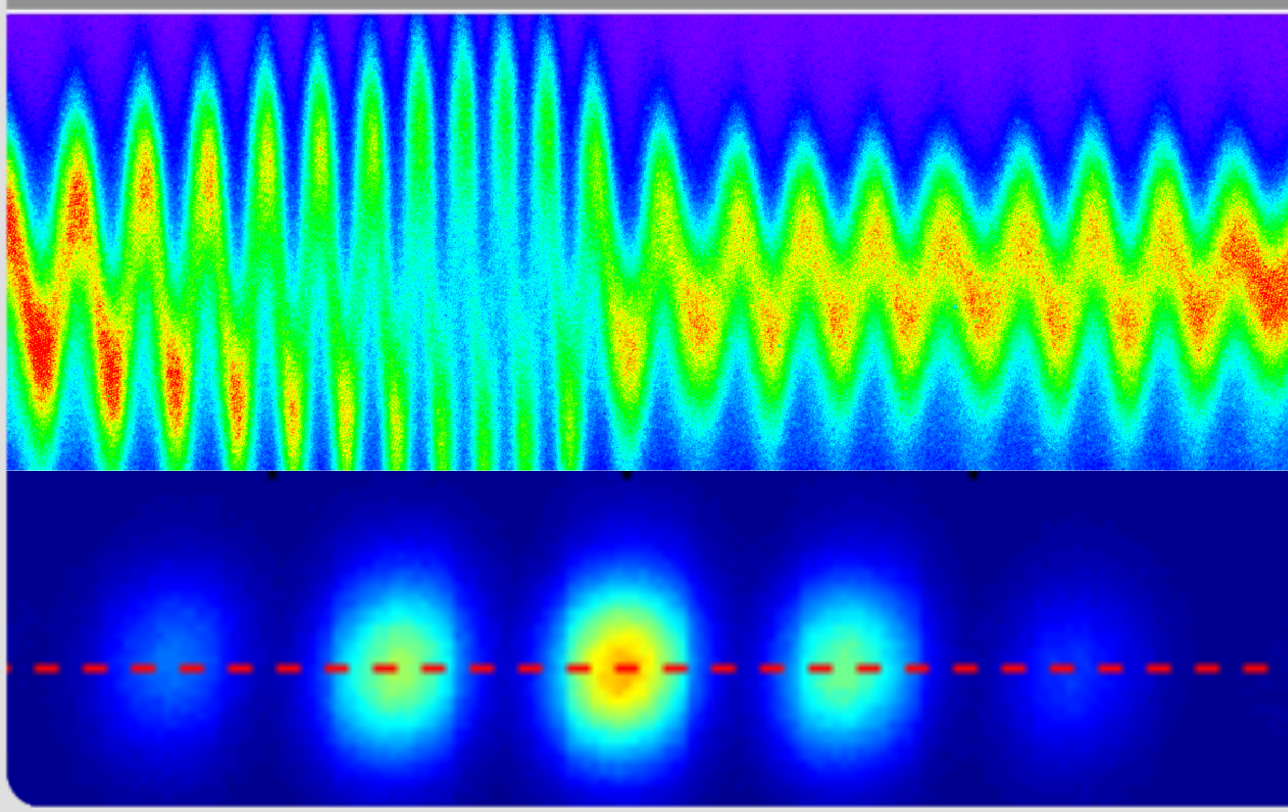
Karlsruher Institut für Technologie

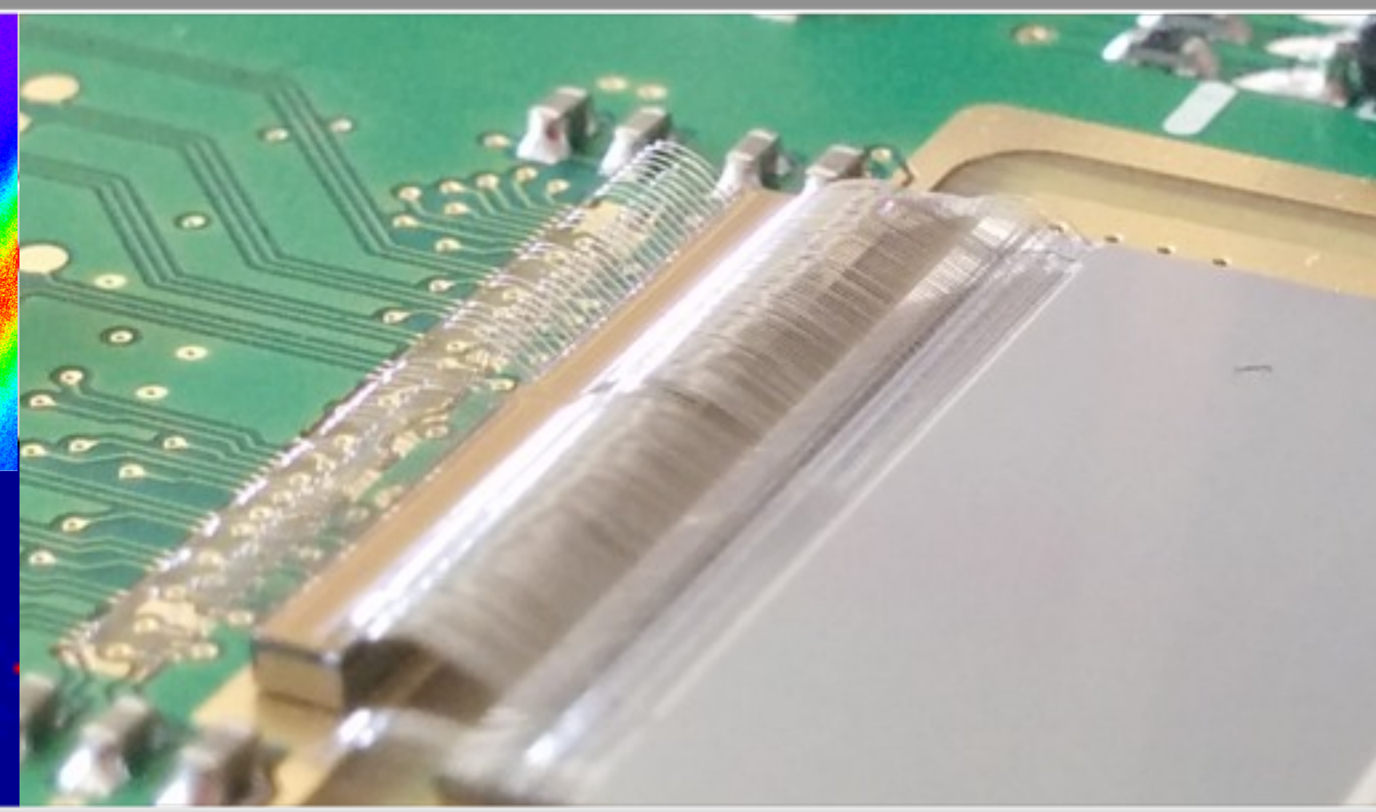
Short Bunches and Fast Diagnostics

Accelerator Science at the Karlsruhe Institute of Technology

Anke-Susanne Müller

ANKA Synchrotron Light Source at KIT





The Karlsruhe Institute of Technology

Karlsruhe Institute of Technology

A legal unit

Karlsruhe Institute of Technology

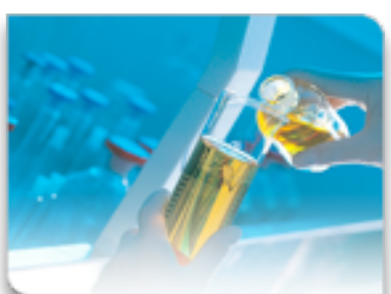
Merging of two missions

State University

HELMHOLTZ GEMEINSCHAFT

National Research Center

Three tasks



Research

Higher Education

Innovation

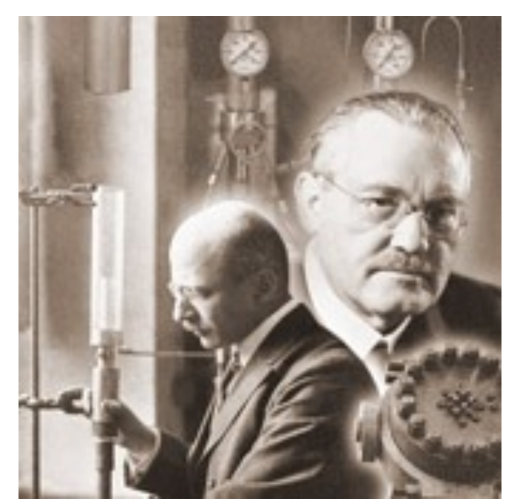
What KIT stands for – Engineering Tradition

Karl Benz: inventor of the modern automobile

Ferdinand Braun: inventor of cathode ray tube → television

Heinrich Hertz: confirmation of electromagnetic waves

1984 first email in Germany

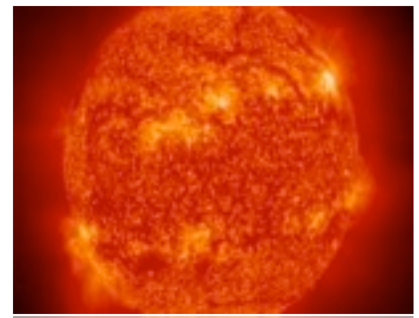


Fritz Haber: fixation of atmospheric N_2 → synthetic ammonia

KIT – Helmholtz Center and State University

The KIT-Centers combine cross-sectoral research and innovation topics

- Currently seven KIT-Centers
- Platforms for cross-sectoral research and innovation activities
- Pooling of teaching activities, for example, in graduate schools
- Showcase for the key topics for research at KIT
- Interdisciplinary working-environment
- Creating synergies
- Communication platforms



Energy

Climate and Environment

Mobility Systems

Humans and Technology

Elementary Particle and Astroparticle Physics

Information Systems Technologies

Materials Structures Functions

Accelerator & detector development at KIT

Karlsruhe Institute of Technology

Andreas Kopmann
Fast DAQ systems

Ivan Peric
ASICs and detectors

Marc Weber
Detectors

John Jelonnek
Pulsed power and microwave technology

Erik Bründermann
THz Technology

Jürgen Becker
Detectors

Christian Koos
Silicon photonics, Tb/s communications

Sara Casalbuoni
Superconducting IDs
Diagnostics

Anke-S. Müller
Accelerators

Axel Bernhard
Superconducting IDs

Michael Siegel
Superconducting terahertz sensors

Mathias Noe
Superconducting Technology

ATP
KIT Accelerator Technology Platform

Some facilities and labs at KIT

Hybrid assemby lab (IPE)

KATRIN Neutrino experiment

ANKA 2.5 GeV Light Source

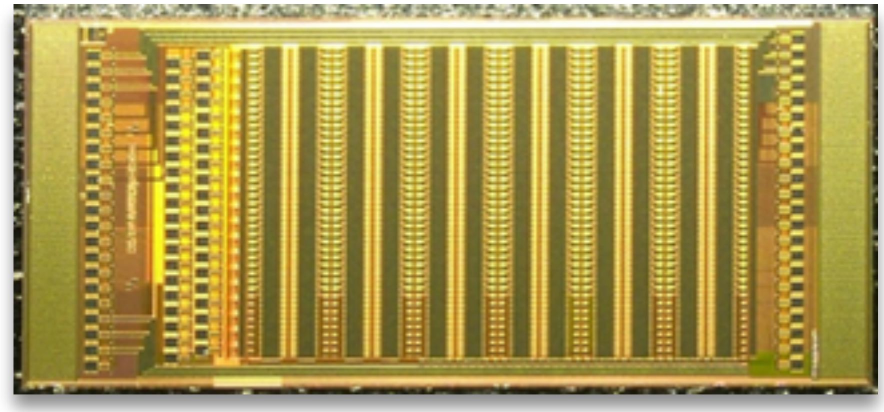
FLUTE fs linac

Karlsruhe Nano Micro Facility

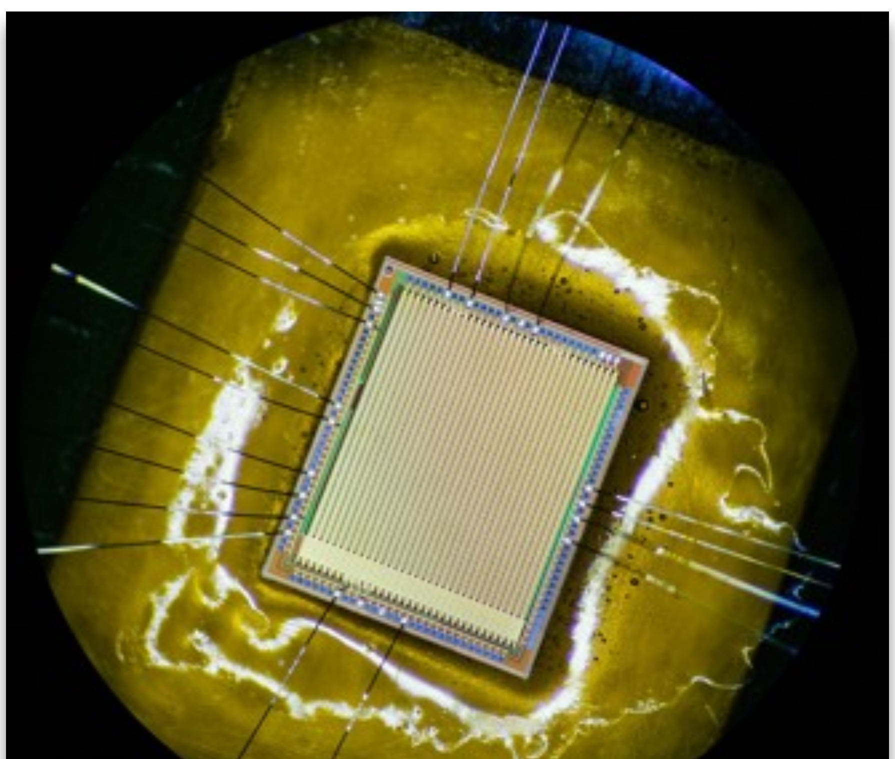
Production of thin NbN-films with reactive magnetron sputtern (IMS)

Irradiation facility (IEKP)

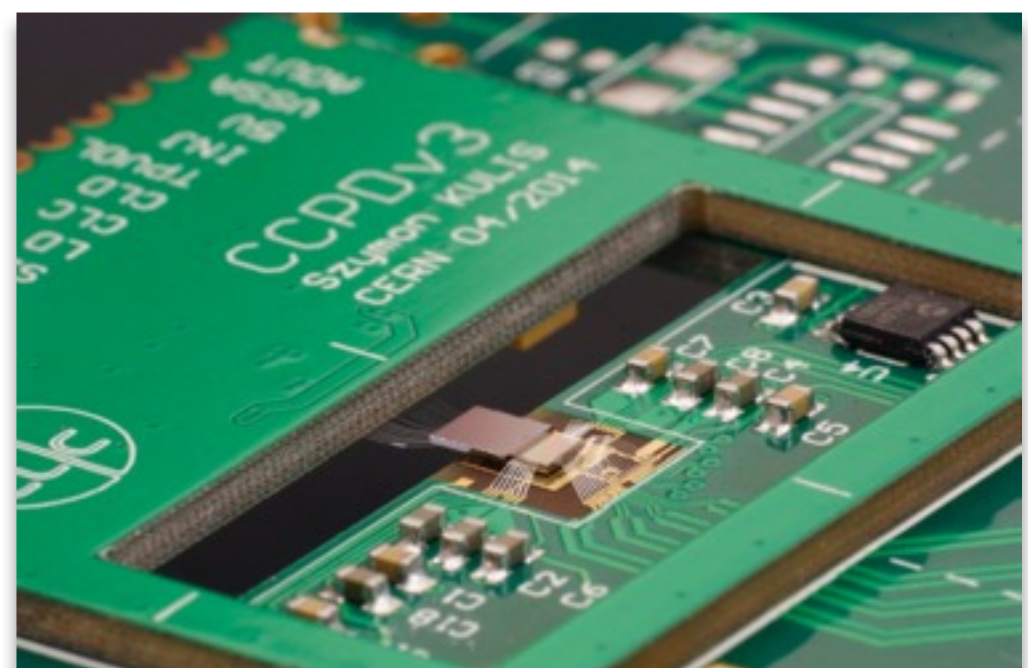
HV-CMOS Sensors



- Fast
- Radiation - hard
- Integrated read-out electronics
- Collaborations with University of Geneva, University of Liverpool, University of California Santa Cruz, Universität Heidelberg, Institut de fisica d'altes energies Barcelona



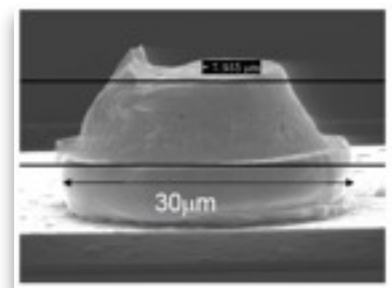
Thin monolithic detectors



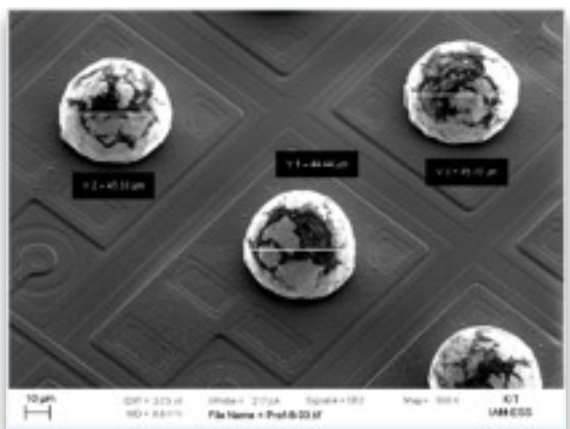
CCPD – Prototypes in AMS H18

Bumping technologies

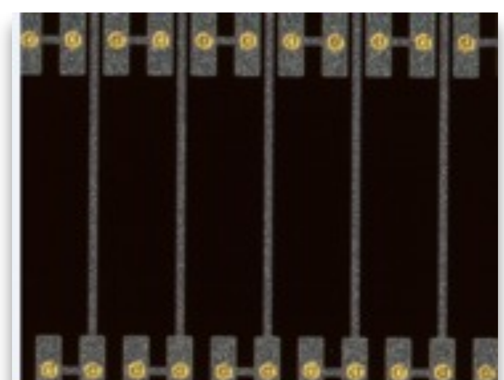
- Micro contacts on silicon for flip-chip interconnects
- Au stud bumping: d=30 µm, UBM-less
- SAC Solder balls (PPS: Precoat by Powder Sheet): d=10-80 µm
- Copper pillars: d=15 µm



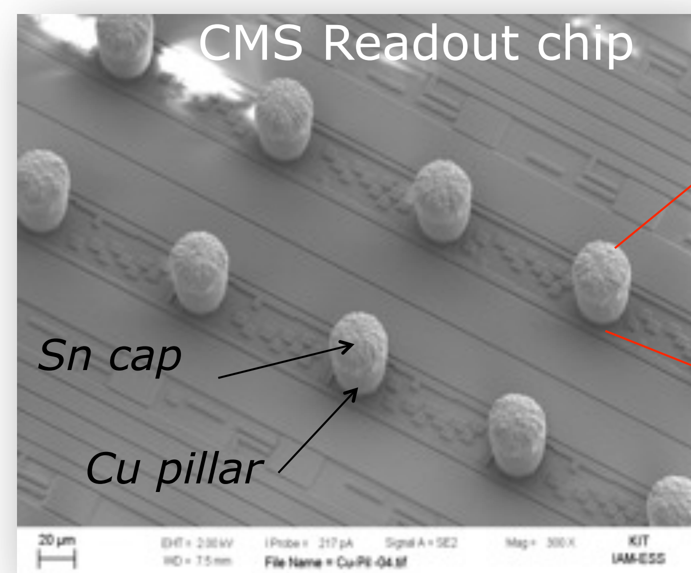
30 µm Au-Stud Bump



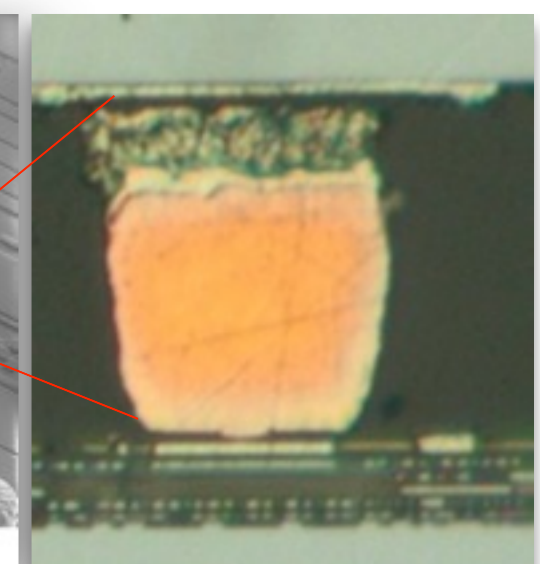
40 µm SAC ball after reflow



30 µm Au-Stud Bump on sensor dummy



15 µm Cu-pillars on ROC-Chip

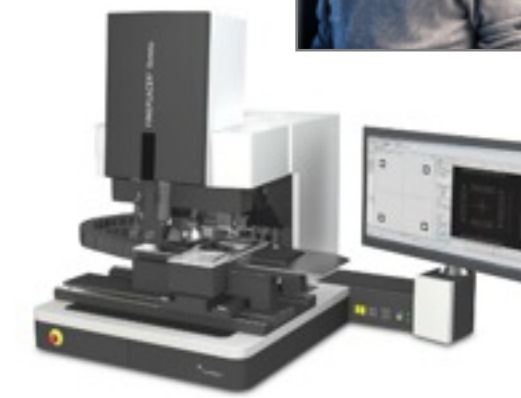


Cross section of Cu-pillar bonded sensor and chip

SAC powder after transfer

Flip chip technologies

- Dominant process for detector bare modules
- Interconnects shrinking from 30 µm to 10 µm
- High placement accuracy: +/-1 µm
- Complex solder processes
- Quality control: production + functional tests

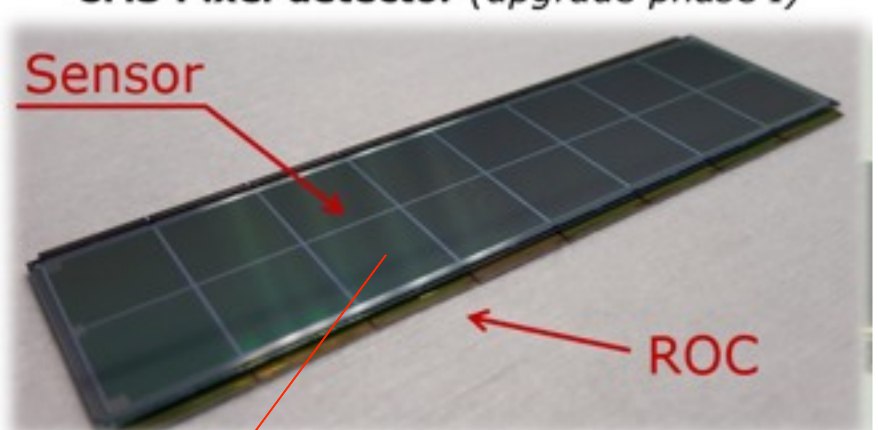


Flip chip die bonder
- *accuracy: +/-1 µm,*
- *speed: ~ 60 dies/h*

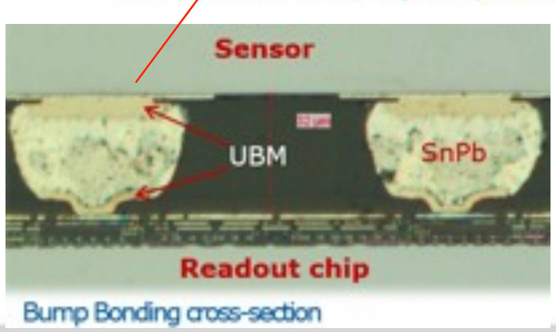
Multi-chip die bonder
- *+/-10 µm*
- *~1000 dies/h*

