* ***of 5 ps rms****.*

Beam test with YBCO detector and KAPTURE system

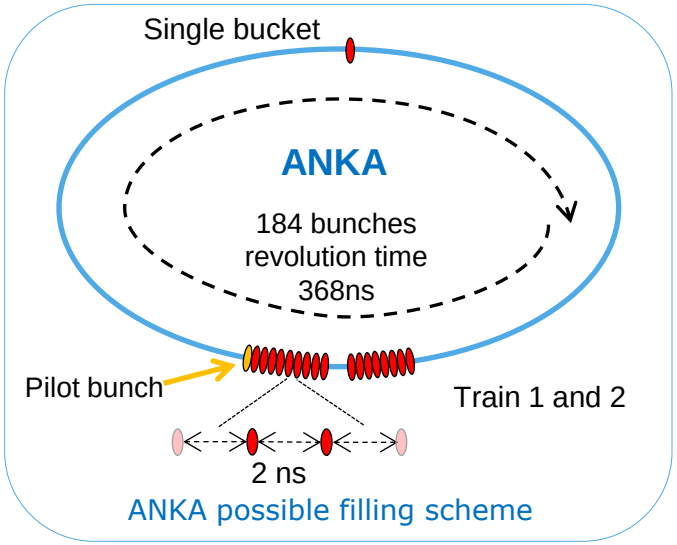




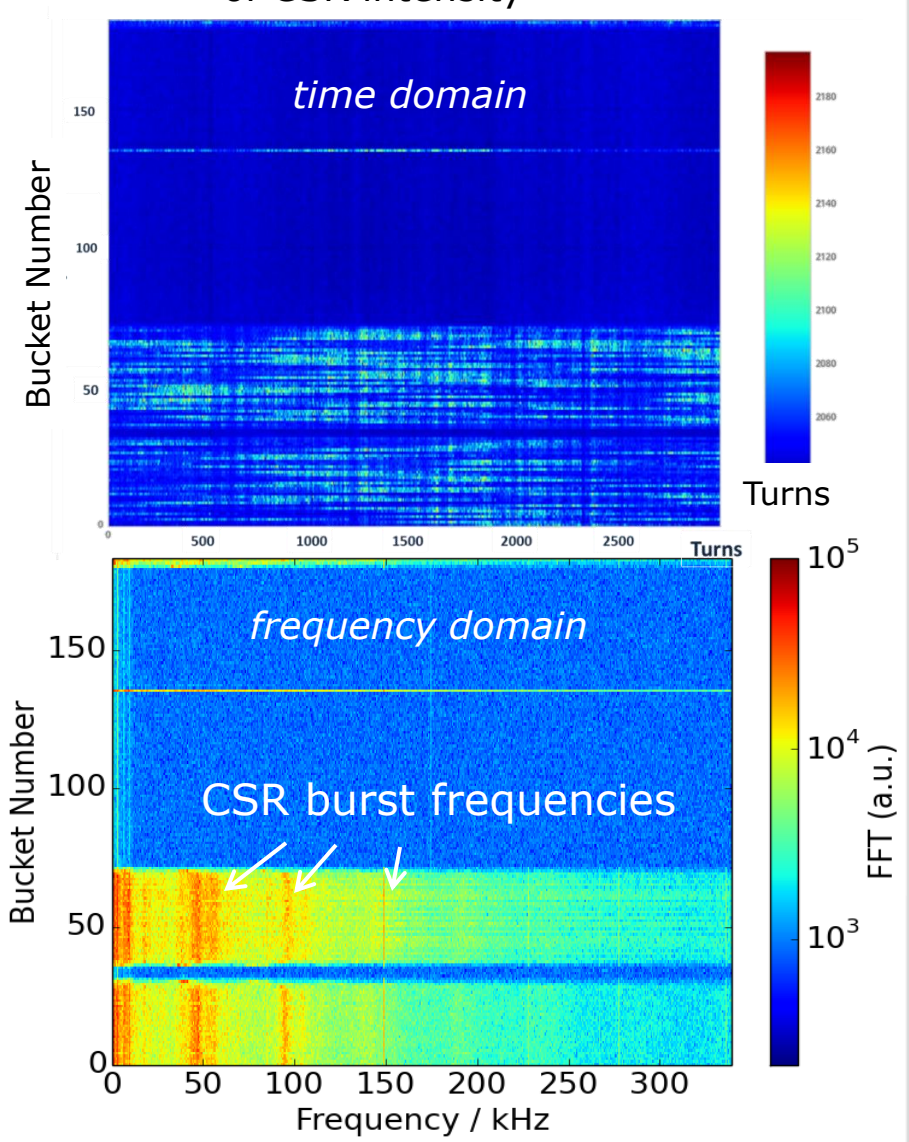
Real-time sampling pulses (zoom)



