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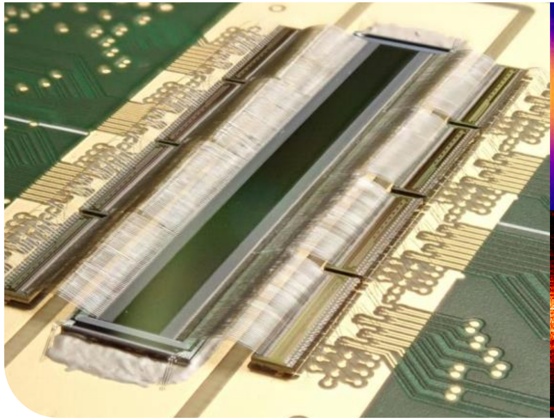
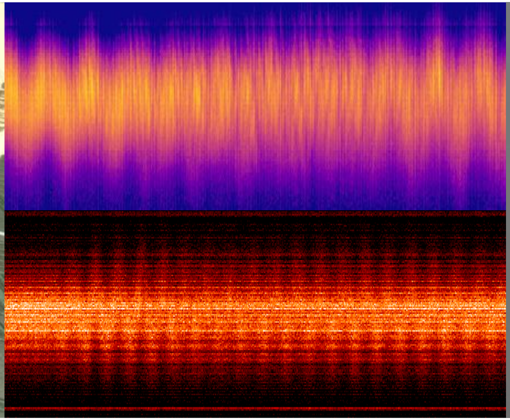
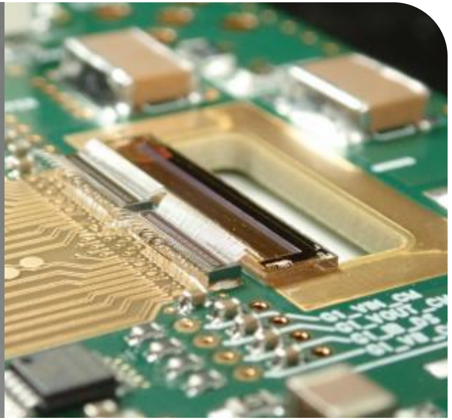
Ultra-fast line-camera KALYPSO for fs-laser based electron beam diagnostics

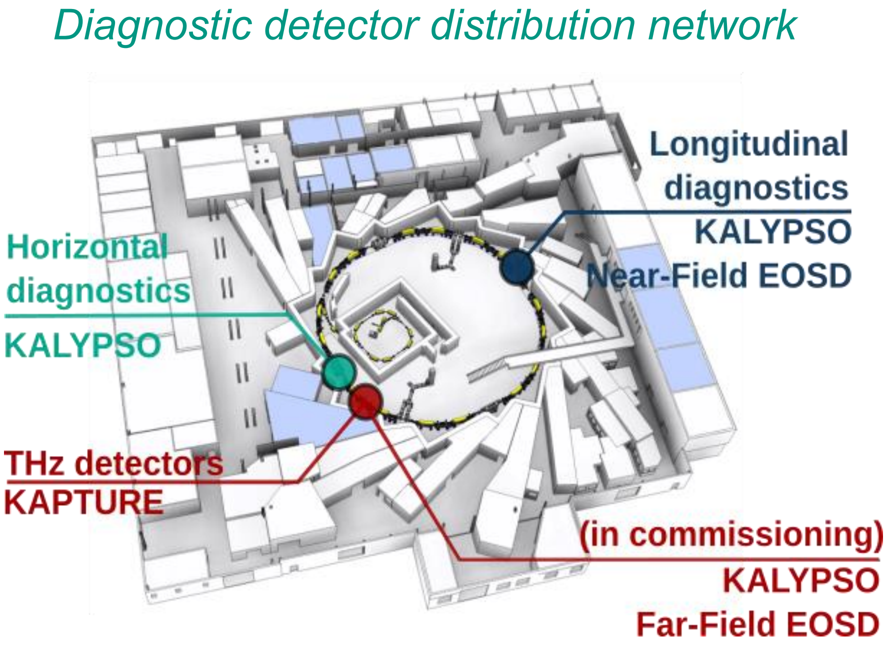
M. M. Patil*, M. Caselle, G. Niehues, E. Bründermann, A. Ebersoldt, S. Funkner, A. Kopmann, M. J. Nasse, M. Reißig, J. Steinmann, C. Widmann, T. Dritschler, S. A. Chilingaryan, M. Weber and A. -S. Müller

***meghana.patil@kit.edu**



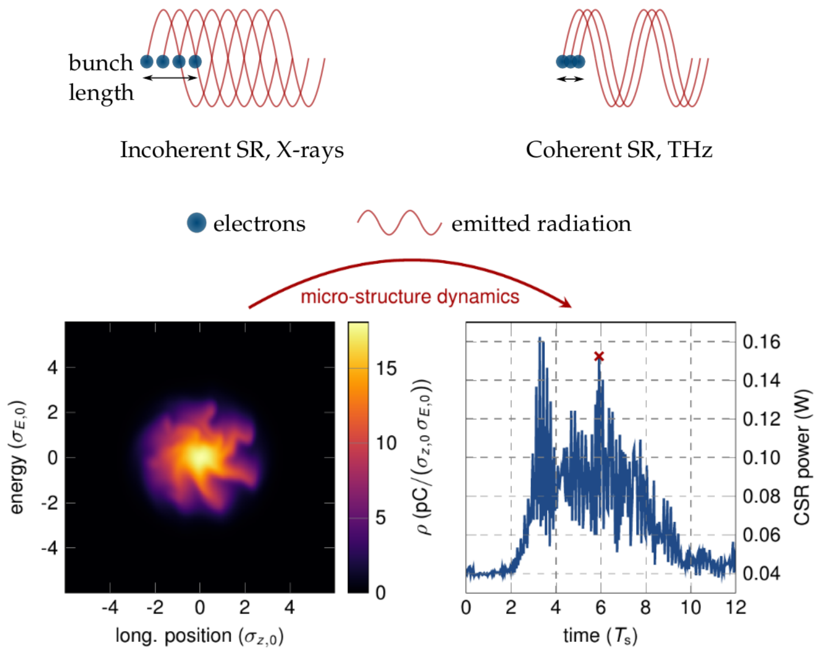
Karlsruhe Research Accelerator – KARA



- Accelerator test facility and synchrotron light source at KIT
- Circumference: 110.4 m
- Energy range: 500 MeV - 2.5 GeV
- Bunch spacing: 2 ns (500 MHz)
- Regular short bunch operation: low α_c
- Studies of micro-bunching instability

Micro-bunching Instability at KARA

- Operation mode: low α_c(momentum compation factor)
- Bunch length reduced to a few ps
  - emission of coherent synchrotron radiation (CSR) in the THz regime
- Self-interaction between the emitted radiation and the electrons
  - Sub-structures in the longitudinal density profile (micro-bunching)
- Necessary to resolve for stable THz emission



Ts synchrotron oscillation period of 6 - 10 kHz

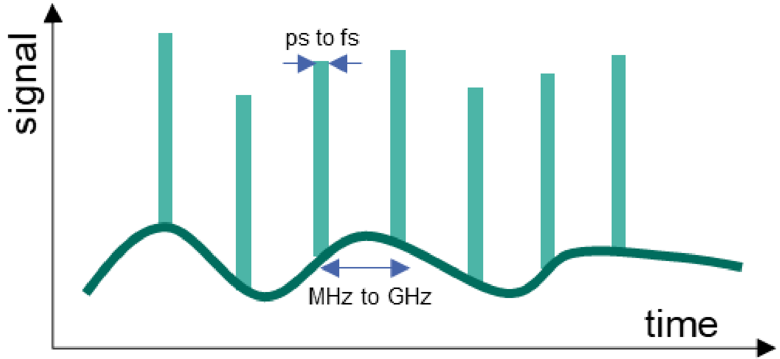
Image Courtesy of Tobias Boltz (KIT)

Why ultra-fast diagnostics?

To understand complex beam dynamics occuring in short time scales, fast real-time measurements are essential

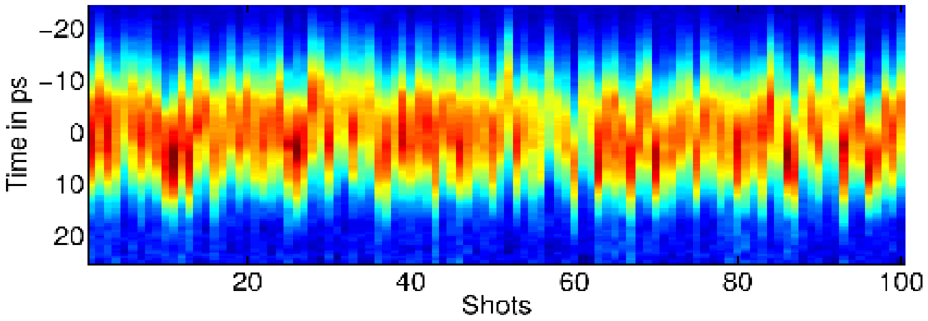
Requirements:

- Repetition rates in MHz regime and fs-ps time resolution
- High spatial resolution, broad field of view and wide spectral sensitivity
- Continous and long acquisiton time → secs to hours or days
- Synchronization



Longitudinal bunch diagnostics

- Resolve temporal shape of an electron bunch → resolution down to sub-ps is necessary
- Measuring the synchrotron radiation → translate temporal to spatial/spectral information
  - Streak camera
  - Photonic time stretch
- Measuring the Coloumb field →Non- destructive techniques to measure single shot bunch profile: Electro Optical Spectral Decoding (EOSD)



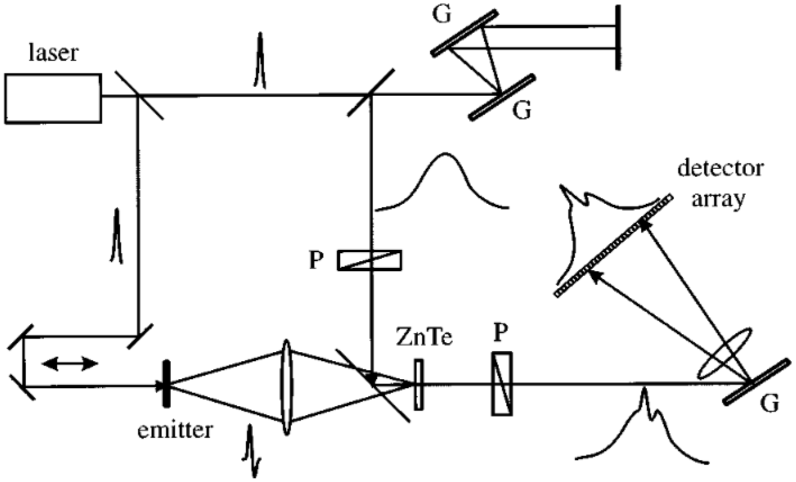
Longitudinal bunch profile measurements recorded with a commercial line scan detector with acquisition rate of 7 Hz

Courtesy of Nicole Hiller

History of EO

Electro-Optic techniques - A brief history

1.