Assembled bare module

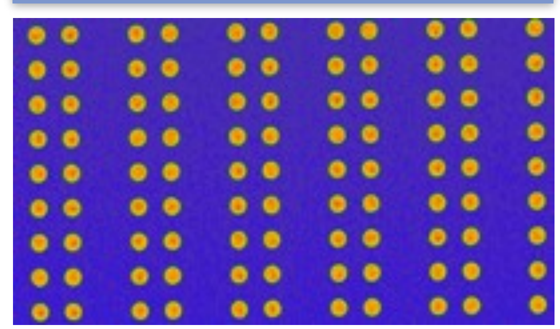
CMS Pixel detector *(upgrade phase I)*



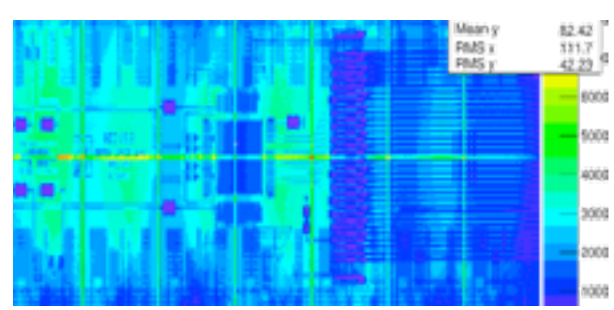
16 ReadOut Chips (ROC) → 66560 pixels



Quality control



Micro-X-ray radiography
-> void free interconnects



X-ray Bare Module Test

Vacuum reflow process with formic acid option

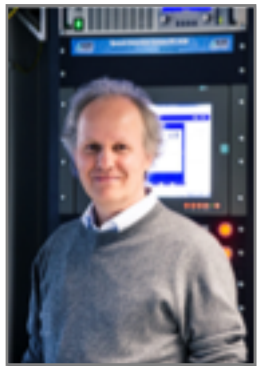
X-ray

Silicon detector production center

- Successful production of 25% of the CMS pixel detector

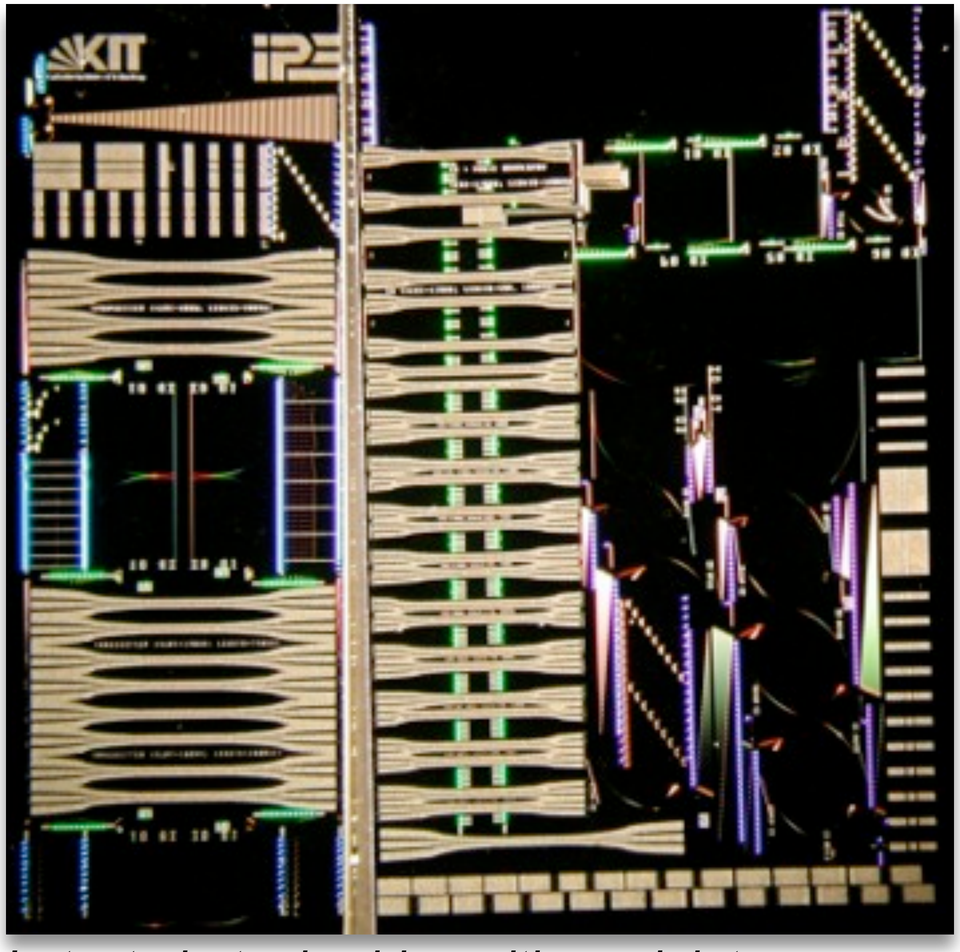
- Production facility of the STS for the CBM experiment at FAIR/GSI

- Production of the CMS silicon tracker for HL-LHC

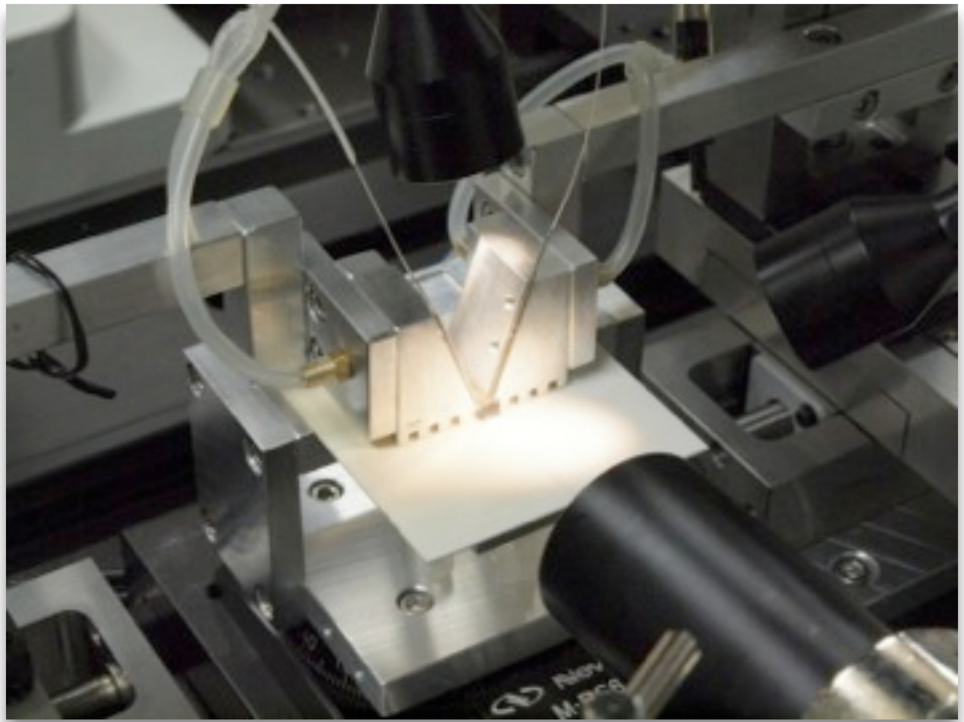


Tb/s optical data transmission

- Device design and simulation
- Monolithically integrated WDM systems
- FPGA algorithms for complex modulation formats
- CMOS compatible
- 160 Gbit/s in the near future
- Up to 5 Tbit/s projected



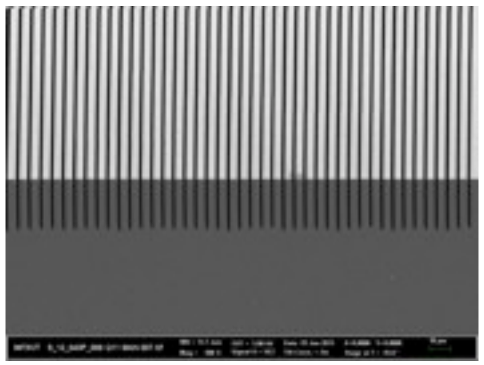
Latest photonic chips with modulators, Echelle gratings, and 4 channel WDM systems



Fiber-chip-coupling experiments

KNMF at KIT

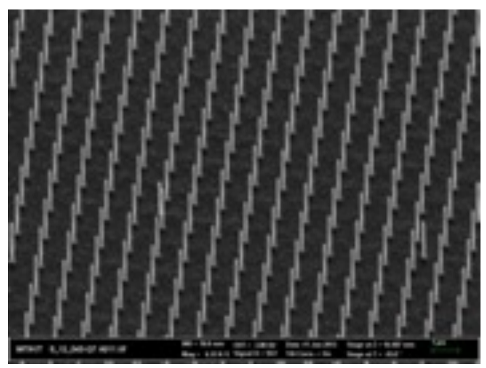
Research Infrastructure: Karlsruhe Nano Micro Facility

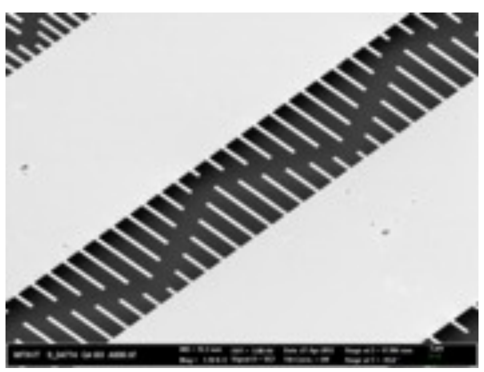


KNMF Example

Deep etched silicon gratings

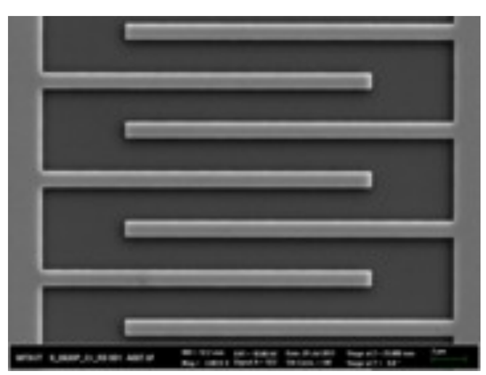
Silicon nanopillars with high aspect ratio





Freestanding cantilevers in silicon

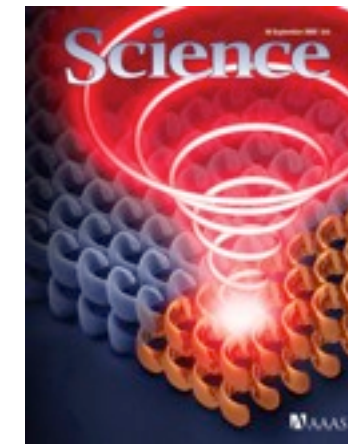
Cantilever structures in chromium

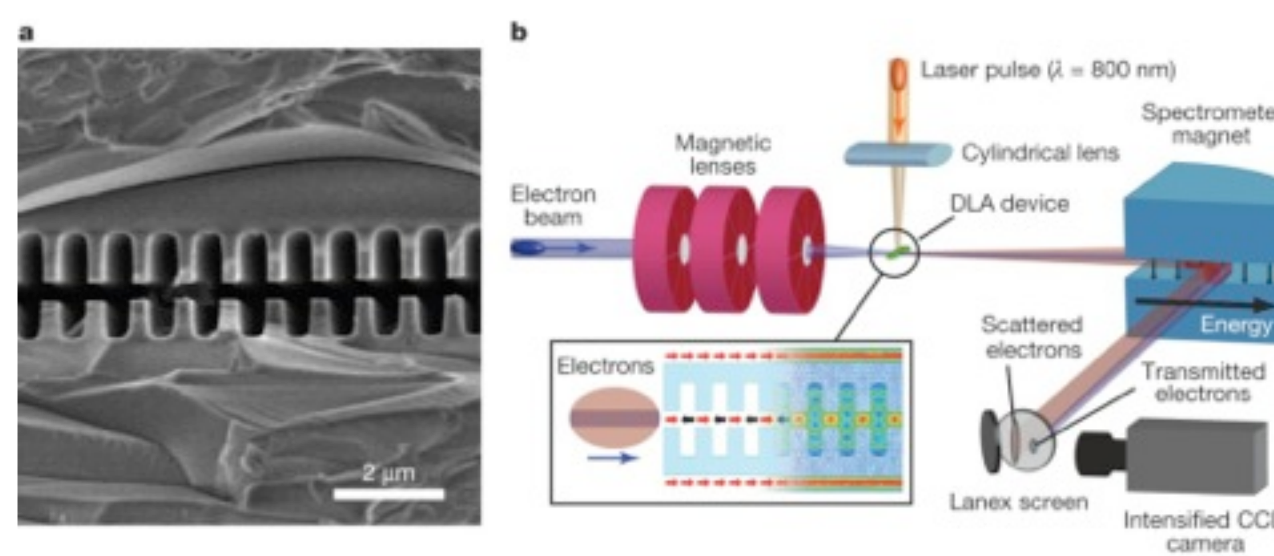


Center for Functional Nanostructures

Metamaterials
Artificial Materials
Photonic Bandgap PBG Materials
Engineered Crystals
Multilayer Dielectrics

Manipulation of electromagnetic waves with materials

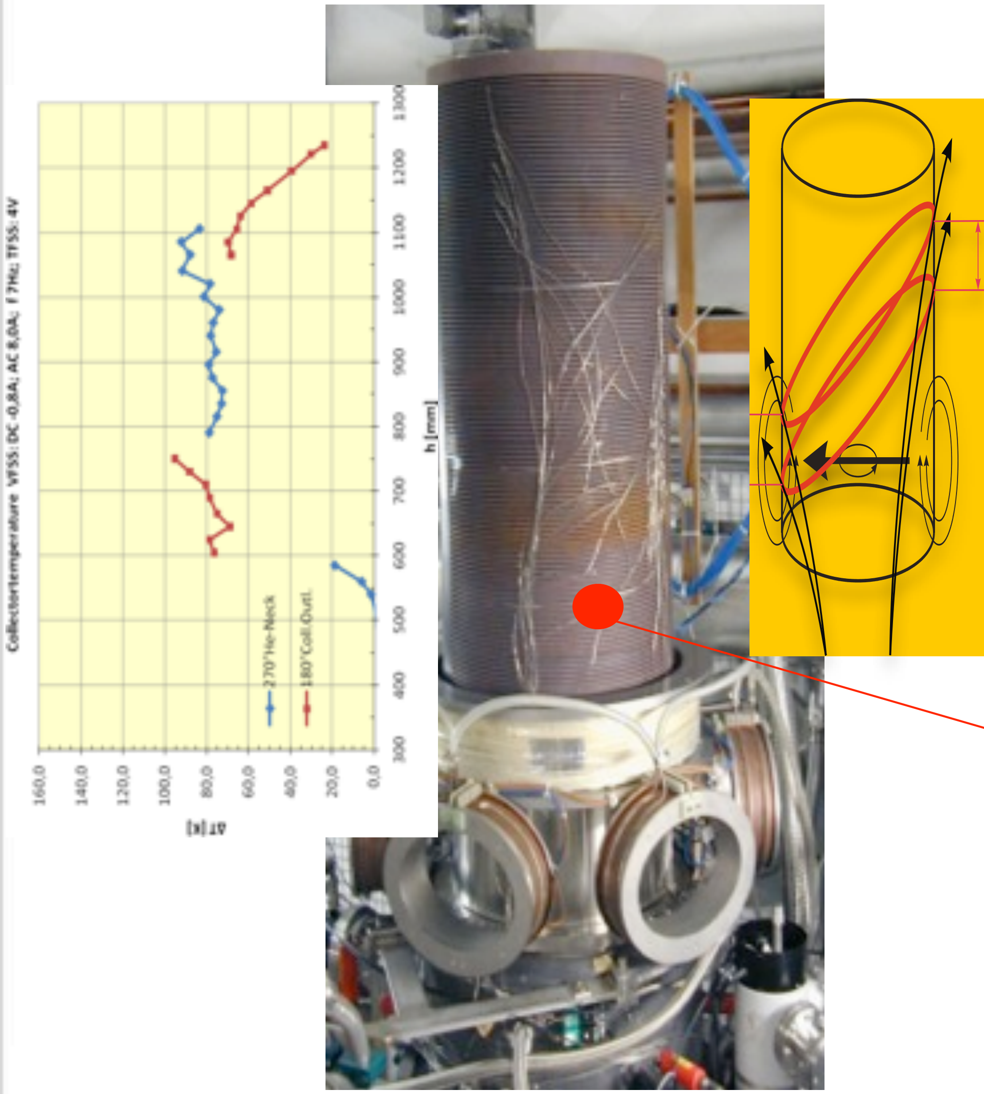




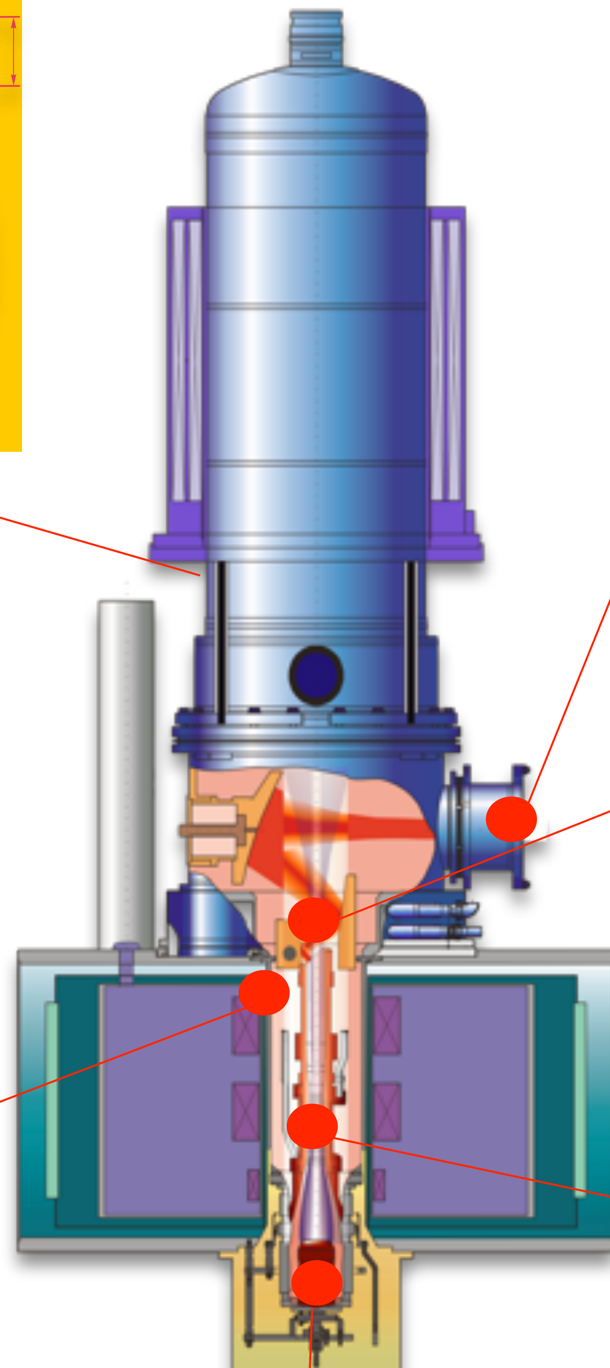
E.A. Peralta et al. Nature 503, 91-94 (2013)

KIT Electron Vacuum Tube (Gyrotron) Development

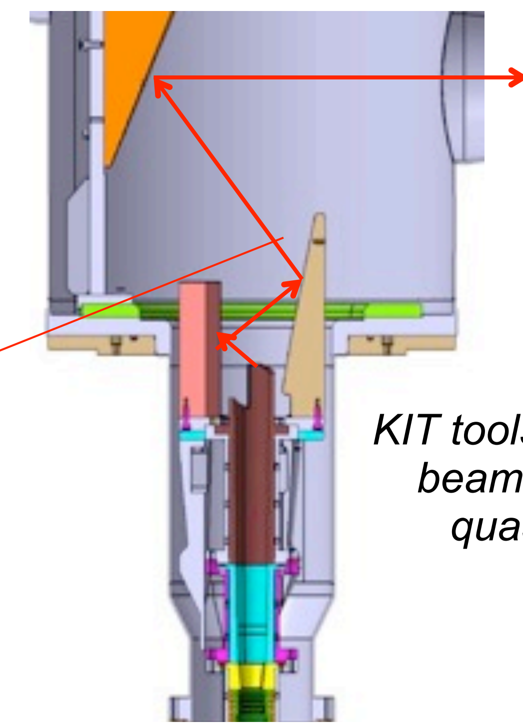
Karlsruhe Institute of Technology



Electron-optics systems for collectors operating at MW levels (IPP/KIT *patent: TVSS*)

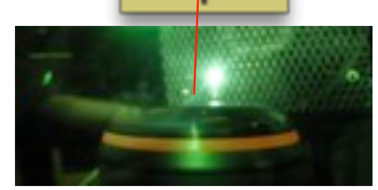


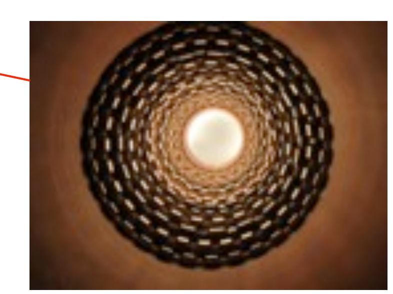
CVD Diamond Brewster-angle window technology (KIT-IAM, *Element Six / Diamond Materials*)



KIT tools and concepts for RF beam transformation and quasi-optical systems

thermo-mechanical designs
Of highly loaded structures



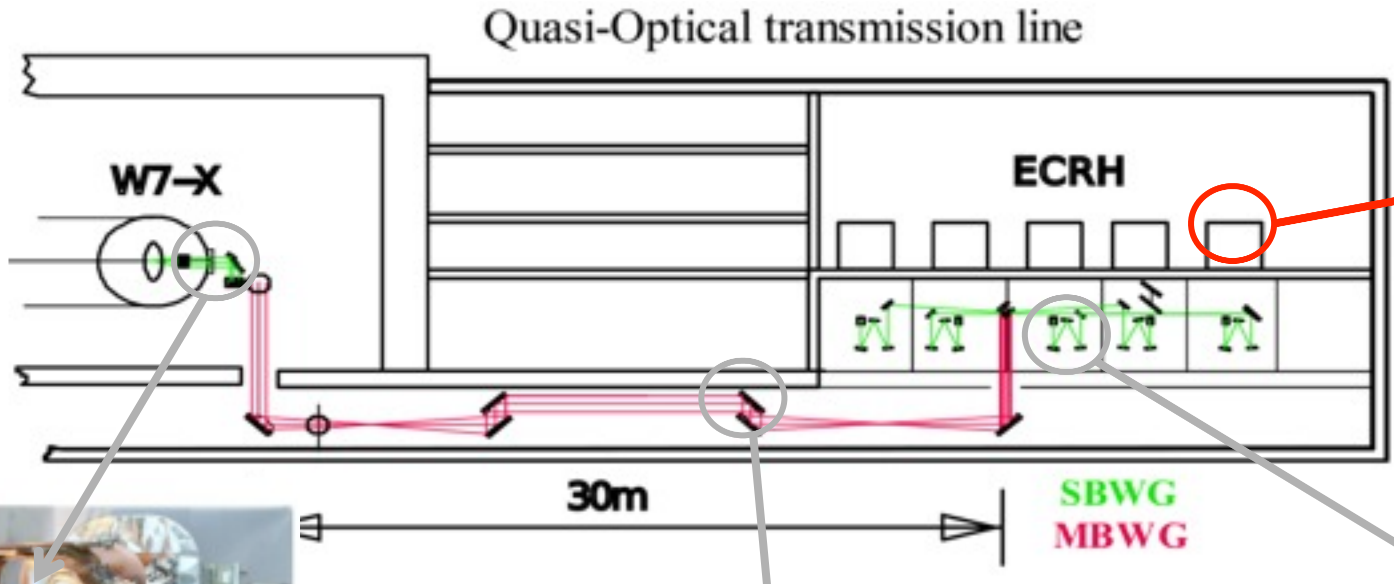


KIT tools and concepts for highly overmoded structures

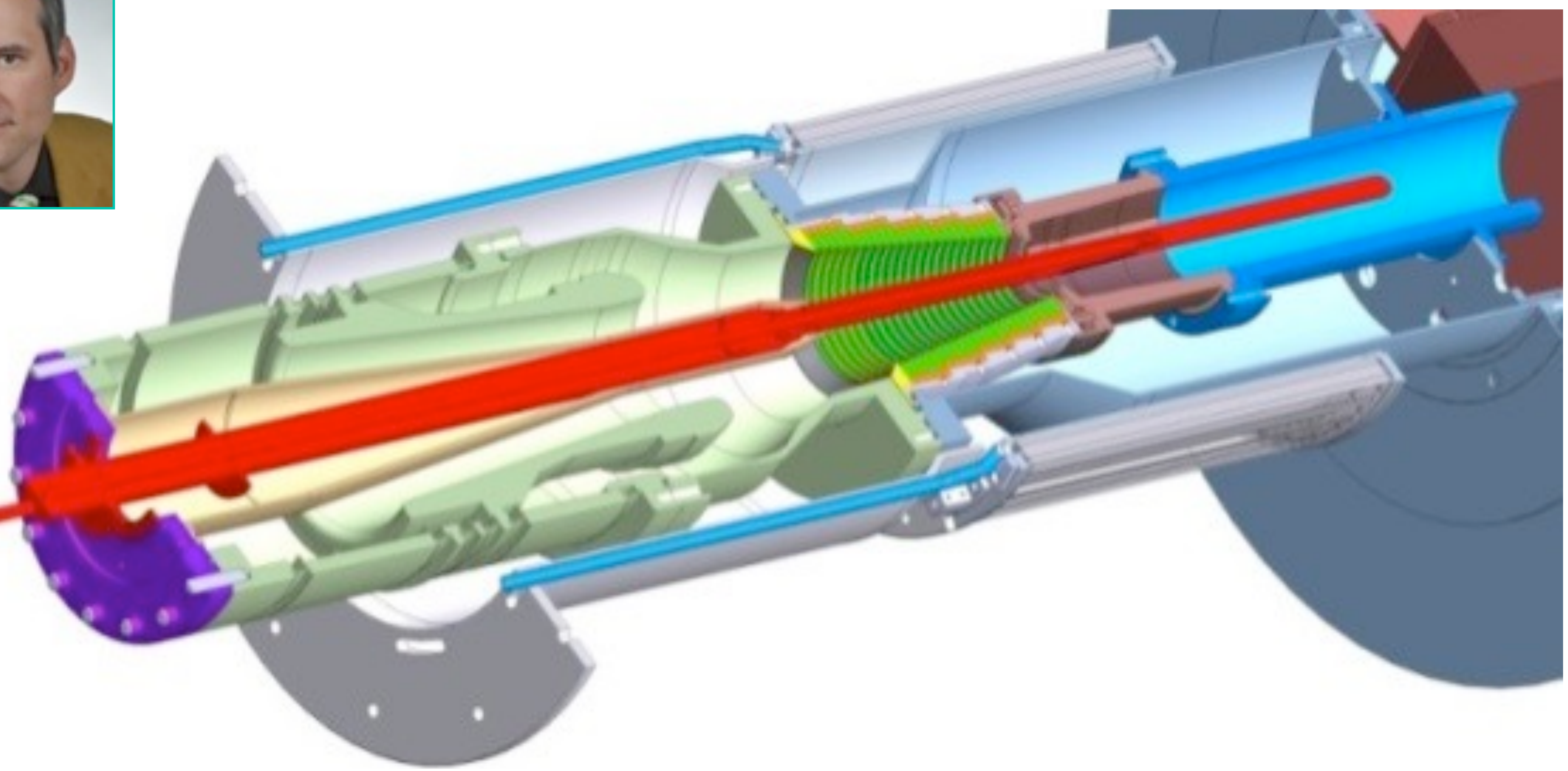
ECRH for Stellarator W7-X

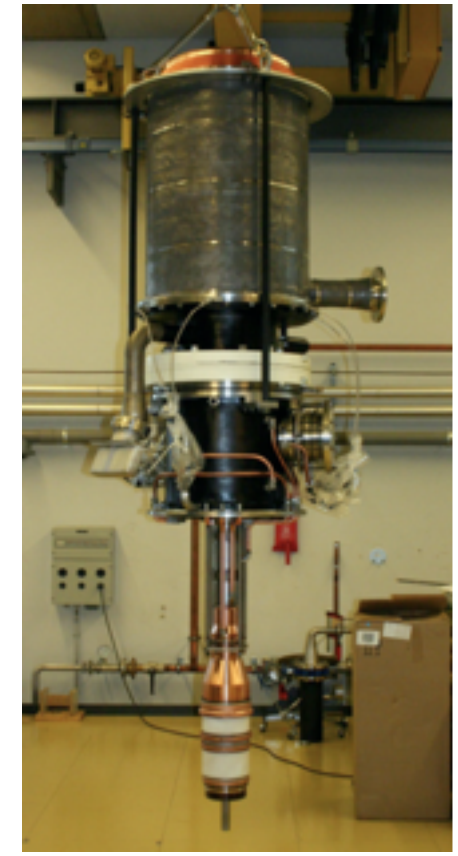
KIT Project PMW

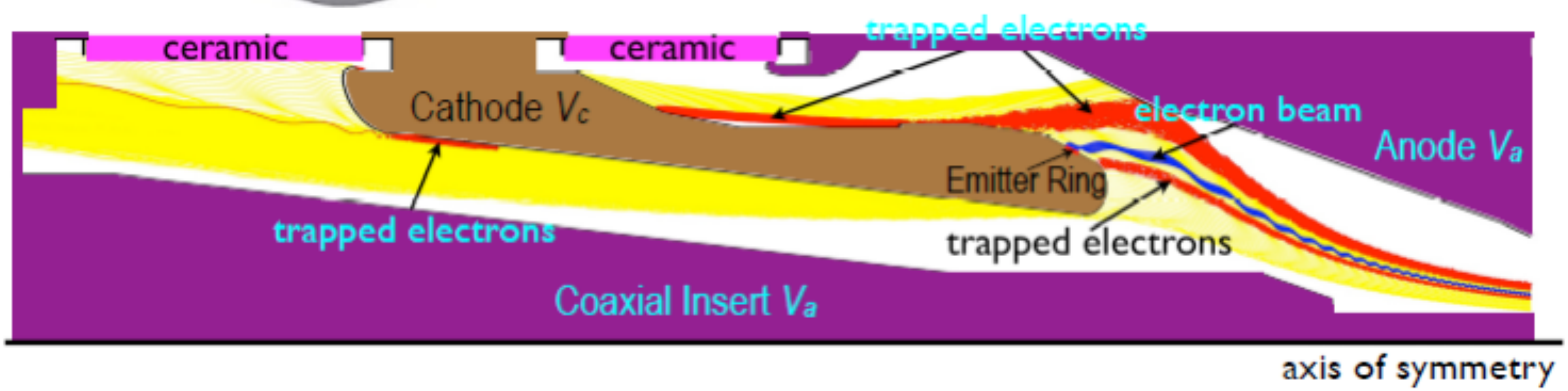
10x 140 GHz 1 MW CW Gyrotron +SC magnets
+ HV modulators + transmission lines + launchers



