Karlsruhe Institute of Technology

Turn-by-turn and bunch-by-bunch diagnostic developments at KIT

J. L. Steinmann, M. Brosi, E. Bründermann, M. Caselle, S. Funkner, A. Santamaria Garcia, G. Niehues, M. M. Patil, L. Scomparin and A.-S. Müller

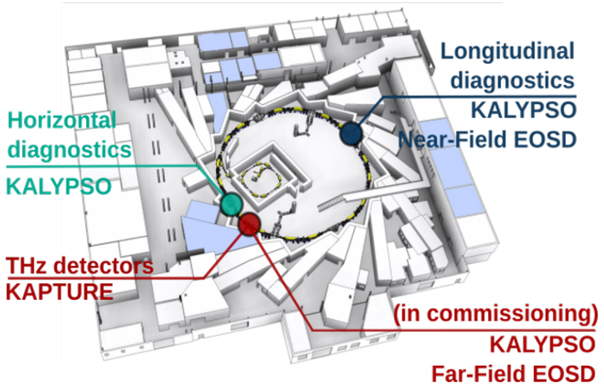
Goal: Analyze Every Bunch

- Novel accelerators require unprecedented accuracy and speed in electron bunch diagnostics

- Measure the 6D phase space of
  - every bunch
  - each turn
  - continuously

- Perform real time analysis and feedback

KARA distributed sensor network



Analyze Longitudinal Phase Space

- **Emitted CSR**
  - THz Detector
    - KAPTURE
- **Energy Spread**
  - Horizontal bunch profile in dispersive section
    - KALYPSO
- **Bunch Profile**
  - Electro-optical spectral decoding
    - KALYPSO

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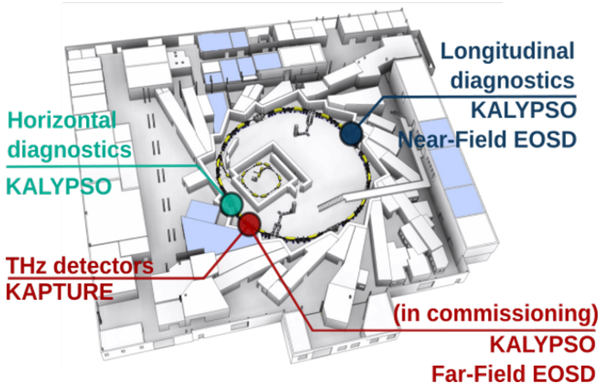

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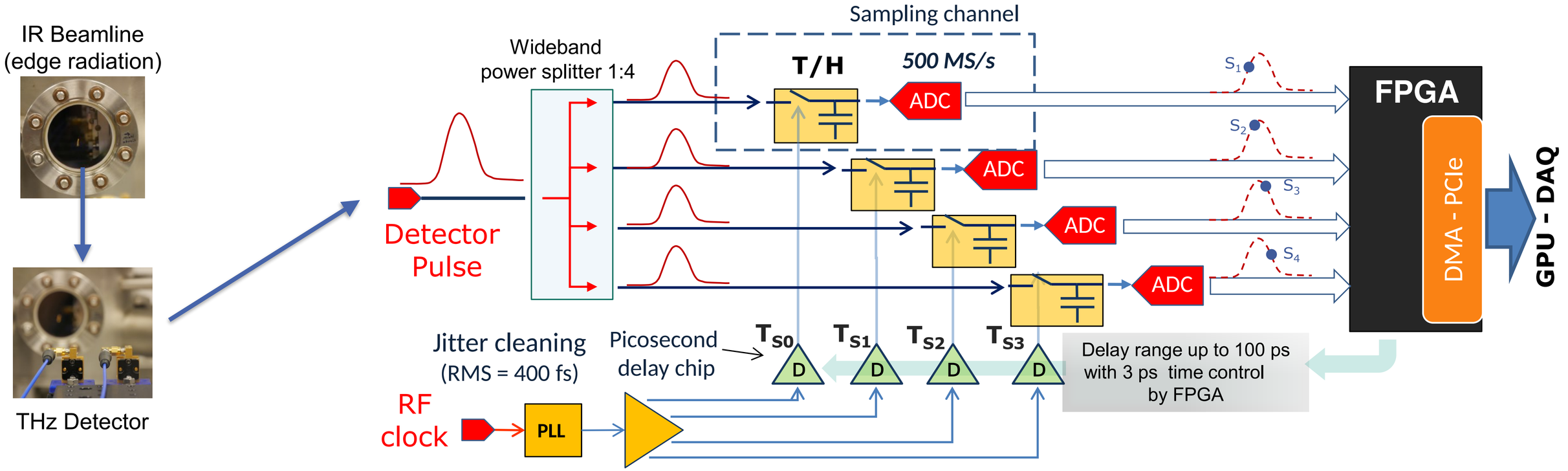
Single Shot CSR Measurements

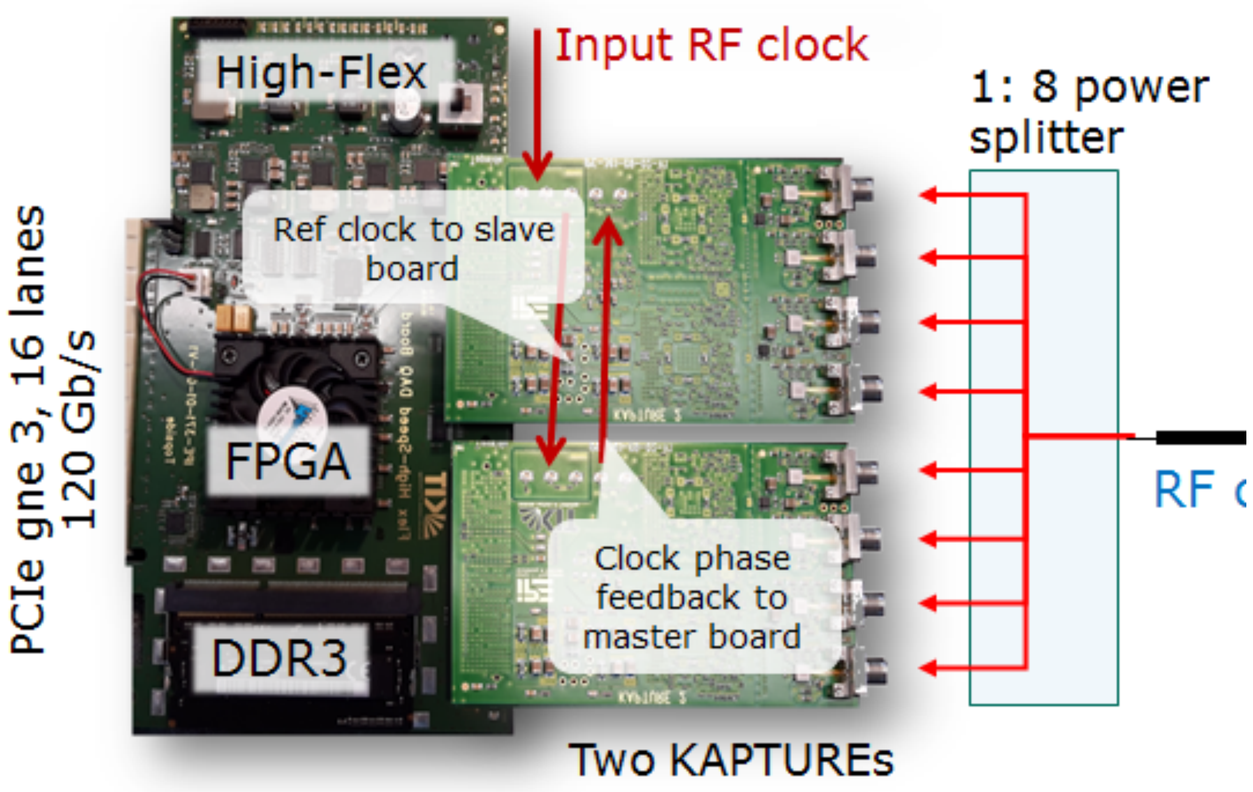


- Coherent Synchrotron Radiation is dependent on the longitudinal bunch profile
- Readout via KAPTURE for continuous bunch-by-bunch diagnostics
- Sampling the pulse allows measurement of width, arrival time and amplitude

M. Caselle, et. al, Journal of Instrumentation 12.01 (2017)
http://stacks.iop.org/1748-0221/12/i=01/a=C01040.

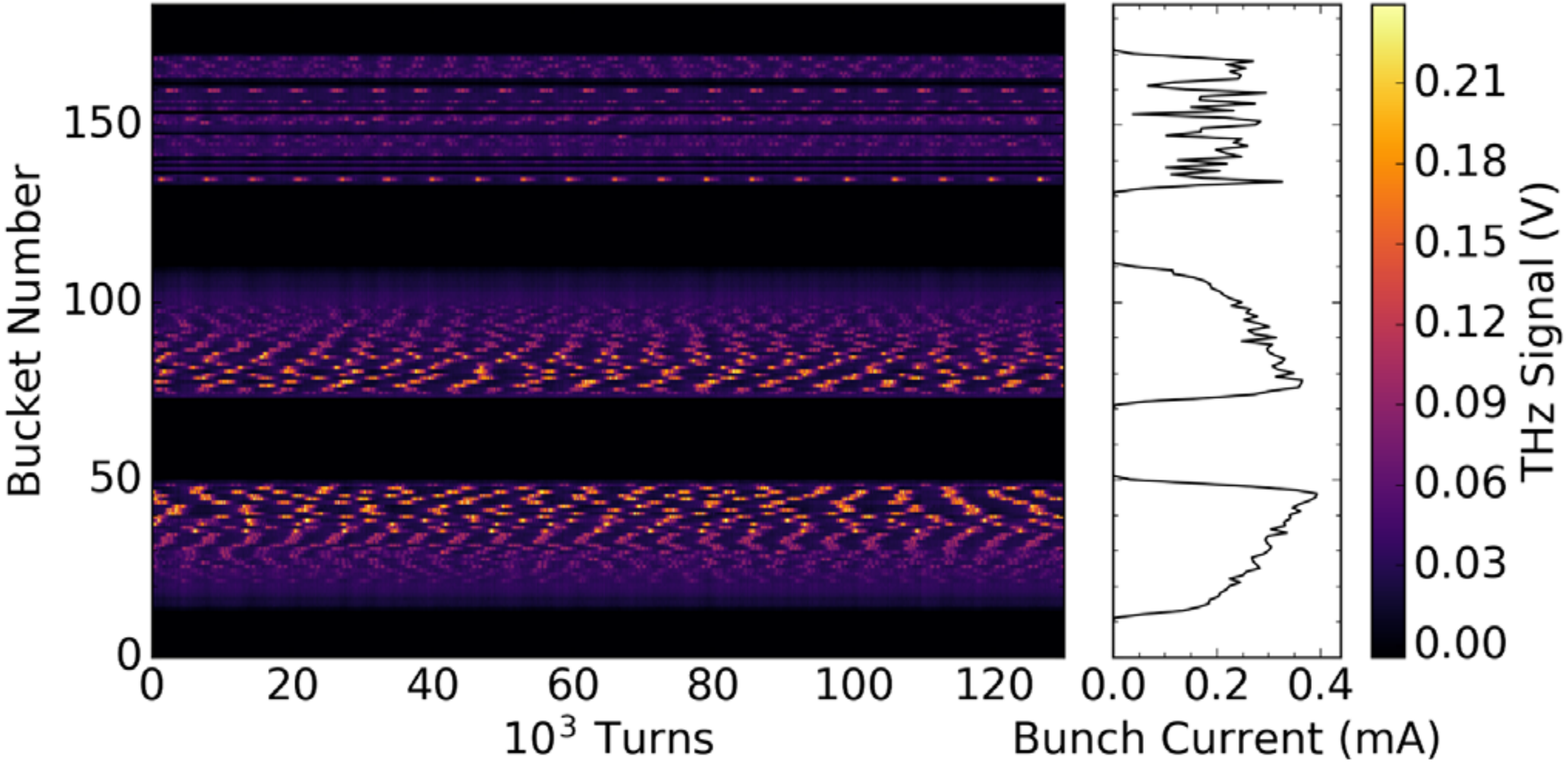
Digitizer with individual sampling times

