HELMHOLTZ

Karlsruher Institut für Technologie

DESY.

RESEARCH FOR GRAND CHALLENGES

M. M. Patil, M. Caselle, E. Bründermann, T. Dritschler, A. Ebersoldt, S. Funkner, A. Kopmann, M. Nasse, G. Niehues, B. Steffen, C. Widmann, A.-S. Müller, M. Weber

KALYPSO – An ultra-fast and versatile detector for wide range spectral measurements

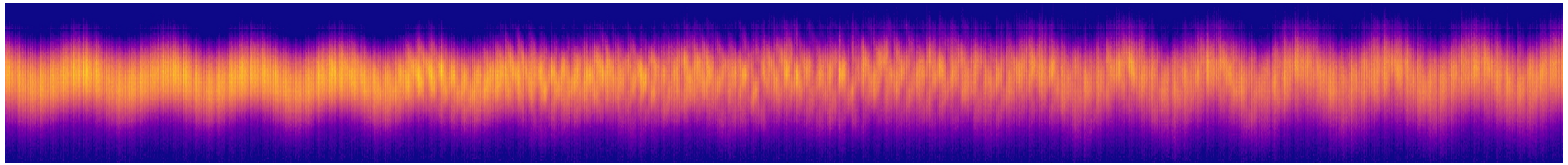
Beam Physics

Motivation

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

Requirements:

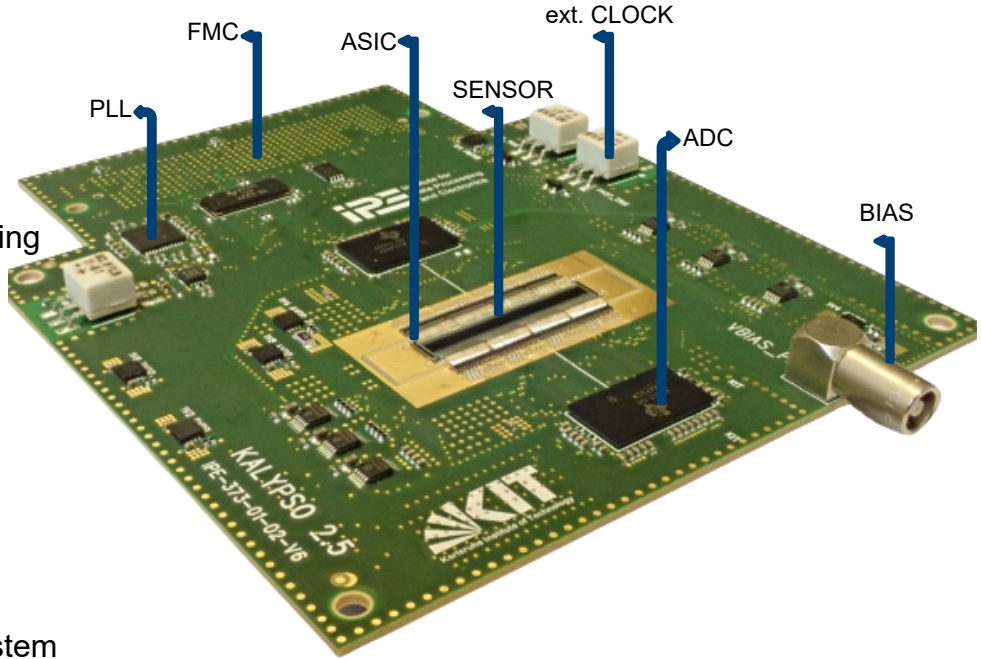
- Detectors with repetition rates in MHz regime and fs-ps time resolution
- High spatial resolution, broad field of view and wide spectral sensitivity
- Continous and long acquisiton time from secs to hours or days
- Synchronize several diagnostic tools



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

Ultra-fast detector system with very wide spectral sensitivity

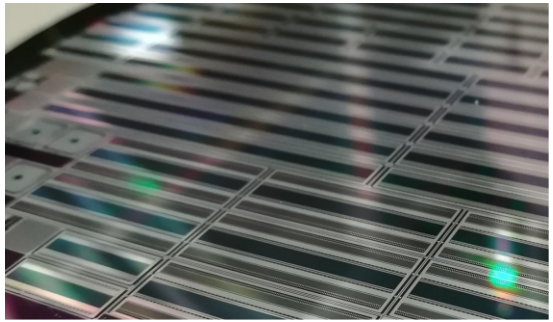
- Sensor
  - Several sensors technologies available
- ASIC – Gotthard
  - Low-noise and MHz frame rate
- ADCs
  - Integrated up to 64 parallel ADC channels each operating up to 125 MS/s
- External clock inputs
  - For synchronizing Kalypso to experimental setup
- Femtosecond time jitter clock distribution
  - Programmable for user applications
- FMC Vita-57.1 connector
  - Compatible with standalone and µTCA based DAQ system

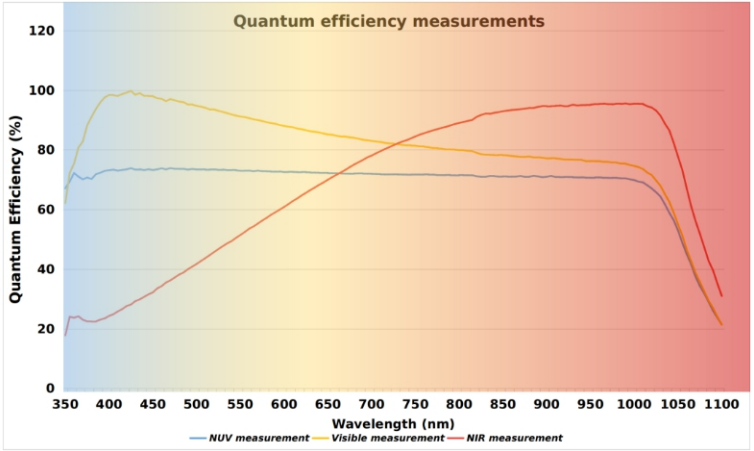


Sensor Technologies

Custom microstrip silicon sensor optimized for photon science

- Designed at KIT and fabricated at FBK, Italy
- Features:
  - Microstrip channels pitch: 25 µm and 45 µm
  - Array size: 256, 512, 1024, 2048 pixels
  - Wide field-of-view compatible with beam spot size (KARA, EuXFEL, TELBE, many others)
- Optimized sensor QE by anti-reflection coating layer:
  - Near-UV (from 350 nm)
  - Visible
  - Near-IR (up to 1050 nm)



