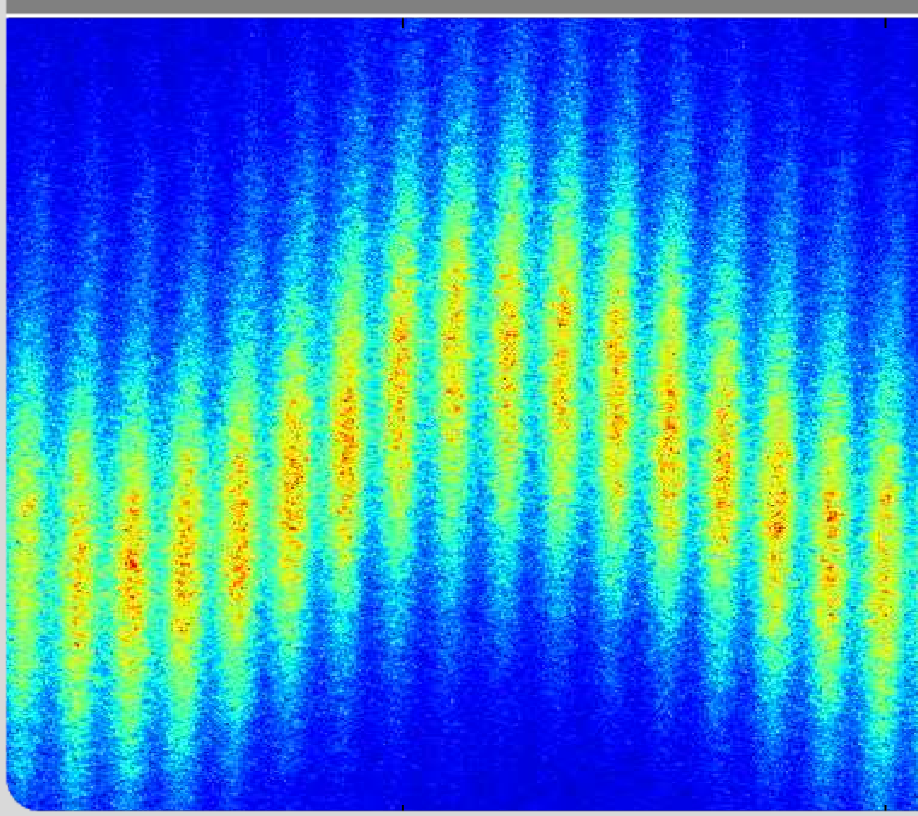
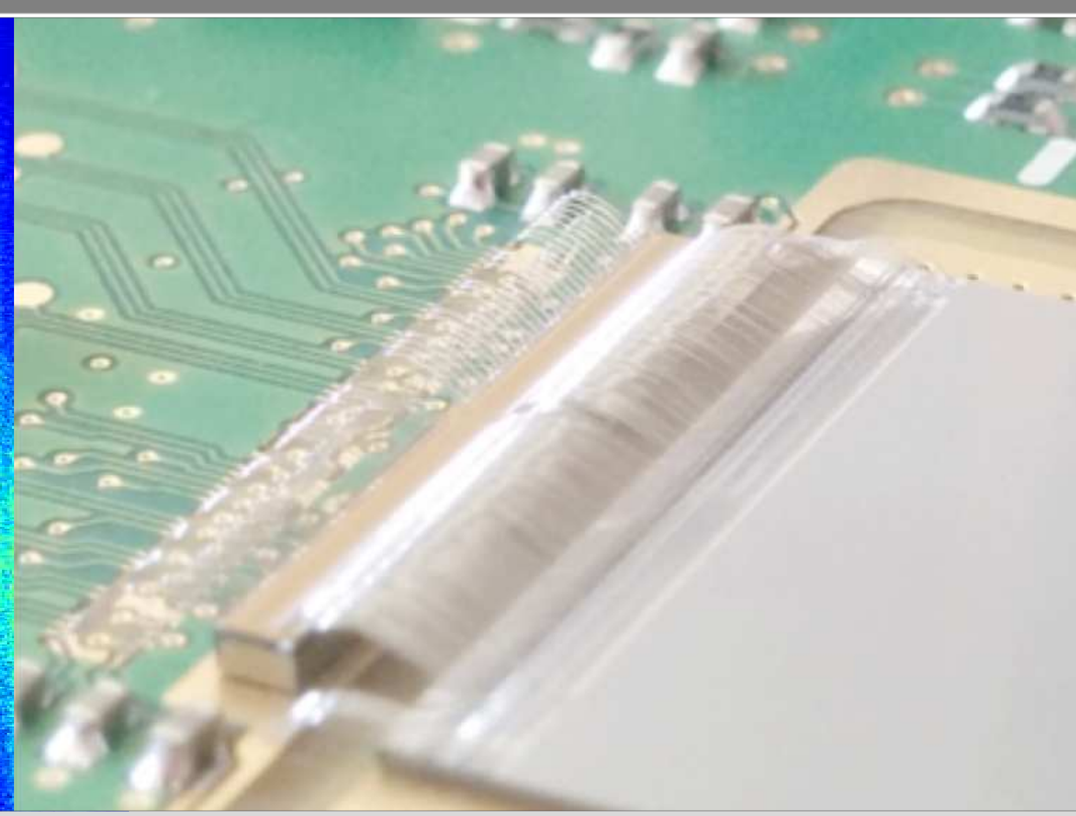
Turn-by-Turn Measurements for Systematic Investigations of the Micro-Bunching Instability