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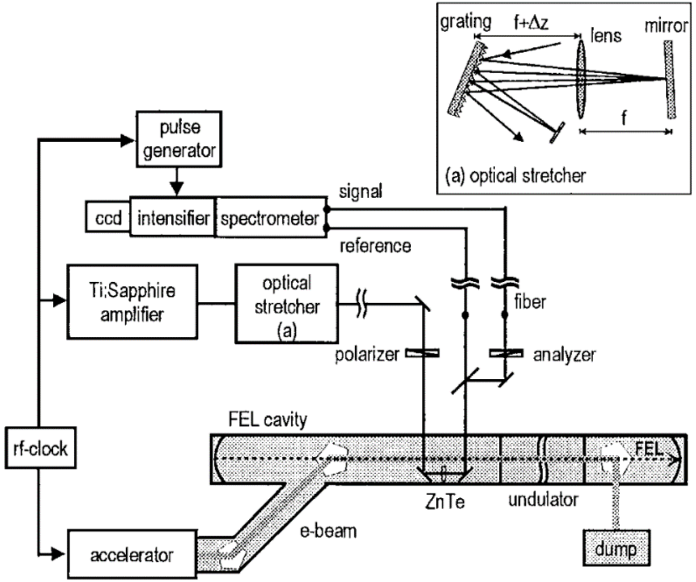

1. Zhiping Jiang and X.-C. Zhang , "Electro-optic measurement of THz field pulses with a chirped optical beam", Applied Physics Letters 72, 1945-1947 (1998) https://doi.org/10.1063/1.121231

2. Wilke I, et.al, Single-shot electron-beam bunch length measurements. Phys Rev Lett. 2002 Mar 25;88(12):124801. doi: 10.1103/PhysRevLett.88.124801. Epub 2002 Mar 6. PMID: 11909465.

Electro-Optic techniques - A brief history

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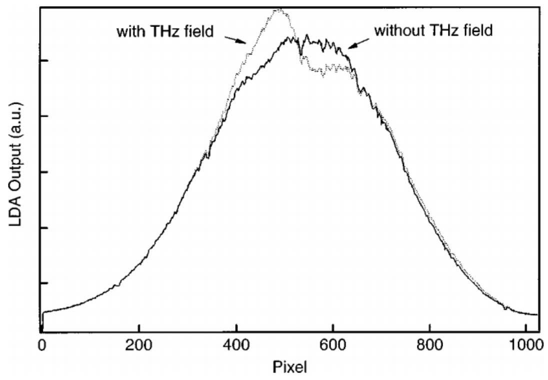


FIG. 2. Spectral distribution of the chirped probe pulse with (dashed line) and without (solid line) a co-propagating THz field pulse.

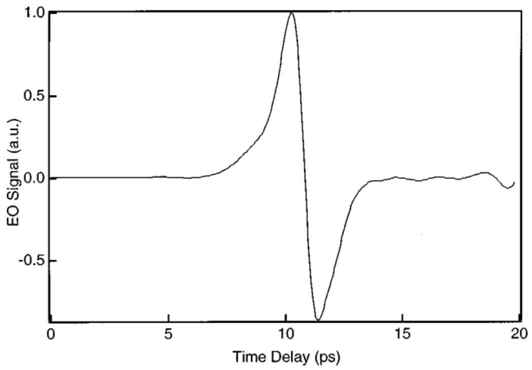
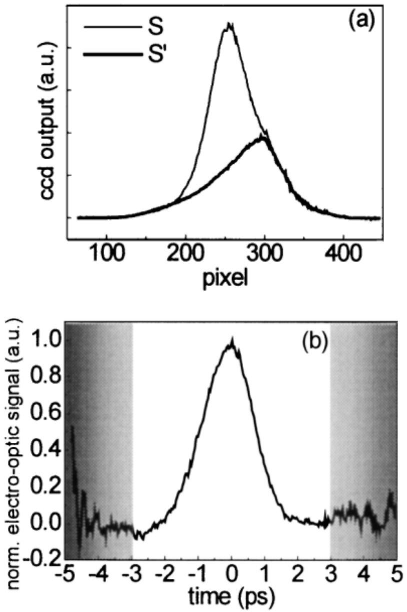


FIG. 4. Same THz signal measured by the conventional electro-optic sampling method (unchirped optical probe beam).

2.



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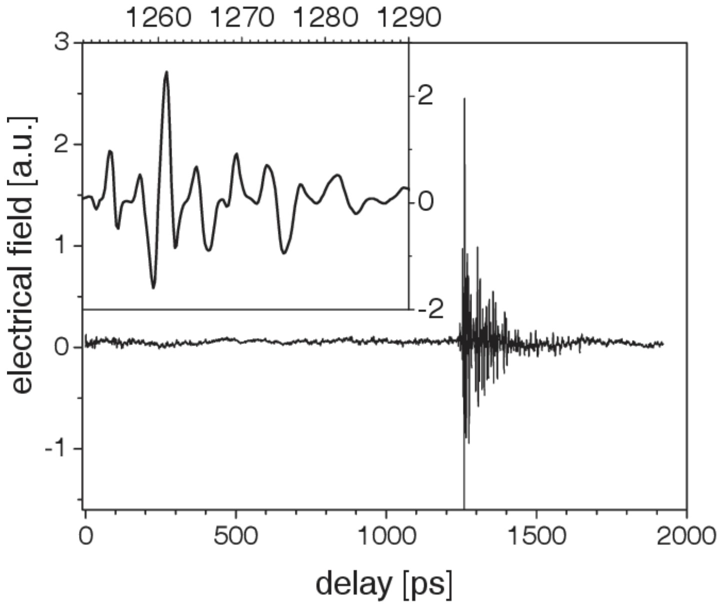
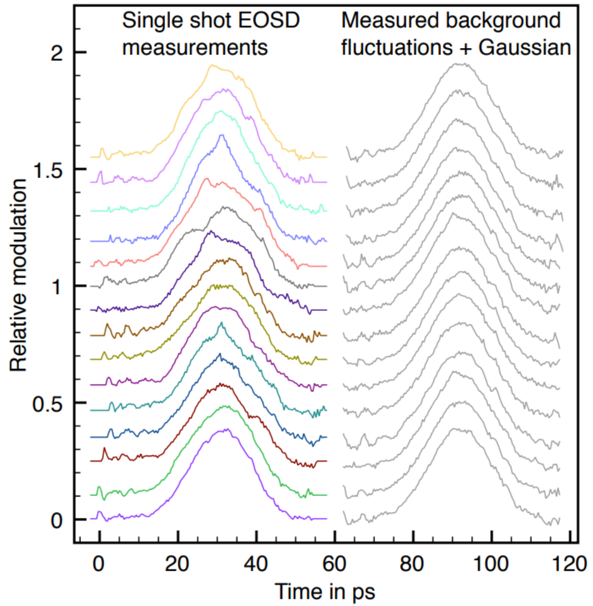
Electro-Optic techniques - A brief history

- 1982: characterize fast electrical transients
- 1998: measuring electric field of a laser generated THz pulse
- 1999 - 2002: FELIX, first EO single-shot meaurements at an accelerator
- 2001: ATF (Brookhaven National Laboratory, USA) and the Fermilab photoinjector (Fermilab, Batavia, USA)
- 2004: SLS injector linac at PSI (far-field)
- 2005: VUV-FEL , FLASH (DESY, Hamburg, Germany), SLAC linac (Menlo Park, USA)
- 2009: far-field measurements using CSR at KARA (Karlsruhe, Germany)
- 2011: far-field EOSD measurements during a femto-slicing operation at SLS, UVSOR II
- 2012: EOS measurements at ELBE at HZDR (Rossendorf, Germany)
- 2013: first single-shot near-field EOSD measurements were performed at a storage ring during low-α c - operation