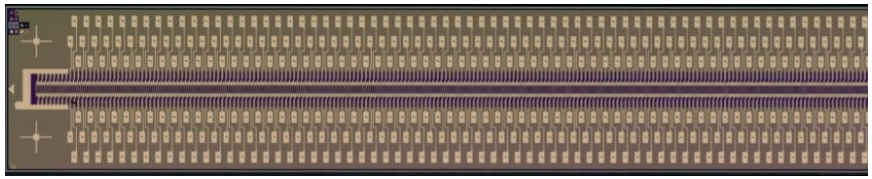


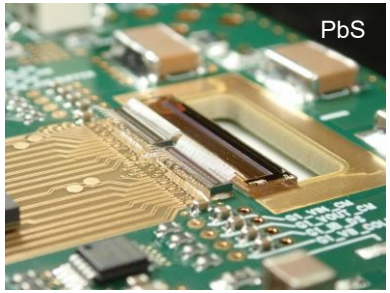
M. M. Patil, et.al, TWEPP 2018, ISSN: 18248039

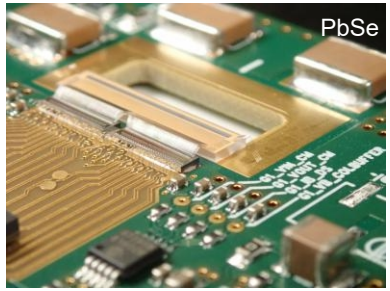
Sensor Technologies

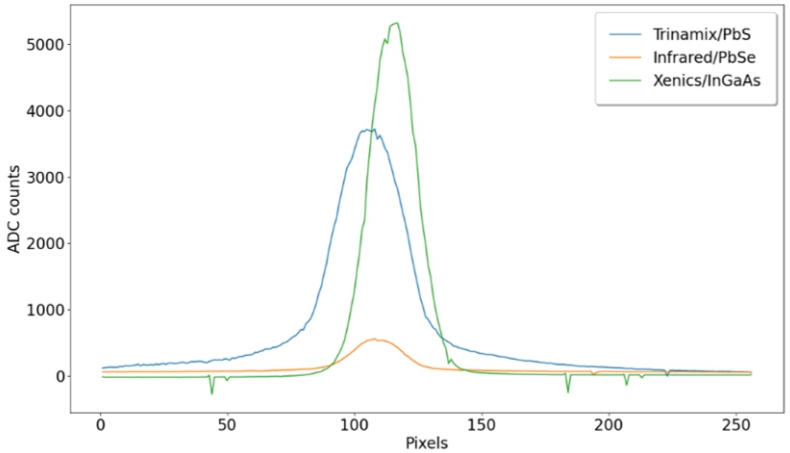
Extending wavelength sensitivity by InGaAs, PbS, PbSe

- Sensor based on PbS has wavelength sensitivity upto 3.3 µm
- Sensor based on PbSe has wavelength sensitivity upto 5 µm
- Inital compatibility test done with Kalypso with a 1560 nm Laser
- *New* InGaAs sensor provided by Hamamatsu under “special user agreement” with 25 µm pitch and array size up to 1024 pixels
  - Spectral response range 900 to 1700 nm





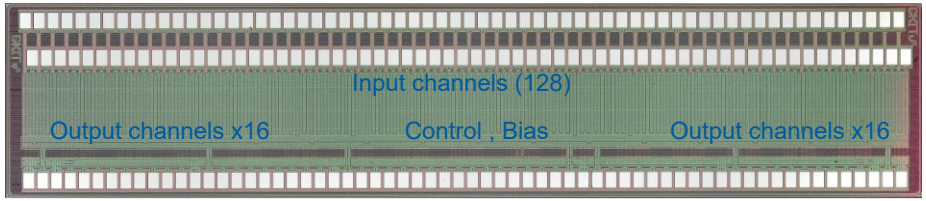


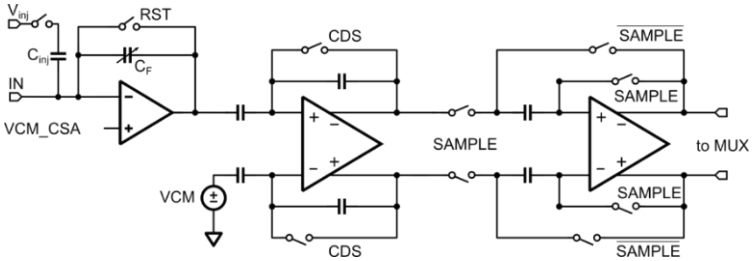


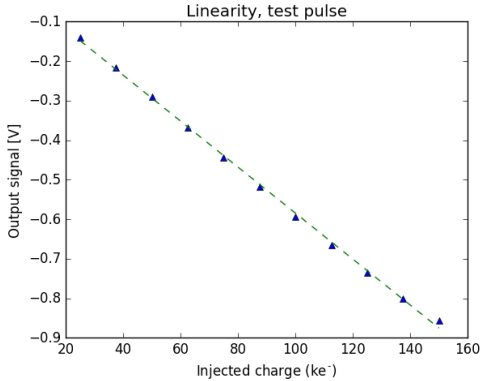
Gotthard version 2

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

- The ASIC has been designed in CMOS UMC 110 nm technology
- 128 input channels and 16 output channels
- Charge Sensitive Amplifier capable of operating with semiconductor sensors: Si, InGaAs, PbS, PbSe
- High linearity and low noise (low to 217 e-) architecture
- High-dynamic range by gain switching
- Radiation hardness achieved by 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⁻