- Kapture is a digitizer
- Synchronized channels
- Adjustable sampling times
- 3 ps minimal steps
- 330 GSa/s “local” sampling rate
- Equivalent sampling possible
- High throughput
- Streaming data
  (4 / 8 Channels x 12 Bit x 500 MHz)



M. Caselle, et al., DOI: 10.1088/1748-0221/12/01/C01040
M. Caselle, et al., DOI: 10.1088/1748-0221/12/03/c03015

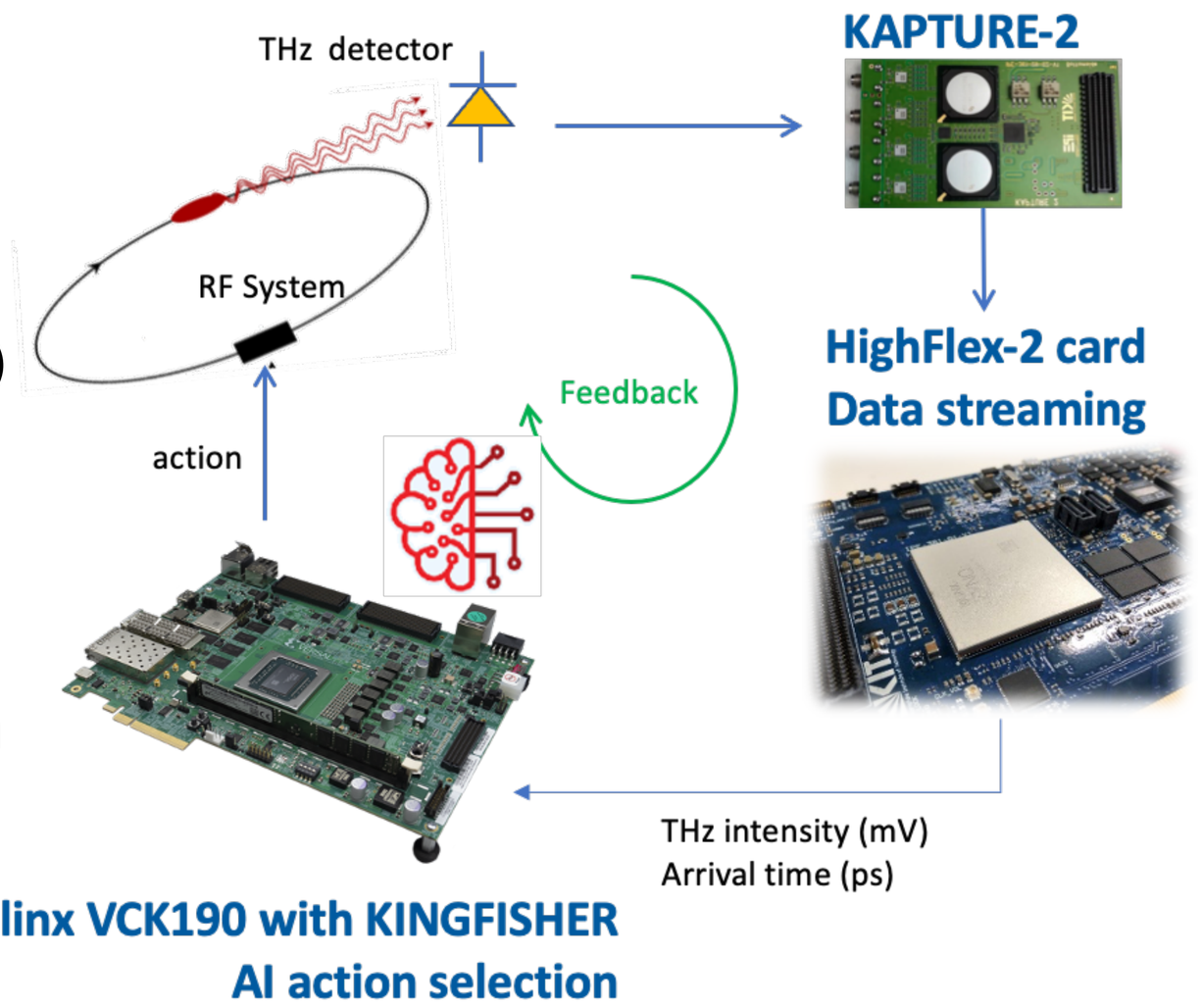
Observing Bunch-by-Bunch Intensity



M. Brosi, et. al., Phys. Rev. Accel. Beams **19**, 110701
DOI: 10.1103/PhysRevAccelBeams.19.110701

Coming soon: Versal AI based control system

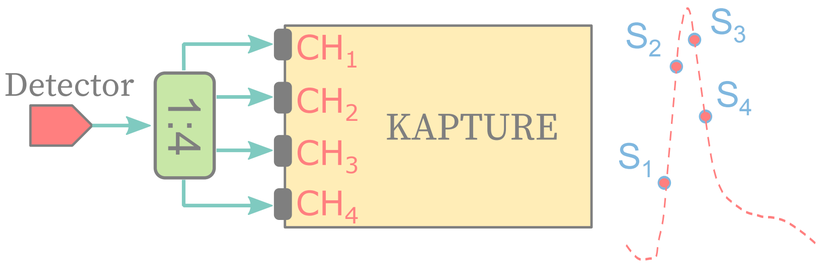
- New Xilinx Versal Adaptive Compute Acceleration Platform:
  - AI engine array (> 1TFLOPS)
  - High speed connectivity (100 GbE, …)
- Readout tests of KINGFISHER system based on Versal completed @ KARA (April 2022)
- Looking forward to implementing action taking part



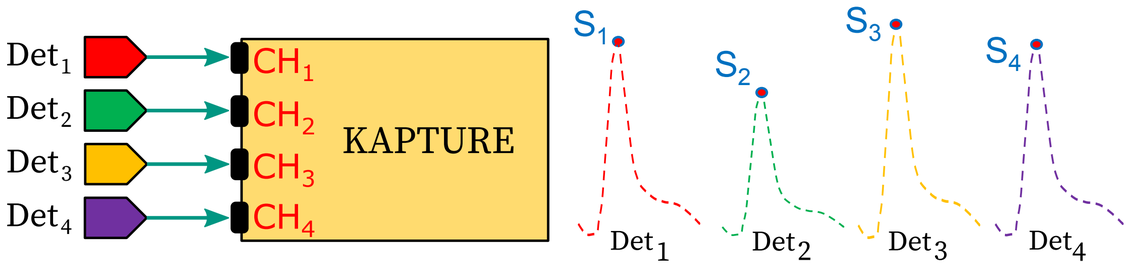
Courtesy Luca Scomparin / Michele Caselle (IPE@KIT)

Single-Shot Spectrometer

- KAPTURE can also be used to read out several detectors (amplitude only)