Electro-Optic techniques - A brief history

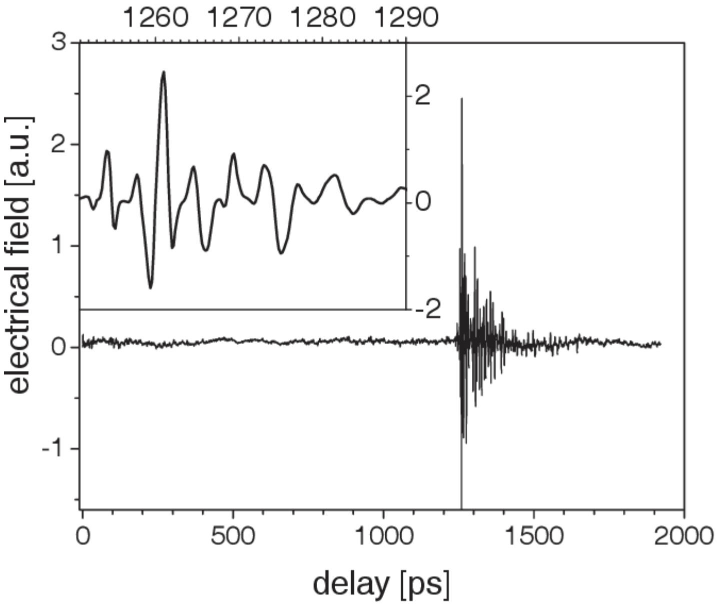


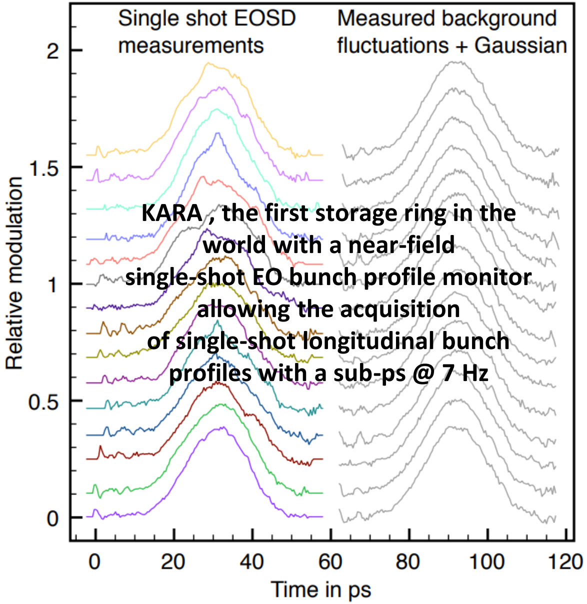


N. Hiller, et.al, “Electro-optical bunch length measurements at the ANKA storage ring”, MOPME014, IPAC’13.

A. Plech, et.al,. Electro-optical sampling of terahertz radiation emitted by short bunches in the ANKA synchrotron. In Proceedings of PAC’09, Vancouver, Canada, 2009. URL:http://accelconf.web.cern.ch/AccelConf/PAC2009/papers/tu5rfp026.pdf.

Electro-Optic techniques - A brief history





KARA , the first storage ring in the world with a near-field single-shot EO bunch profile monitor allowing the acquisition of single-shot longitudinal bunch profiles with a sub-ps @ 7 Hz

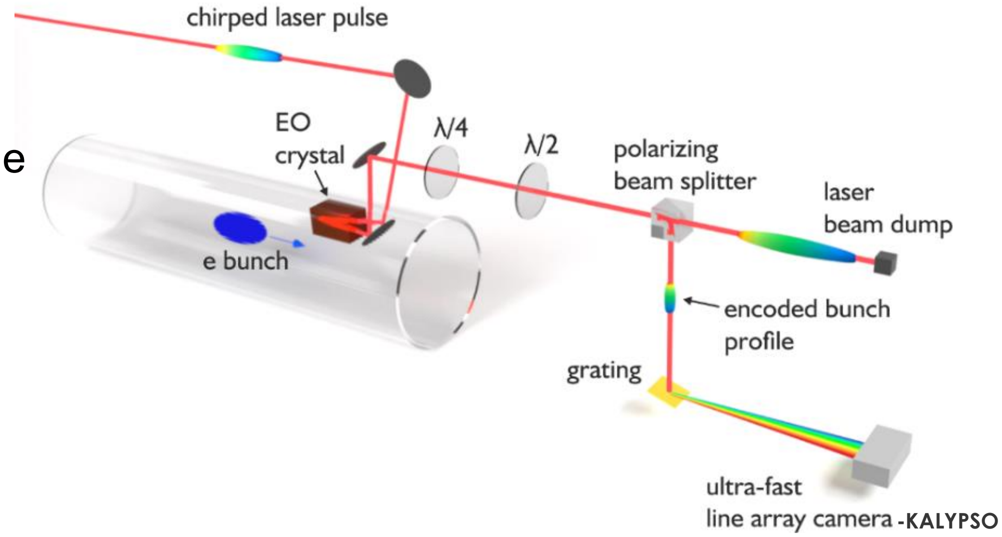
N. Hiller, et.al, "Electro-optical bunch length measurements at the ANKA storage ring", MOPME014, IPAC'13.

A. Plech, et.al,. Electro-optical sampling of terahertz radiation emitted by short bunches in the ANKA synchrotron. In Proceedings of PAC'09, Vancouver, Canada, 2009. URL:http://accelconf.web.cern.ch/AccelConf/PAC2009/papers/tu5rfp026.pdf.

EOSD at KARA

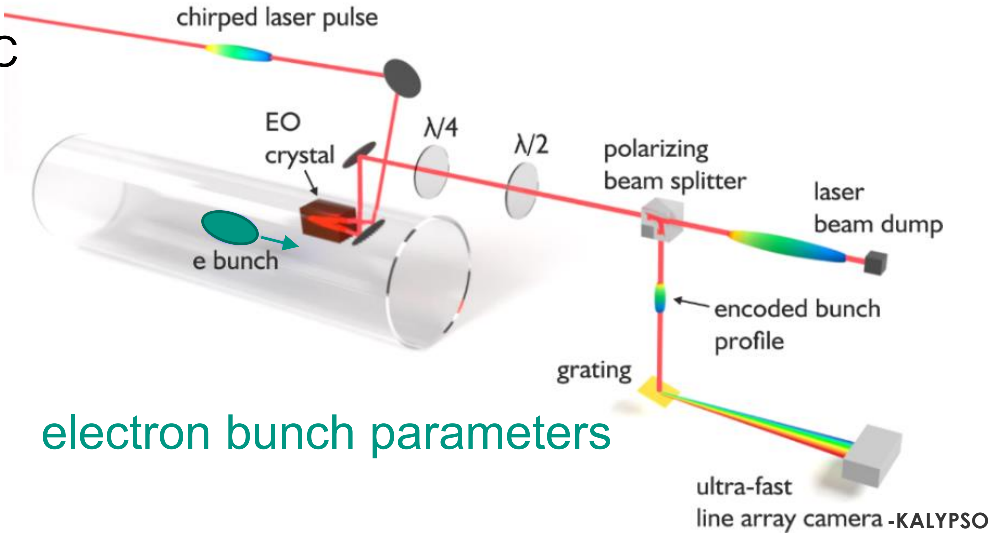
EO spectral decoding @ KARA

- Is based on Pockels effect
- Changes birefringence inside the EO crystal e.g. GaP (gallium phosphide)
- In the presence of electric field the refractive indices of the crystal become a function of the electric field
- Coloumb field or field of coherent synchrotron radiation



EO spectral decoding @ KARA

- Operation energy of 1.3 GeV, single bunch
- Bunch charges from 1000 pC to 30 pC
- Operation mode: low α_c (momentum compaction factor)
- Bunch length reduced to a few ps with dynamic sub-ps/fs sub-structures



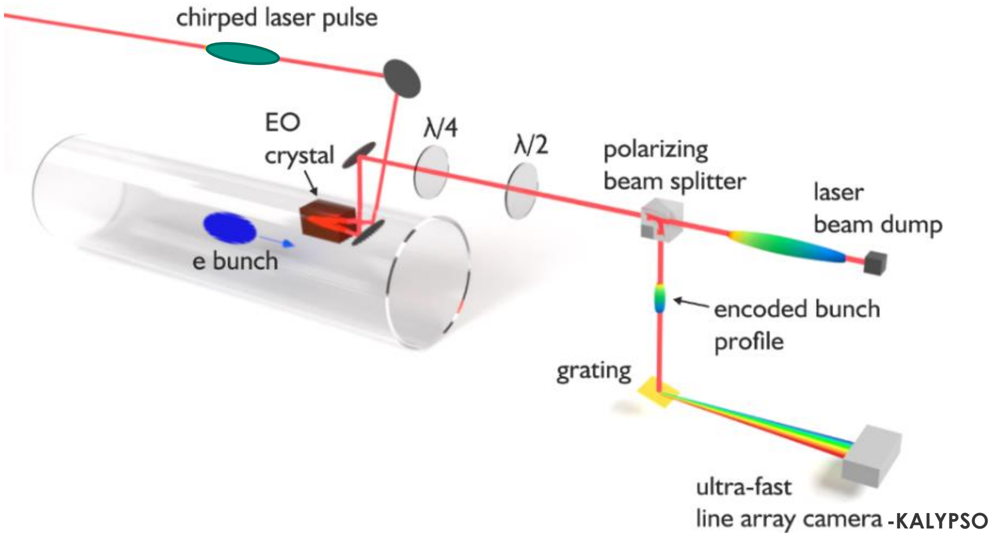
electron bunch parameters

EO spectral decoding @ KARA

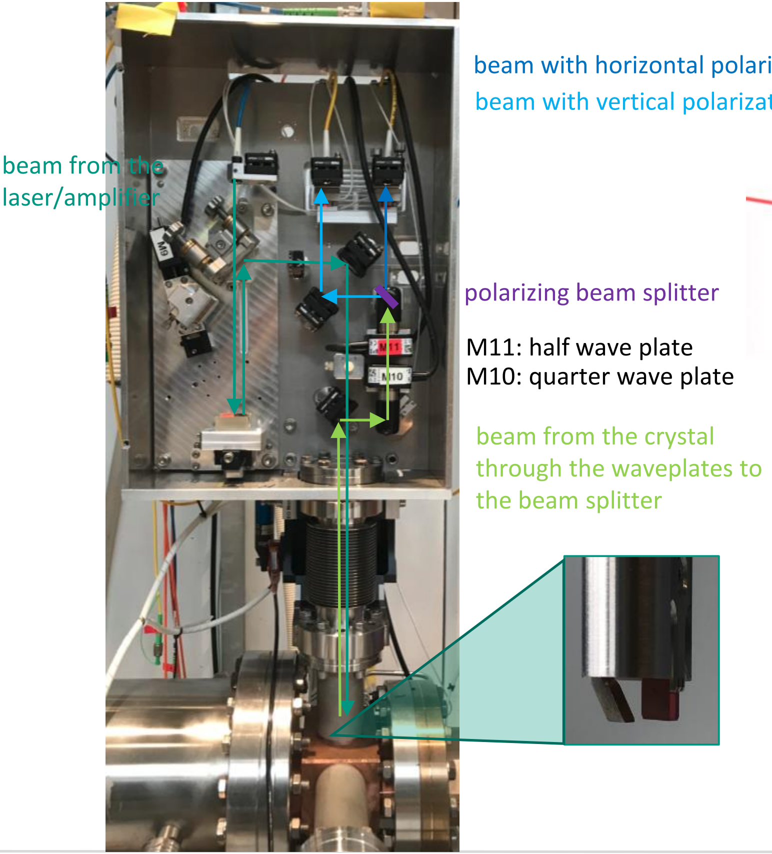
- Self built ytterbium-doped fiber laser @ 1060 nm
- 40 nm spectral bandwidth
- Operating and synchronised to the repetition rate of the synchrotron (2.7 MHz)
- 35 m-long fiber into the ring acts like a pulse stretcher