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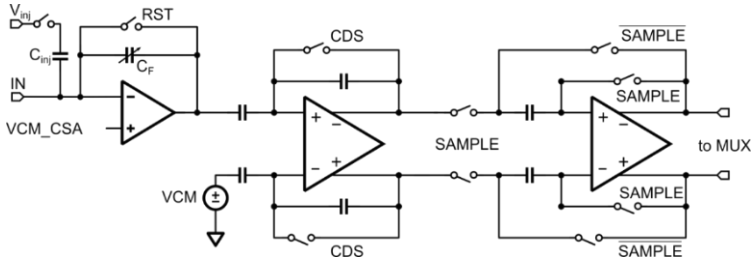
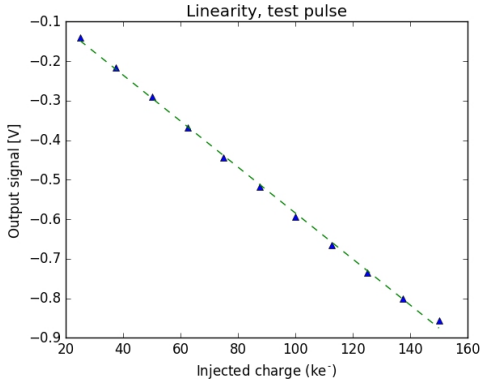
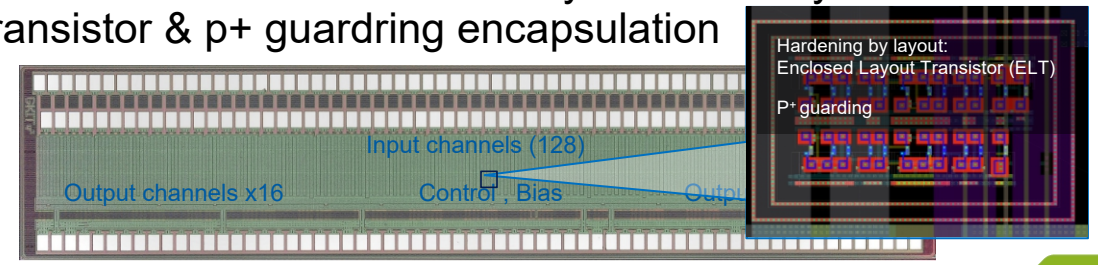


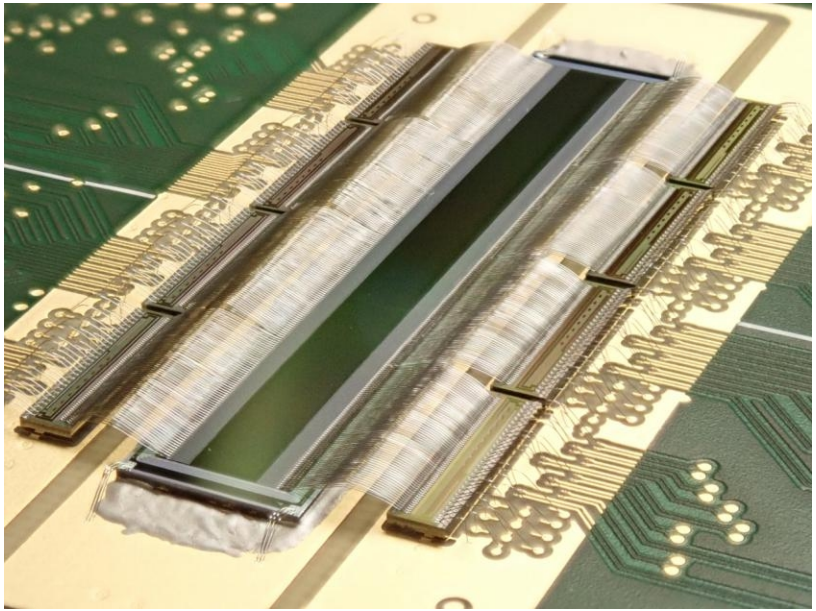




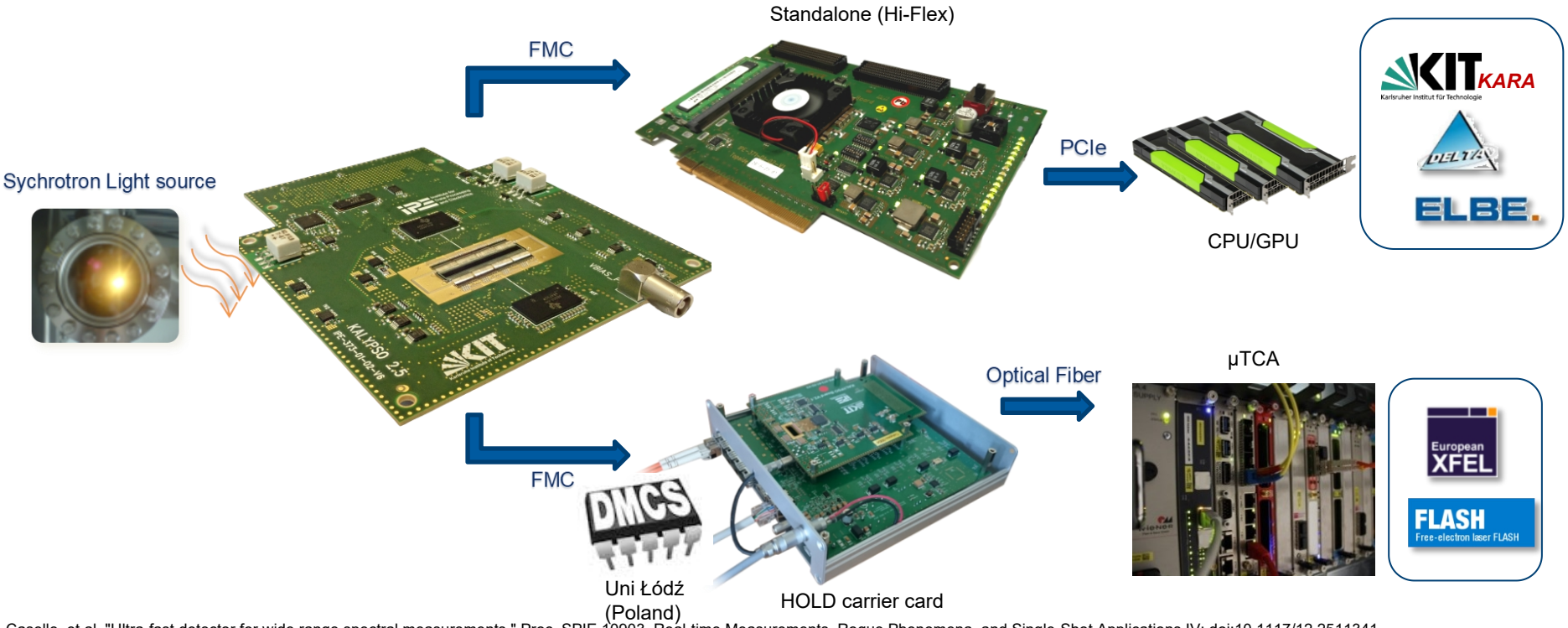
Gain HIGH	Gain MIDDLE	Gain LOW
up to 125 Ke⁻	up to 625 Ke⁻	up to 2.3 Me⁻