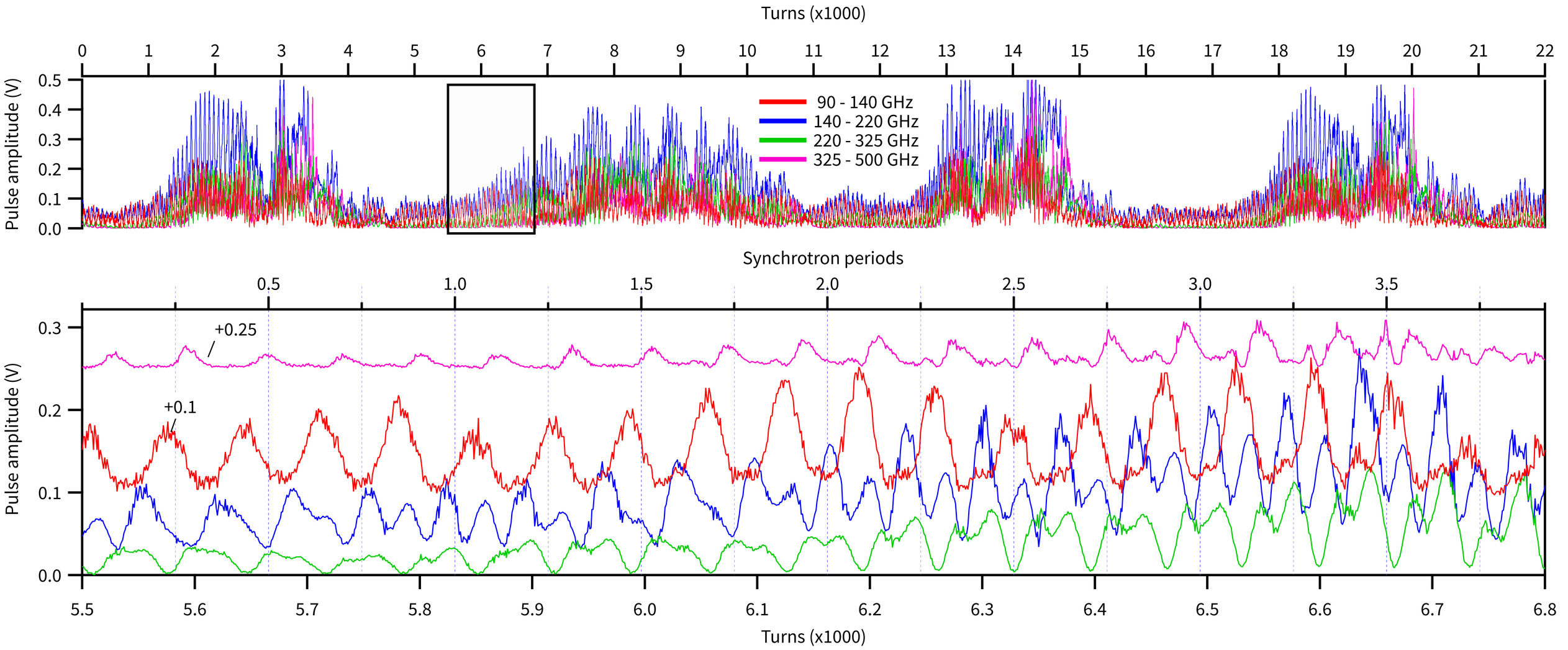
Configuration 1



Configuration 2

- Detectors sensitive in different frequency range → Spectrometer

Single-Shot High-Repetition-Rate Spectrometer



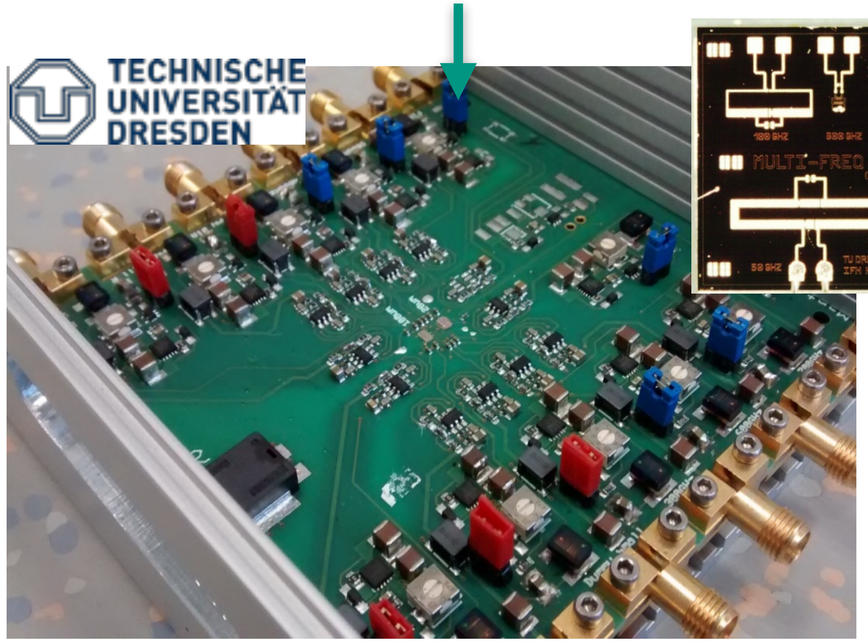
Johannes Steinmann

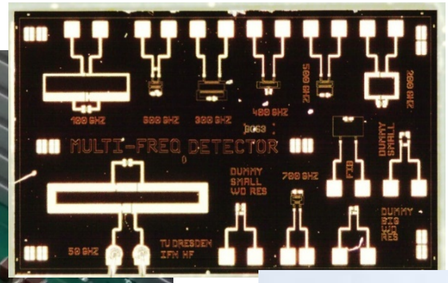
J. L. Steinmann et al., PhysRevAccelBeams.21.110705
J. L. Steinmann, DOI: 10.5445/KSP/1000090017

Institute for Beam Physics and Technology

Next: On-Chip Spectrometer

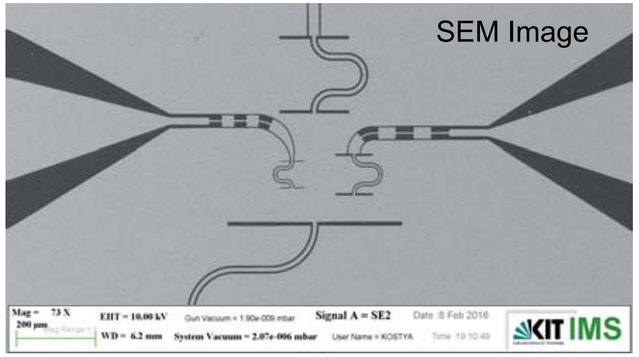
- Up to 8 Channels, 1 GHz repetition rate (1 sample between bunches)
- Narrow-band detectors
- Single chip
- Highly-sensitive high-T superconducting (YBCO)
- Room temperature (Schottky)

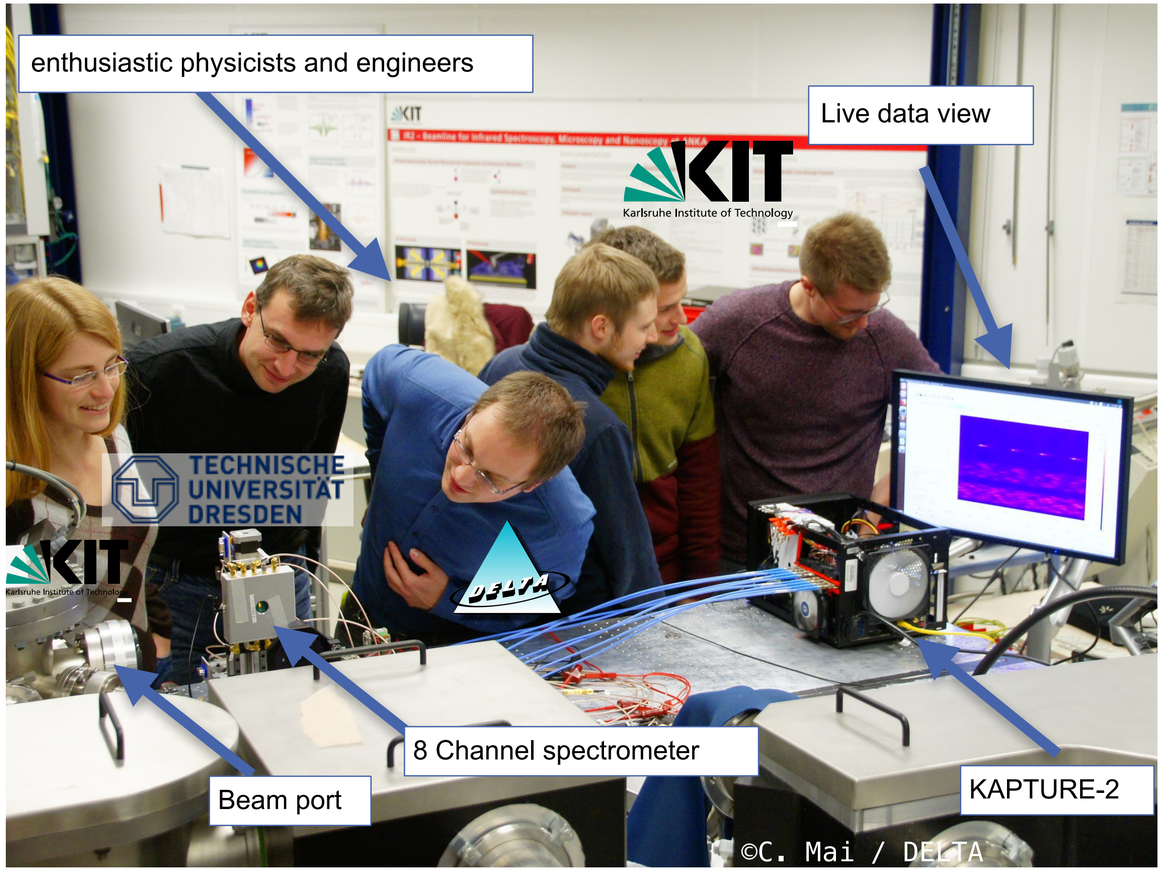




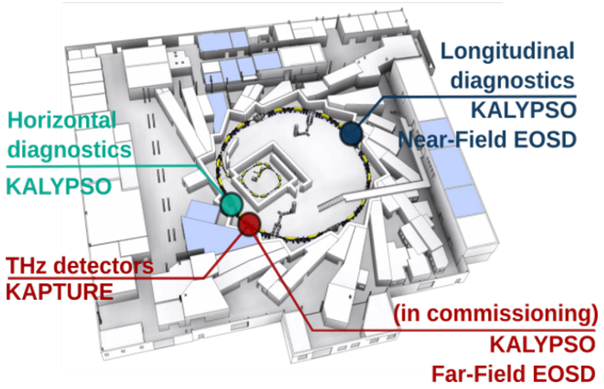
M. Laabs, N. Neumann, et al. J. Synchrotron Rad. (2018). **25**, 1509-1513
DOI: 10.1107/S1600577518010184