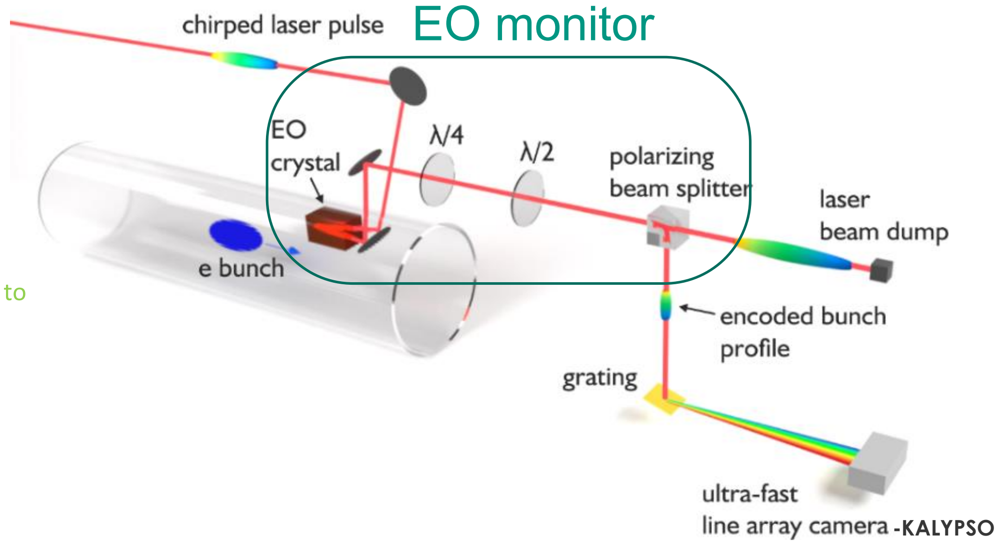
Image: S. Funkner

fs laser pulse



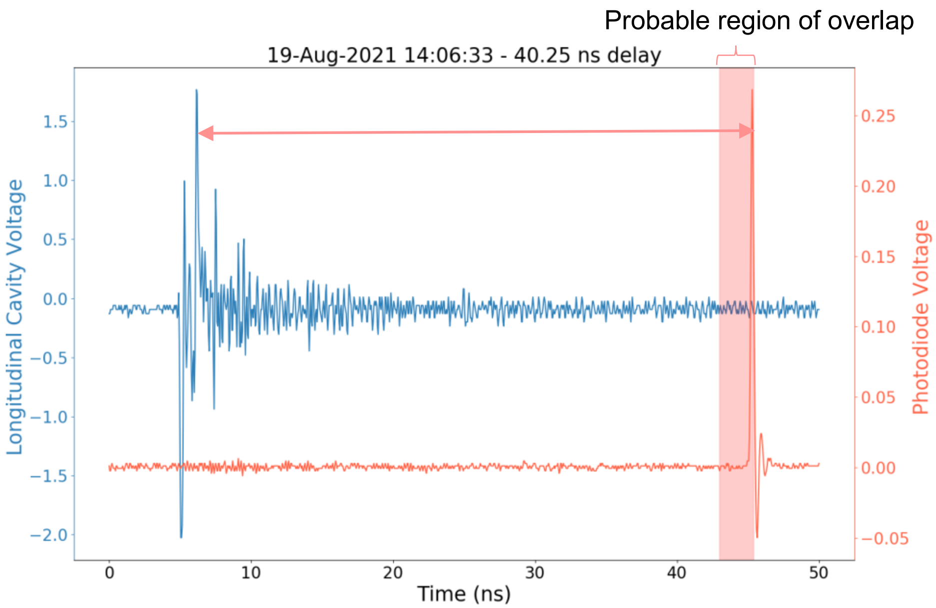
EO spectral decoding @ KARA



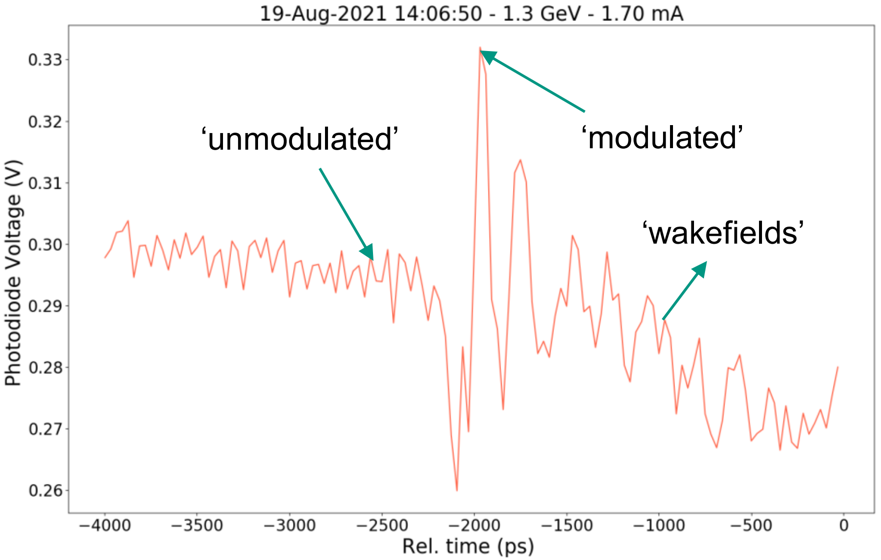


EO spectral decoding @ KARA

Finding the temporal overlap using EOS



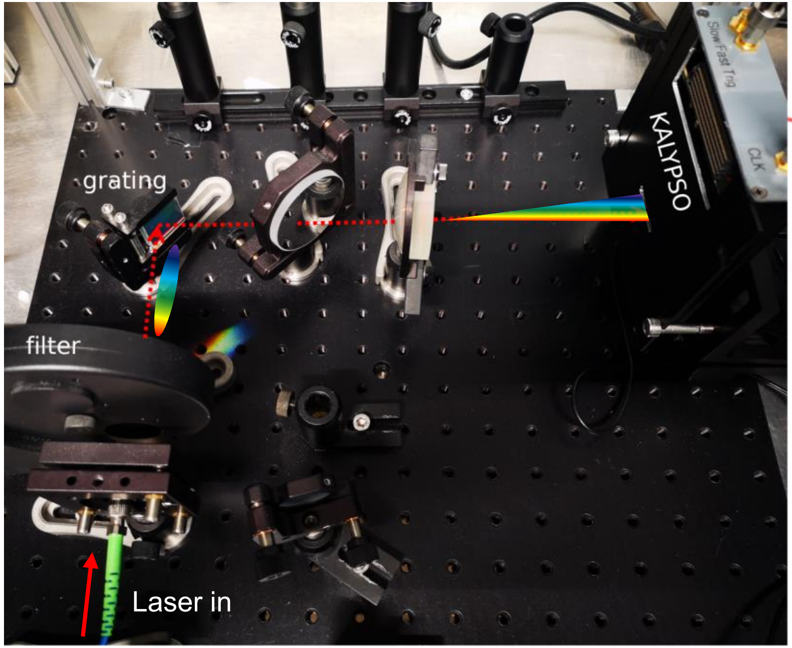
Delay scan of the laser pulse with reference to the Beam Position monitor signal