High density interconnections and packaging

- Wire-bonding by aluminium wedge to wedge ultrasonic process,
- Channel pitch of < 50 µm by 23 µm wire
- Glob-top encapsulation for damage prevention
- 8 ASICs to be glued and wire-bonded
- 1 large sensor (~1300 wirebondings)



Data acquisition flow - current

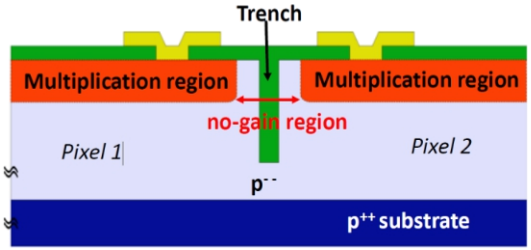


M. Caselle, et.al, "Ultra-fast detector for wide range spectral measurements," Proc. SPIE 10903, Real-time Measurements, Rogue Phenomena, and Single-Shot Applications IV; doi:10.1117/12.2511341

KALYPSO based on LGAD

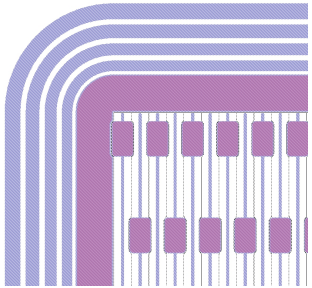
Shot-to-shot measurements of at hundreds Mfps

- Fine-pitch LGAD sensor with continuous data acquisition at hundreds of MHz
- Fine pitch achieved by trench isolation (down to 50 µm)
- Rise time in few tens of ps
- The LGAD is currently in production @FBK, Trento, and will soon be available at KIT for priliminary tests



Trench isolated LGAD structure
no-gain region of ~ few µm

- Initial tests and characterizations to be done @ 12 MHz
- Readout ASIC in SiGe technology to be designed by 2024



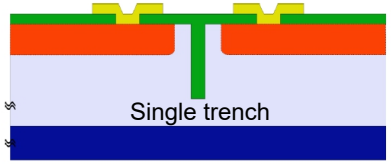
RD50

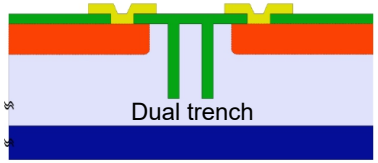
Microstrip sensors
50 × 3000 µm²

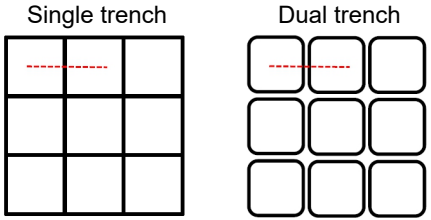
New TI-LGAD

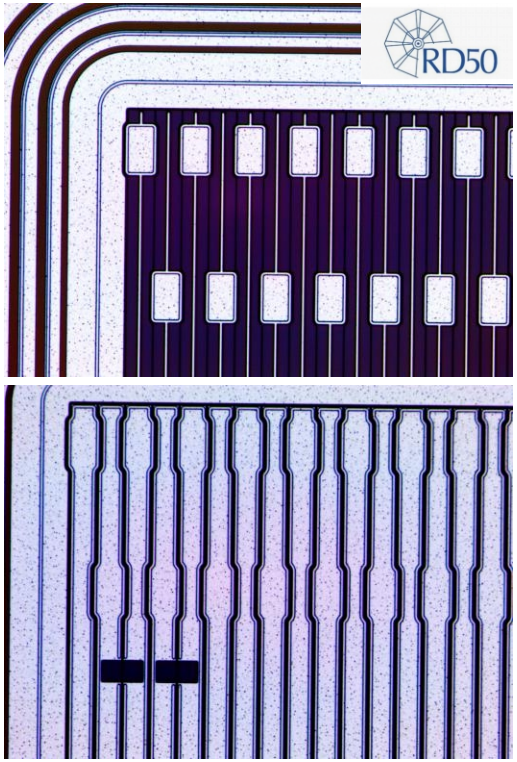
For fast timing and high spatial resolution applications

- Several shallow trench insulation characterisitcs to be studied
- Designed for particle physics as well as photon science
- The layout optimized for photon science (minimum metalization)
- The wafers are now in a final stage of passivation lithography