A. Schmid, et al., DOI: 10.18429/JACoW-IPAC2016-MOPMB016





KARA distributed sensor network



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Bunch Profile
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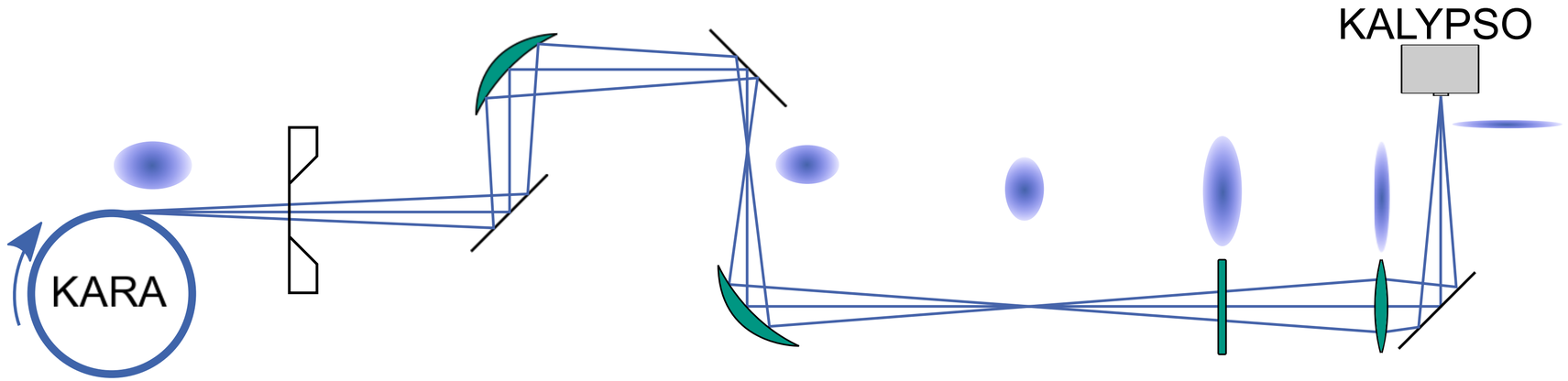
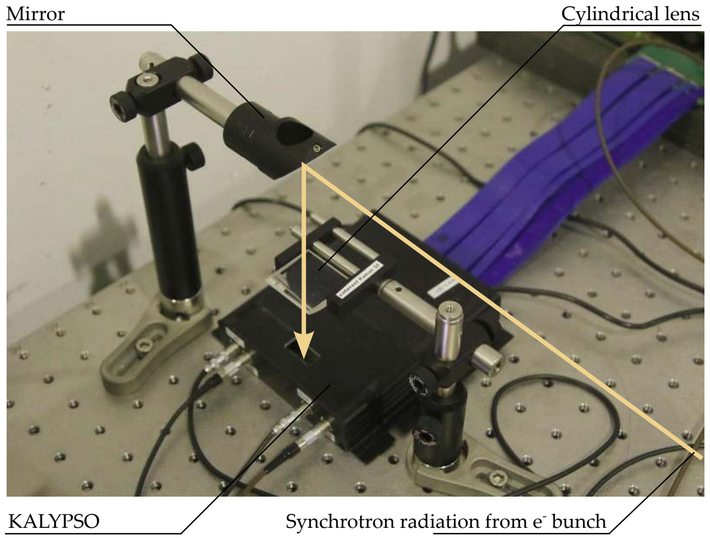
Energy Spread Measurement Setup



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

Courtesy: Paul Schütze (Masterthesis @KIT)

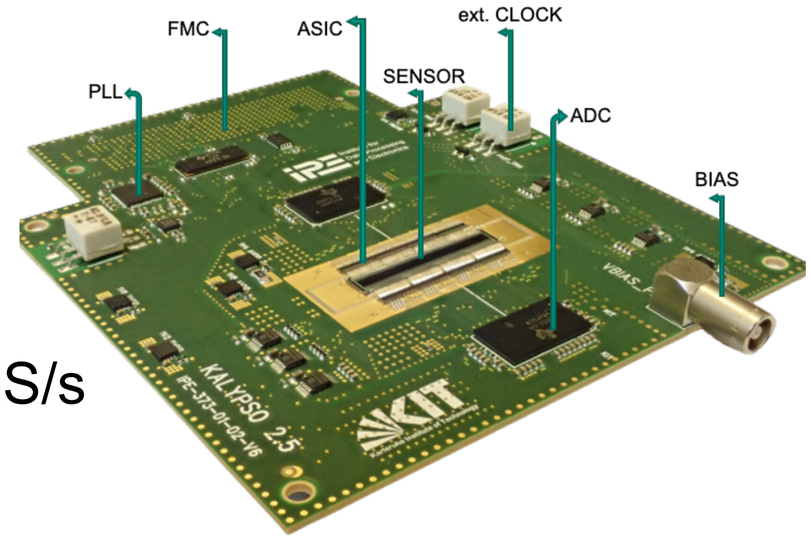


L. Rota, PhD Thesis, KIT

- Incoherent synchrotron radiation in dispersive section
- Horizontal bunch profile linked to energy spread
- Previous setup: Fast-Gated Camera
- Now: Line array detector readout → KALYPSO

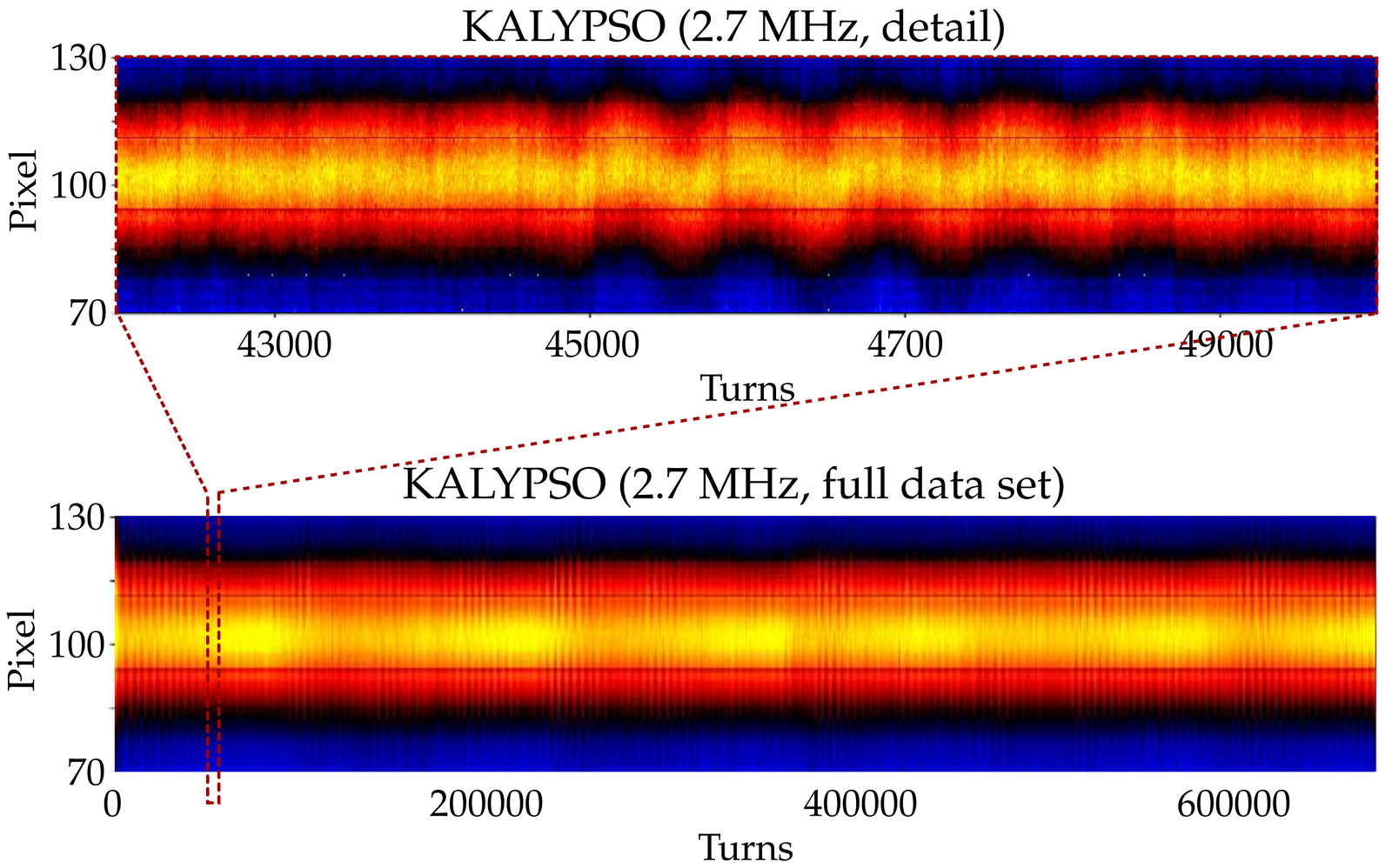
KALYPSO

- Emerged from a fruitful collaboration with PSI, DESY and University of Łódź
- Scientific goal: develop the “ideal” detector for TbT measurements:
  - High-repetition rate with single-shot resolution
  - Continuous data acquisition ➜ turn-by-turn monitoring over > 10^6 turns
  - Detect radiation in visible & near-infrared spectrum
  - Real-time data analysis ➜ FPGA / GPU heterogeneous DAQ



- Sensors: Si, InGaAs, PbS, PbSe
- ADCs : Up to 64 parallel channels each operating up to 125 MS/s
- External clock inputs : synchronization to experimental setup
- ASIC – Gotthard-KIT : Low-noise and MHz frame rate