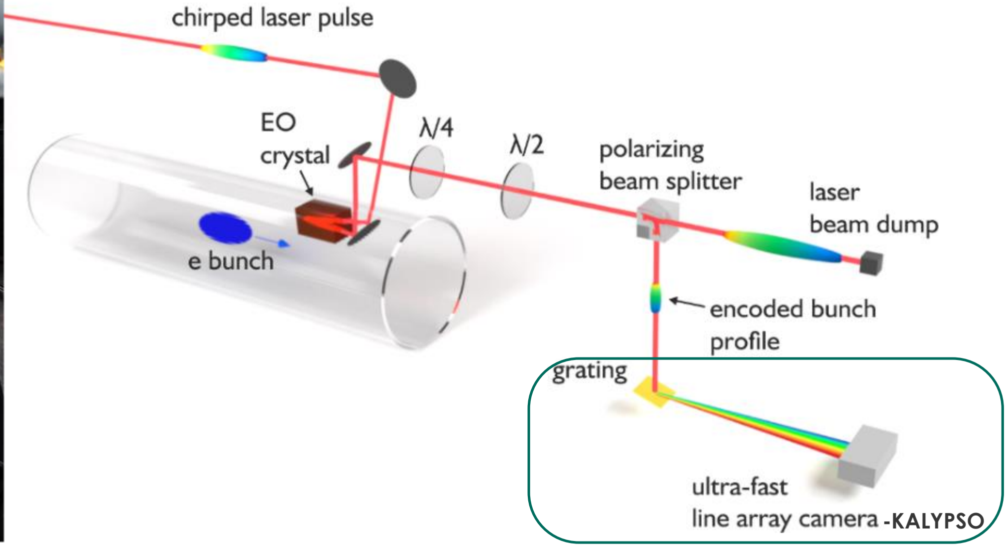


Laser pulse scan in the overlap region

EO spectral decoding @ KARA

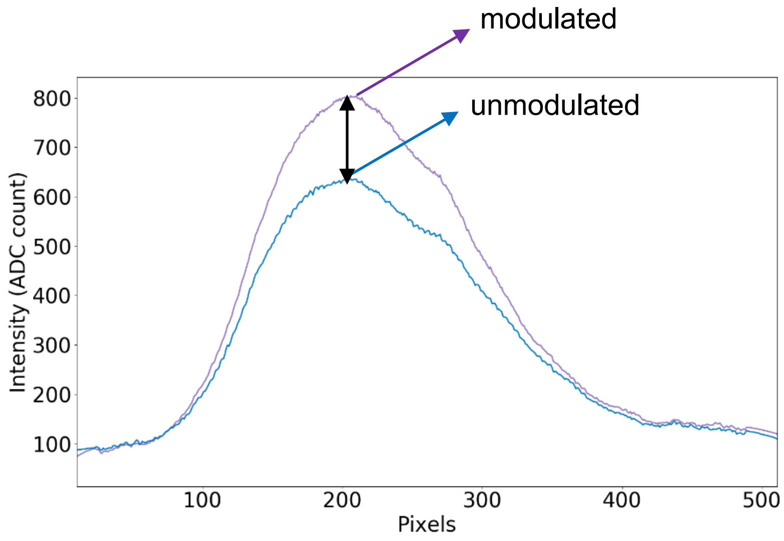
Karlsruhe Institute of Technology



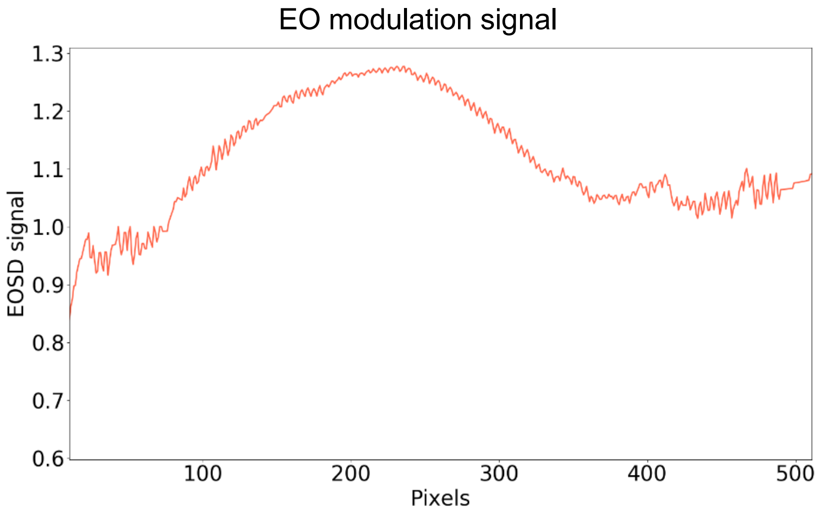


Spectrometer setup

EO spectral decoding @ KARA



Single shot spectrally decode laser pulse



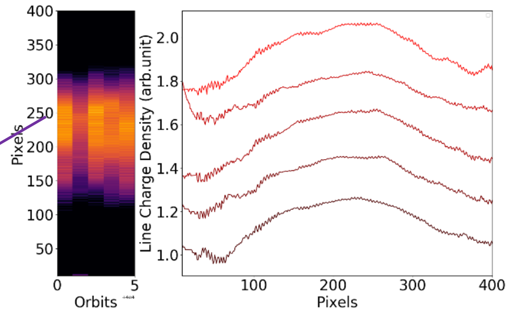
Modulation → ratio of modulated to unmodulated amplitude

$$Modulation = \frac{modulated\ (background\ subtracted)}{unmodulated\ (background\ subtracted)}$$

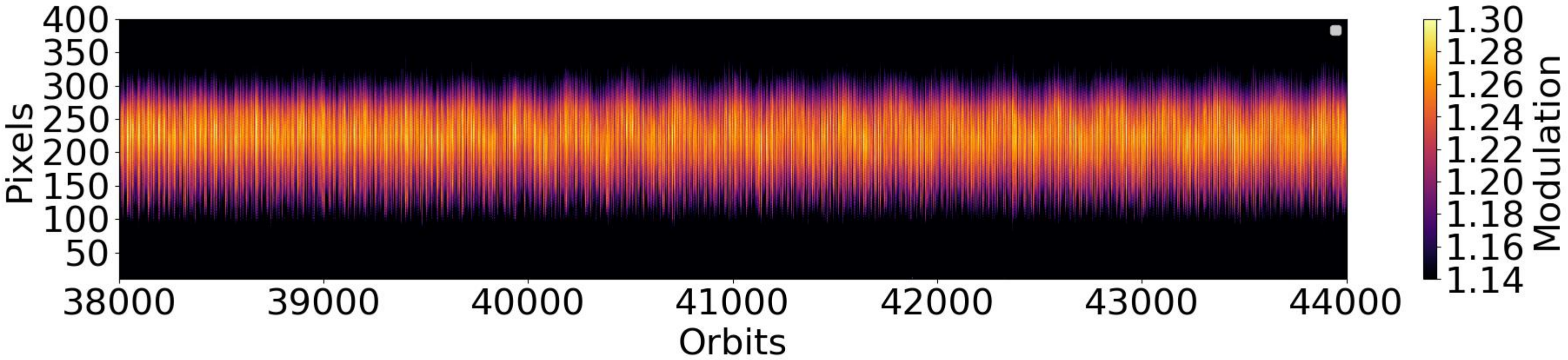
EO spectral decoding @ KARA

- Resolving electron bunch profile in every turn @ 2.7 MHz
- Capable of uninterrupted data acquisition for up to several millions of turns

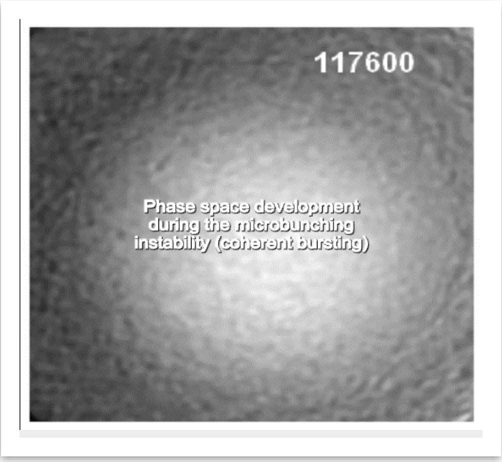
5 consecutive bunch profiles



Section of a measurement dataset acquired by KALYPSO consisting of the longitudinal bunch profile evolution of 100000 turns

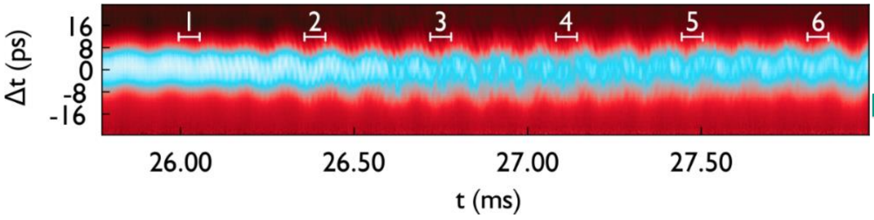


Phase space distribution reconstruction



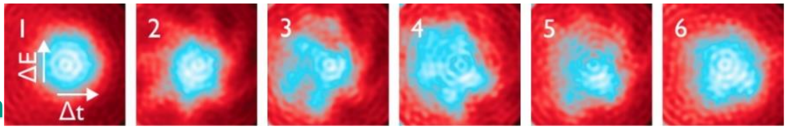
- Complete phase space image reconstructed from time interval of 61 µs
- “Randon morphing“ between independent measurement

revolution plots/ sinograms



filtered backprojection

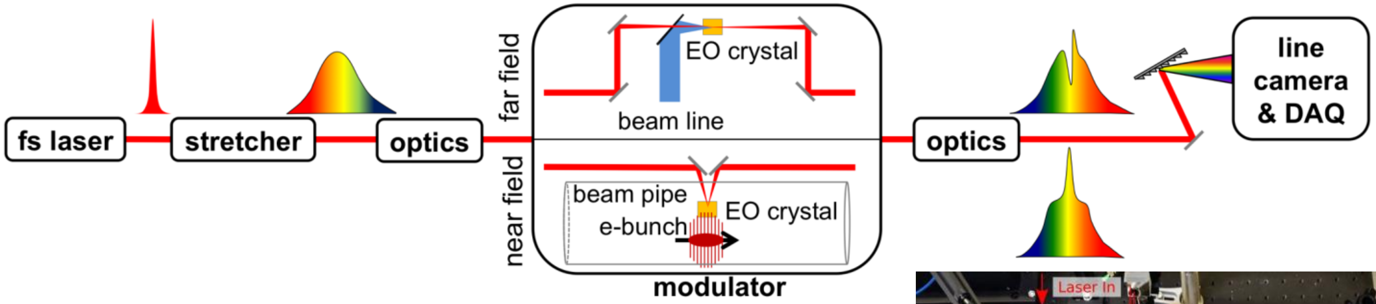
phase space density



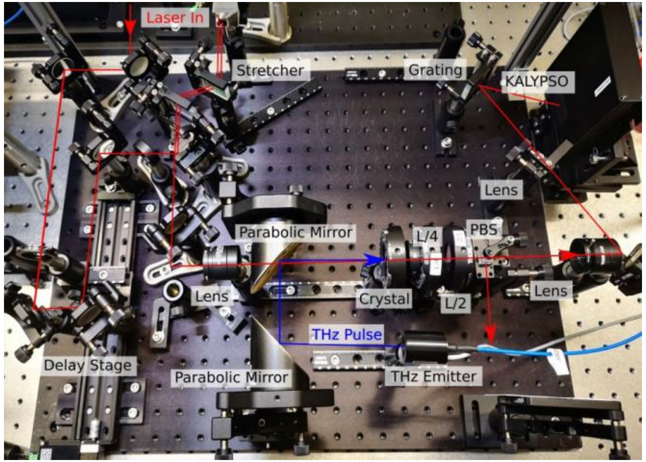
S. Funkner, et.al, arXiv preprint, arXiv:1912.01323
G. Niehues, et al., DOI:10.18429/JACoW-IPAC

Other diagnostics

More EO diagnostics: far-field EO measurements of synchrotron radiation/THz signals