Time and frequency domains



Turn by turn monitoring
of CSR intensity

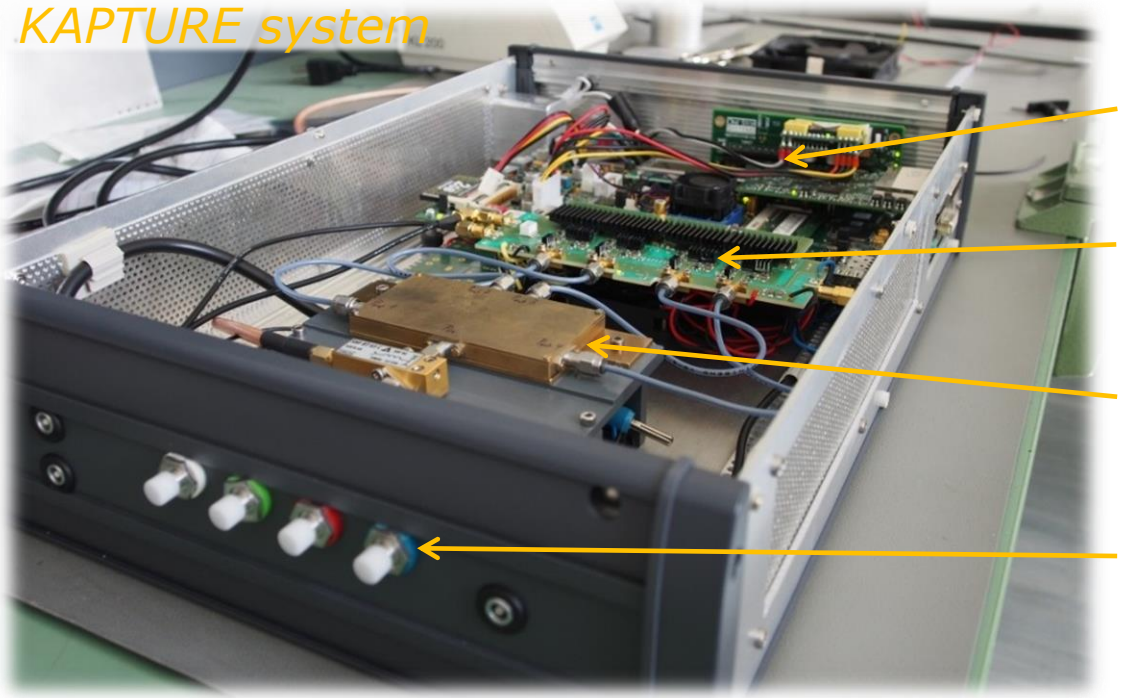


KAPTURE system:

- ✓ Real-time pulse sampling for long observation time
- ✓ Simultaneous turn by turn measurement of all 184 buckets
- ✓ Real-time pulse reconstruction by GPU
- ✓ Measurements of pulse amplitude and peaking time for each pulse by GPU
- ✓ Real-time FFT and measurements of the CSR fluctuations by GPU