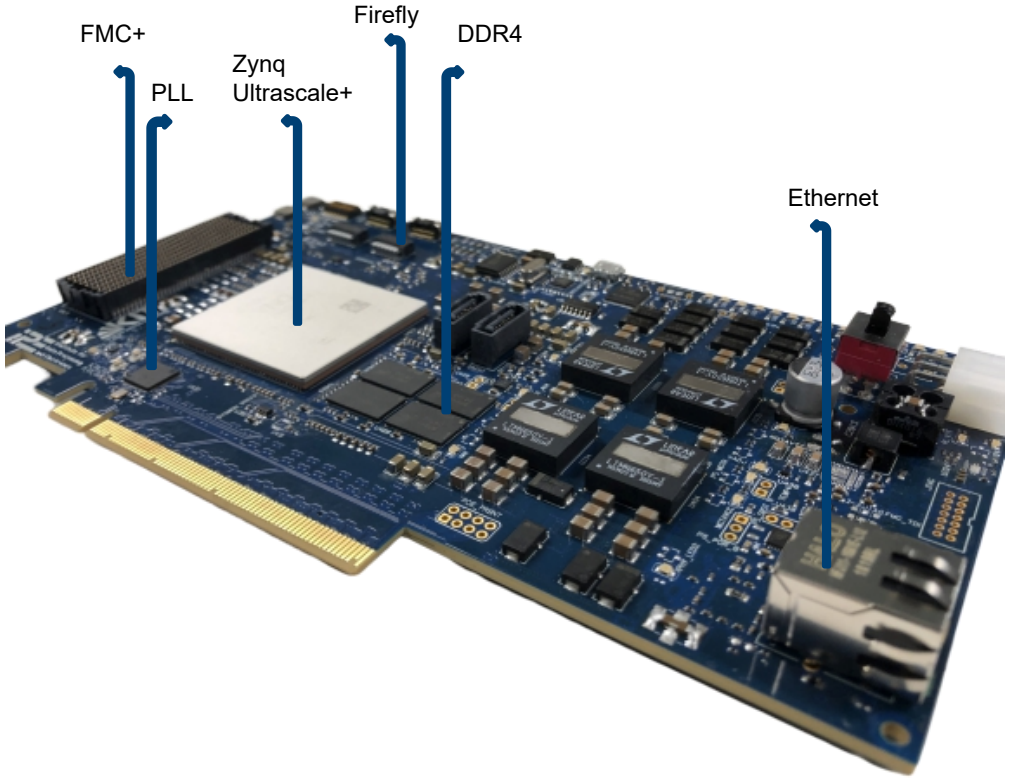
Courtesy of G. Paternoster , Giacomo Borghi (FBK) Work performed in the framework of RD50

High-Flex 2

Readout FPGA card for realtime control and machine learning

FEATURES

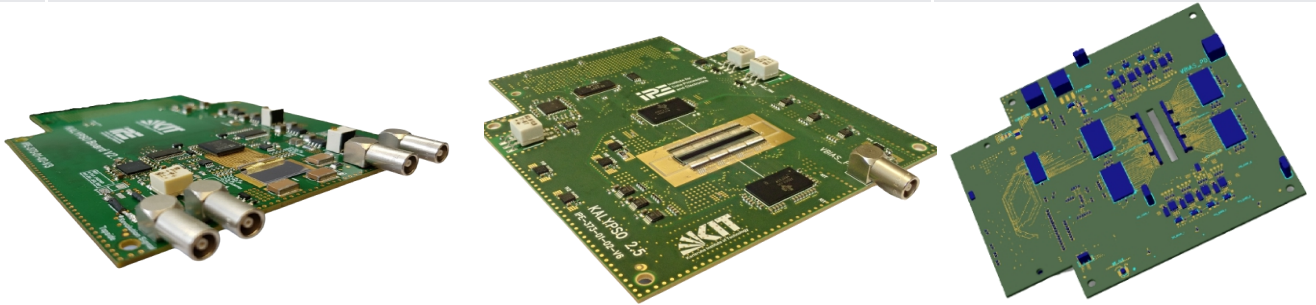
- Zynq Ultrascale+ MPSoC
- 12 duplex FireFly data link (336 Gbps)
- PCIe Gen 3 and Gen 4 (240 Gbps)
- DDR4 Chips for Programmable Logic (PL)
- Ethernet, SD, USB for PS



DTS talk by A. Ebersoldt

KALYPSO Evolution

	2014-2019	2020-2021	From 2021 …
Specifications	**KALYPSO v 1**	**KALYPSO v 2**	**KALYPSO v 3**
Sensor	Si, InGaAs, PbS, PbSe		
Pitch	50 µm →	25 µm/ 45 µm	
ASIC	Gotthard v1.6	→	Gotthard v2
Framerate (max)	2.7 MHz		12 MHz
DAQ	Hi-Flex v1	→	Hi-Flex v2
Status/Phase	Production		Design

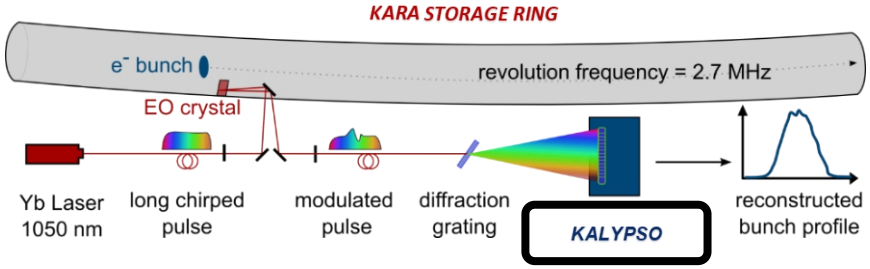


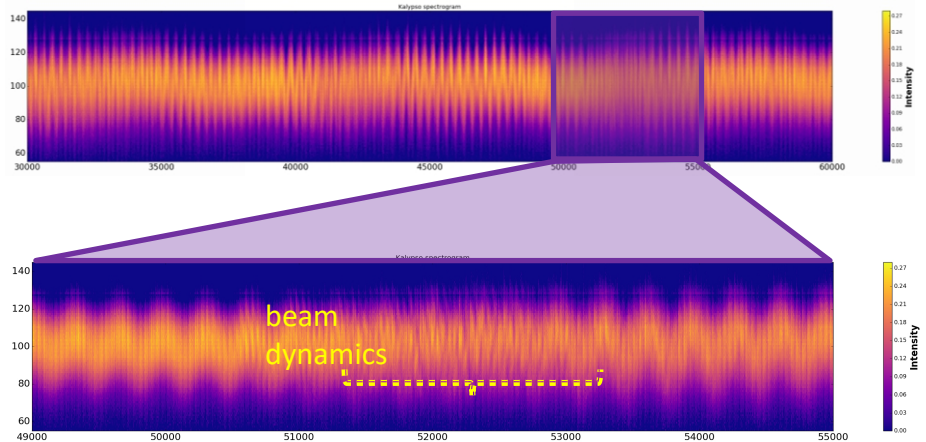
Applications of KALYPSO

EO spectral decoding @ 1050 nm

- Non destuctive measurement of longitudinal profile with fs time resolution at MHz repetition rate
- Yb Laser @1060 nm, synchronised to the repetition rate (2.7 MHz) of the strorage ring
- Single-shot mode
- Near-field setup, far-field setup currently being worked on