- Far-field experiment under commission, current status: off-line demonstrator tests
- Measuring the complete THz pulse in single-shot

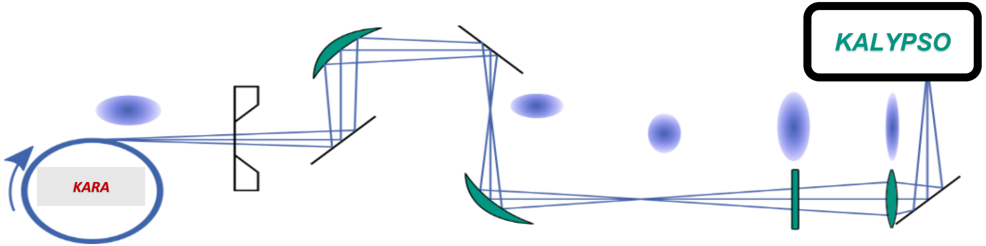


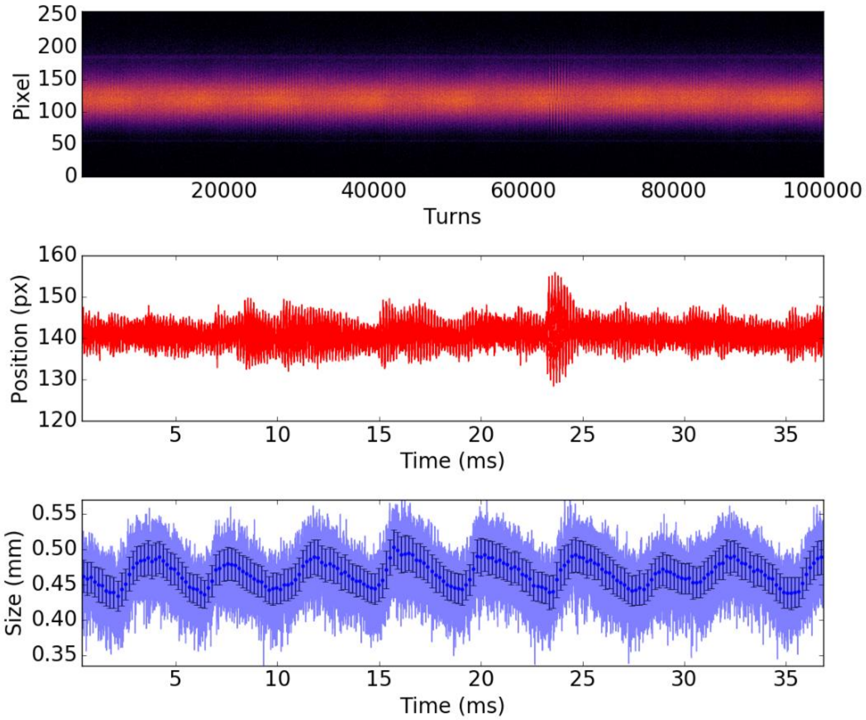
C. Widmann et al. MOPAB294, IPAC 2021.

Horizontal bunch profile measurements

- Energy spread of electron bunches is an important parameter to understand micro-bunching instability, but it cannot be measured directly
- Horizontal bunch profile measurements in a dispersive section
- Measuring emitted incoherent synchrotron radiation (> 400 nm)

$$\sigma_x = \sqrt{\beta_x \epsilon_x + (D_x \sigma_\delta)^2}$$



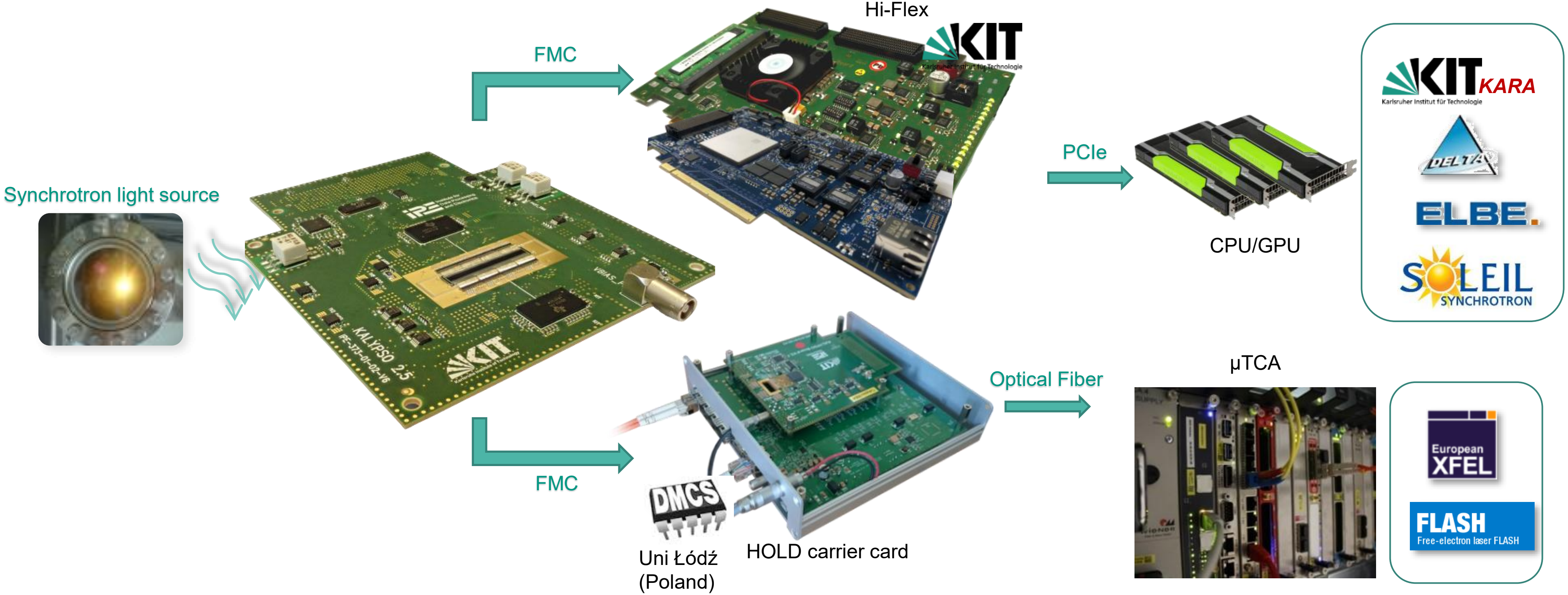


B. Kehrer, et.al, 10.1103/PhysRevAccelBeams.21.102803

KALYPSO

KALYPSO - data acquisition flow

Modular and flexible data acquisition system with data process based on heterogenous FPGA-GPU architecture

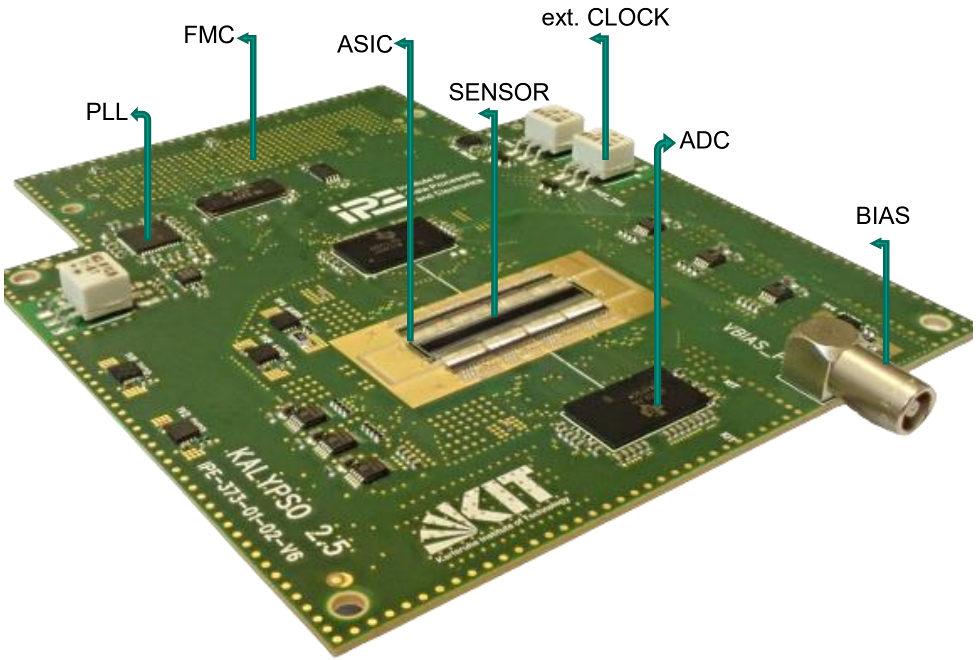


M. Caselle, et.al; doi:10.1117/12.2511341

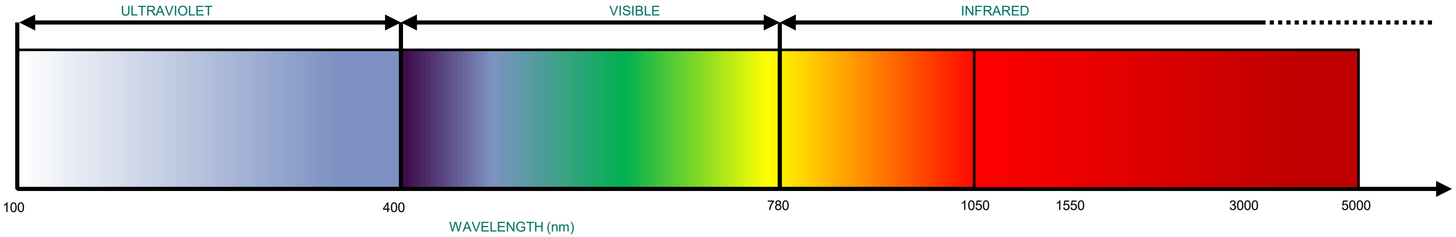
KALYPSO
(KArlsruhe Linear arraY detector for MHz rePetition rate SpectrOscopy)