Long-Term Turn-by-Turn Measurements

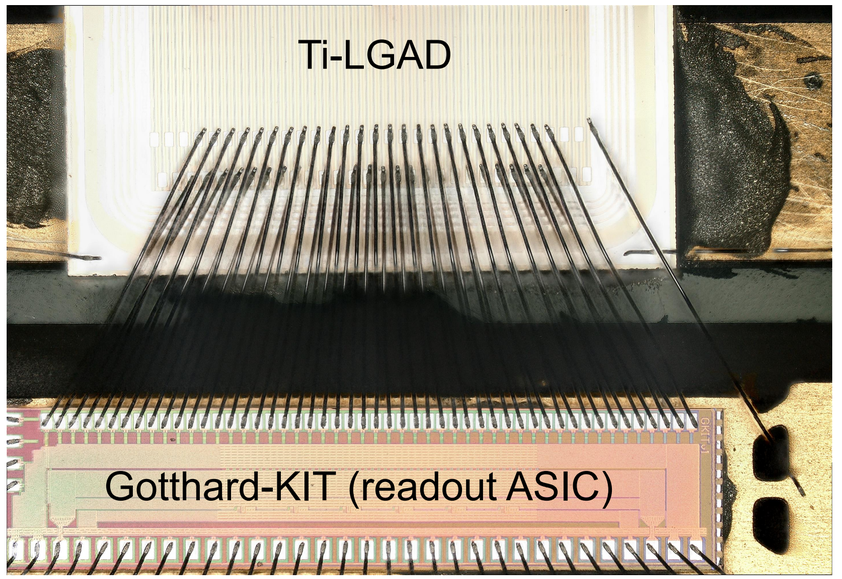


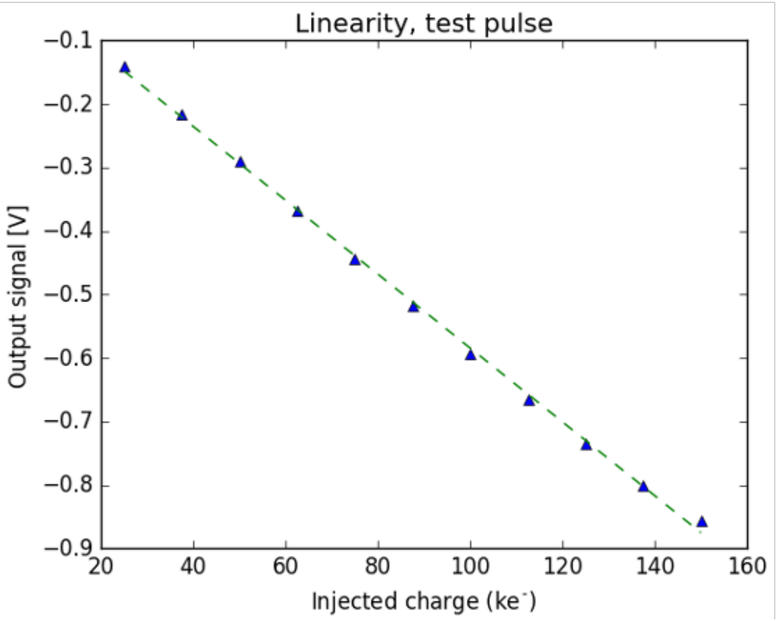
Energy spread fluctuations due to micro-bunching instability

L. Rota, PhD Thesis, KIT

Next: TI-LGADs for improved timing and sensitivity

- Small beams need interferometric readout and more sensitive imaging
- Line array based on Trench-Isolated Low Gain Avalanche Diodes (TI-LGADs)
- Aim to fully replace Fast Gated Intensified Cameras (FGC)
  - Comparable sensitivity and resolution
  - Up to 12 Mfps
- First tests are ongoing





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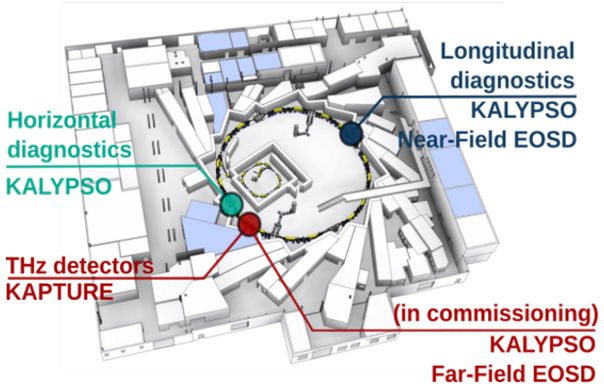

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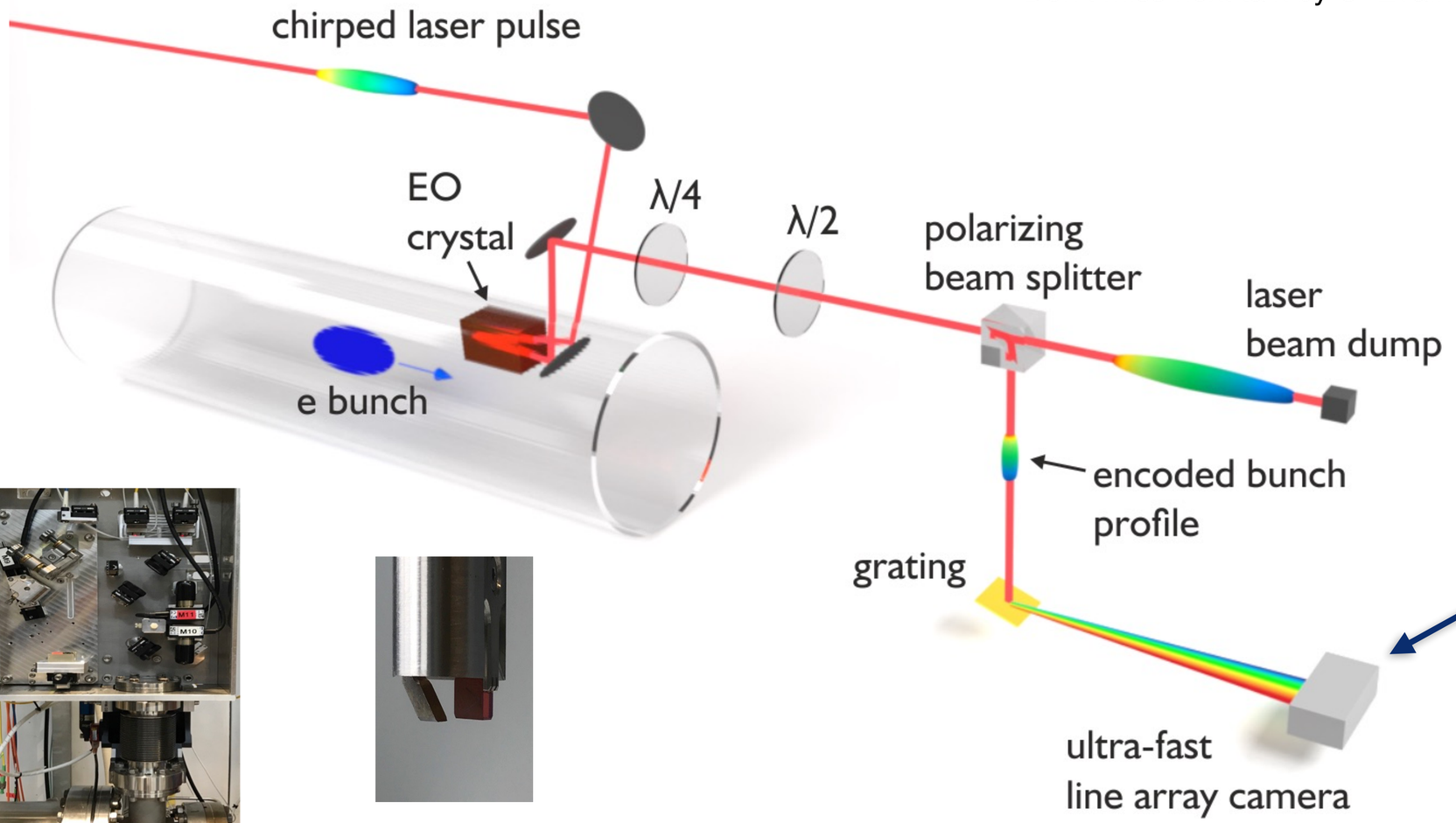
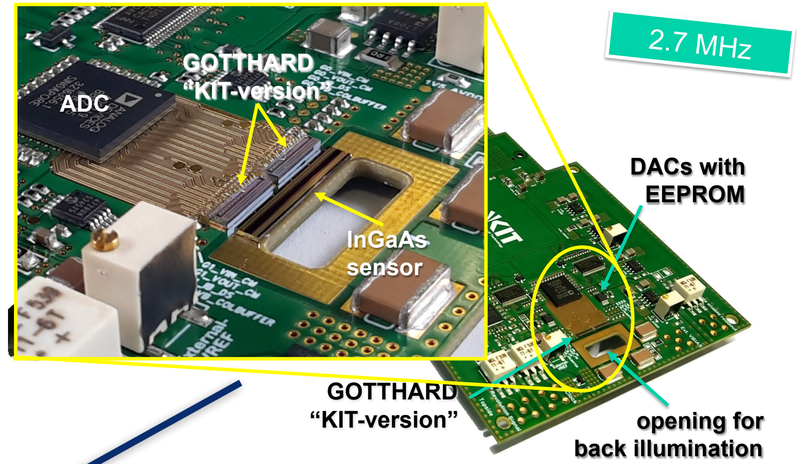
Electro-Optical Spectral Decoding (EOSD)

Don’t miss next talk by C. Evain about time-stretch electro-optic sampling technique!