Advanced Electron Gun Design Concepts and Tools (Thermionic Emission)



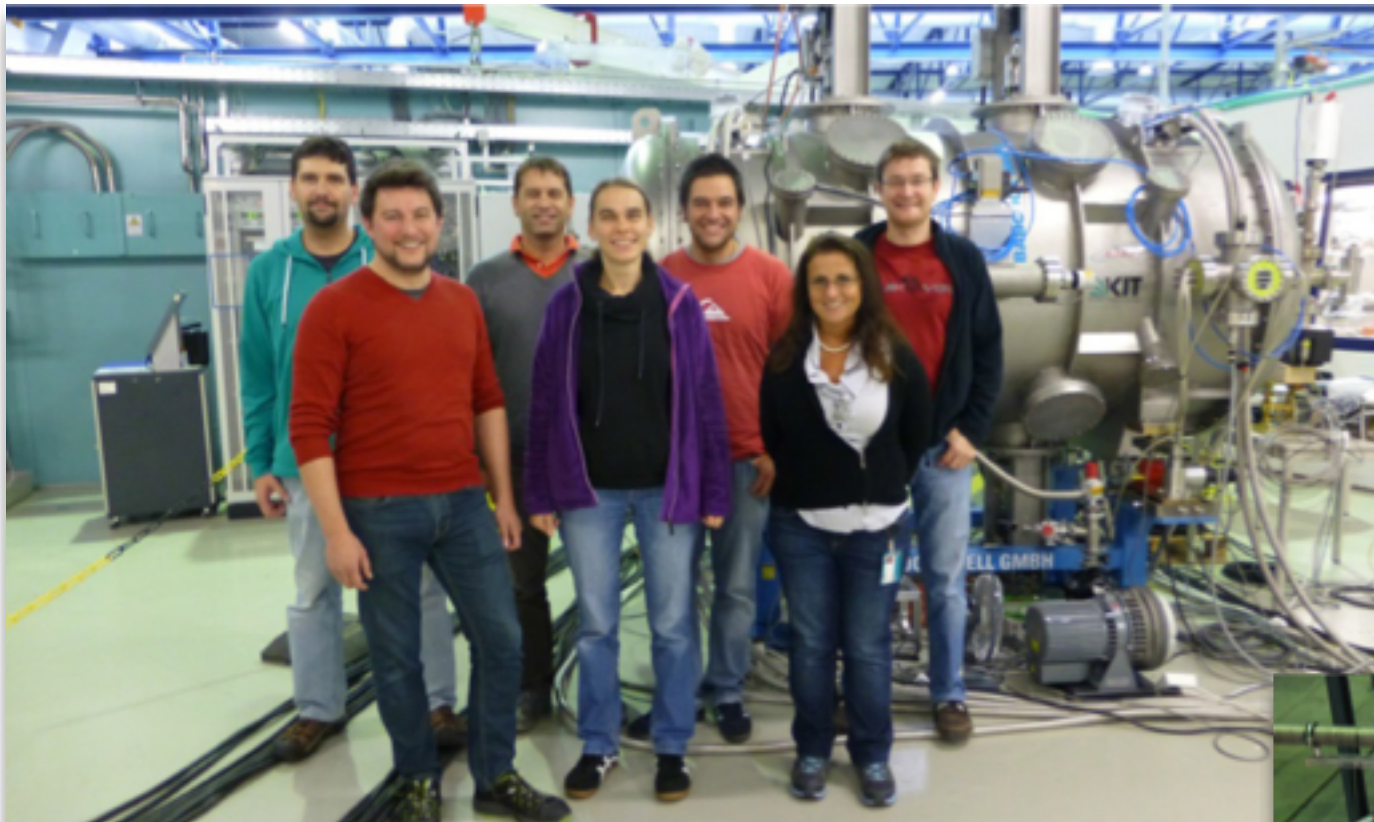




Pagonakis et al., "An Additional Criterion for Gyrotron Gun Design", Oral Presentation, 37th ICOPS, USA, 2010

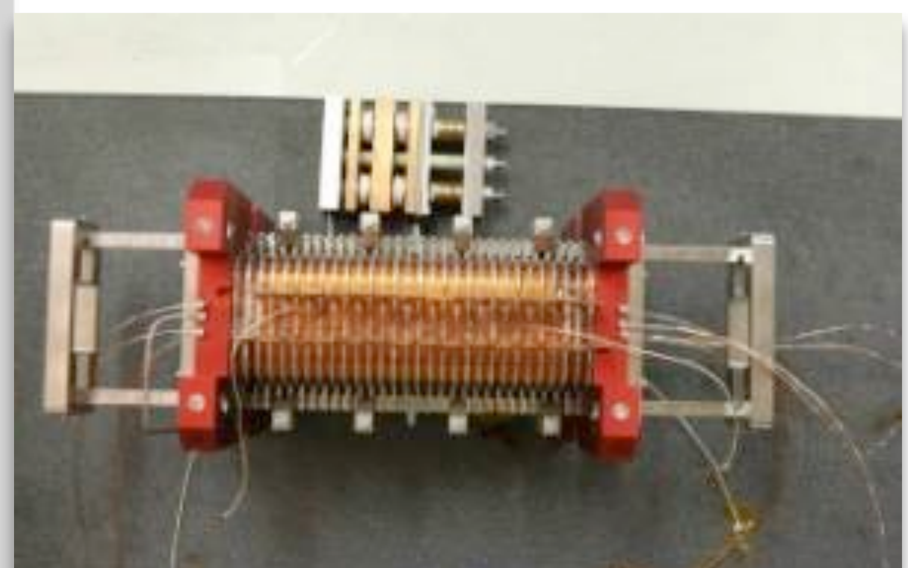
Development & beam tests of superconducting insertion devices

- experienced teams
- successful collaborations with CERN and BINP (CLIC-DW) and with industry (Babcock Noell SCU15)



SCU15 at KIT before installation

Damping wiggler test in Novosibirsk



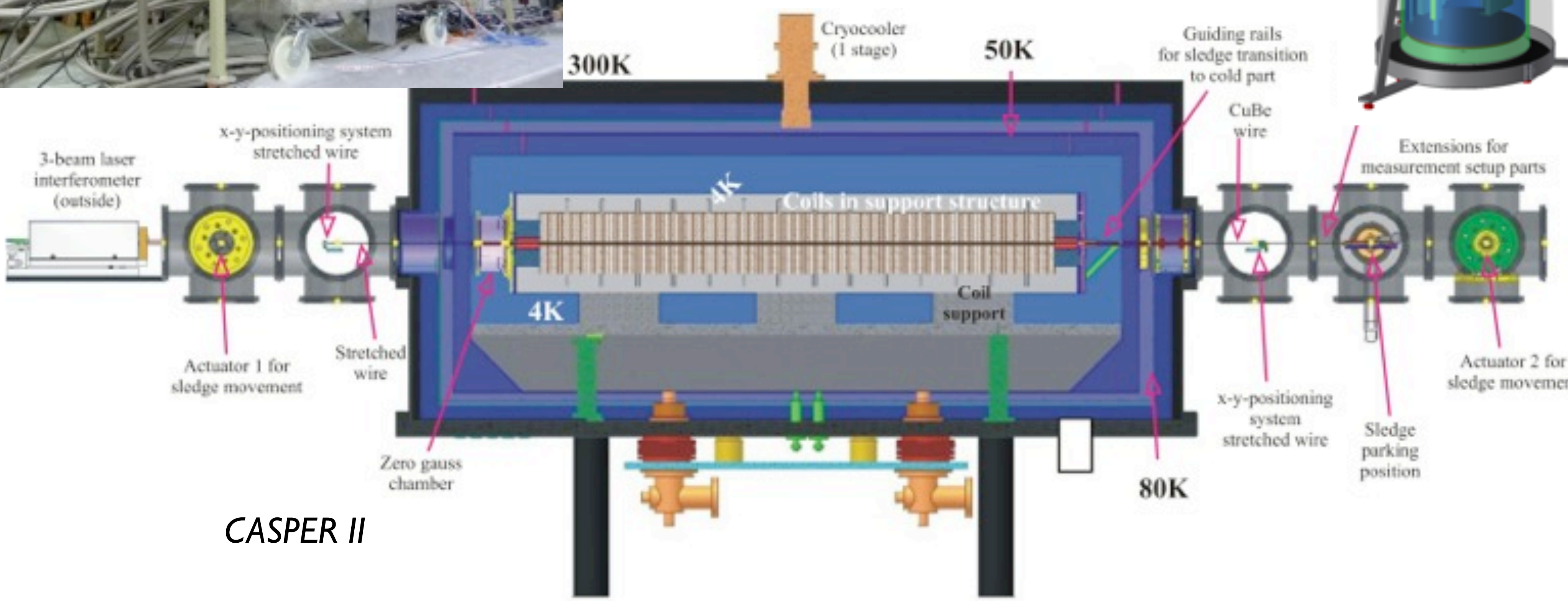
SCU20 Mockup

Quench detection

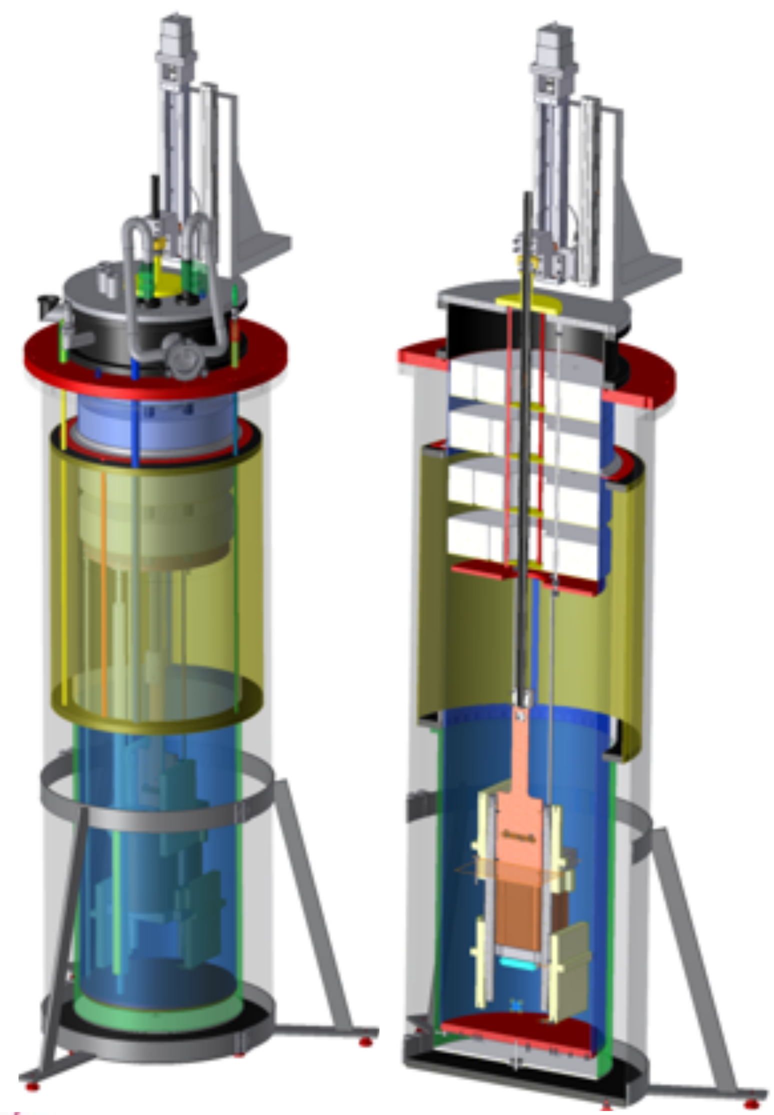
- Turn-key quench detection system with custom FPGA-based electronic detector design (EU patent pending)
- Combines reliable specific analogue signal processing (differential detector input) with computer-based detector parametrization, quench event data logging and operation diagnostics
- The KIT quench detection system is a modular and scalable device with complete soft-ware package *“QVision”* to operate up to 65536 detectors
- In operation or commissioning at W7-X, KATRIN, HZB, ANKA, GSI, TOSKA

Superconducting ID characterisation

- CASPER I: short (30 cm) coils in LHe
- CASPER II: up to 2 m coils in conduction cooling



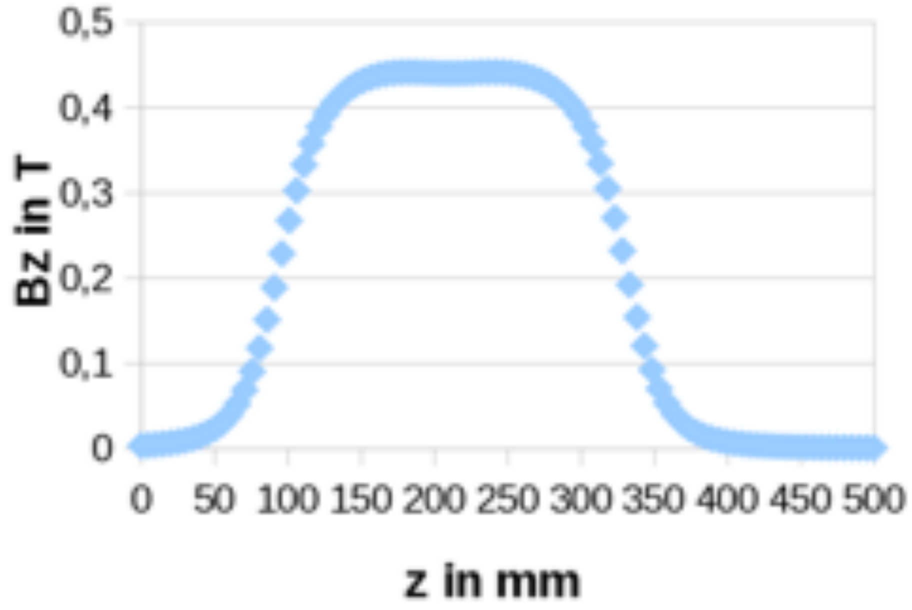
CASPER II

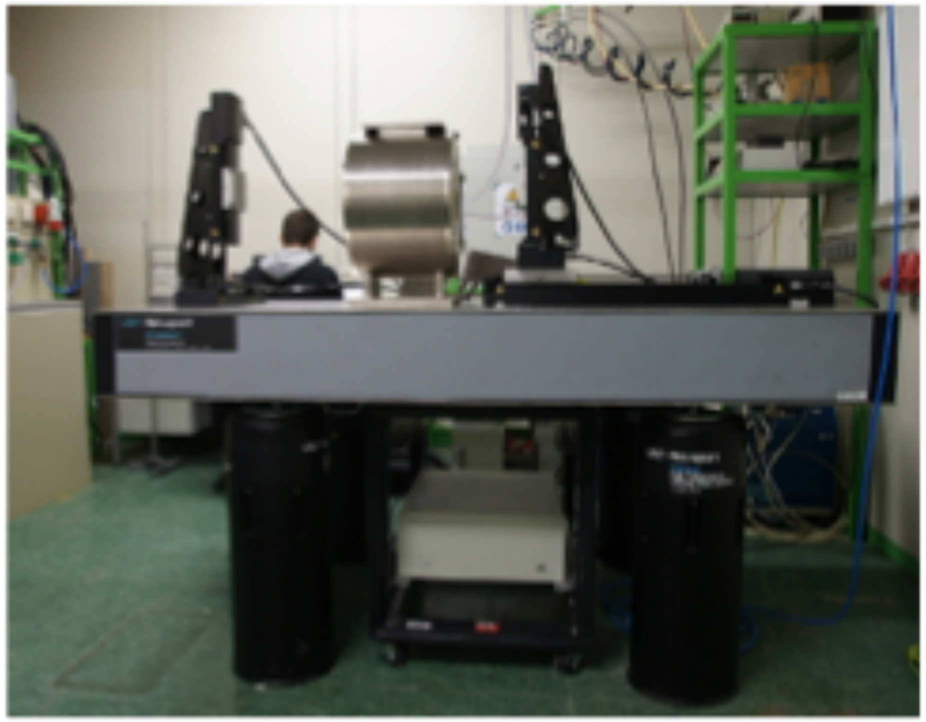


CASPER I

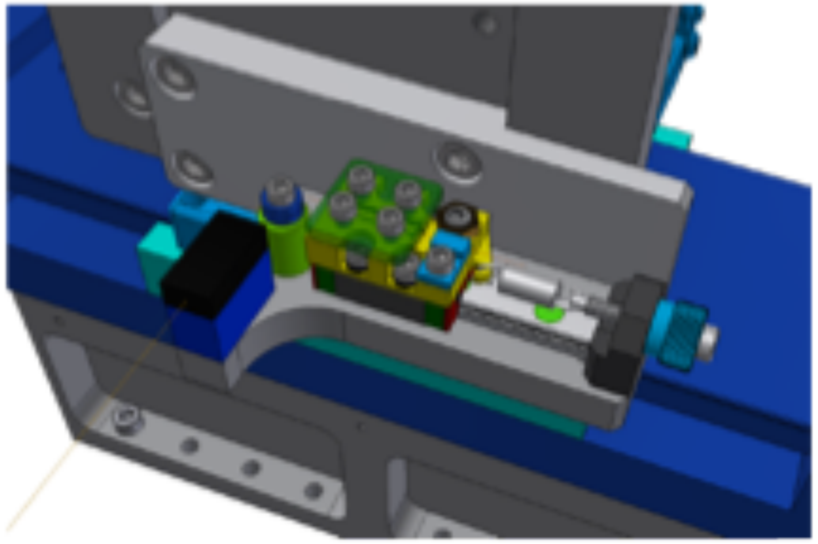
Conventional magnet fabrication & characterisation

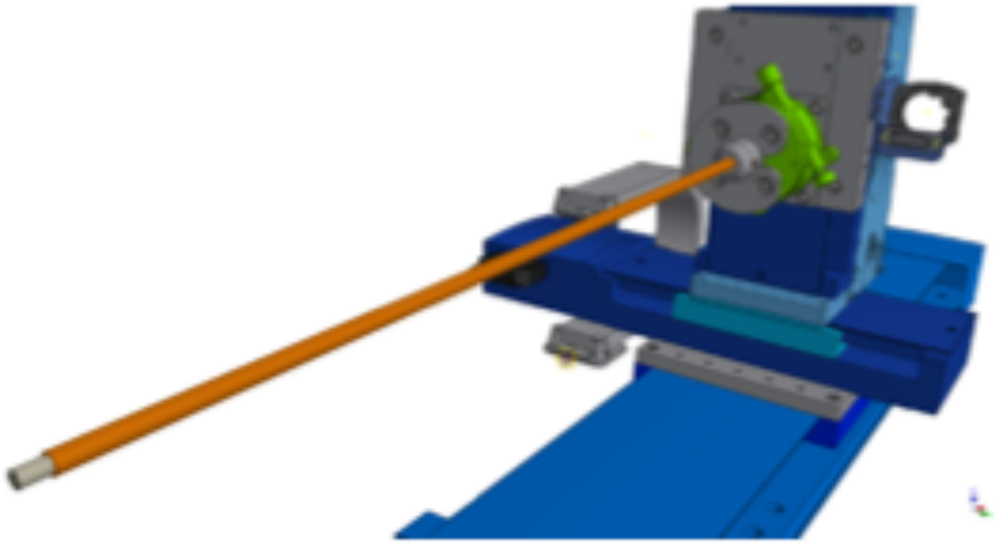
- Magnetic characterisation of various magnets
- Techniques: Hall-Probe and Stretched-wire
- In-house winding of conventional and super-conducting coils





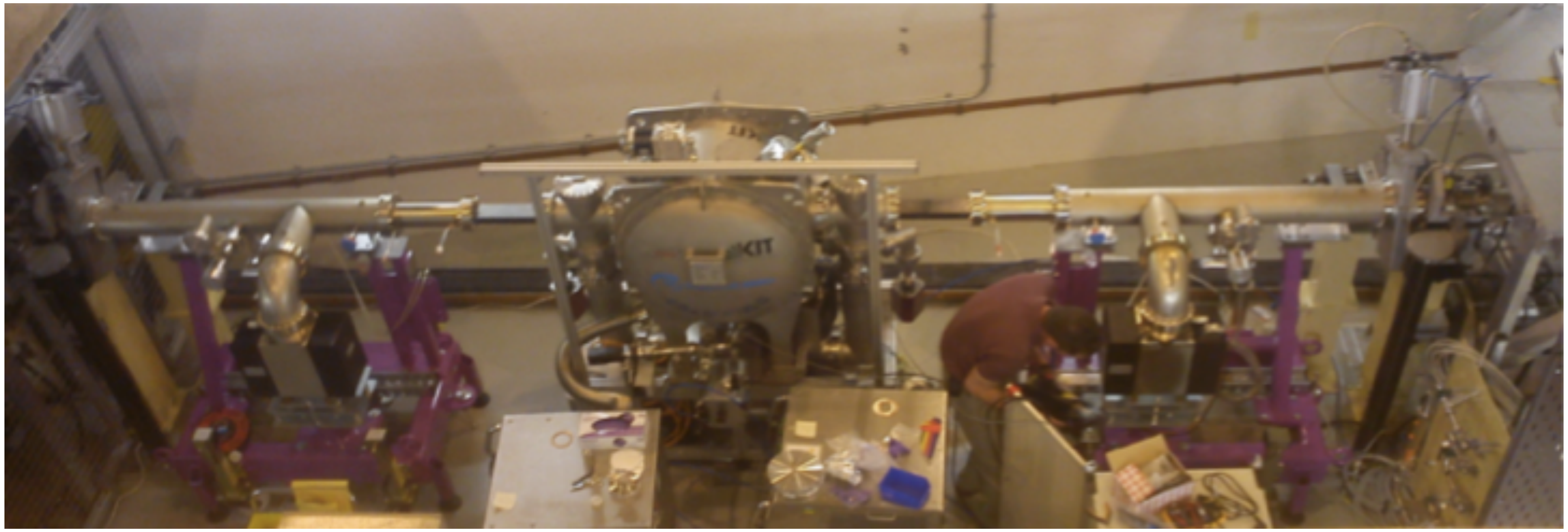
Magnet test bench



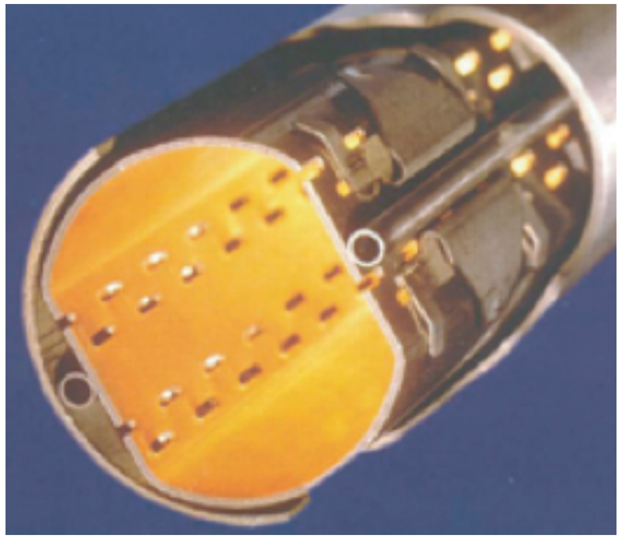


Diagnostics of cold surfaces

- COLDDIAG set-up to analyse beam heat load on cryogenic surfaces; Experiments at DIAMOND
- EuroCirCol: test of FCC vacuum chamber prototype