KALYPSO enables resolving fast dynamics of e- bunches with fs time resolution

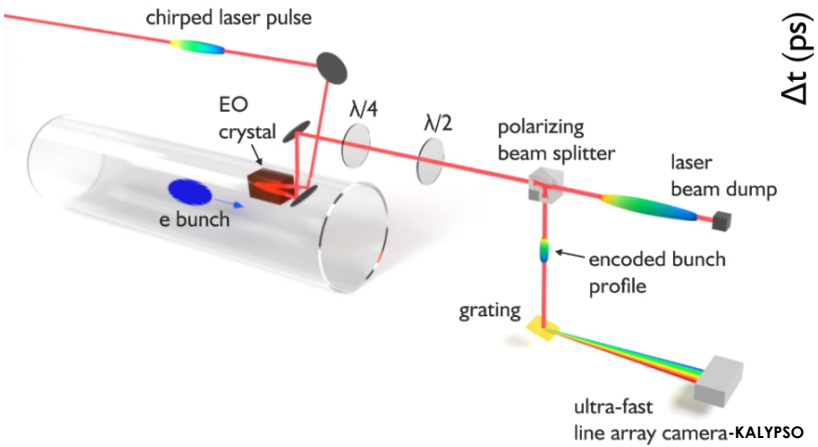




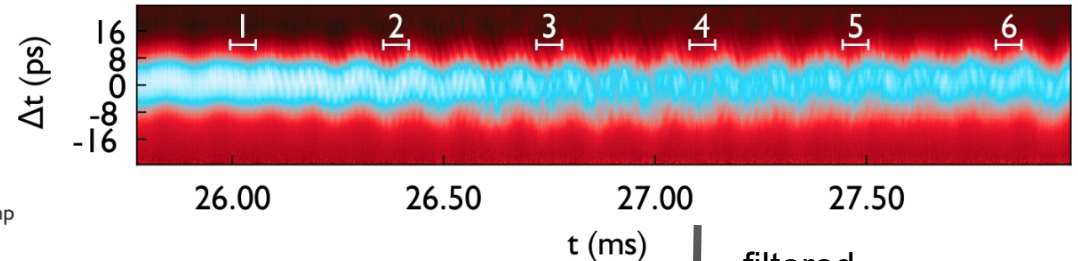
S. Funkner, et.al, DOI:10.1103/PhysRevAccelBeams.22.022801
G. Niehues, et al., DOI:10.18429/JACoW-IPAC

Phase Space Tomography of Electron Bunches during the Microbunching Instability

EOSD experiment



revolution plots/ sinograms



S. Funkner, et.al, arXiv preprint, arXiv:1912.01323

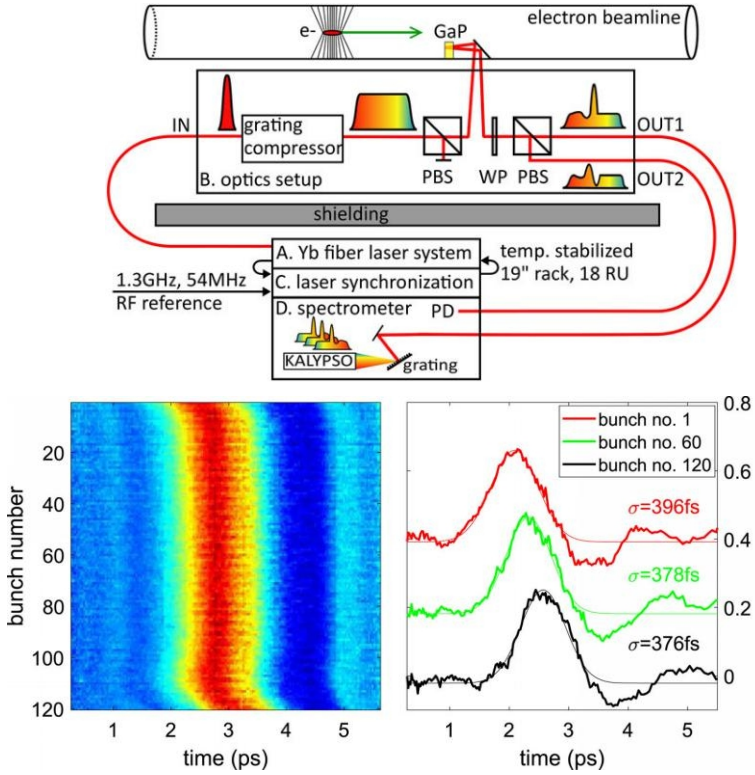
Courtesy: S. Funkner, G. Niehues

Applications of KALYPSO

Eu-XFEL

- Single-shot longitudinal bunch profile monitoring at the European X-ray Free Electron Laser (XFEL) for electron bunch lengths down to 200 fs (rms)
- EO detection system, includes the Yb-fiber laser, optics setup with the GaP crystal at the accelerator beamline
- Kalypso has been integrated to operate at 2.7 MHz, with readout electronics based on µTCA architecture