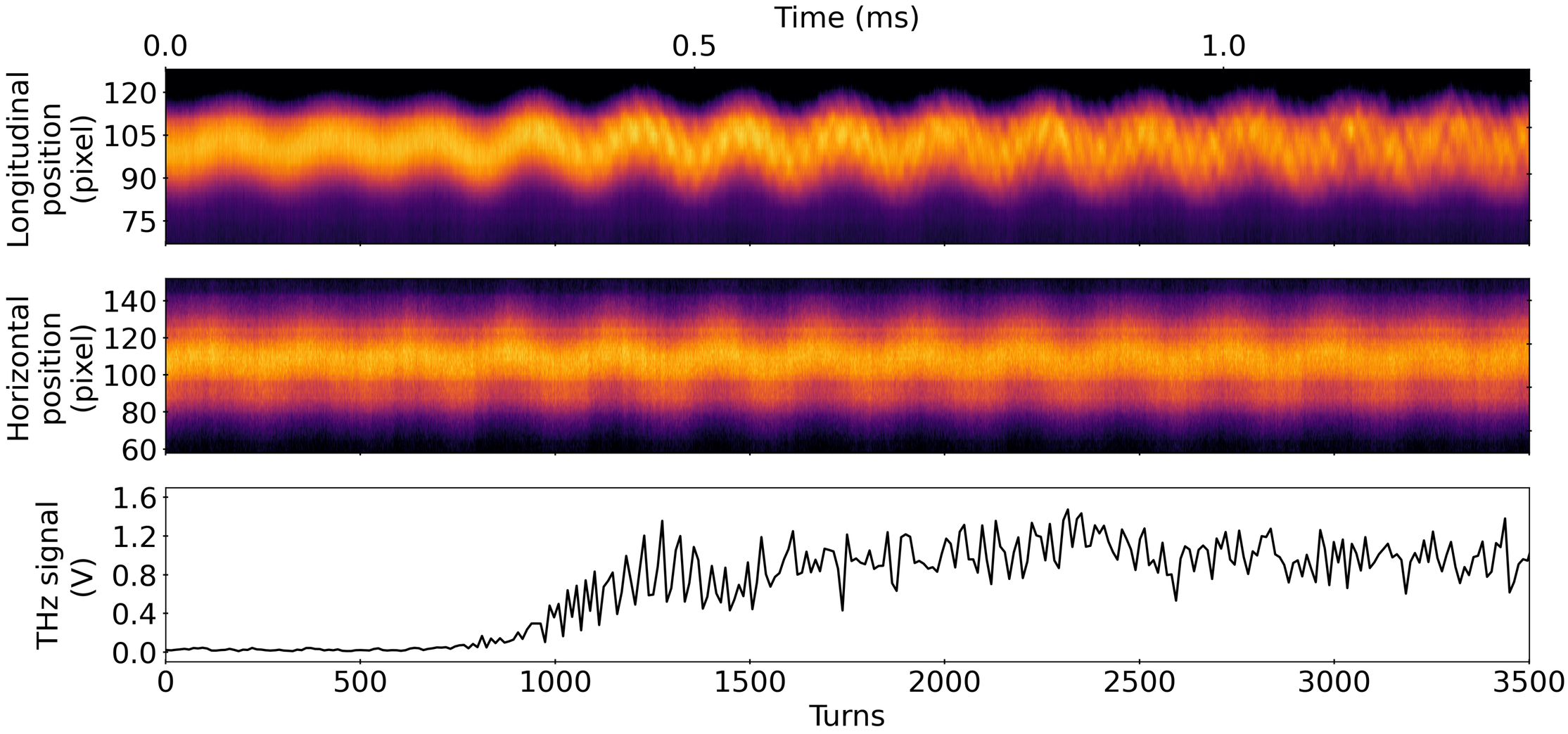


KALYPSO: a 2.7 Mfps linear-array detector for visible to NIR radiaton



S. Funkner et al., PRAB 22, 022801, 2019
P. Schönfeldt et al., IPAC 2017, MOPAB055, 2017
G. Niehues et al., DOI: 10.18429/JACoW-IPAC2021-MOPAB293

Synchronized Measurements



M. Brosi et al. DOI: 10.18429/JACoW-IPAC2019-WEPTS015
B. Kehrer et al. DOI: 10.1103/PhysRevAccelBeams.21.102803

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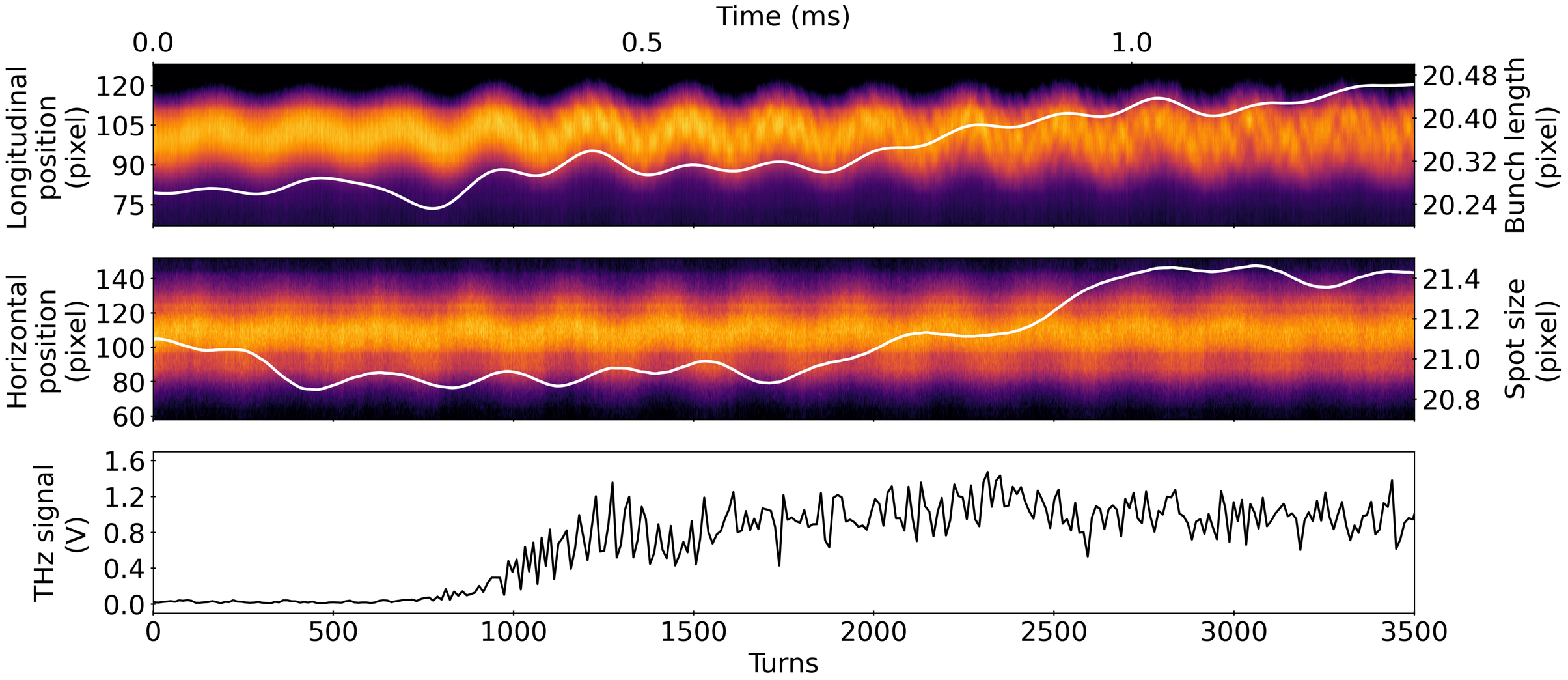

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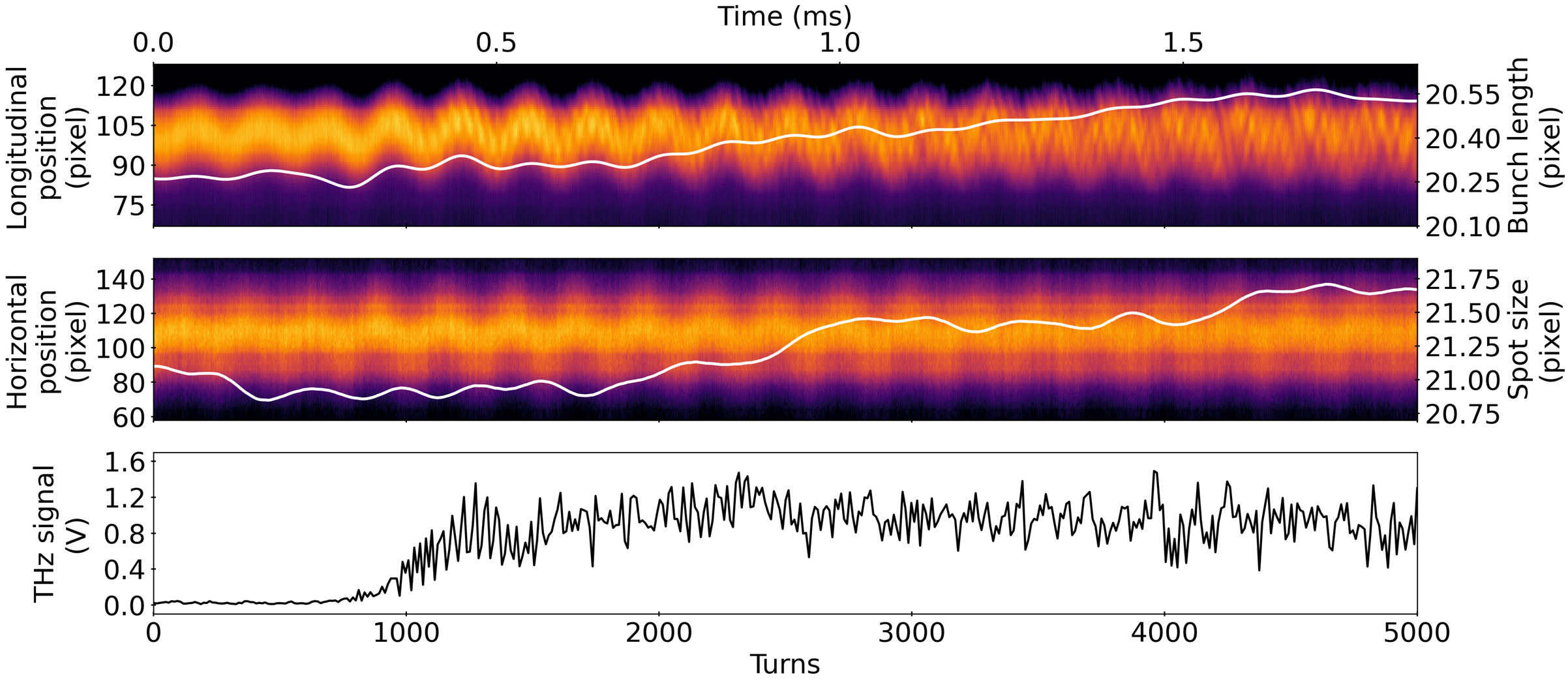