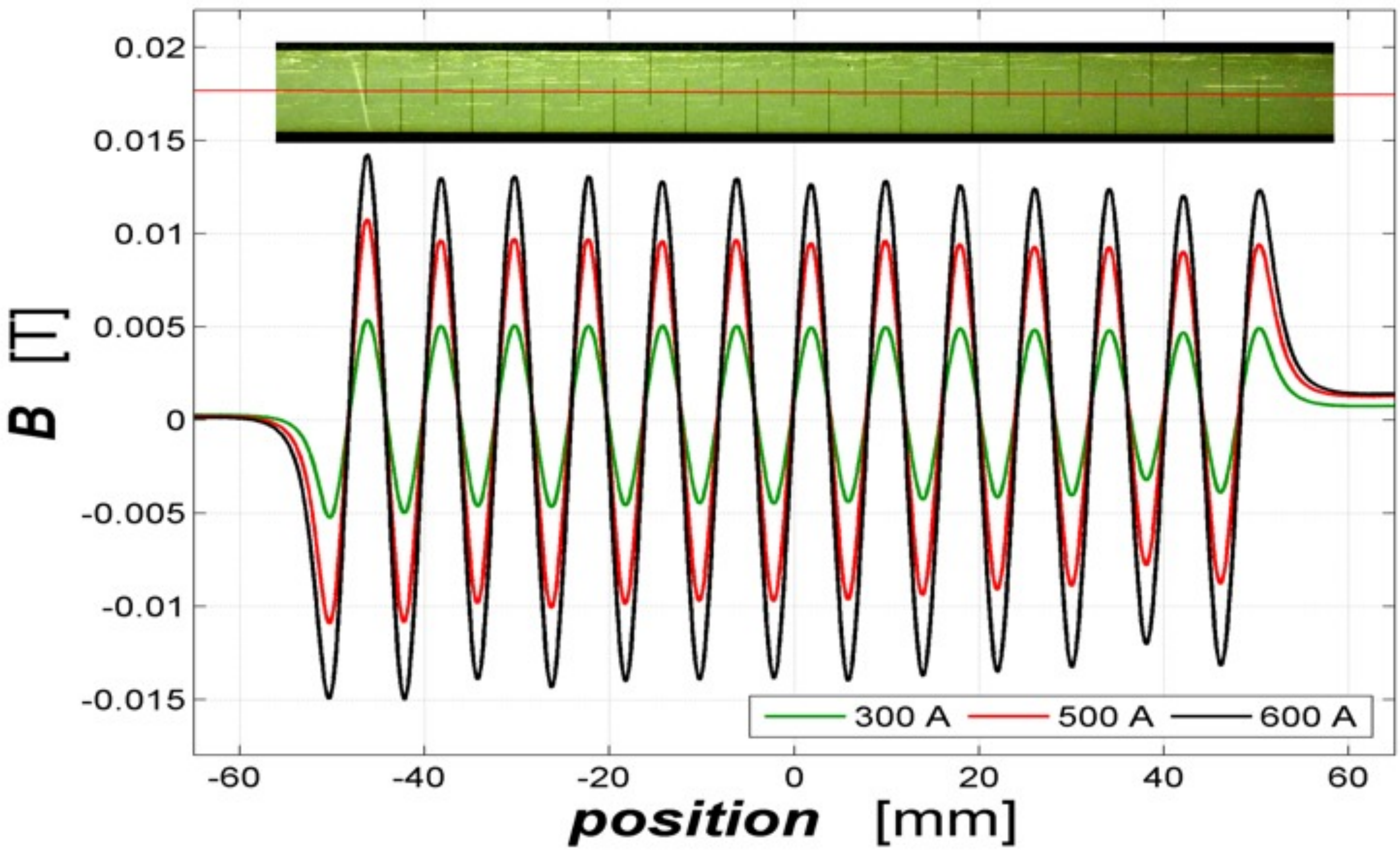
COLDDIAG at DIAMOND



EuroCirCol
A key to New Physics

HTS developments

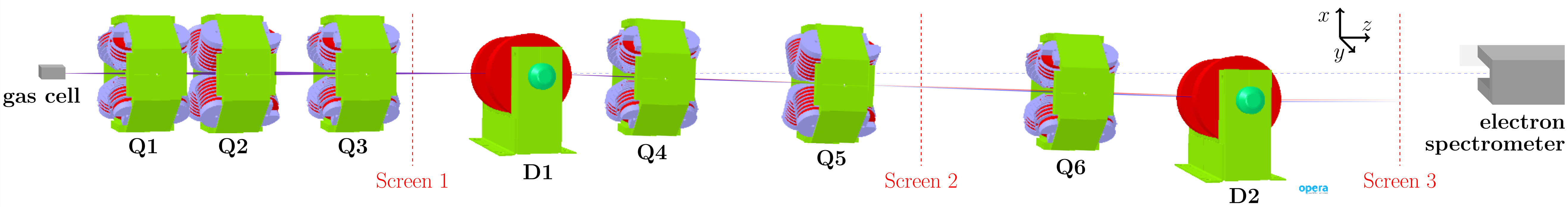
- HTS tape stacked undulator



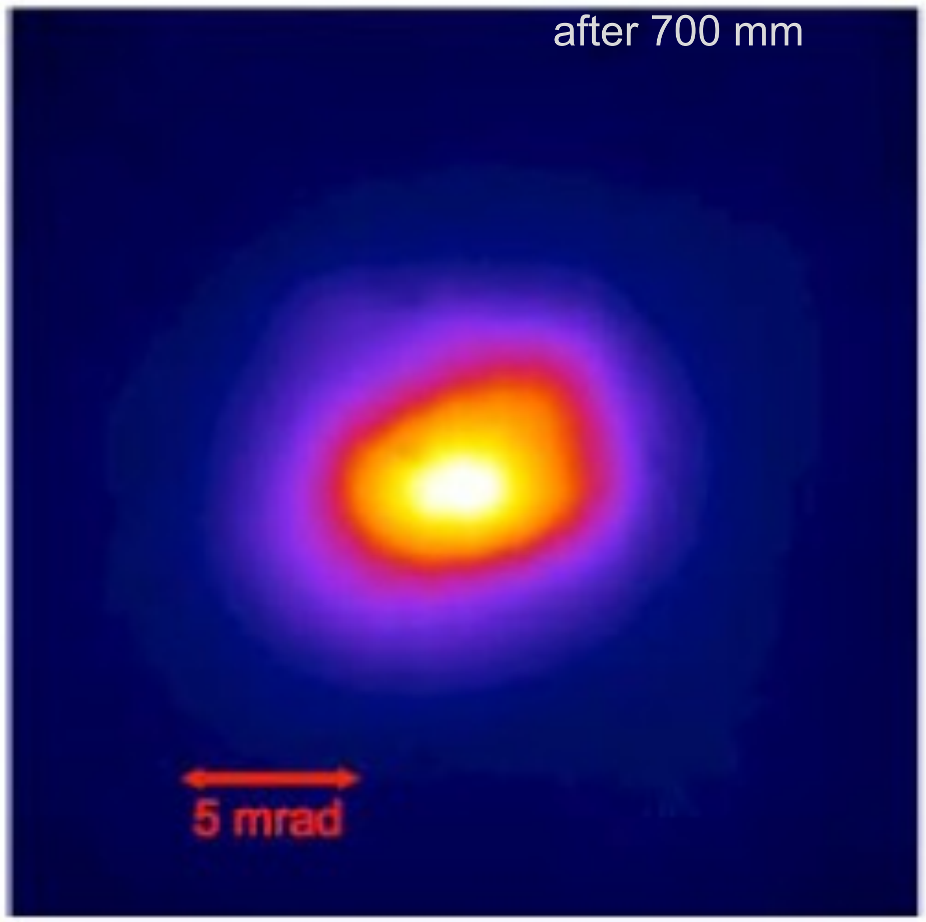
T. Holubek et al., IEEE Trans. on Appl. Supercond. 4602204, 23-3 (2013)

Measured magnetic field profile of a HTS stacked undulator

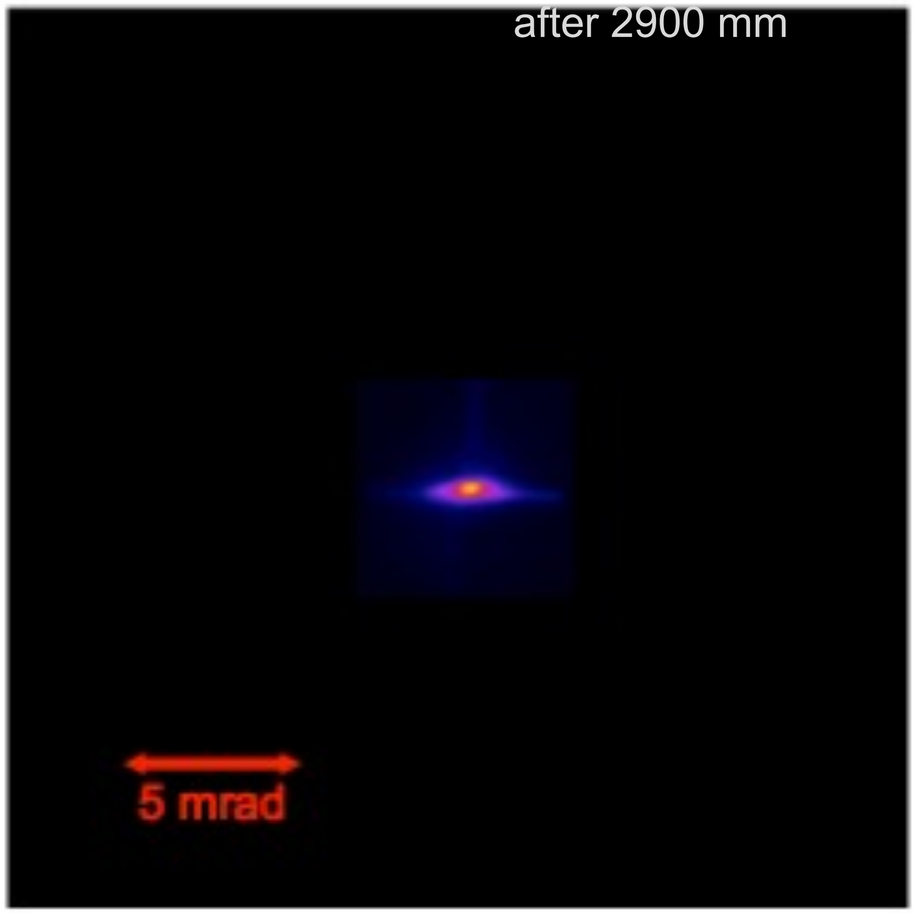
Beam transport from the laser wakefield accelerator JETI to a SC transverse gradient undulator



Courtesy M. Kaluza (HI Jena), C. Widmann (KIT), et al.



without electron transport line

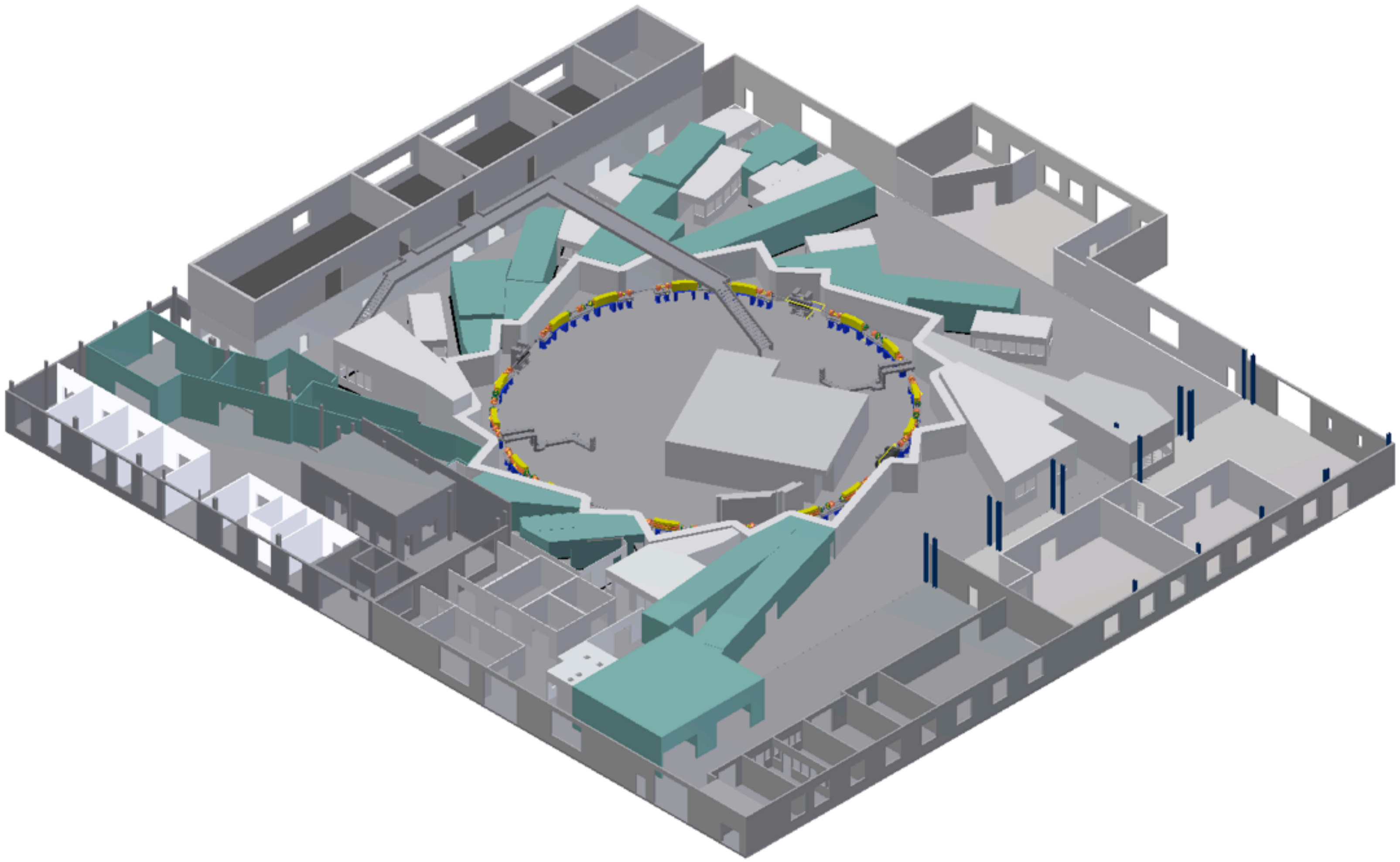


with electron transport line

C. Widmann et al., IPAC2015 MOPWA045

The ANKA synchrotron radiation facility

- **Normal operation:**
- Energy 2.5 GeV
- Current 200 mA
- **Bunch length σ ≈ 45 ps**



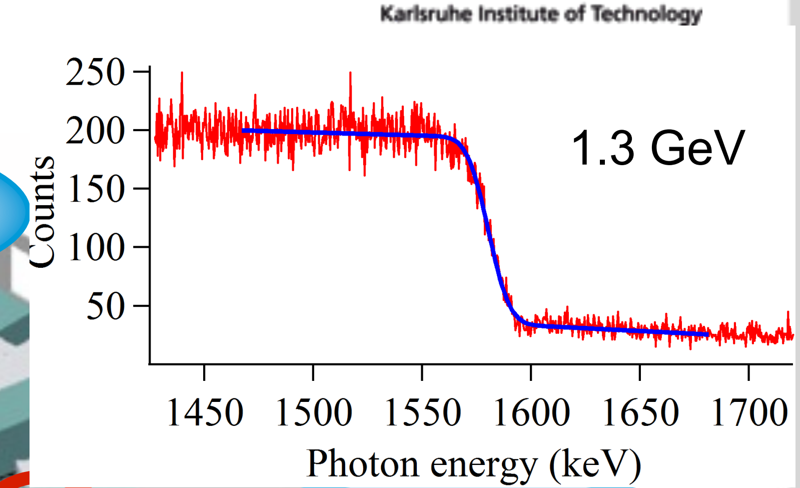
- **Low Alpha mode:**
- Energy 0.8 - 1.6 GeV
- Current ≈ 70mA
- **Bunch length**
  σ ≈ 10 ps down to 1-2 ps
- **Coherent THz radiation**

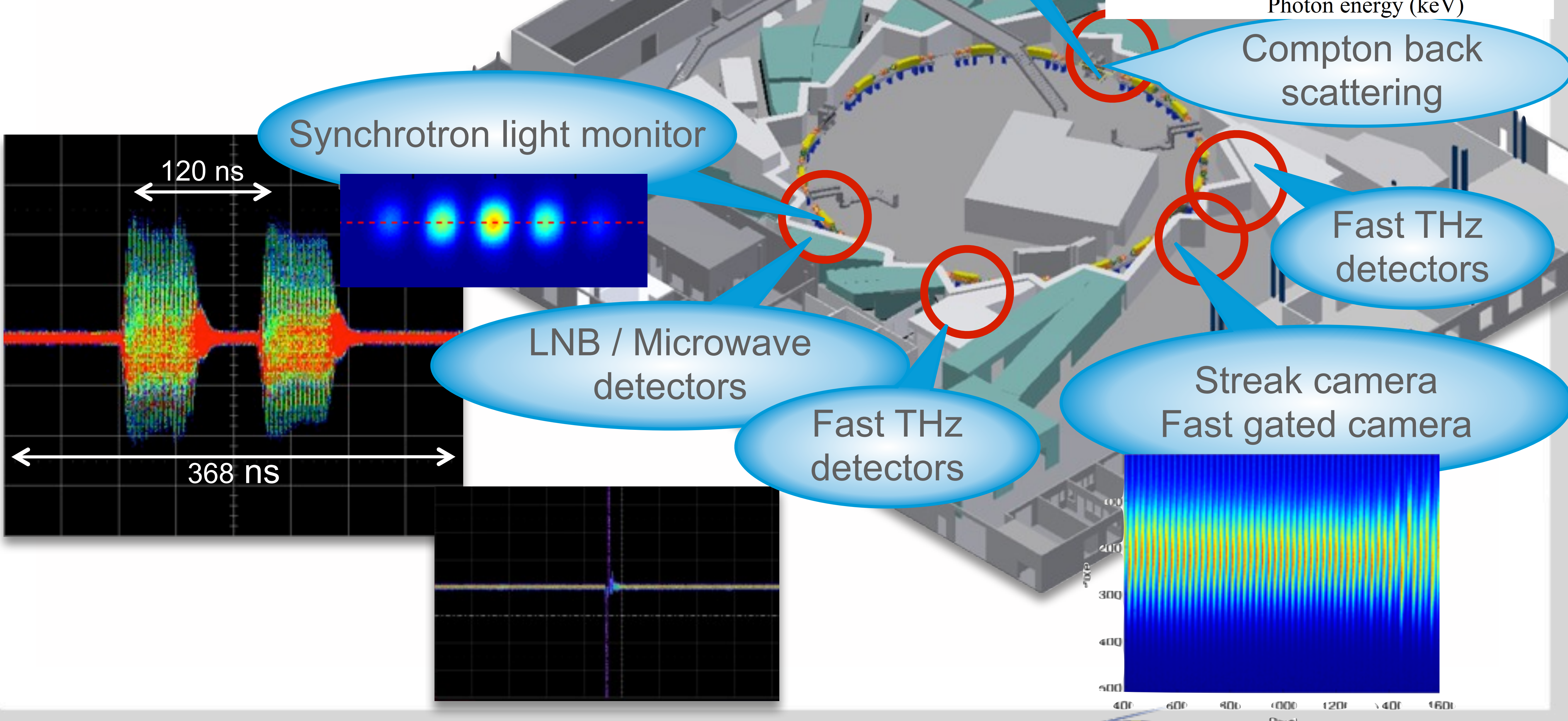
- **Photon science facility and technology platform**

➜ new operation/usage strategy in preparation: open for R&D!

The ANKA synchrotron radiation facility

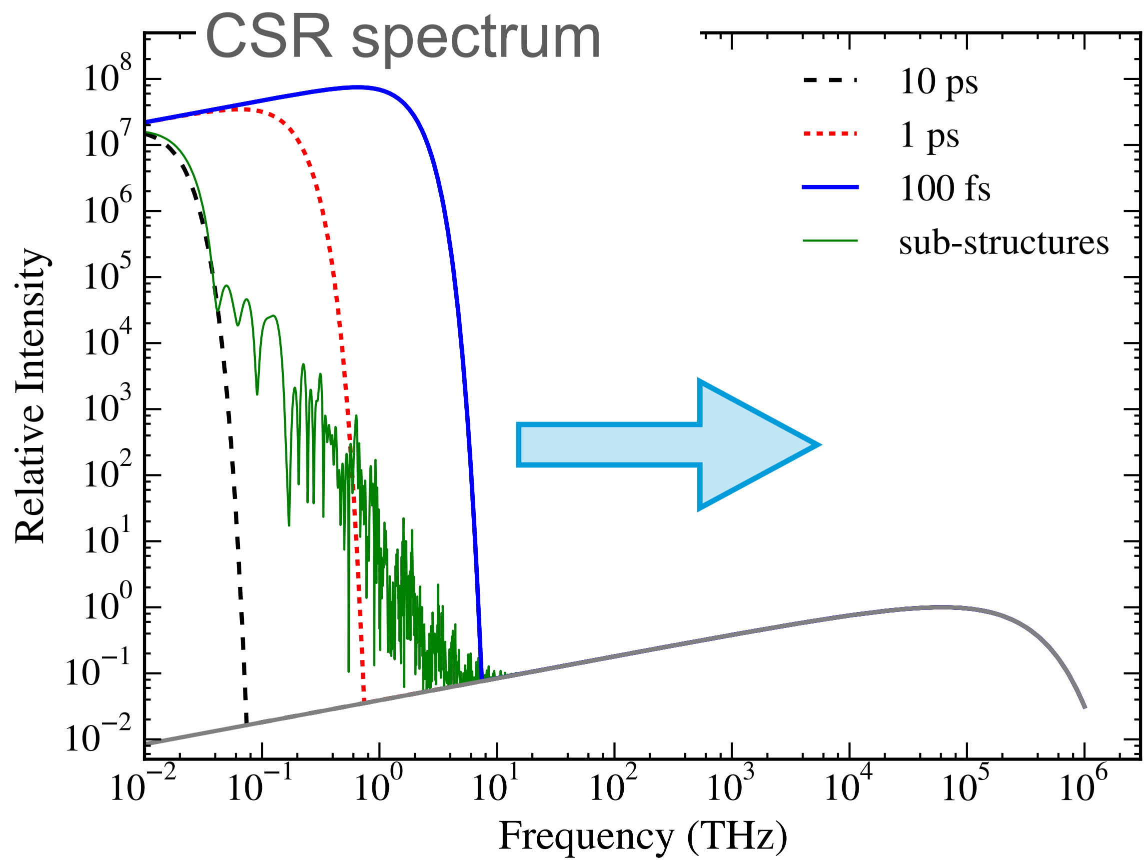
- Circumference: 110.4 m
- Energy range: 0.5 - 2.5 GeV
- RF frequency: 500 MHz
- Revolution time: 368 ns





Short bunches: physics & phenomenology

- CSR spectrum
  - high radiation power
  - strong e.m. fields
  - self-interactions

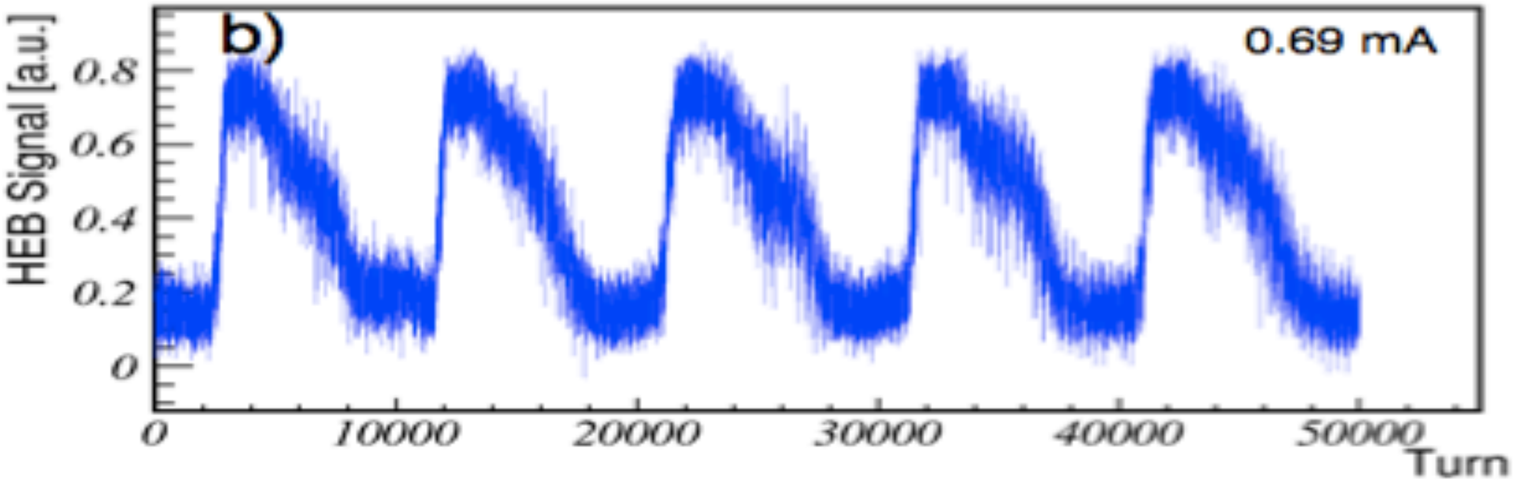


- (μ-bunching) instabilities
  - occur above a threshold current
  - threshold depends on, e.g., RF voltage, vacuum chamber geometry, bending radius, but also on the filling pattern
  - really short bunches only for low bunch currents