KALYPSO enables resolving arrival time and bunch length with fs time resolution

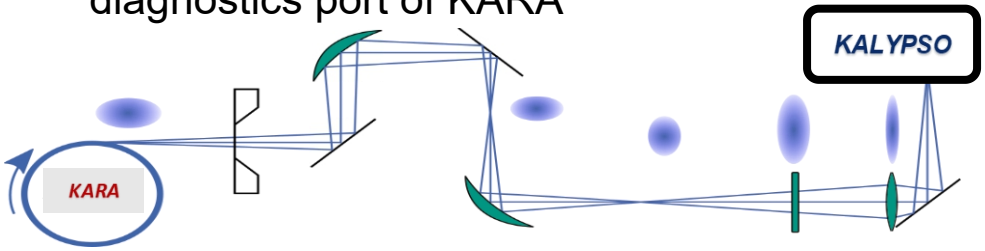


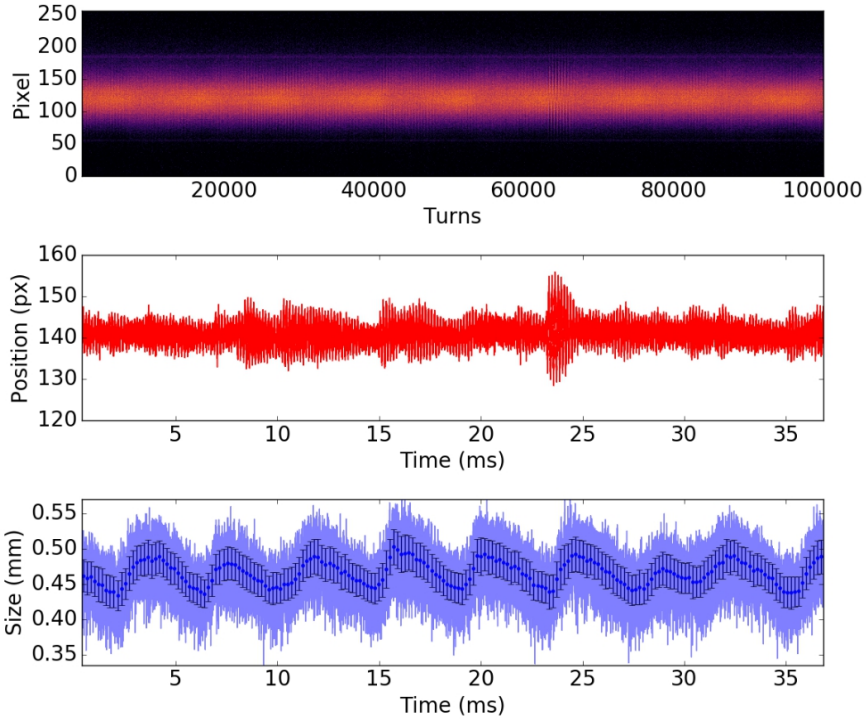
B. Steffen, et.al.https://doi.org/10.1063/1.5142833

Applications of KALYPSO

Horizontal bunch profile measurements @ 400 nm to 700 nm

- 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) at visible light diagnostics port of KARA



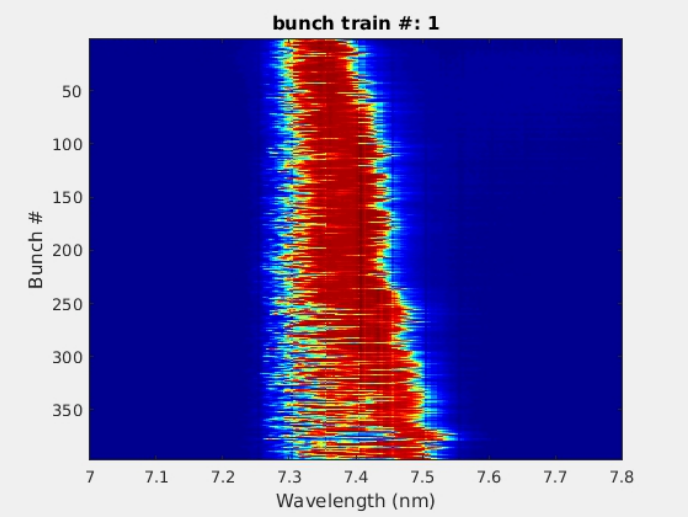


B. Kehrer, et.al, 10.1103/PhysRevAccelBeams.21.102803

Applications of KALYPSO

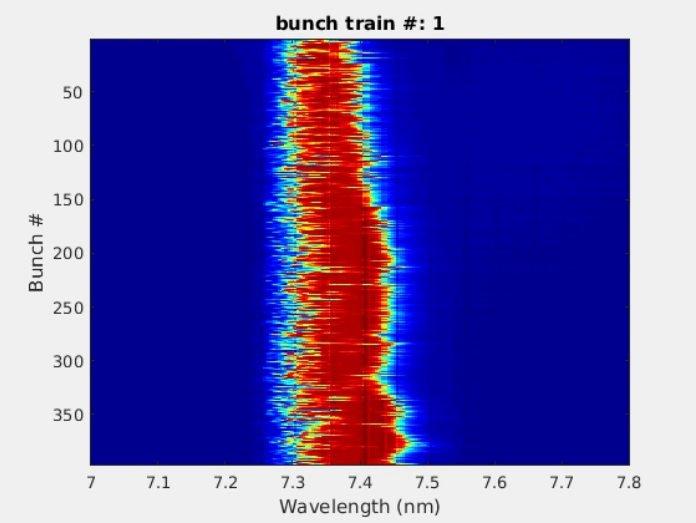
Fine tuning of Free Electron Lasers (FELs) @ FLASH, DESY at 1 MHz