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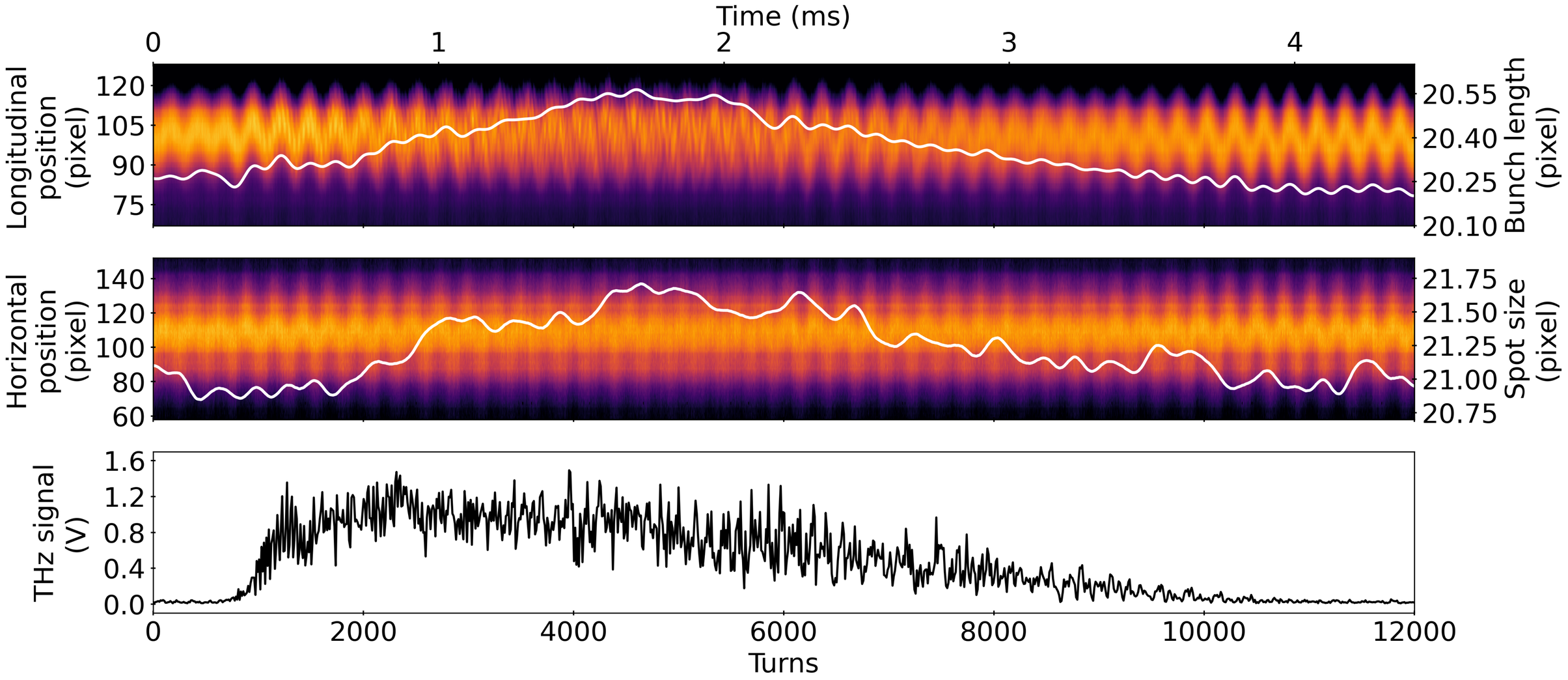

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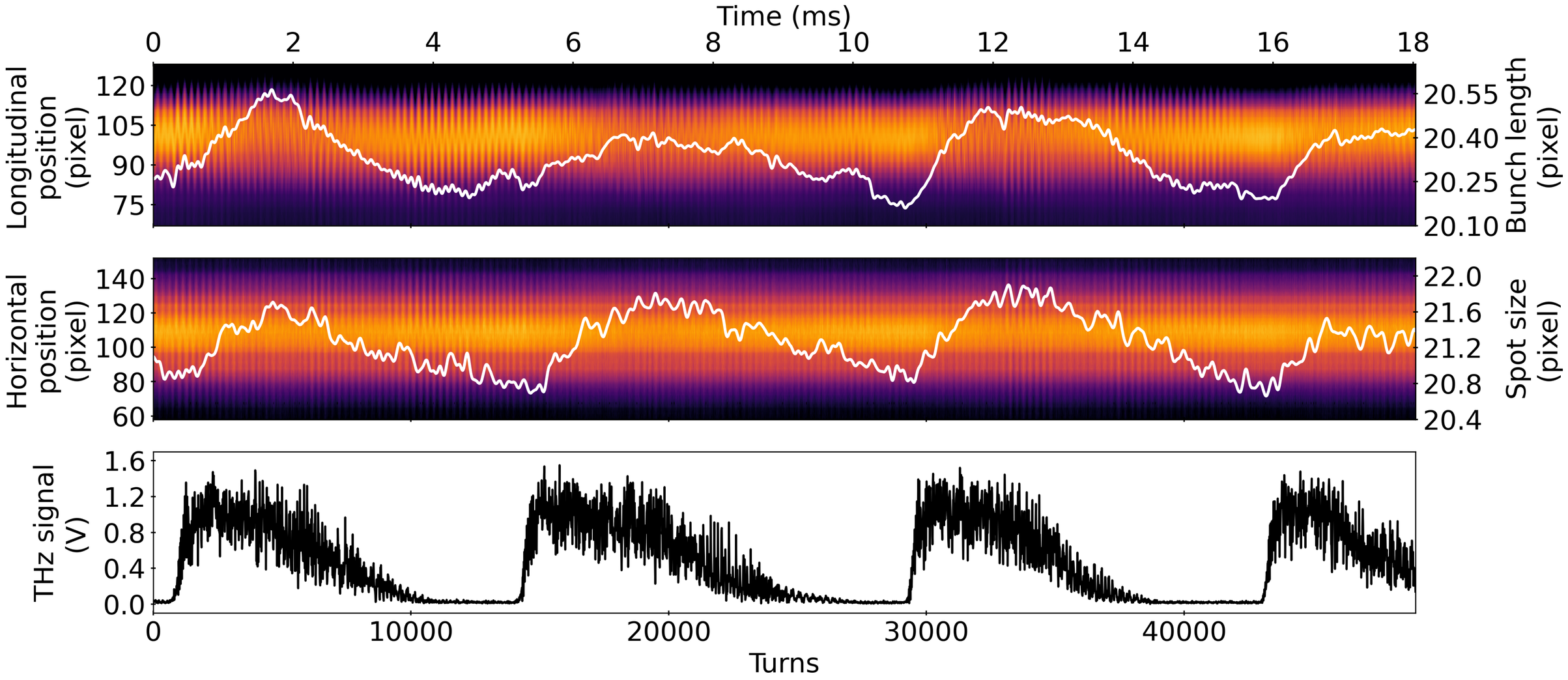

Johannes Steinmann

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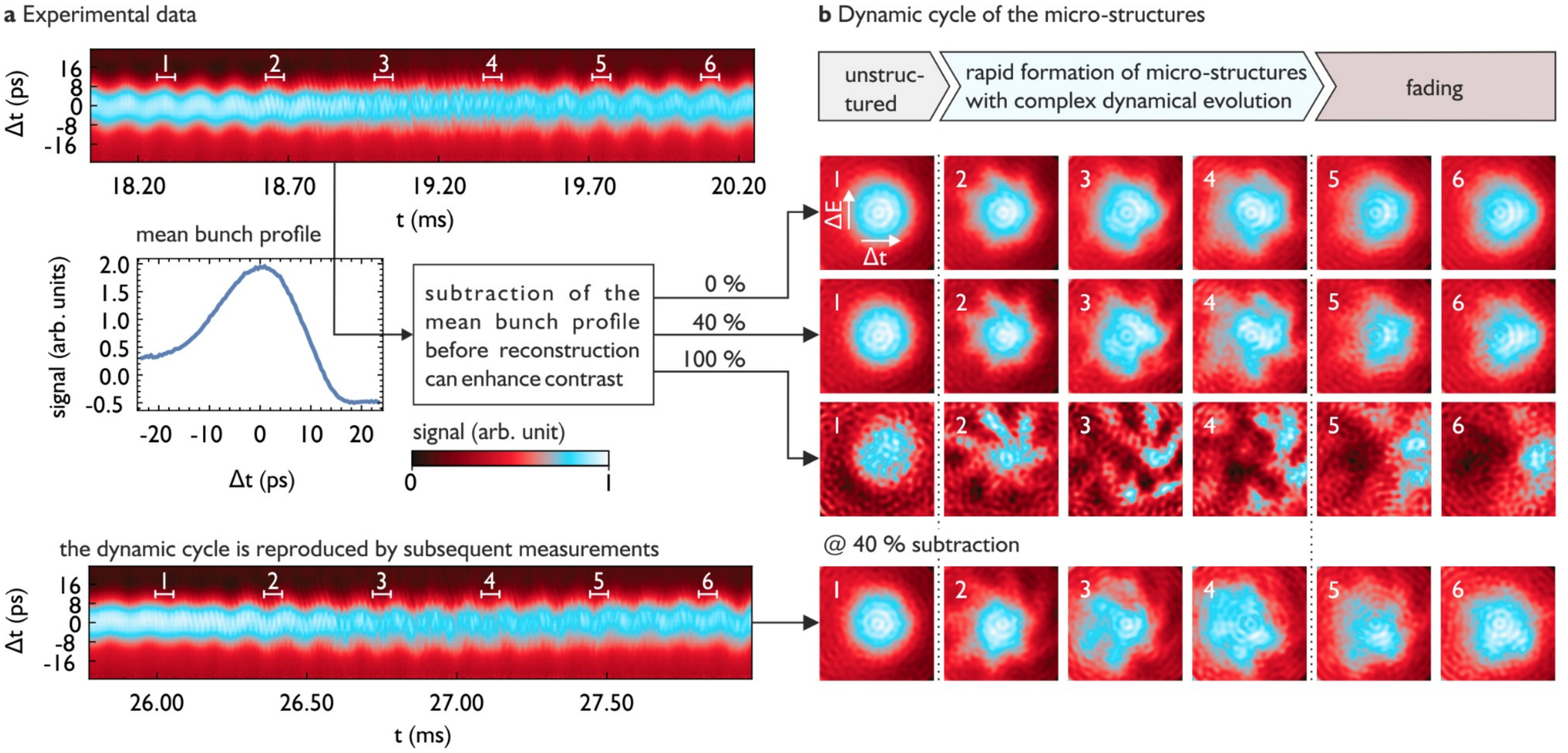
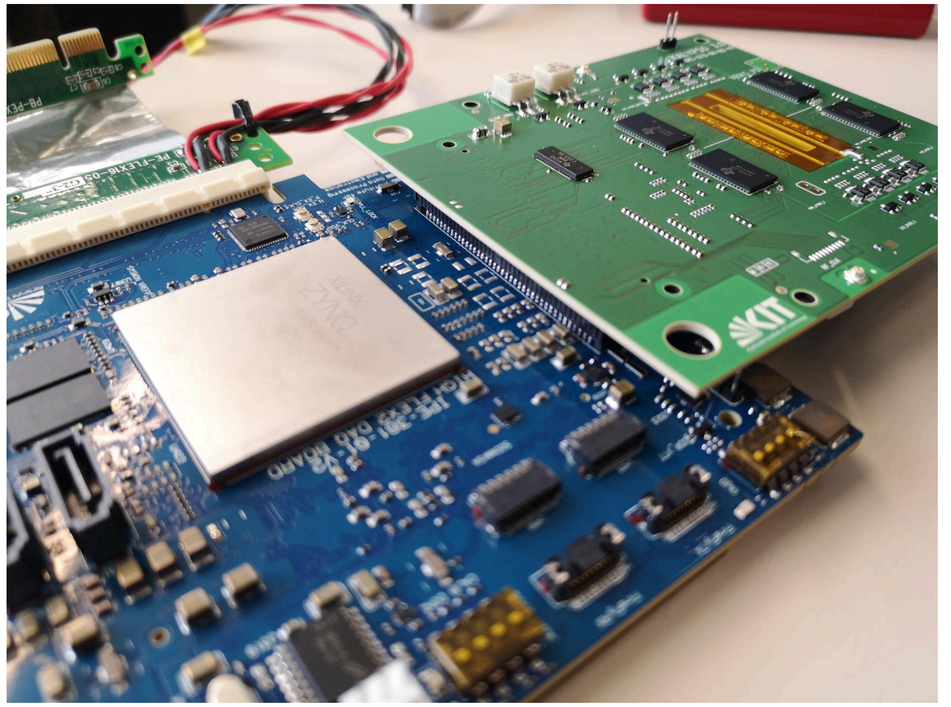
Phase-Space Tomography