- Key issues for short bunch diagnostics
  - high resolution (ps) - high rate (500 MHz) - long term observation (secs - hrs)
  - 2 categories:
    indirect: *detection of coherent and incoherent radiation (microwave - vis)*
    direct: *detection of bunch Coulomb fields*

µ-bunching instability

- Dynamic sub-structures lead to bursts in the THz signal -> signature

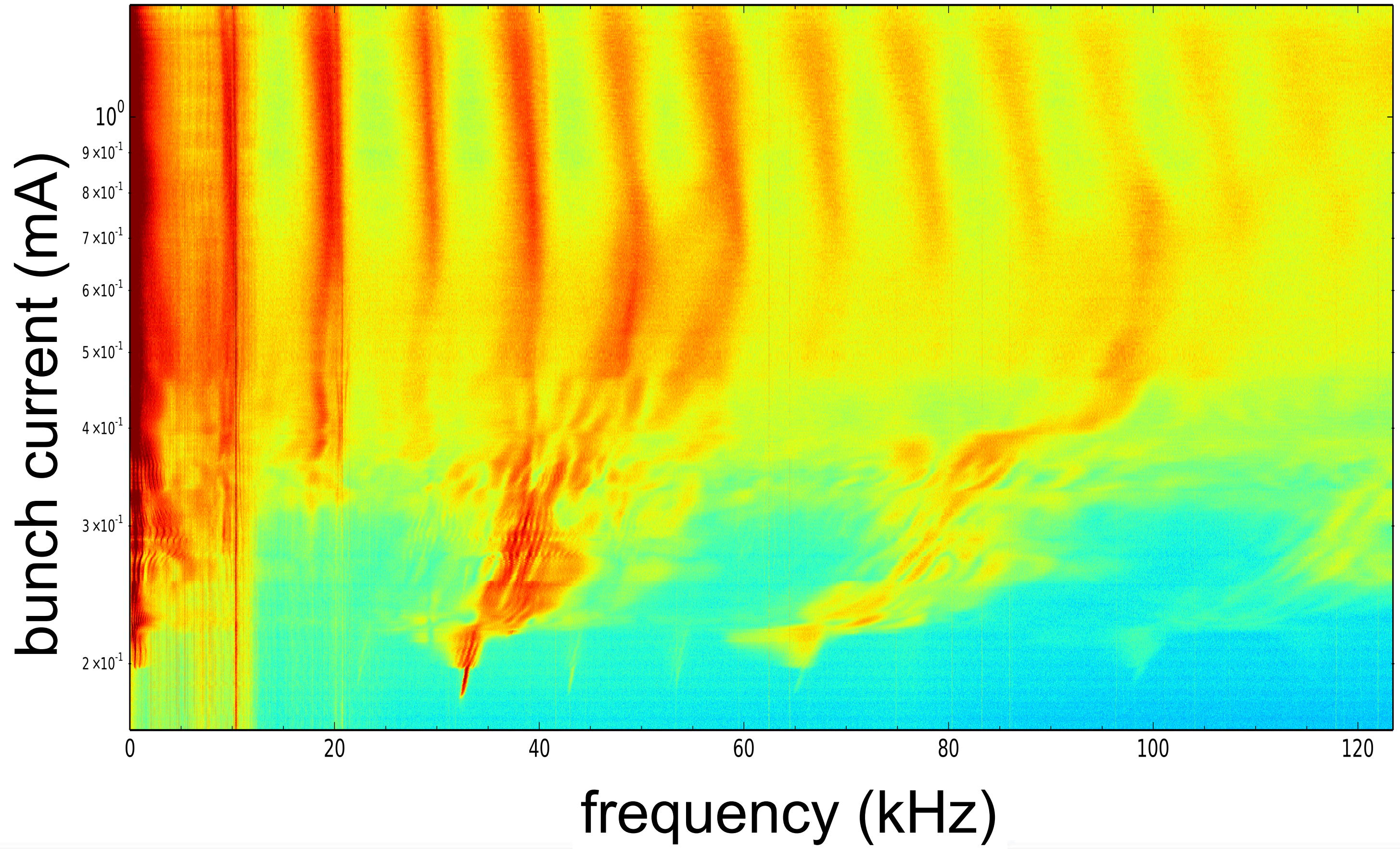


THz signal measured with an ultra-fast detector system

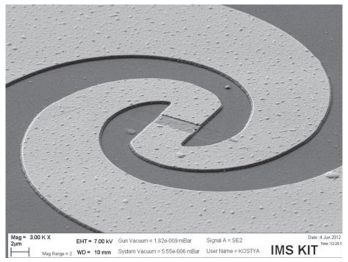
V. Judin et al., IPAC2010, WEPEA021

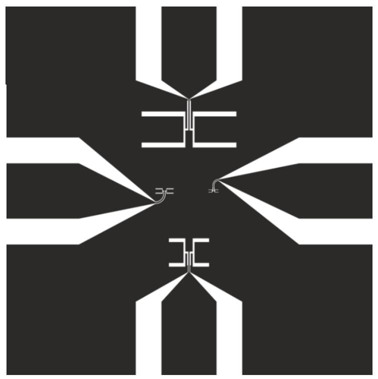
FFT of THz signal as a function of bunch current

V. Judin et al., IPAC 2014, MOPRO063



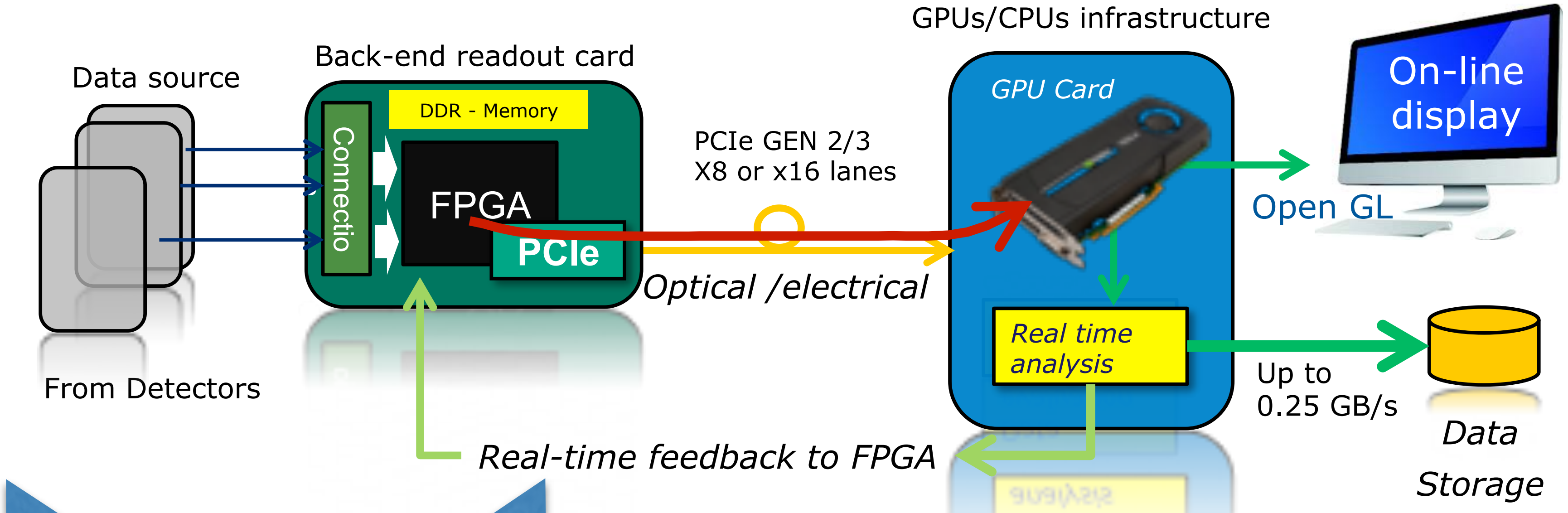
THz signal dynamics - development of detectors, readout & (online) analysis





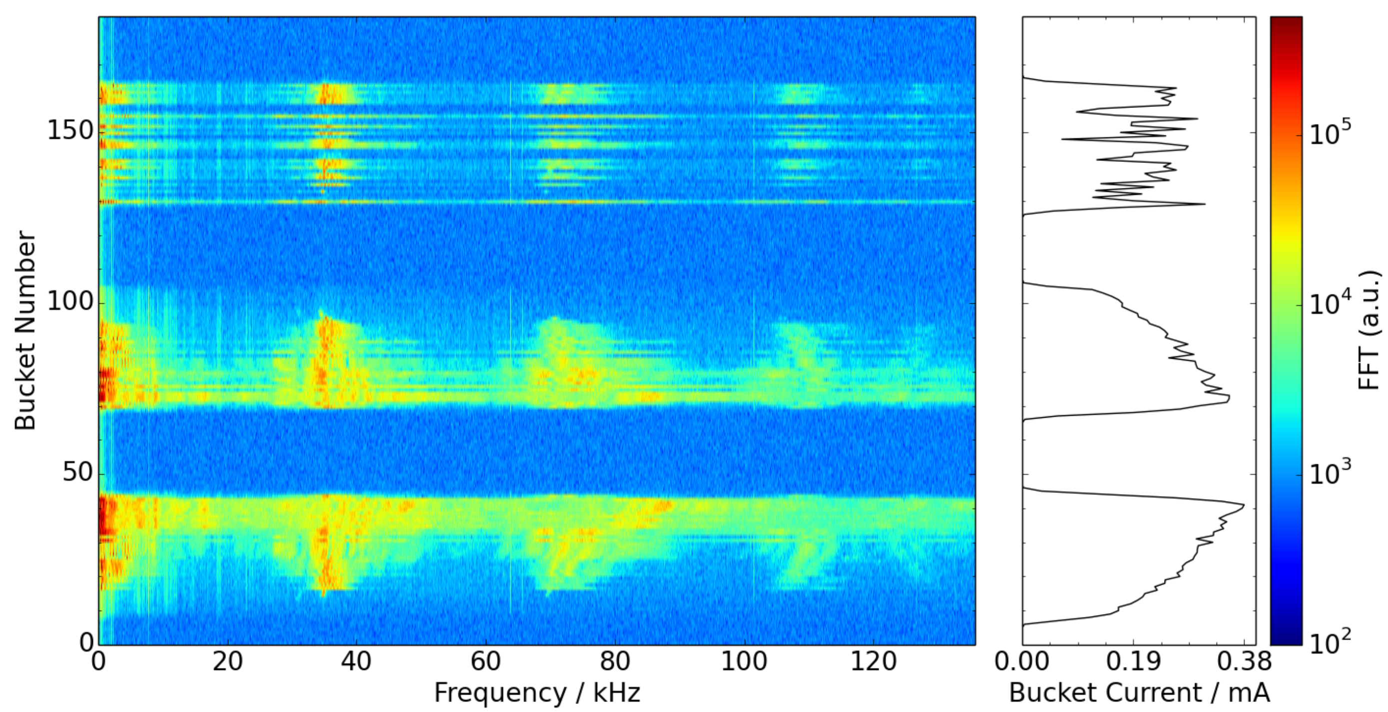
P. Thoma et al., Appl. Phys. Lett. 101, 142601 (2012)

A. Schmid et al., 3rd ARD ST3 Workshop (2015)



M. Caselle, et al., Journal of Instrumentation, 9(01):C01024 (2014)

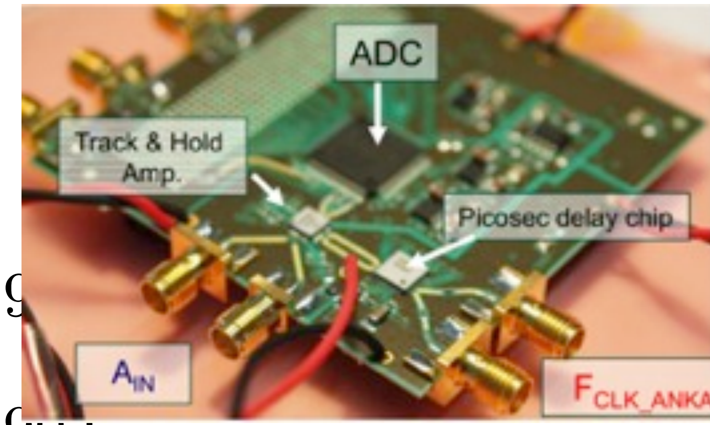
Instantaneous acquisition of full bursting spectrogram

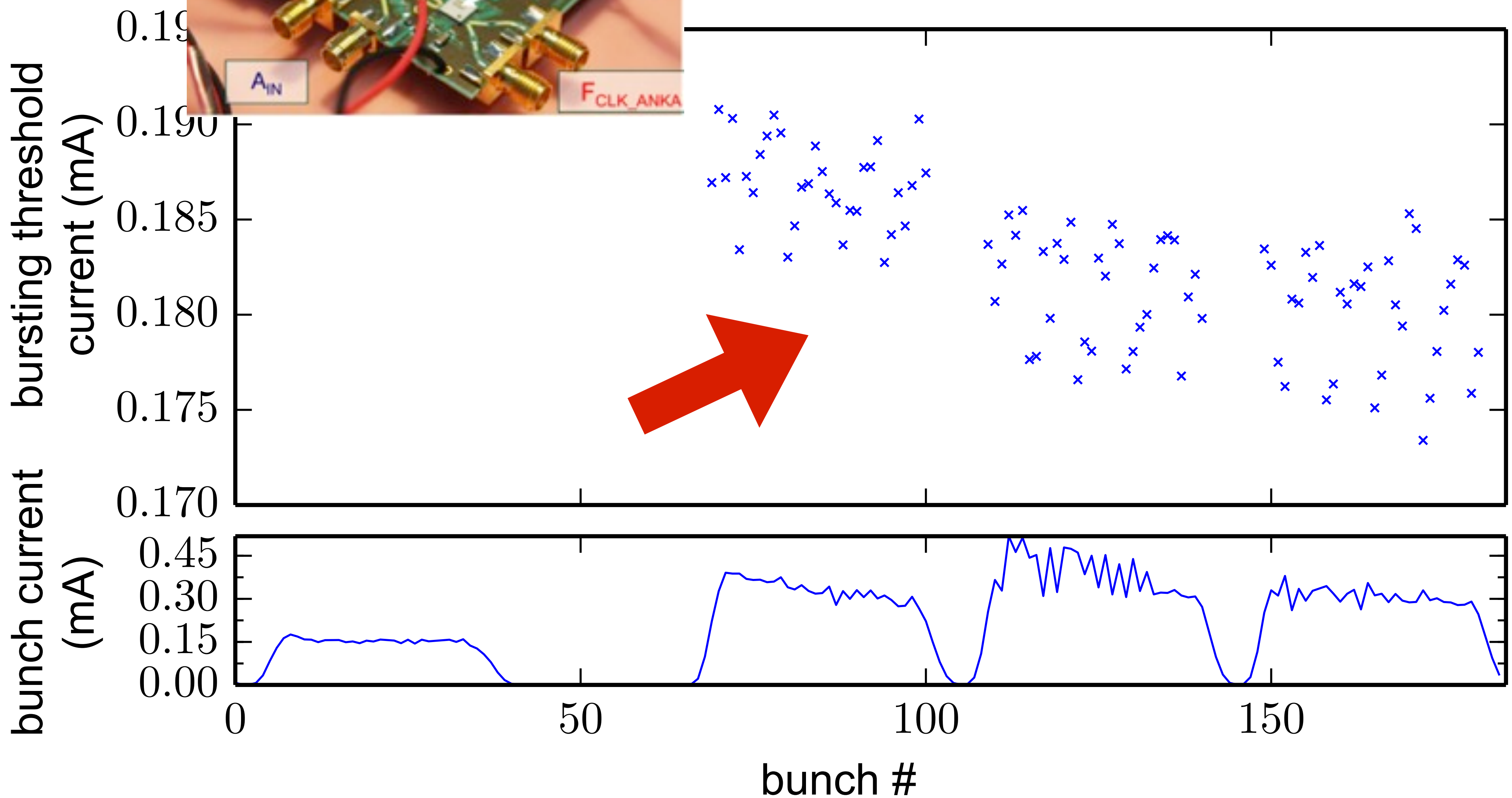


M. Brosi, et al., IPAC 2015, MOPHA042

THz signal dynamics - development of detectors, readout & (online) analysis

P. Schreiber, Bachelor thesis

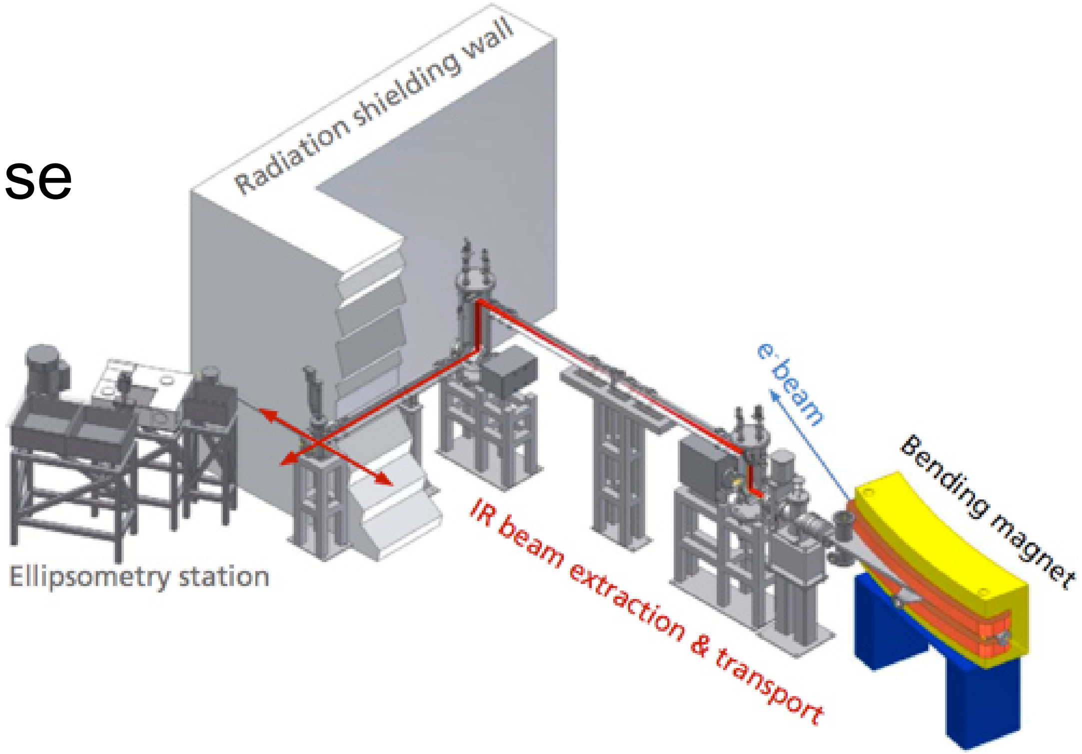


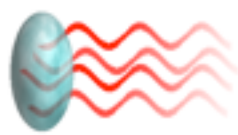


M. Caselle, M. Balzer, S. Chilingaryan, M. Hofherr, V. Judin, A. Kopmann, N.J. Smale, P. Thoma, S. Wuensch, A.-S. Müller, M. Siegel and M. Weber, An ultra-fast data acquisition system for coherent synchrotron radiation with terahertz detectors, IOPscience, Journal of Instrumentation 9, C01024 (2014).

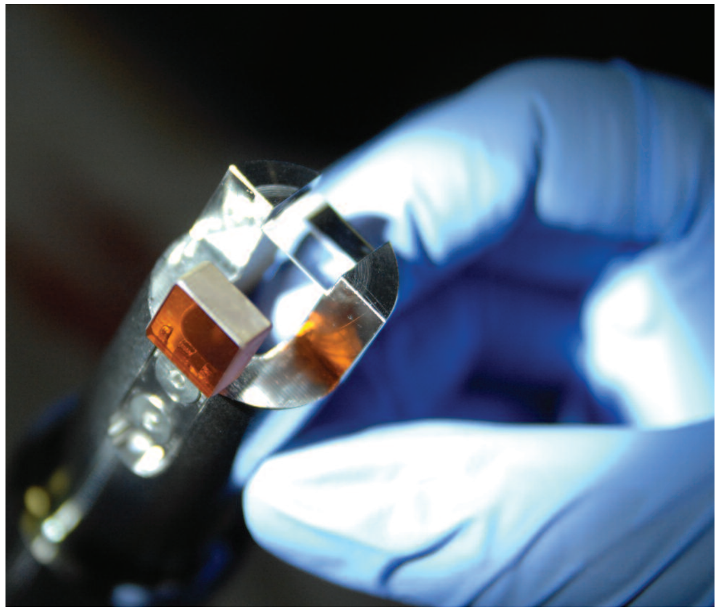
Direct detection of bunch fields

- Measurements in two basic set-ups
  - detection of synchrotron radiation THz pulse in the beam line (“far-field”)
  - (direct) detection of bunch electric field (“near-field”)



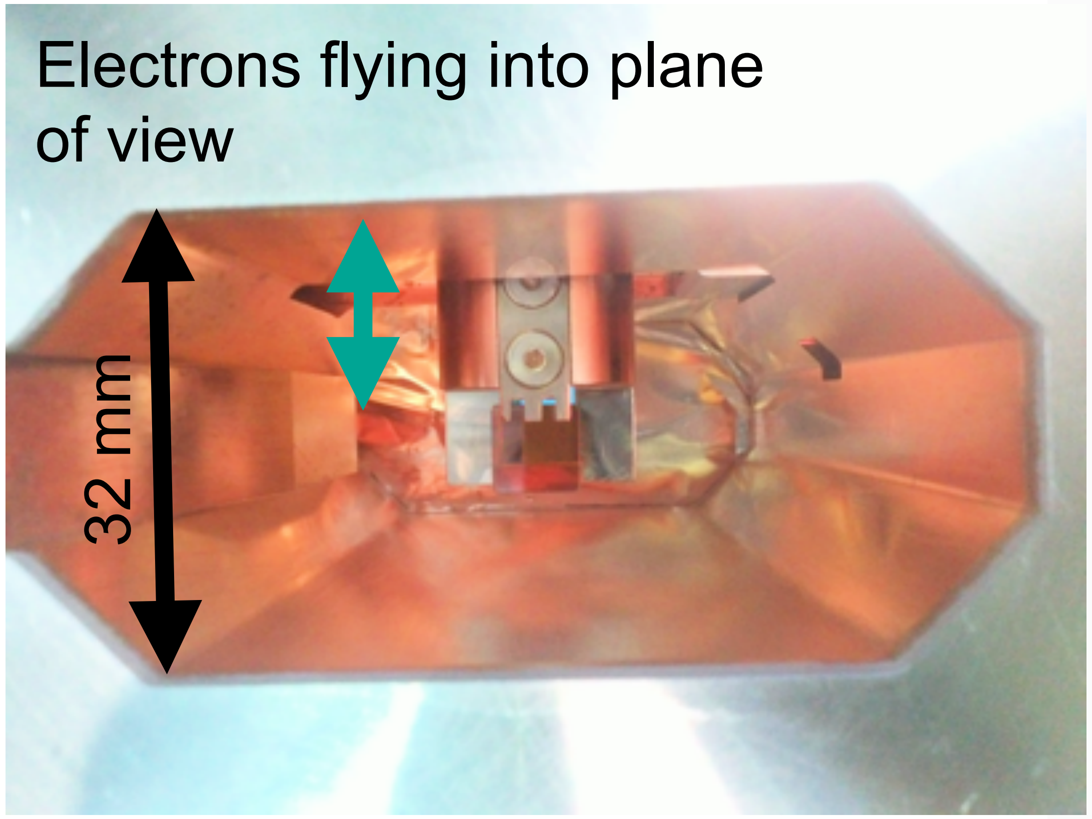


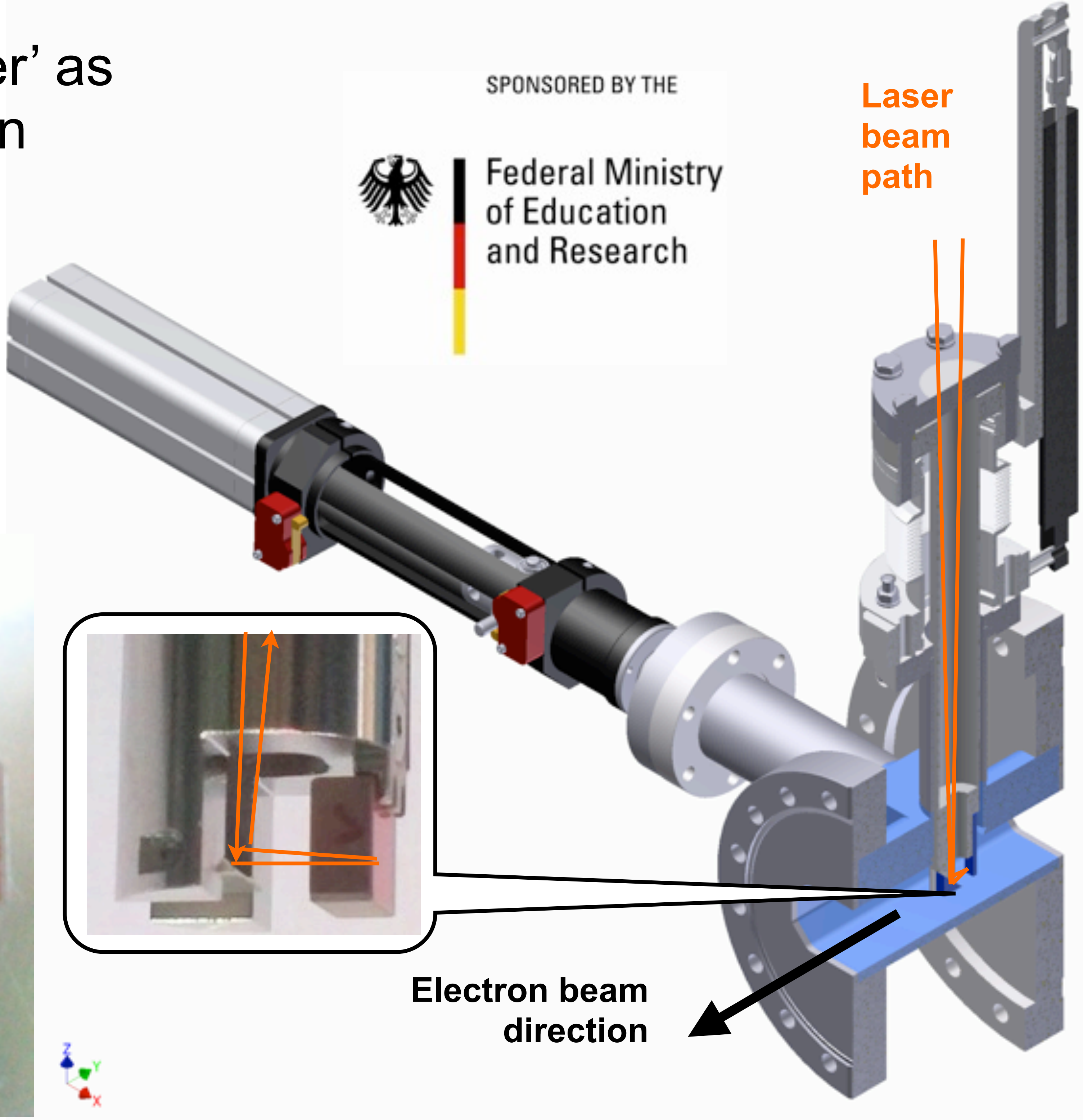
- Electro-optic (EO) methods measure
  - wake field (EO sampling)
  - bunch shape (EO spectral decoding, single shot!)