Start up of FEL tuning
Instabilities at the end of pulse train



Before KALYPSO

After machine tuning
FEL spectra more uniform over pulse train



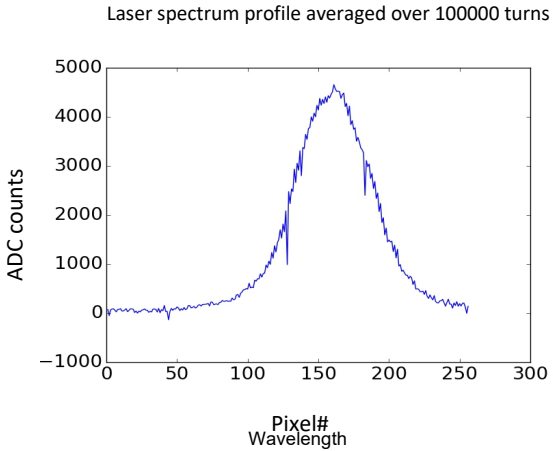
After KALYPSO

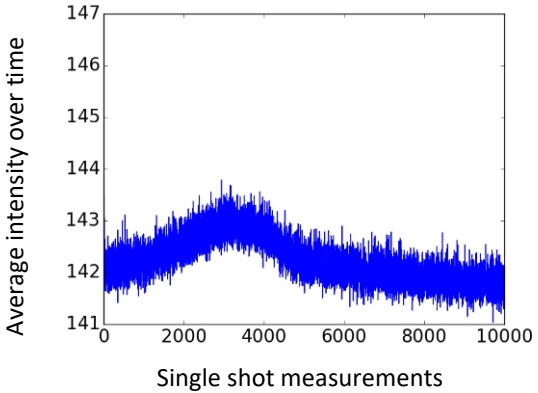
courtesy of S. Düsterer

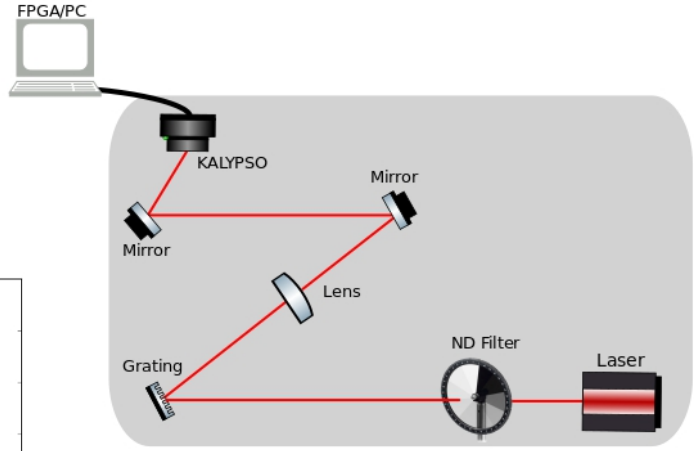
Applications of KALYPSO

Laser Diagnostics

- Measurments of a 1560 nm, < 90 fs laser using KALYPSO based on : InGaAs sensor, frame rate : 2.7 MHz , repetition rate of laser : 62.5 MHz







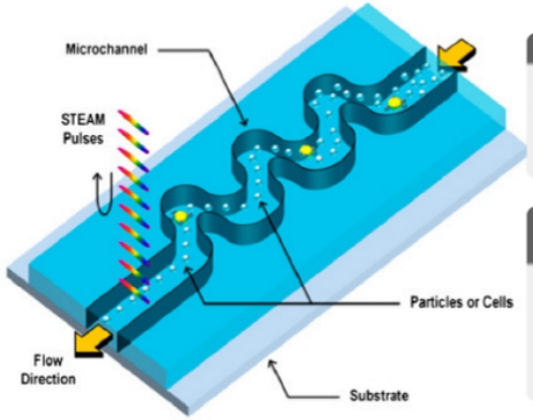
G. Niehues, et.al, doi: 10.1109/IRMMW-THz.2018.8510133

Applications of KALYPSO - prospects

Medical imaging

KALYPSO in ultrafast microscopy?

UCLA



Principle

Obtain 2d images from a 1d camera by scanning cells.
- cells flowing in a microfluidic channel.
- or add transverse scanning

Possible applications of "fast scanning of cells" (from literature)

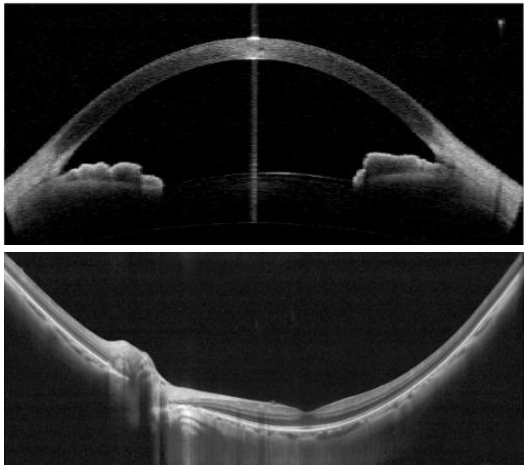
- Identify rare cancer cells in blood
- "Sorting" of cells
- Requires real-time analysis
- records ≈ 100000 cells/s

Keisuke Goda, Bahram Jalali, et al. High-throughput single-microparticle imaging flow analyzer, PNAS 109, 11630 (2010).

courtesy of B. Jalali

Spectral Domain Optical Coherence Tomography (SD-OCT)

CASE WESTERN RESERVE UNIVERSITY



courtesy of A. Rollins, B. Blackburn

Applications of KALYPSO - prospects

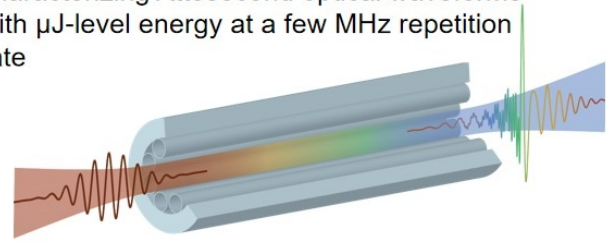
Material Science

MegaAtto

Attosecond optical waveforms at MHz repetition rates for strong-field physics in condensed matter

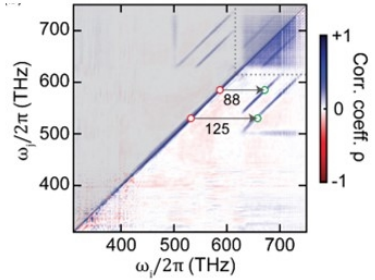
MPL Max Planck Institute for the science of light

MegaAtto aims at generating and characterizing Attosecond optical waveforms with µJ-level energy at a few MHz repetition rate



A high acquisition rate spectrometer will be used for:

- Monitoring the carrier-envelope phase (CEP)
  Currently, there is a lack of techniques for measuring the CEP stability of pulse trains with 0.5-10 MHz repetition rates -> Phase tagging
- Study of CEP-dependent soliton dynamics
- Acquisition of single-shot spectra at MHz repetition rate for studies of CEP-dependent currents in 2D materials via unsupervised machining learning



- Covariance spectroscopy
  Acquisition of CARS spectra on sub-ms timescale with a compact and low-cost system, this requires recording single-shot spectra at MHz repetition rates

courtesy of F. Tani

Conclusion

- 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
- Close collaboration between physicists and electronic engineers
- *KALYPSO* is a fundamental tool for understanding beam dynamics of ultra-short bunches
- This detector system has been successfully installed at various synchrotron facilities