Coming Soon: Kalypso III

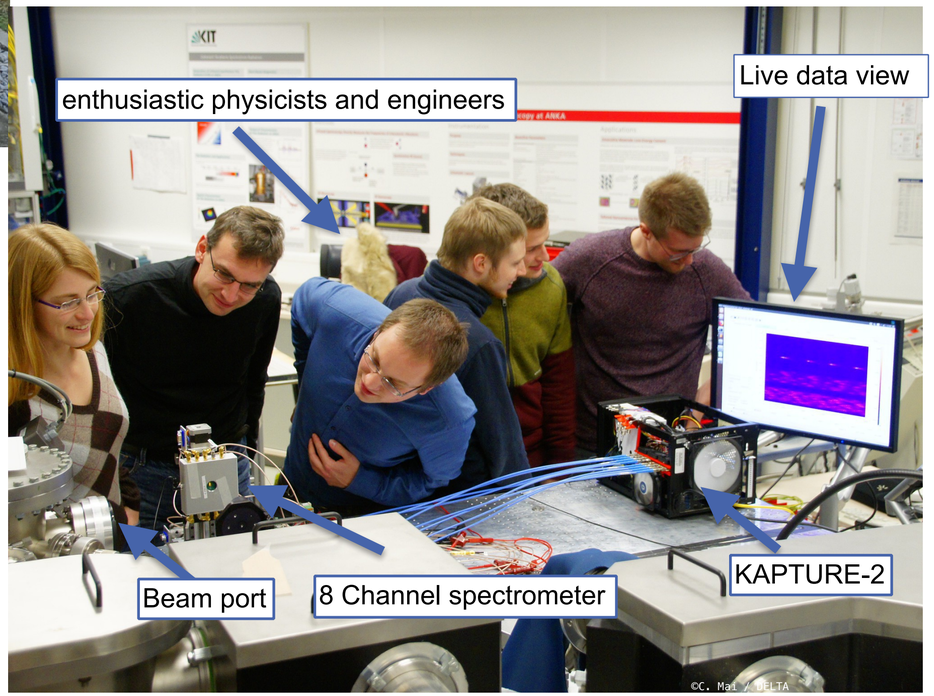
- 12 Mfps @ 512 pixels
- ASIC on CMOS 110 nm, prototype being tested
- Custom Si sensor
- Array size: 512, 1024 and 2048 channels
- Channel pitch: 25 and 45 µm
- Anti-reflecting coating layers, optimized:
  - Near – InfraRed (1050 nm)
  - Visible-light (400-850 nm)
  - Near – UltraViolet (350 nm)



Kalypso v3 prototype working at 12 MHz connected to the HiFlex 2 DAQ

Thank you so much!

Questions?



Literature

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- M. Brosi, et al., “Synchronous Measurements of Electron Bunches Under the Influence of the Microbunching Instability”, DOI: 10.18429/JACoW-IPAC2019-WEPTS015
- M. Caselle, et. al, „KAPTURE-2. A picosecond sampling system for individual THz pulses with high repetition rate“. In: Journal of Instrumentation 12.01 (2017)
- S. Funkner, et. al., “High throughput data streaming of individual longitudinal electron bunch profiles” , PRAB 22, 022801, 2019
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- M. M. Patil, “Modern Ultra-Fast Detectors for Online Beam Diagnostics”, IPAC’21, DOI:10.18429/JACoW-IPAC2021-FRXC03
- L. Rota, PhD Thesis “KALYPSO, a novel detector system for high-repetition rate and real-time beam diagnostics”, DOI: 10.5445/IR/1000082349
- L. Rota, et al. ,“KALYPSO: Linear array detector for high-repetition rate and real-time beam diagnostics”, Nucl. Instrum. Methods Phys. Res. A, 936, pp. 10-13, 2019
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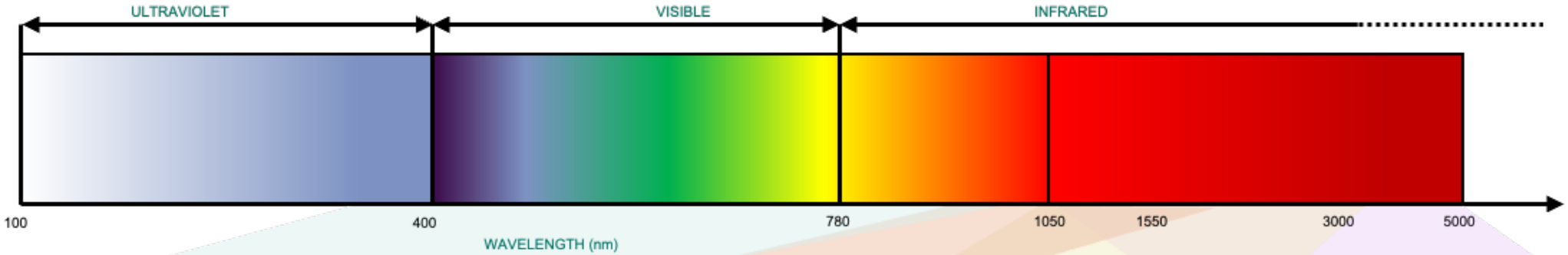
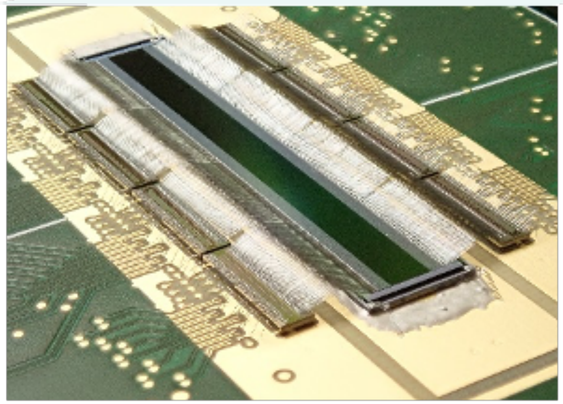
- P. Schütze (2018). “Transversale Strahldynamik bei der Erzeugung kohärenter Synchrotronstrahlung”. BestMasters. Springer Spektrum, Wiesbaden. , DOI: 10.1007/978-3-658-20386-3_4
- J. L. Steinmann, et al., “Turn-by-Turn Measurements for Systematic Investigations of the Micro-Bunching Instability”, DOI: 10.18429/JACoW-FLS2018-TUP2WD03
- J. L. Steinmann, et al., “4-Channel Single Shot and Turn-by-Turn Spectral Measurements of Bursting CSR”, DOI: 10.18429/JACoW-IPAC2017-MOPAB056
- J. L. Steinmann, et al, “Continuous bunch-by-bunch spectroscopic investigation of the microbunching instability”, DOI: 10.1103/PhysRevAccelBeams.21.110705
- J. L. Steinmann, PhD Thesis, “Diagnostics of Short Electron Bunches with THz Detectors in Particle Accelerators”, DOI: 10.5445/KSP/1000090017

Sensor Technologies

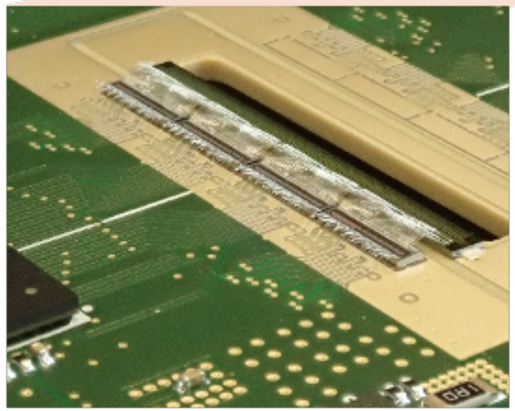


350-1050 nm



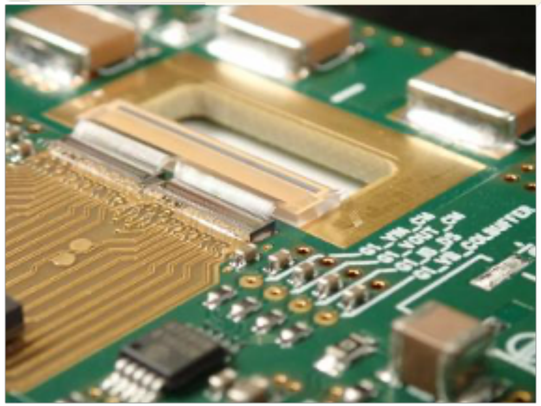
Si

950-2000 nm



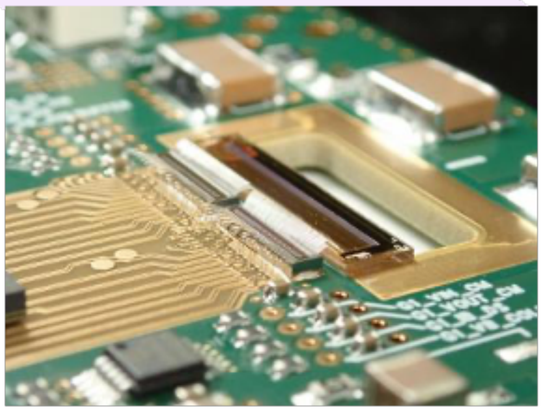
InGaAs

1000-3300 nm



PbS

1000-5000 nm



PbSe

M. M. Patil, “Modern Ultra-Fast Detectors for Online Beam Diagnostics”, IPAC’21, DOI:10.18429/JACoW-IPAC2021-FRXC03