EO set-up in the ANKA vacuum chamber

- Retractable arm with 'slider' as shielding for user operation
- EO monitor designed at PSI & DESY adapted for use with ANKA





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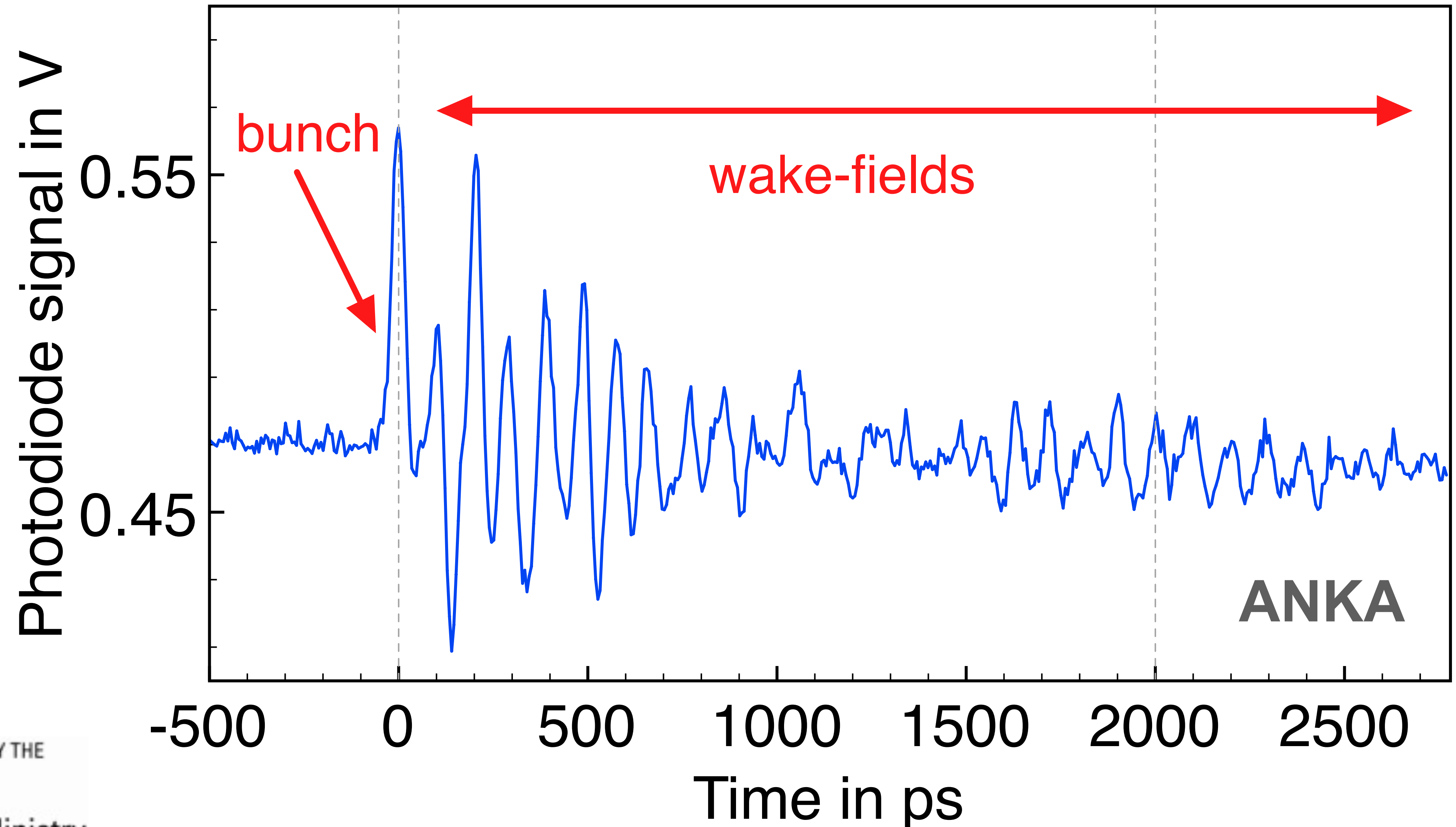
EO sampling: bunch & wake field

- EOS measurement of the E-field induced birefringence inside GaP crystal from passing bunch



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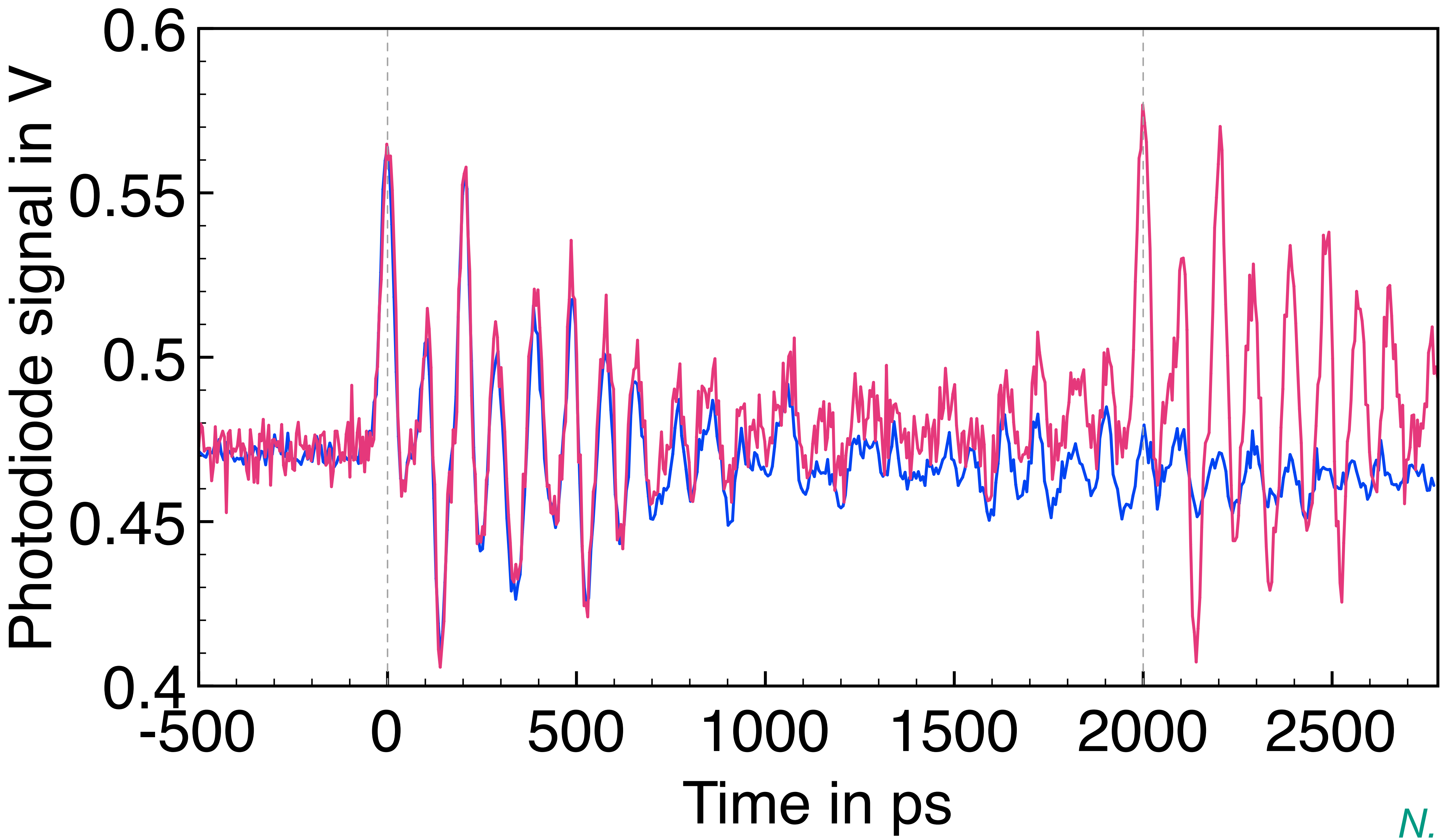
N. Hiller et al., IPAC'13, MOPEA014
B. Kehrer et al., IPAC'13, MOPEA015

EOS with two consecutive bunches

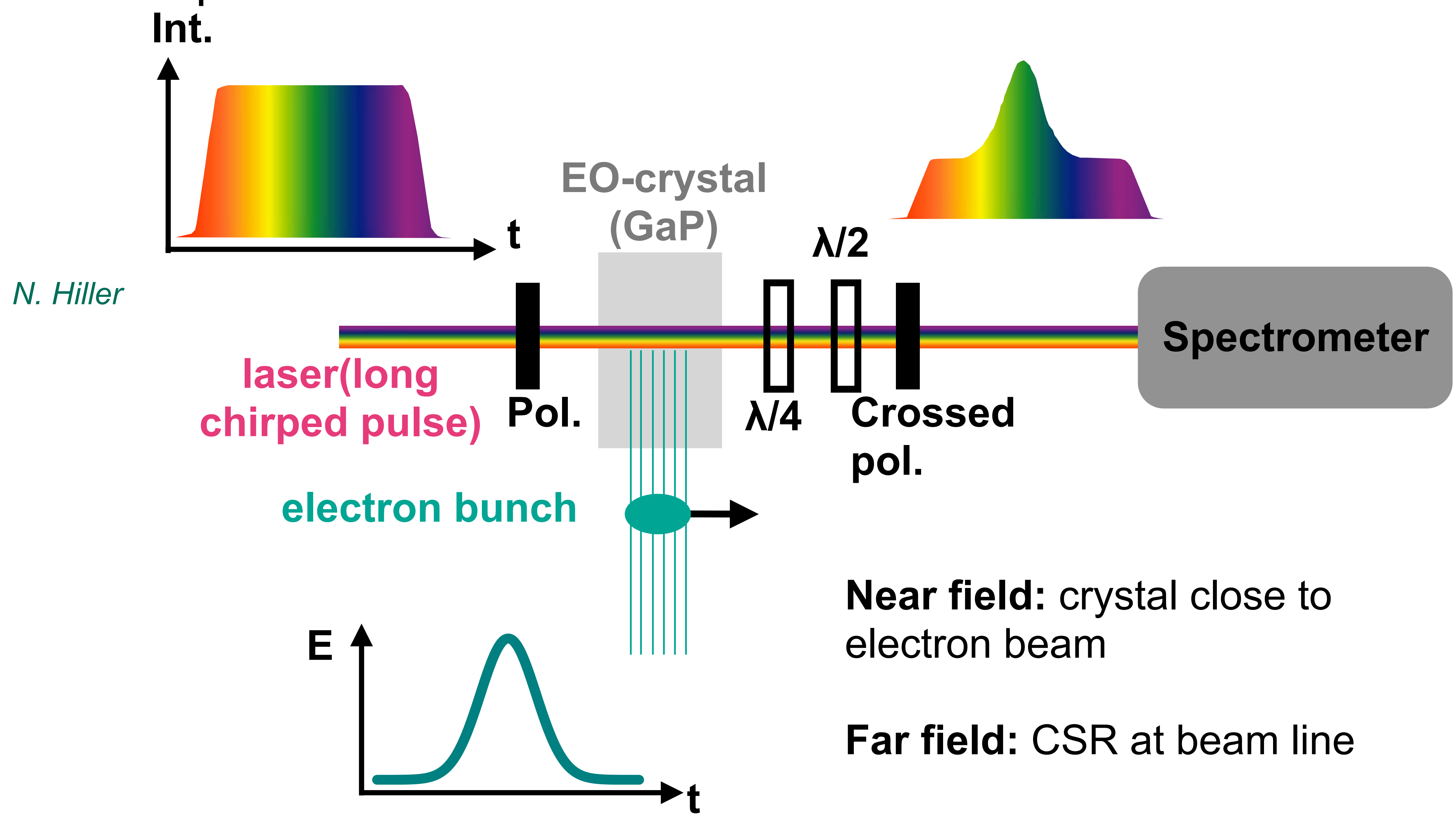
- blue: single bunch; red: 2-bunch fill (second bunch with lower current)



N. Hiller

Electro-Optical Spectral Decoding

- Single shot method: allows to record transient changes in longitudinal bunch profile



Near field: crystal close to electron beam

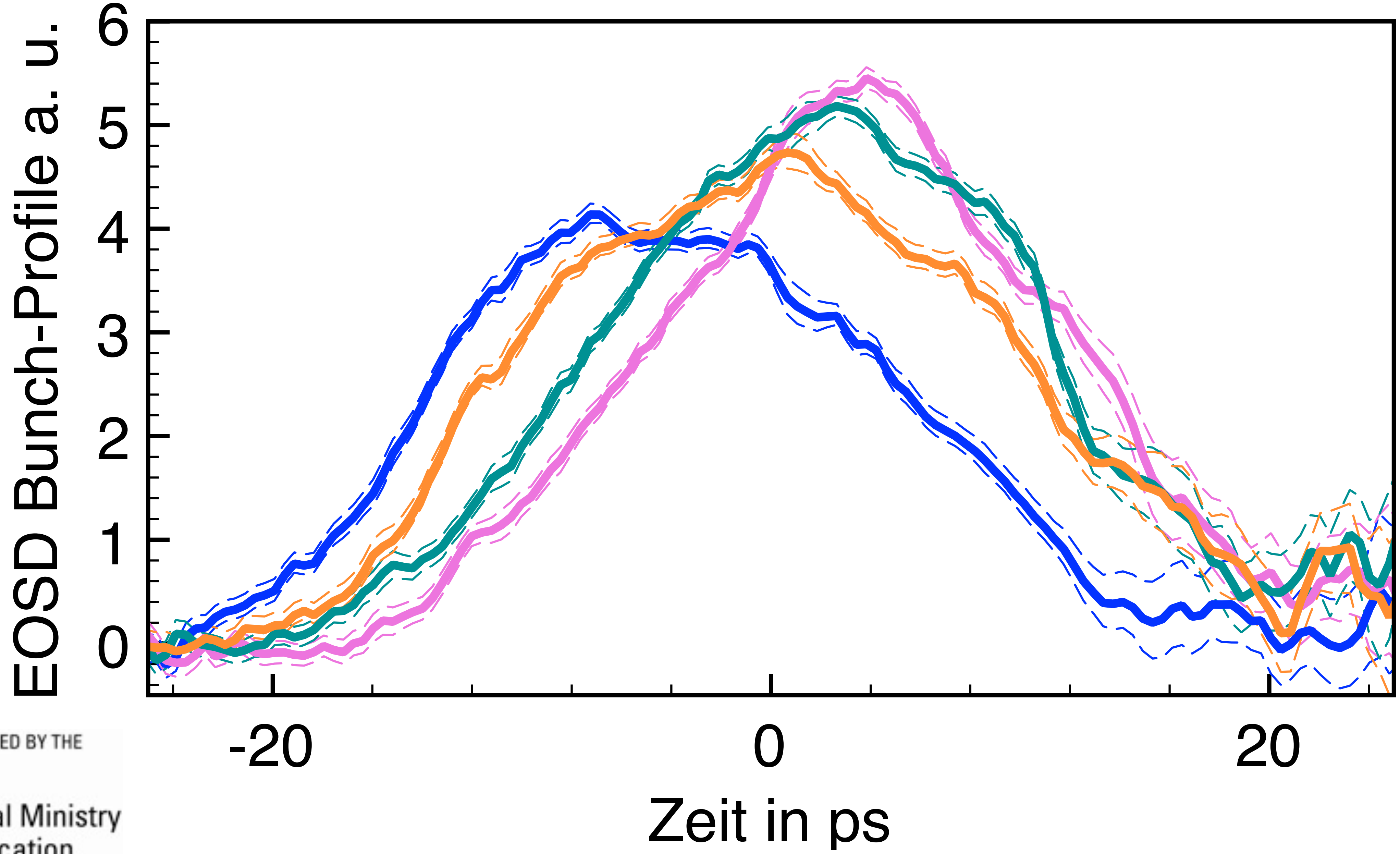
Far field: CSR at beam line

λ/4: compensate intrinsic birefringence of crystal
λ/2: control transmission through crossed polariser

N. Hiller

EO spectral decoding: bunch shape

- Single shot EOSD measurements indicate dynamic sub-structures



N. Hiller

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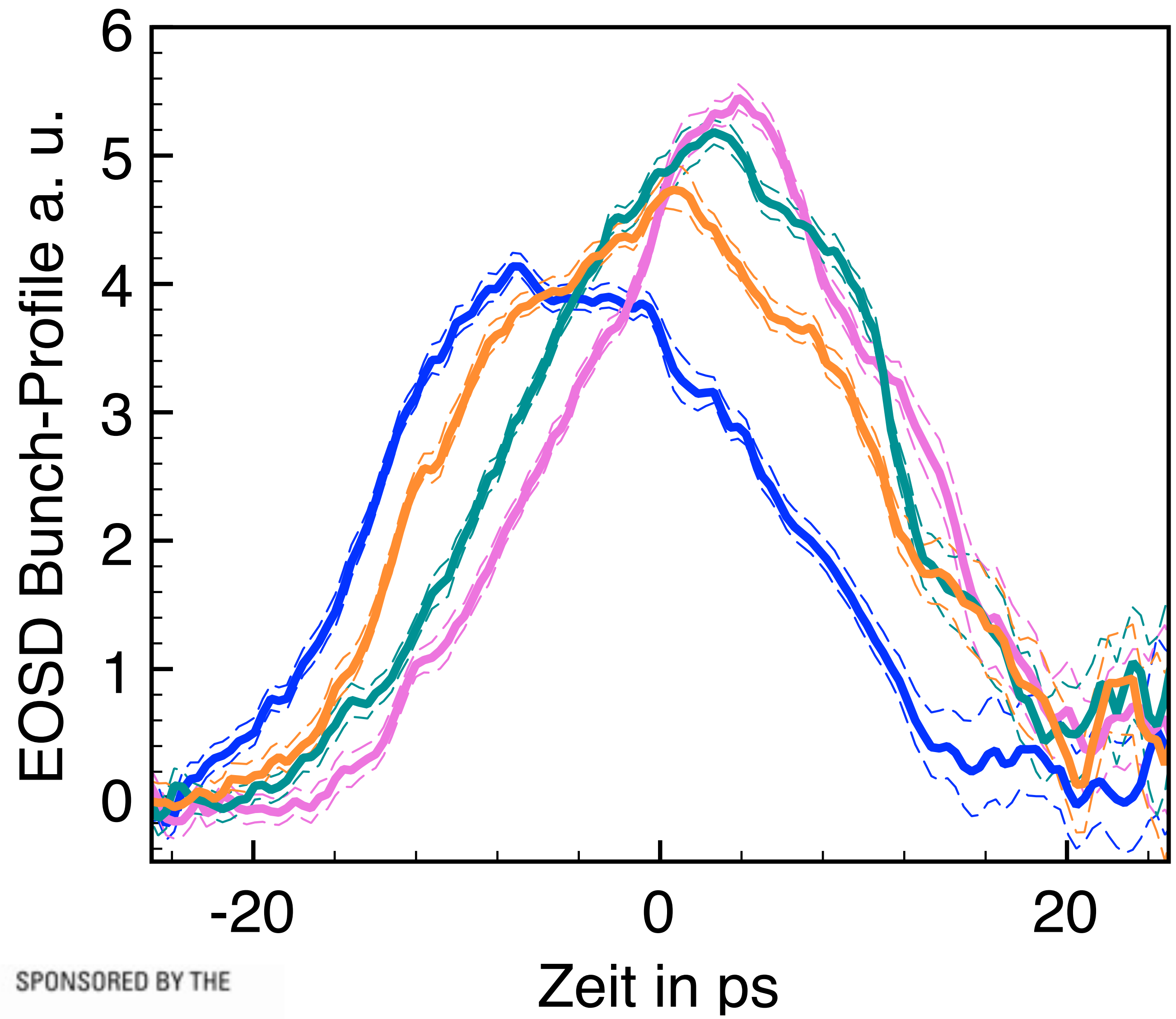
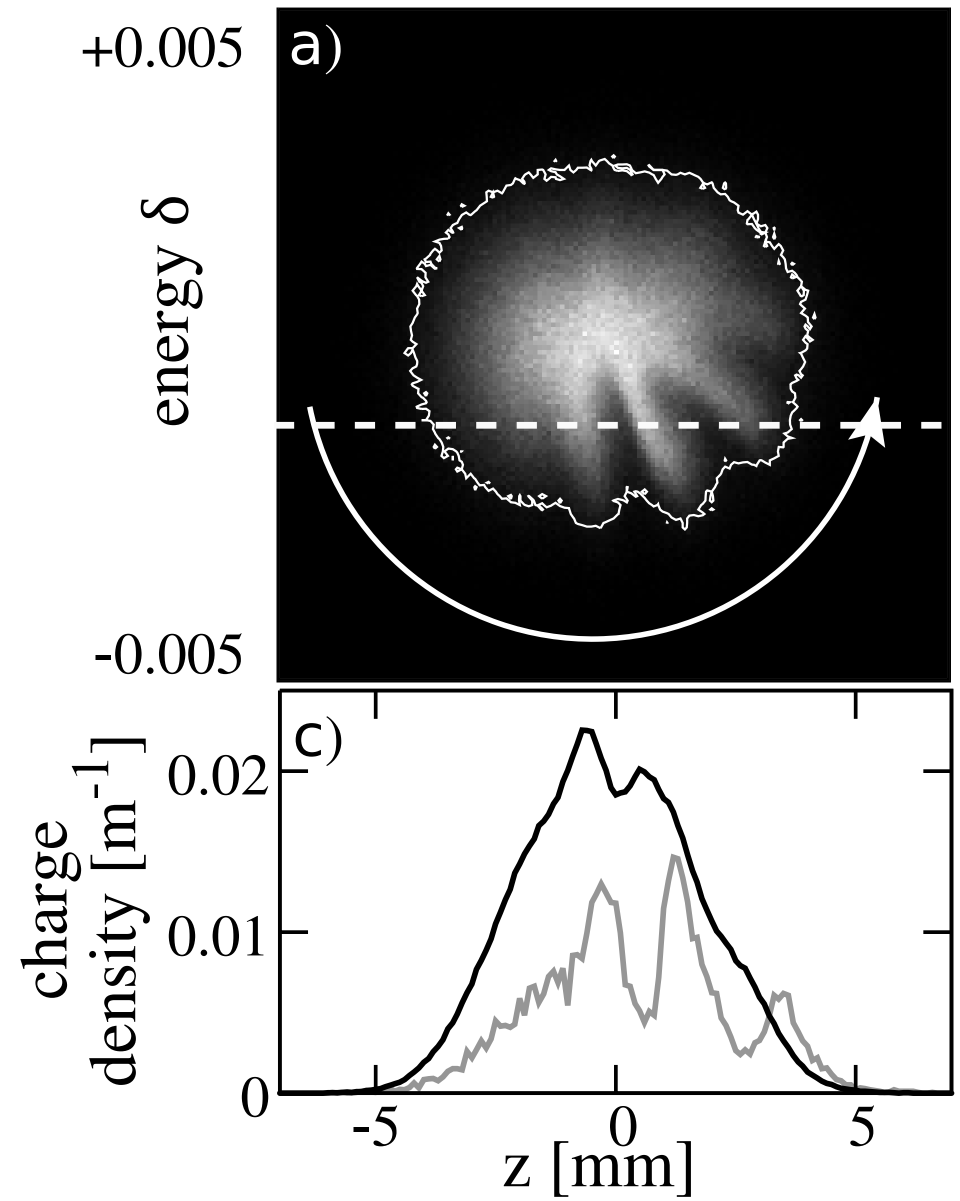
EO spectral decoding: bunch shape