Commissioning of KAPTURE system

KAPTURE system



Readout card and PCIe connection

KAPTURE board

1:4 Power splitter and LNA

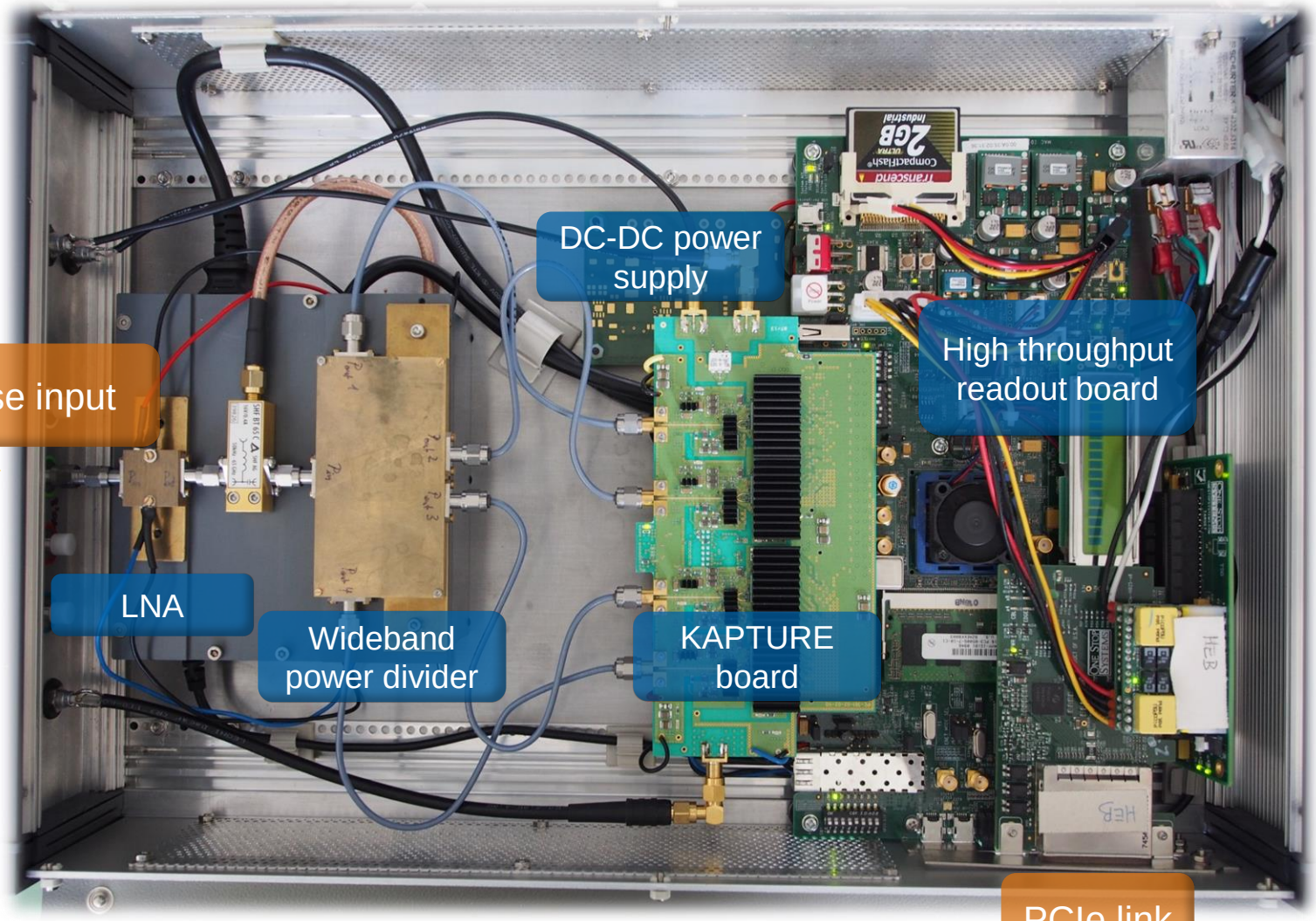
Analog bandwidth DC-50 GHz

M. Caselle, et al *Commissioning of an Ultra-fast Data Acquisition System for Coherent Synchrotron Radiation Detection*. 29/01/2015. http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/thpme113.pdf

Key features

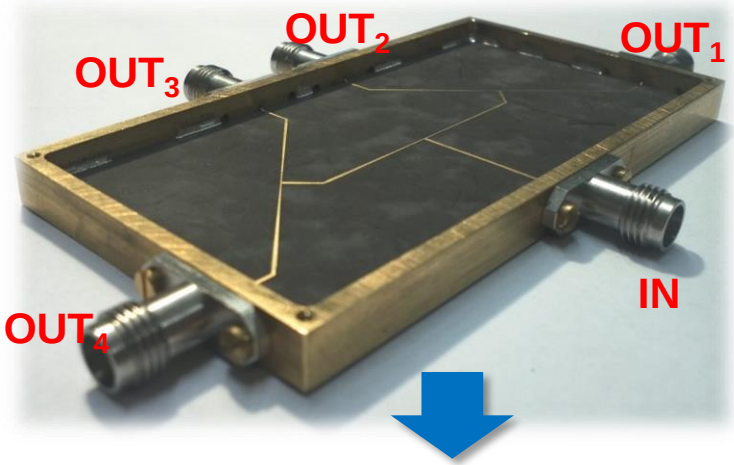
- Readout compatible with: YBCO, HEB, and Schottky diode detectors
- Pulse amplitude "mV" and arrive time measurements "ps" accuracy
- Simultaneous acquisition of all buckets turn-by-turn in streaming mode
- Continuous acquisition for long observation time.
- Real-time data elaboration by GPUs