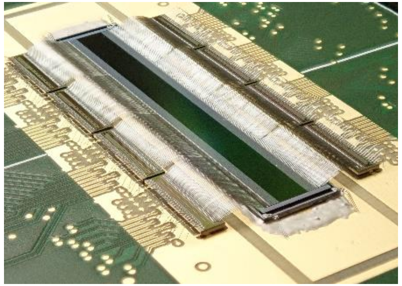
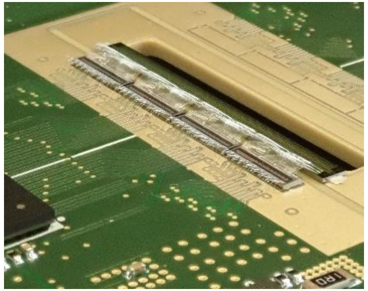
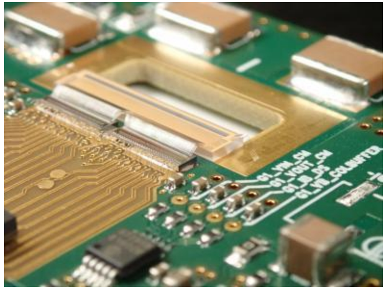
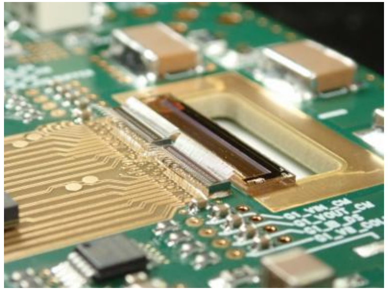
Karlsruhe Institute of Technology

- **Sensor** : Si, InGaAs, PbS, PbSe
- **ASIC – Gotthard-KIT** : Low-noise and MHz frame rate
- **ADCs** : Up to 64 parallel ADC channels each operating up to 125 MS/s
- **External clock inputs** : Synchronization to experimental setup
- **Femtosecond time jitter clock distribution** : Programmable for user applications
- **FMC Vita-57.1 connector** : Compatible with standalone and μTCA based DAQ system



Sensor Technology



350-1050 nm	950-2000 nm	1000-3300 nm	1000-5000 nm
			
Si	InGaAs	PbS	PbSe

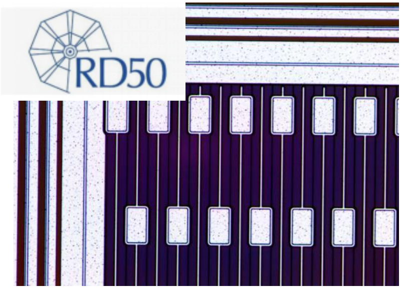
Designed @ KIT   Hamamatsu   Infrared   Trinamix

KALYPSO future developments

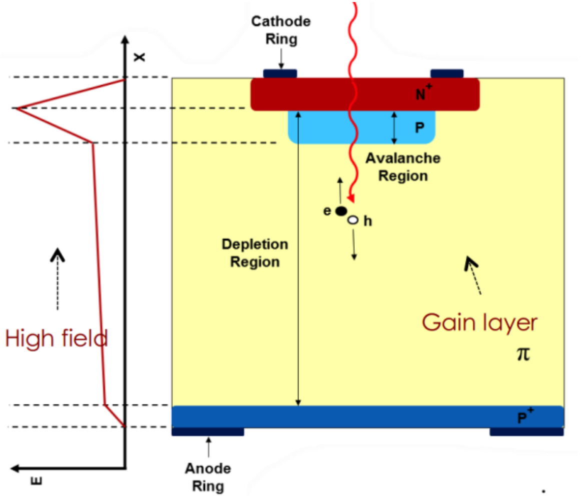
LGAD - Low Gain Avalanche Detector

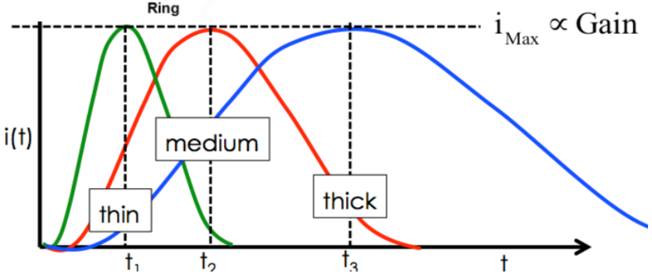
Shot-to-shot measurements of at hundreds Mfps

- Diagnostics with hundreds of MHz necessary for multi-bunch operation
- High dynamic range for low intensity incoherent synchrotron radiation



Microstrip sensors
50 × 3000 μm²



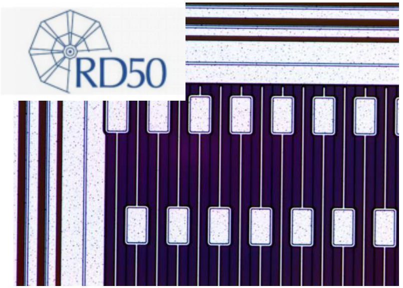


Courtesy of G. Paternoster , Giacomo Borghi (FBK) Work performed in the framework of RD50

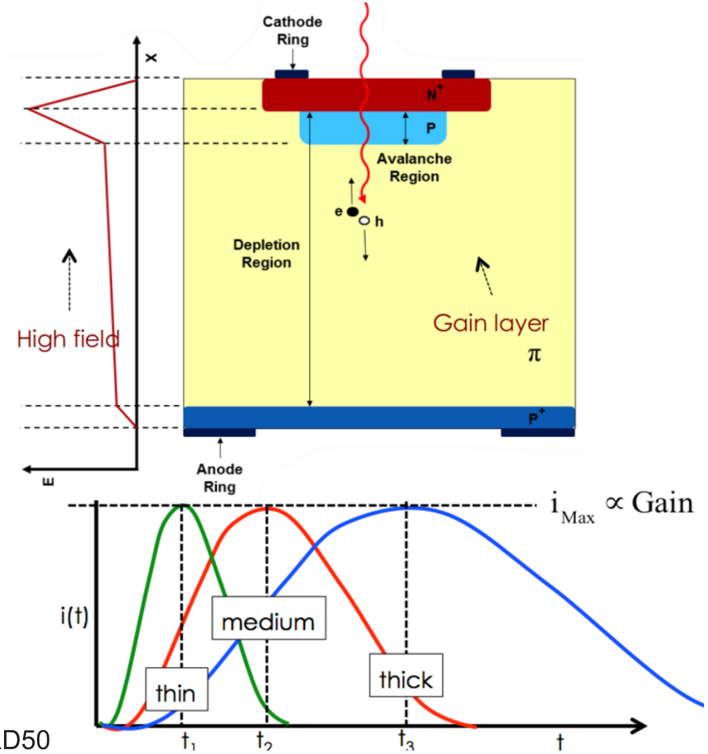
LGAD - Low Gain Avalanche Detector

Shot-to-shot measurements of at hundreds Mfps

- Internal gain of ~ few tens
- Gain variable with bias voltage
- Rise time in few tens of ps
- Continuous data acquisition at hundreds of MHz



Microstrip sensors
50 × 3000 μm^2



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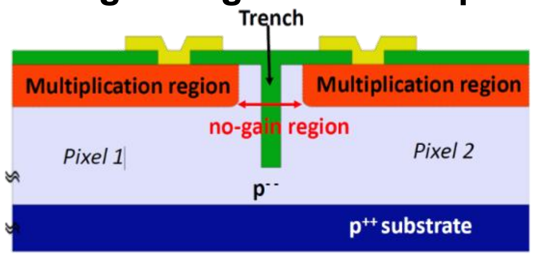
LGAD - Low Gain Avalanche Detector

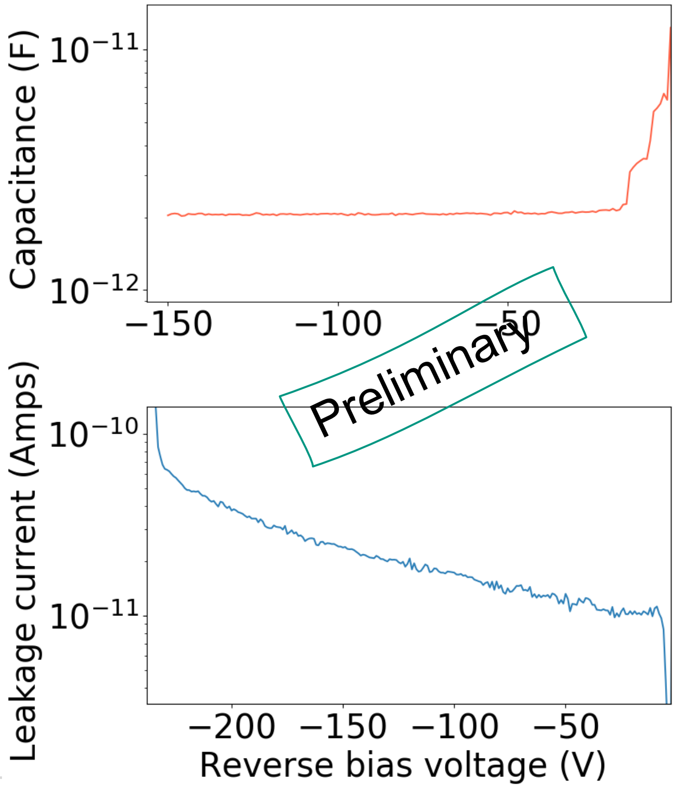
Shot-to-shot measurements of at hundreds Mfps

- Internal gain of ~ few tens
- Gain variable with bias voltage
- Rise time in few tens of ps
- Continuous data acquisition at hundreds of MHz

Trench isolated LGAD structure

no-gain region of ~ few µm



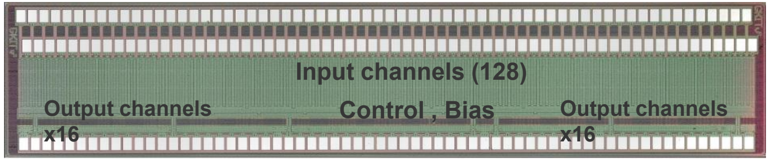


Courtesy of G. Paternoster , Giacomo Borghi (FBK) Work performed in the framework of RD50