- Single shot EOSD measurements indicate dynamic sub-structures





N. Hiller

C. Evain et al.,
EPL, 98 (2012) 40006

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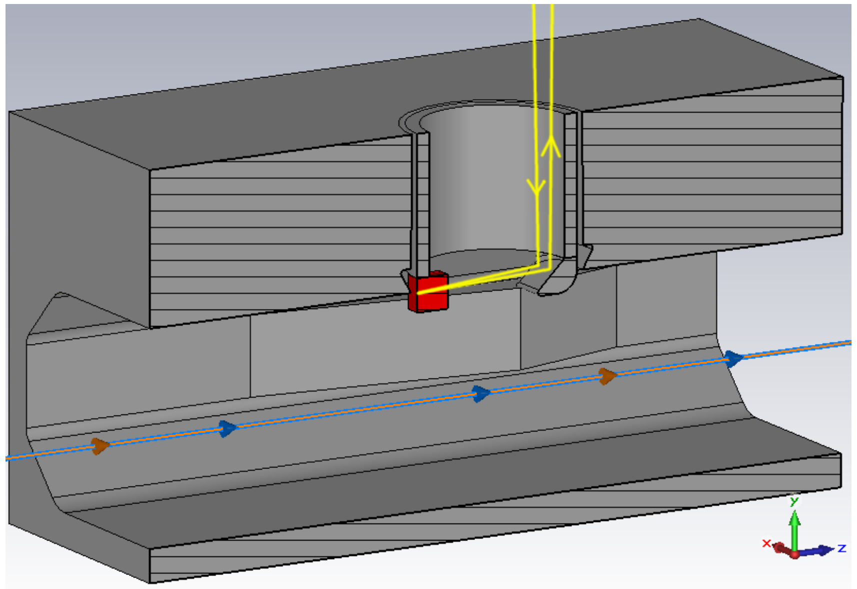
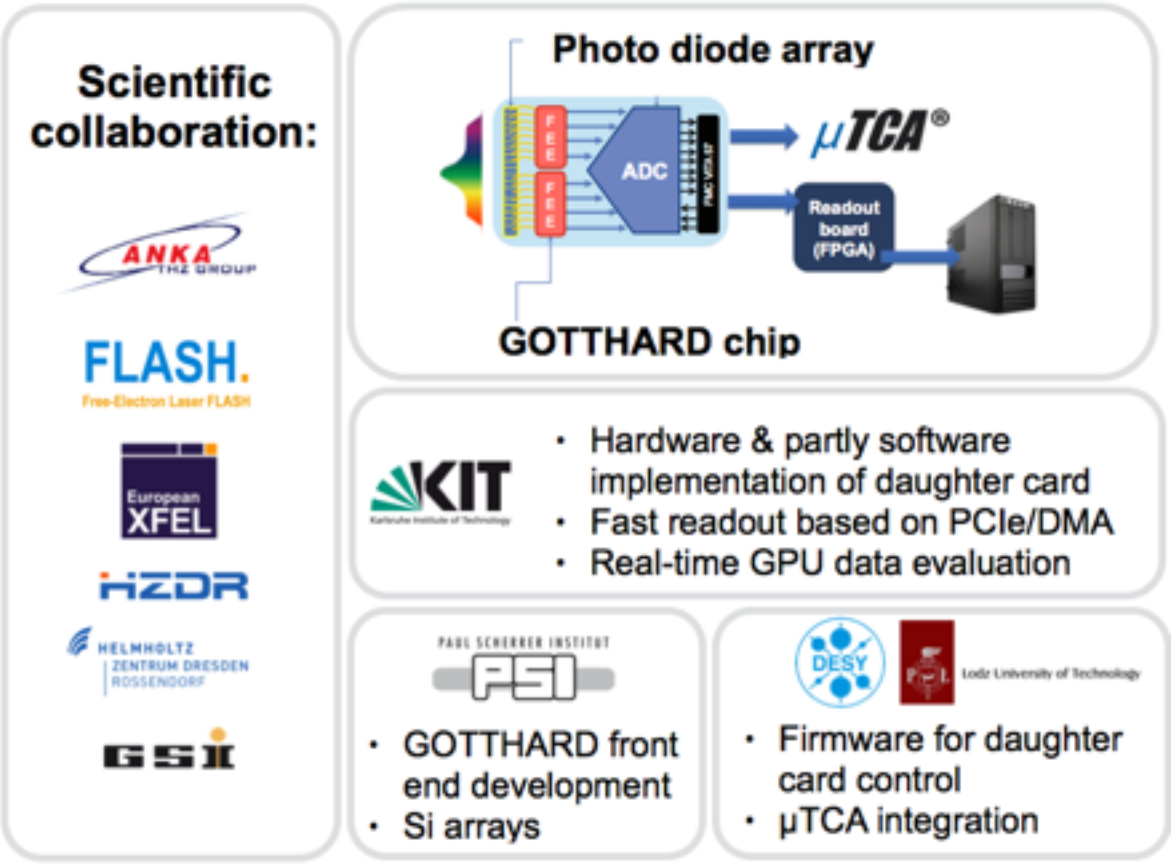
EO - Upgrades at ANKA

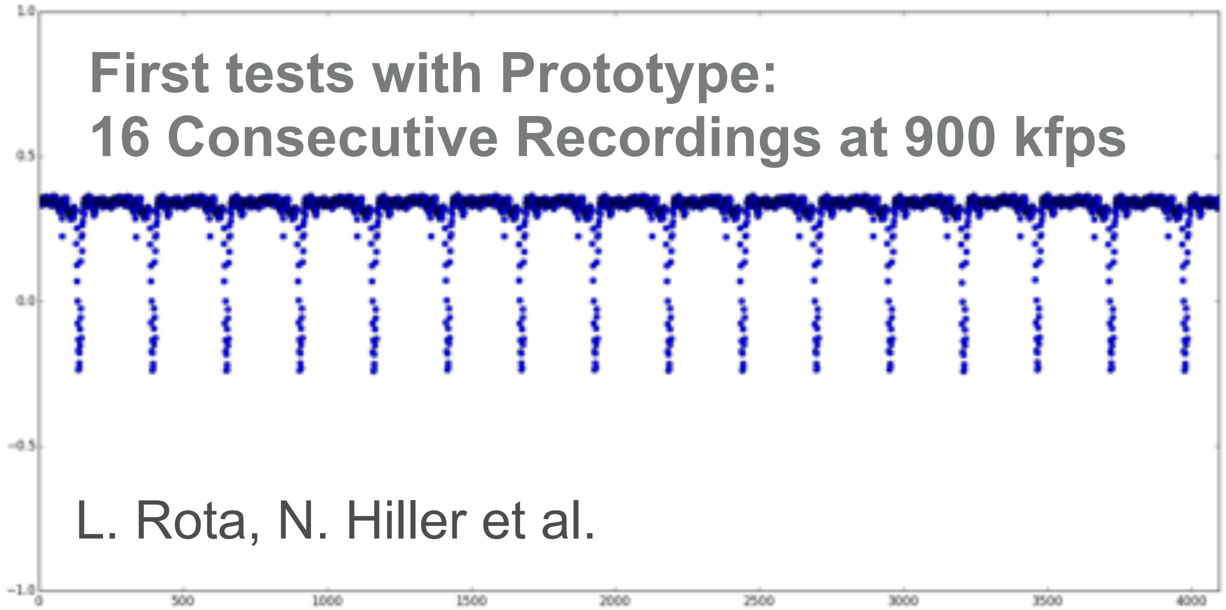
- Studies to reduce the effects of wake-fields in the vacuum chamber



P. Schönfeldt et al., IPAC2015 MOPHA038

- Ultra-fast linear detector array with MHz rep. rate
  Readout rate of commercial InGaAs spectrometers is limited to ~100 kHz
  Aim: 2.7 MHz (XFEL 5 MHz)
  Applications: turn-by-turn long. & transv. profiles

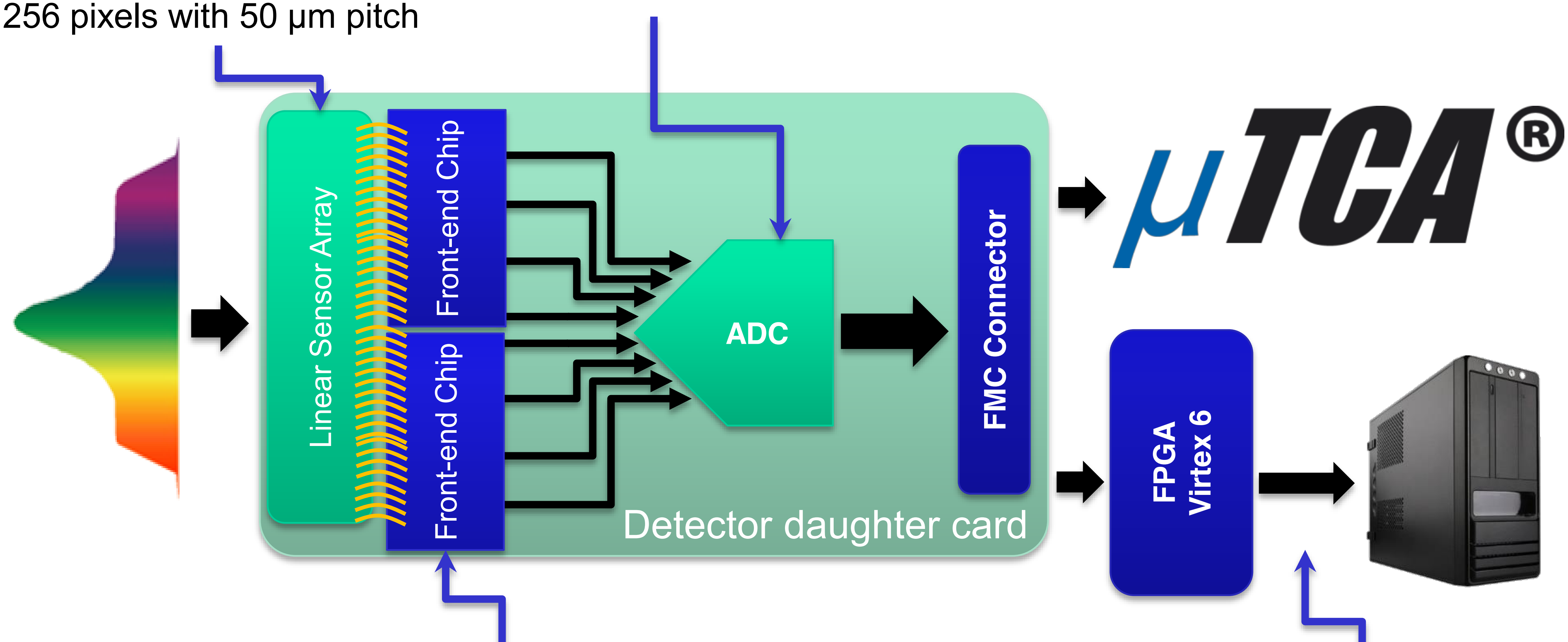




Setup - Version 1: 900 kfps (2015, now)

InGaAs (Xenics) / Si (PSI):
256 pixels with 50 µm pitch

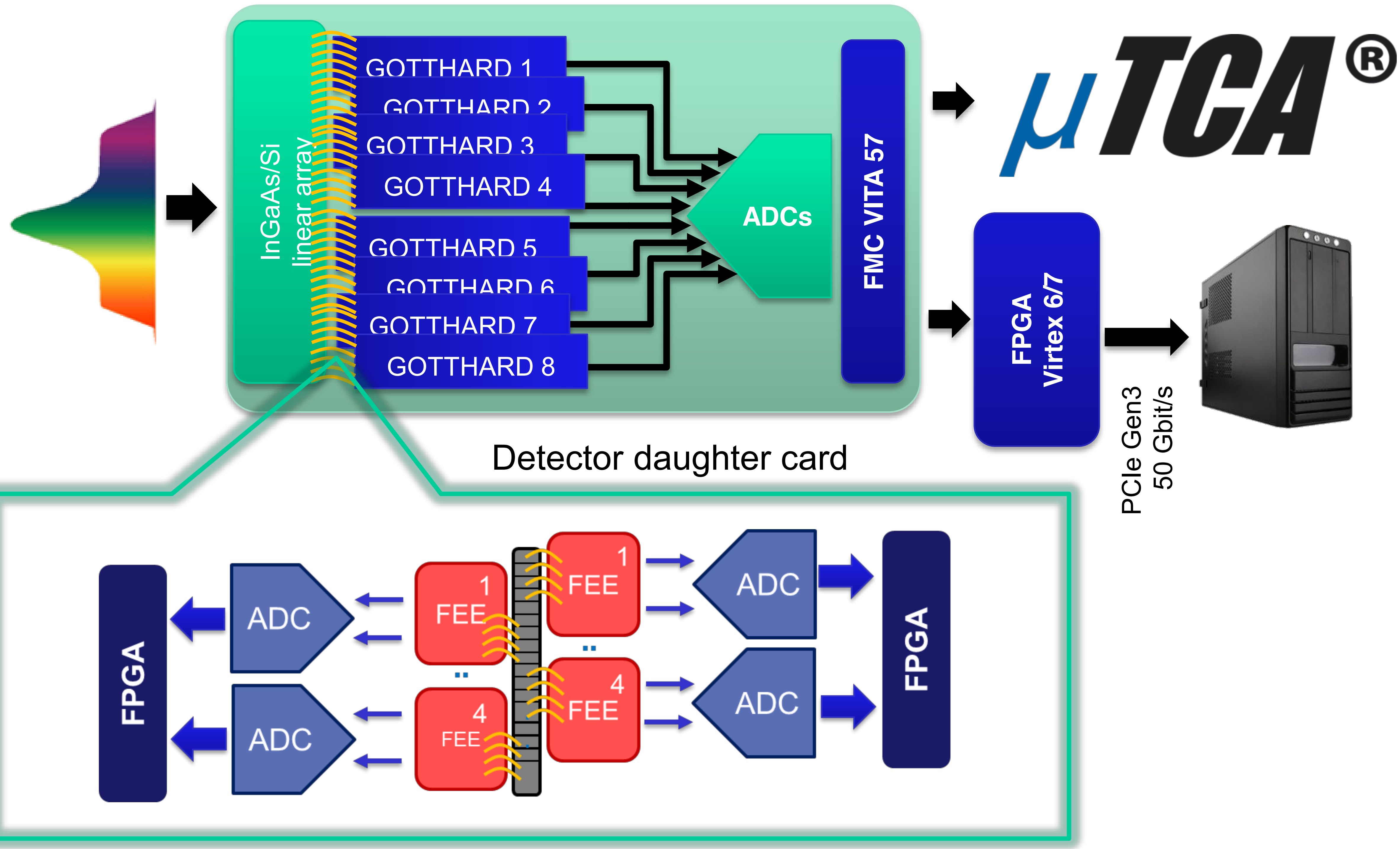
ADC9252: 8 channels @ 14-bit, 50 MSPS



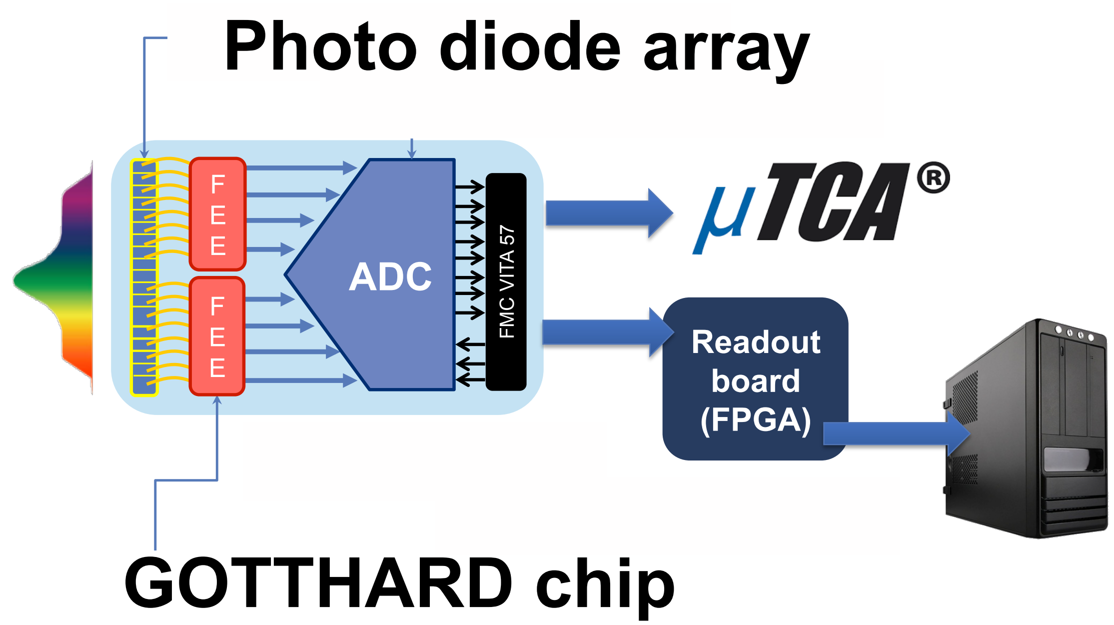
GOTTHARD chip (PSI) v1.4:
Gain **O**ptimizing microsT**r**ip sys**T**em wit**H** **A**nalog **R**ea**D**out
Charge Integrating readout for XFEL strip-detector - IBM 0.13um
128 inputs, 4 analog outputs operating at 32 MHz
Max. read-out rate: 1 Mfps

Fast KIT-DAQ:
Based on PCIe/DMA

Setup - Version 2: 5 Mfps (2015/2016)



Ultra-Fast Line Array Collaboration



Scientific collaboration:

ANKA THz GROUP

FLASH. Free-Electron Laser FLASH

European XFEL

HZDR

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

GSI

KIT Karlsruhe Institute of Technology

- Hardware & partly software implementation of daughter card
- Fast readout based on PCIe/DMA
- Real-time GPU data evaluation

PAUL SCHERRER INSTITUT PSI

- GOTTHARD front end development
- Si arrays

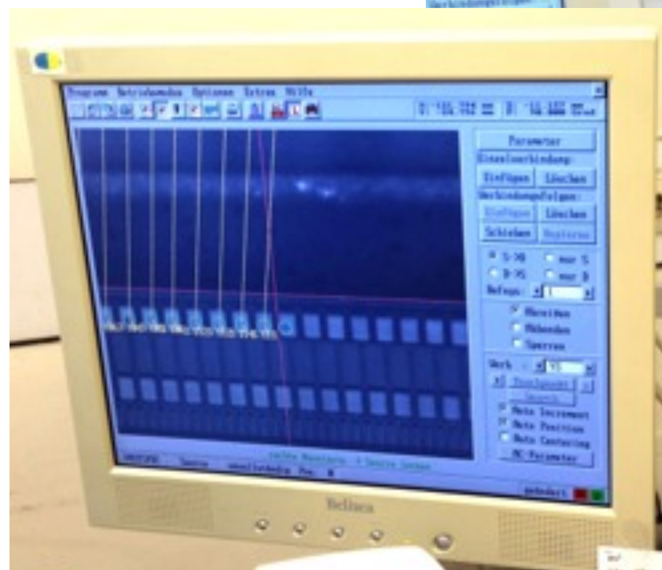
DESY

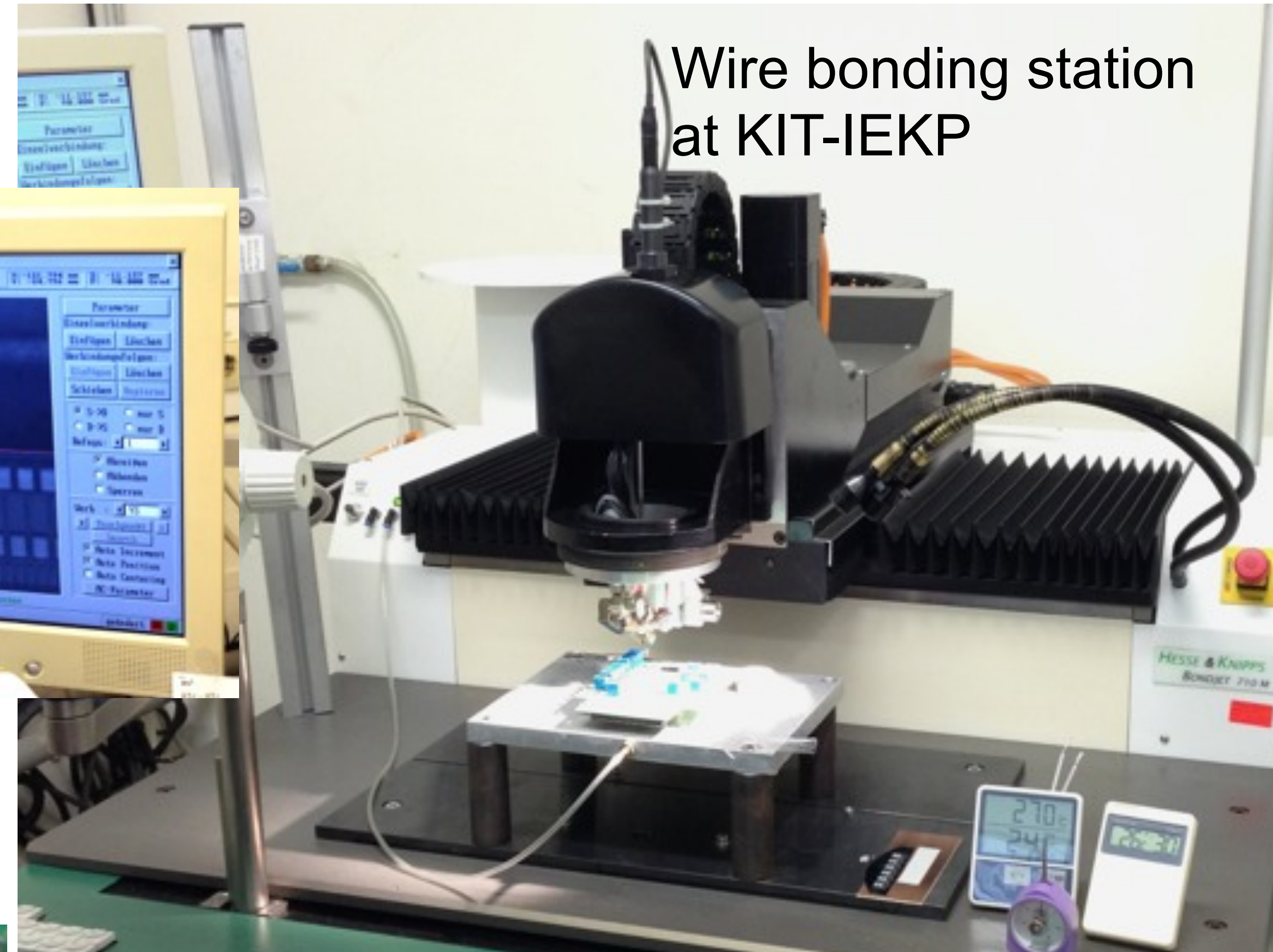
Lodz University of Technology

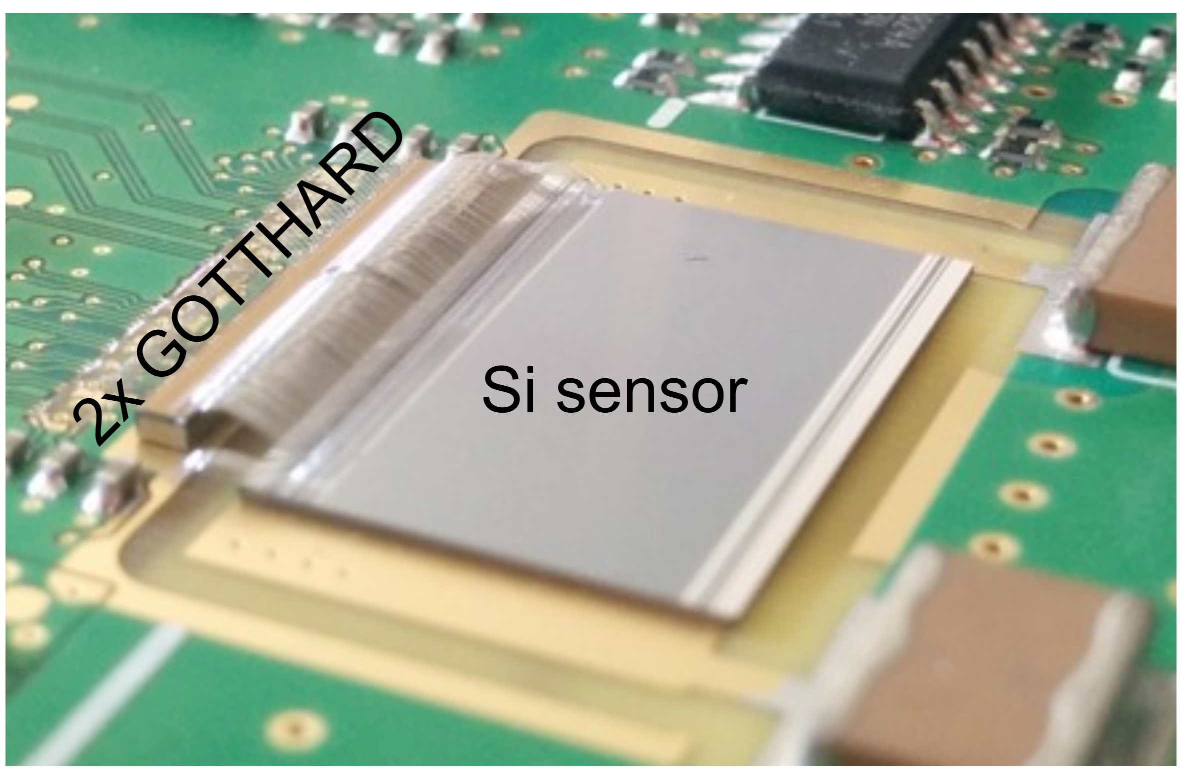
- Firmware for daughter card control
- µTCA integration