KAPTURE version 1



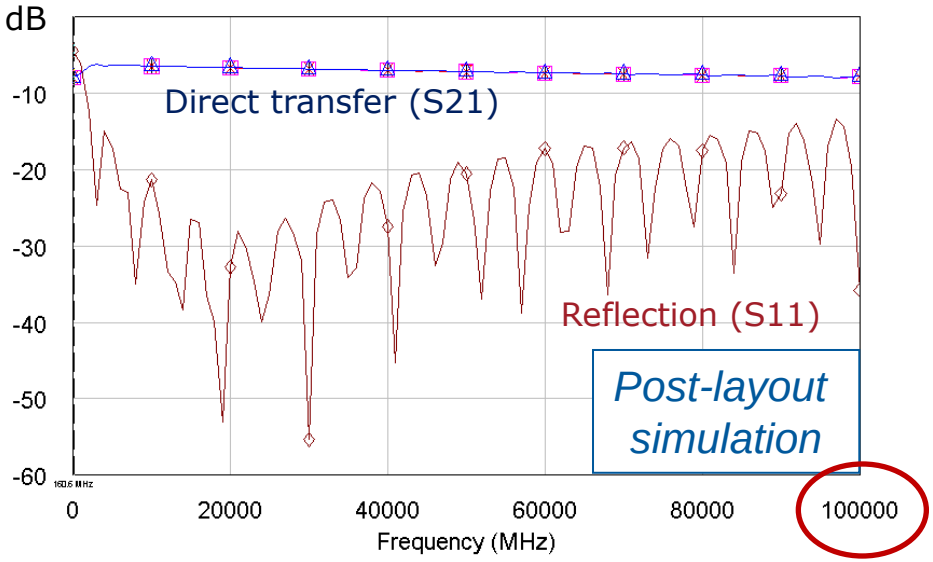
Wideband power divider (KIT)

Power divider 1:4 outputs

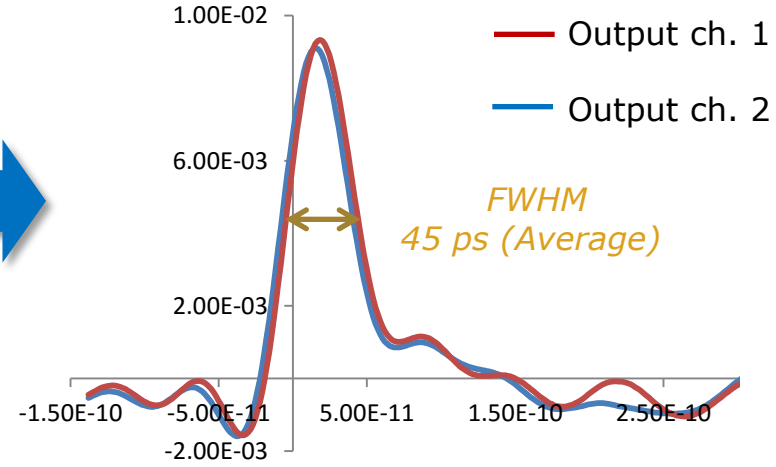


Power divider 1:2 outputs

KIT power splitter 1:4 (S parameters)



Outputs channels (time)



Input pulse FWHM ~ 42 ps (average)

Terahertz detectors with picosecond time resolution

Several cryogenic and room temperature detects are available to study of the coherent in the THz range → high time accuracy detector, spectrum of hundred GHz -> Terahertz

Cryogenic detectors developed at KIT:

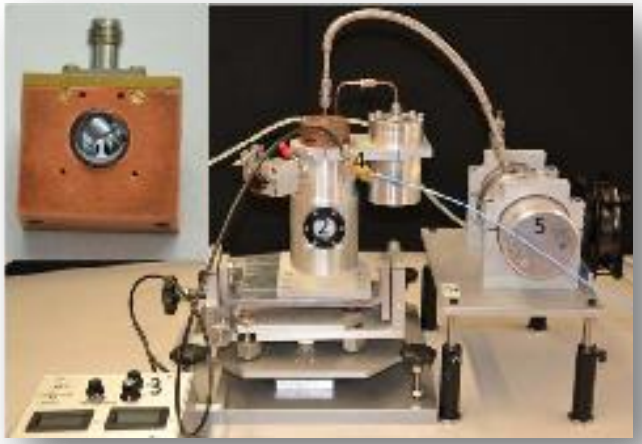
Cryogenic HEB detector IR1 - ANKA

HEB *(Hot Electron Bolometer)* detector based on niobium nitride material

- response time < 165 ps
- spectral range 150 GHz - 1.5 THz

YBCO (Yttrium barium copper oxide) detector

- response time: down to 1 ps
- spectral range: up to 7 THz



Cryogenic YBCO detector IR1 - ANKA