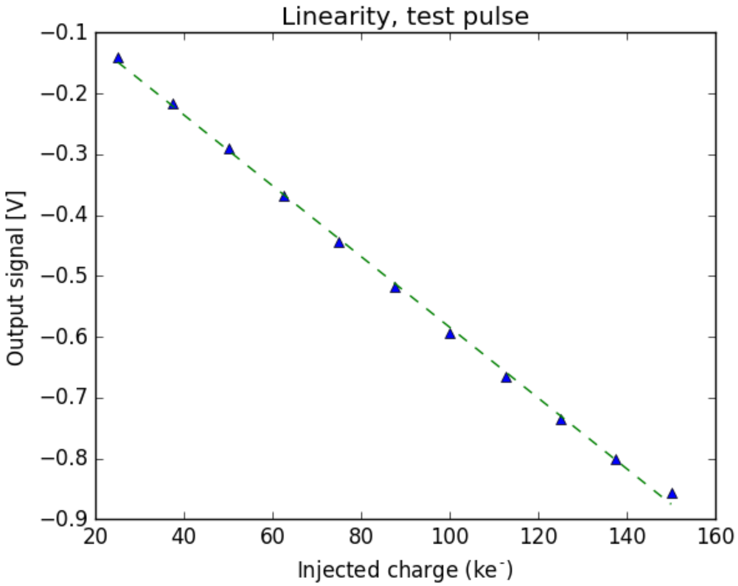
Gotthard-KIT - Performance

A low-noise ASIC with a frame rate up to 12 MHz

- Designed in CMOS UMC 110 nm technology
- 128 input channels and 16 output channels
- Charge sensitive amplifier operating with different semiconductor sensors
- High linearity and low noise (low to 217 e-)
- High-dynamic range - gain switching
- Radiation hardness - enclosed layout transistor & p+ guardring encapsulation

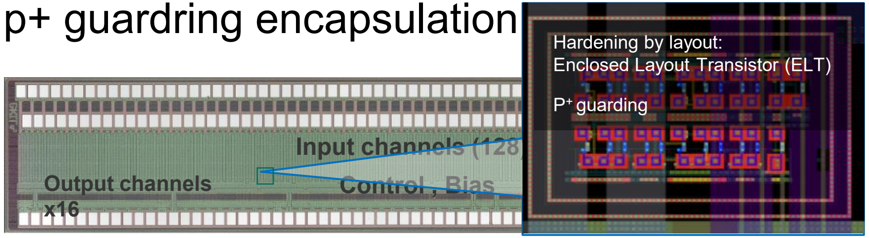


Gain HIGH	Gain MIDDLE	Gain LOW
up to 125 Ke-	up to 625 Ke-	up to 2.3 Me-

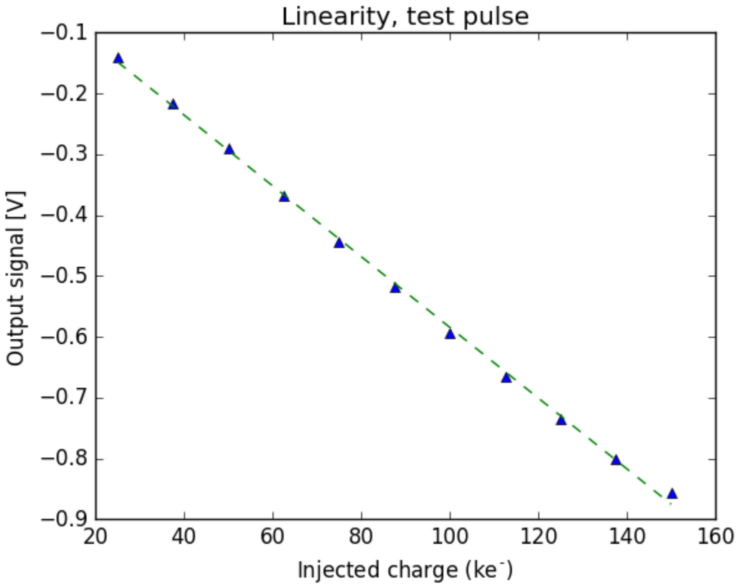


Gotthard-KIT - Performance
A low-noise ASIC with a frame rate up to 12 MHz

- Designed in CMOS UMC 110 nm technology
- 128 input channels and 16 output channels
- Charge sensitive amplifier operating with different semiconductor sensors
- High linearity and low noise (low to 217 e-)
- High-dynamic range - gain switching
- Radiation hardness - enclosed layout transistor & p+ guardring encapsulation

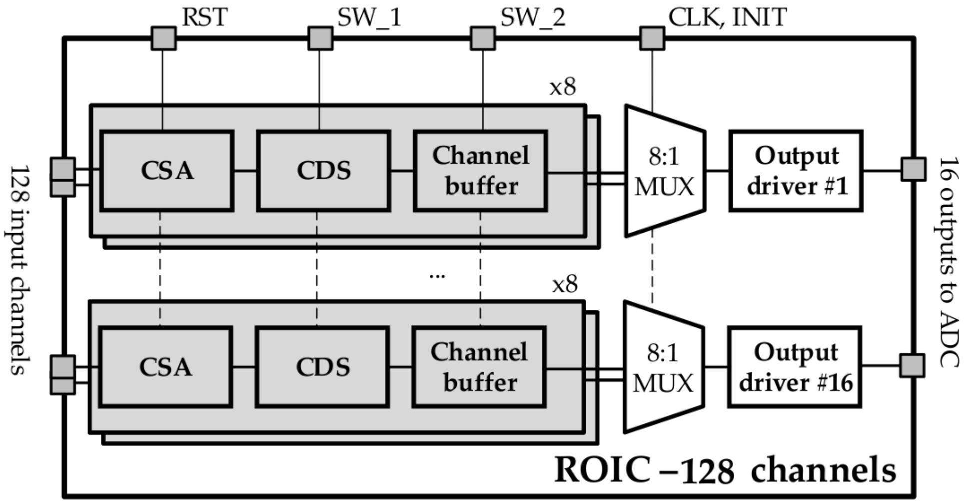


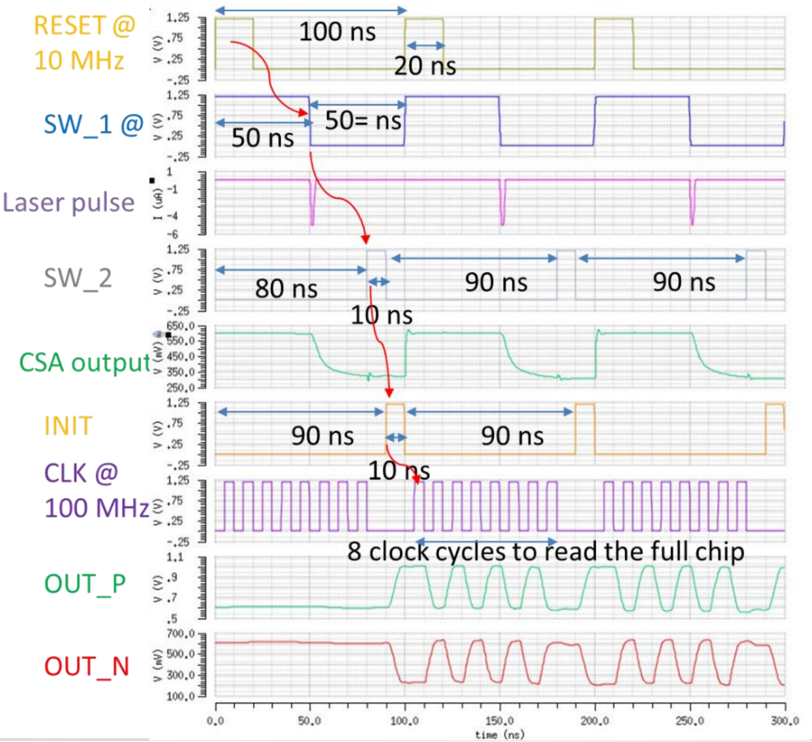
Gain HIGH	Gain MIDDLE	Gain LOW
up to 125 Ke^-	up to 625 Ke^-	up to 2.3 Me^-



Gotthard-KIT – Working principle

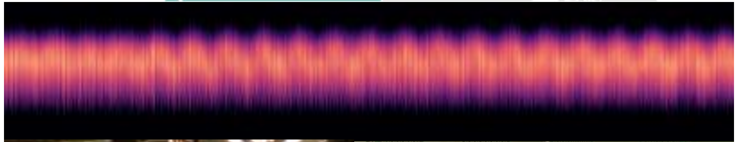
A low-noise ASIC with a frame rate up to 12 MHz

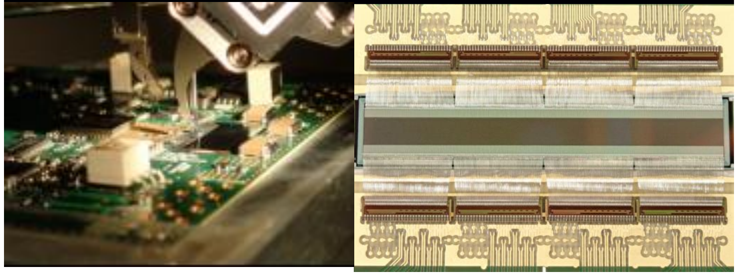




Summary

- Modern photon science detectors relies on: custom ASIC design, semiconductor sensor design and fabrication, high-density interconnect technologies, high-throughput DAQ, data processing by AI and more
- Study and explore beam dynamics with fs time resolution at high repetition rates
- EOSD → single shot electron bunch profile measurements with 2.7 MHz repetition rate implemented and phase space dynamics from experimental data (sawtooth bursting) reconstructed
- Close collaboration between physicists and electronic engineers
- Exploring possible applications in medical imaging, material science etc..
- Successfully exported to other accelerator facilities





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