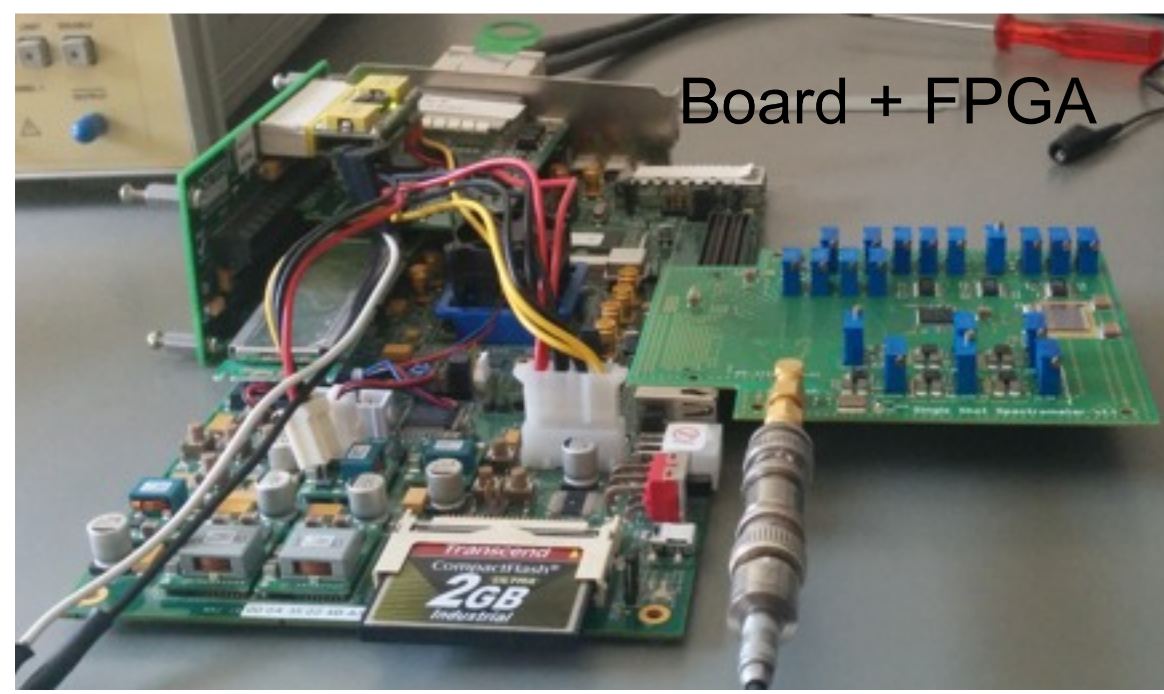
In-House Hybrid Assembly

- In-House glueing & wire-bonding at KIT 29th May 2015
- First bonded the Si sensor, InGaAs will follow now



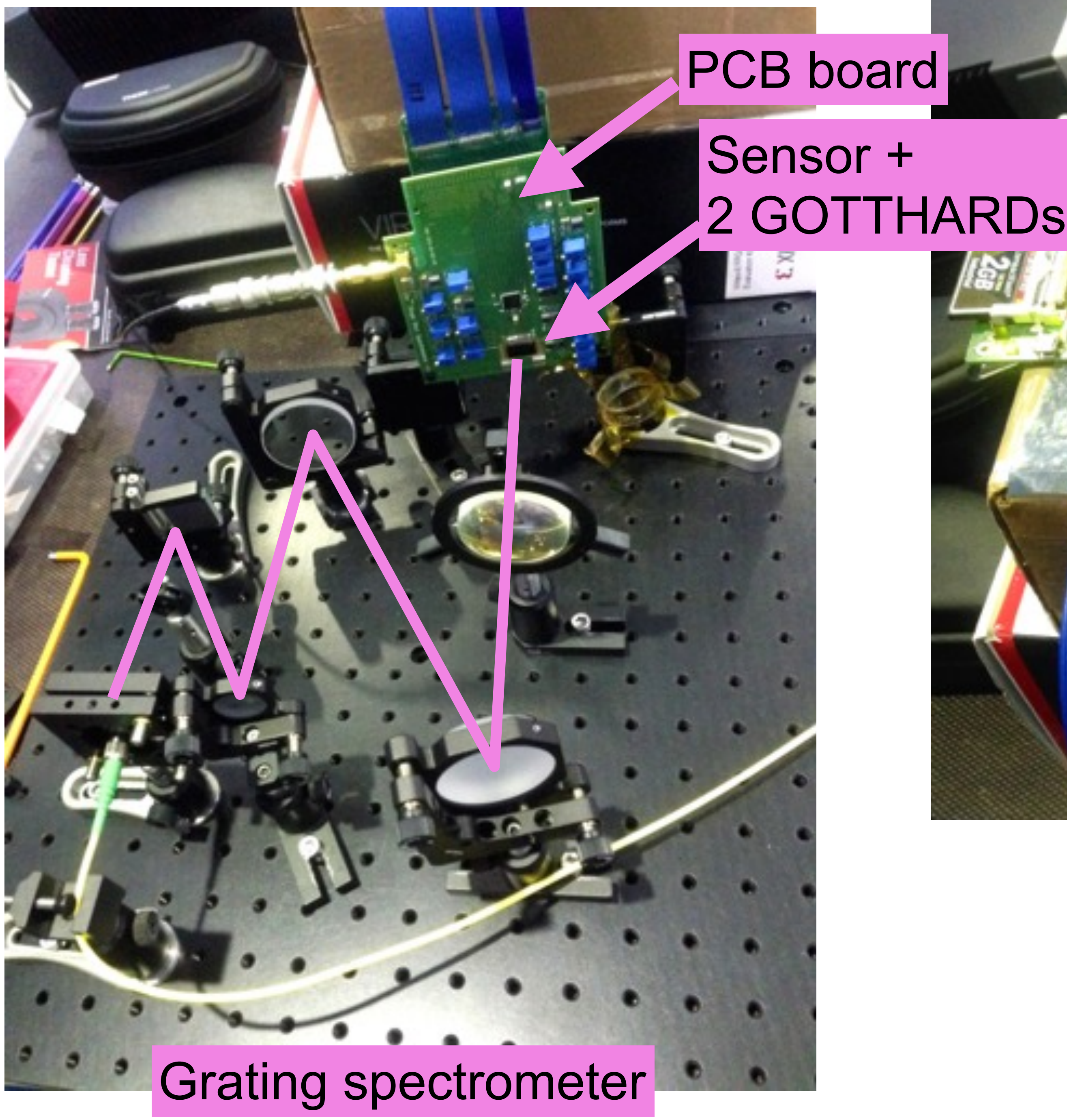


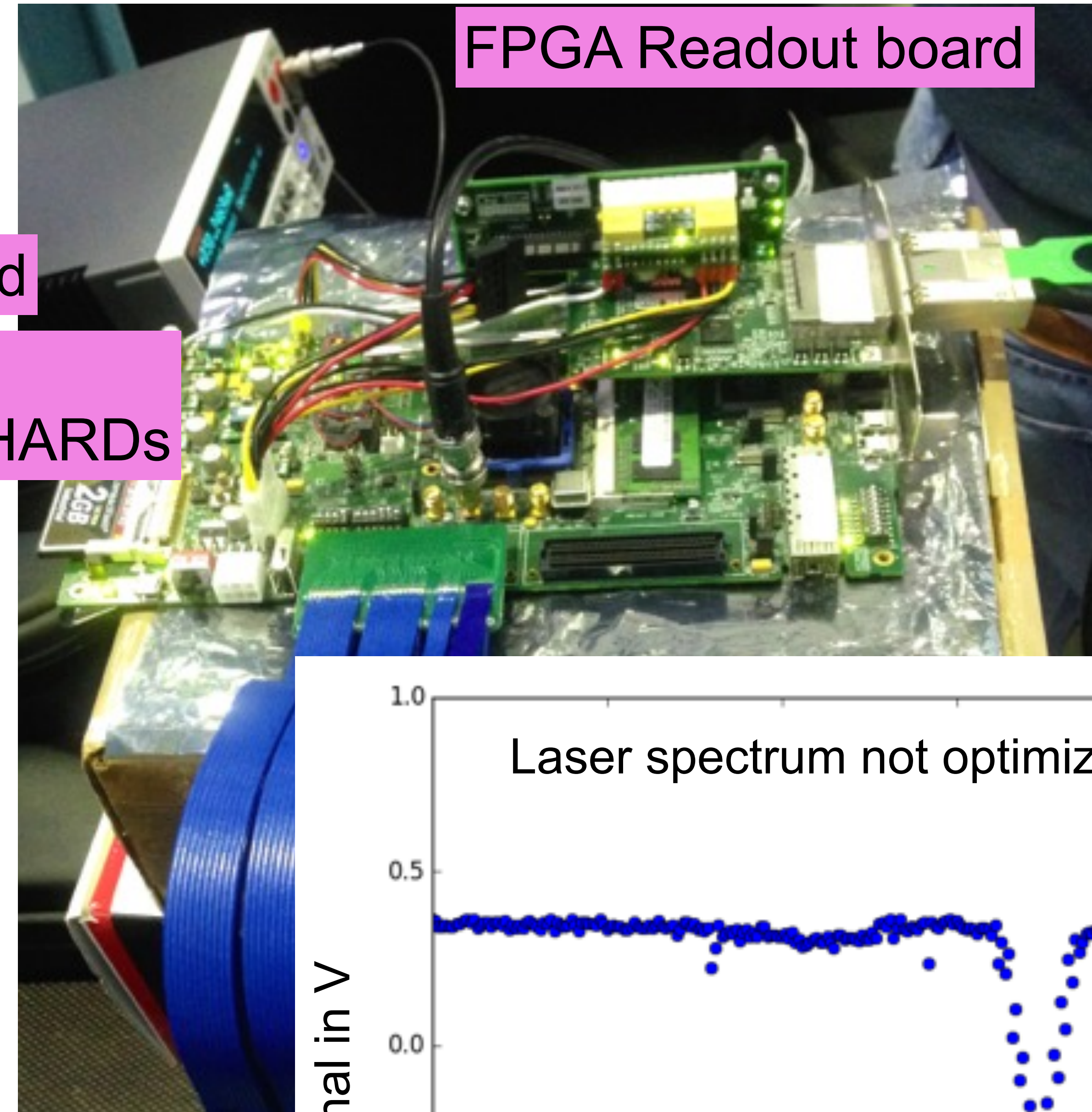


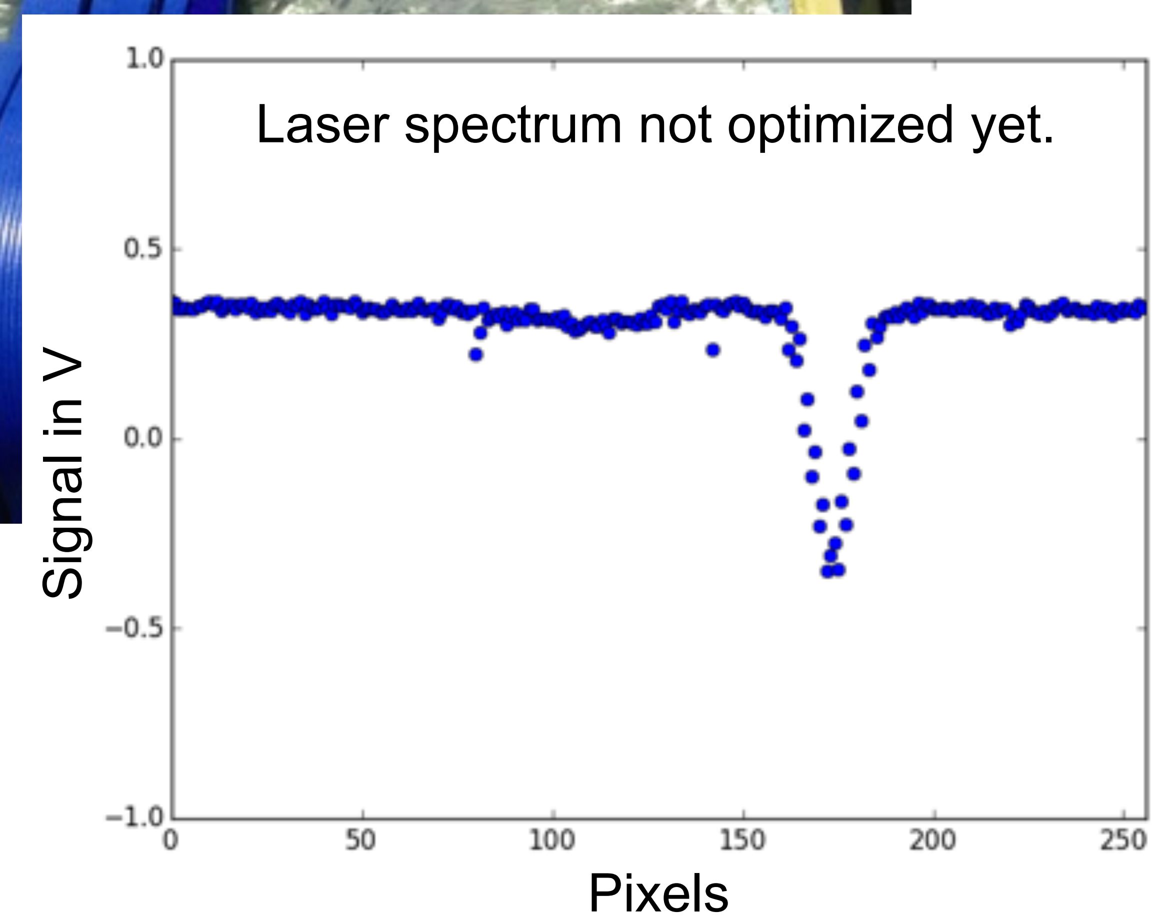


First tests with the Prototype & Laser

- 10th June 2015

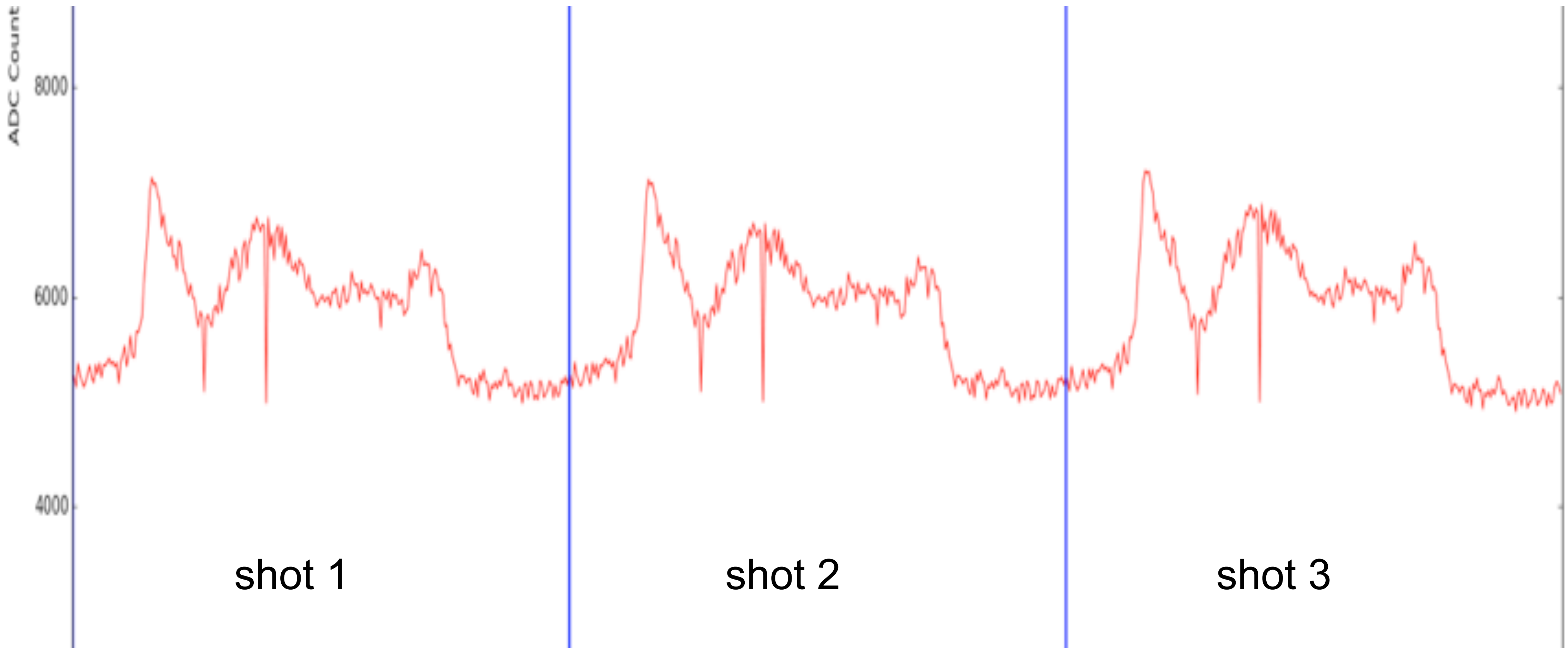






Three consecutive laser spectra

- Last week: laser spectrum with InGaAs sensor for 3 consecutive laser shots, recorded at 900 kfps.

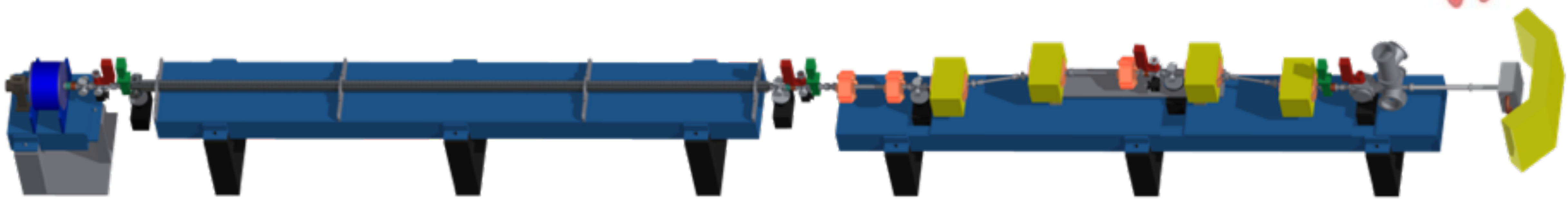


L. Rota, N. Hiller et al.

- EO spectral decoding with 900 kfps now possible!

FLUTE: Accelerator test facility at KIT

- FLUTE (Ferninfrarot Linac- Und Test-Experiment)
  - Test facility for **accelerator physics within ARD**
  - **Experiments** with THz radiation



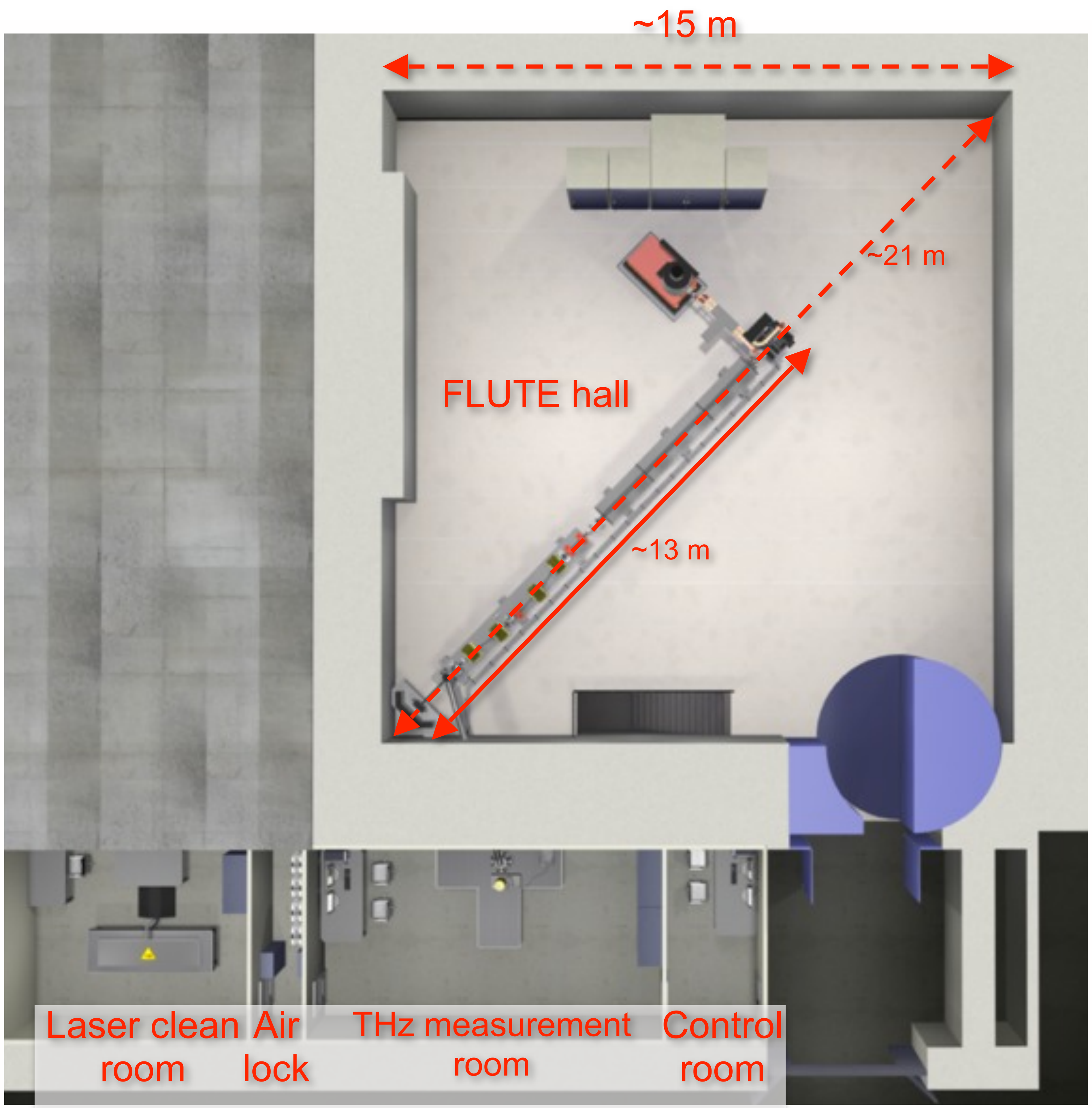
- Serve as a test bench for new beam diagnostic methods and tools
- Develop single shot fs diagnostics
- Synchronization on a femtosecond level
- Systematic bunch compression studies
- Generate intense THz radiation
- Compare different coherent THz radiation generation schemes in simulation and experiment

Final electron energy	~ 41	MeV
Electron bunch charge	0.001 - 3	nC
Electron bunch length	1 - 300	fs
Pulse repetition rate	10	Hz
THz E-Field strength	up to 1.2	GV/m

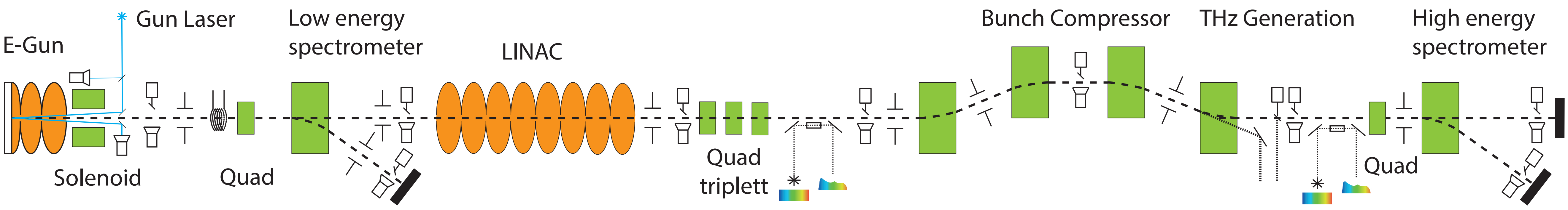
M. Nasse et al. , Rev. Sci. Instrum. 84, 022705 (2013)

FLUTE Layout & Hardware

- Civil engineering finished
- Gun laser operational
  - Transport system in planning
  - Laser sync in preparation
- RF system in assembly
  - Klystron and waveguide delivered
  - New linac module
  - LLRF system shipped from DESY
- Magnets in progress
  - Solenoid on test bench
  - Dipole design studies



Diagnostics



- **Large dynamic range:**
  - **Charge: 1 pC - 3 nC**
  - **Energy: 7 - 42 MeV**
  - **Bunch length: 2-3 ps (after gun), few fs (after chicane)**
  - **Transverse bunch size: 20 µm - 4 mm**
- Charge, position, size:
  - Integrating current transformer
  - Faraday cup
  - 7-8 cavity BPMs (XFEL, SwissFEL)
  - 6 movable screens (PSI)
- Energy:
  - 2 spectrometers (7 & 42 MeV)
- Bunch length:
  - 2 electro-optical monitors (PSI / DESY)
- Laser-Diagnostic:
  - Virtual cathode
  - Cathode imaging
  - Auto-Correlator / Grennouille
- THz-Diagnostic:
  - Fast THz-detectors (e.g. HEB, Schottky Diodes)
  - Martin-Puplett interferometer
  - Michelson interferometer
  - Electro-optical methods (far-field)

N. Hiller, B. Smit

Summary

- A large variety of technologies, methods and competences are available for accelerator R&D at KIT

- Accelerator technologies under development include, e.g.
  - superconducting insertion devices
  - ultra-fast radiation detectors from the X-ray to the THz regime
  - high data-throughput data acquisition systems for beam diagnostics with MHz repetition rates

- Accelerator test facilities
  - 2.5 GeV electron storage ring (ANKA)
  - 50 MeV fs linear electron accelerator (FLUTE)

- Open for new ideas/cooperations