J. L. Steinmann, M. Brosi, E. Bründermann, M. Caselle, S. Funkner, B. Kehrer, M. J. Nasse, G. Niehues, L. Rota, P. Schönfeldt, M. Schuh, M. Siegel, M. Weber, A.-S. Müller

Laboratory for Applications of Synchrotron Radiation (LAS)





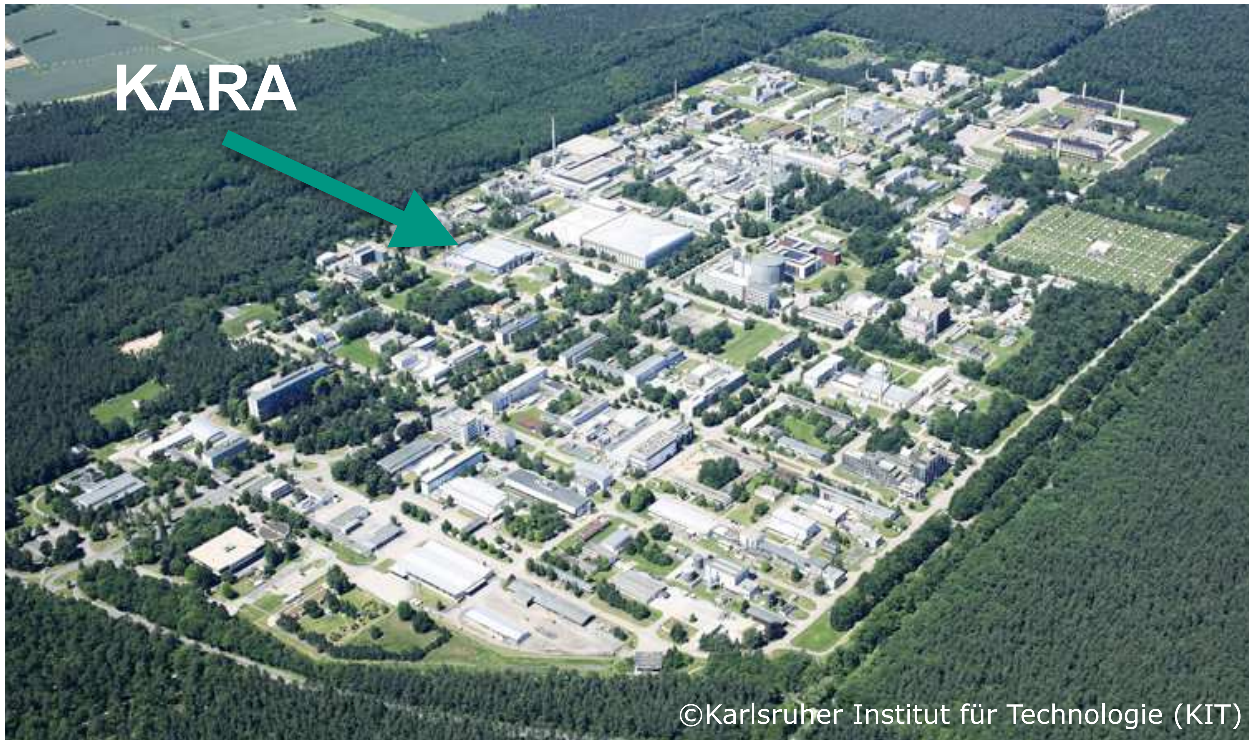
Outline

- Karlsruhe Institute of Technology
- Micro-bunching instability
- Detector systems and requirements

- THz emission (KAPTURE)
- Energy spread (fast gated camera)
- Longitudinal bunch profile (KALYPSO)

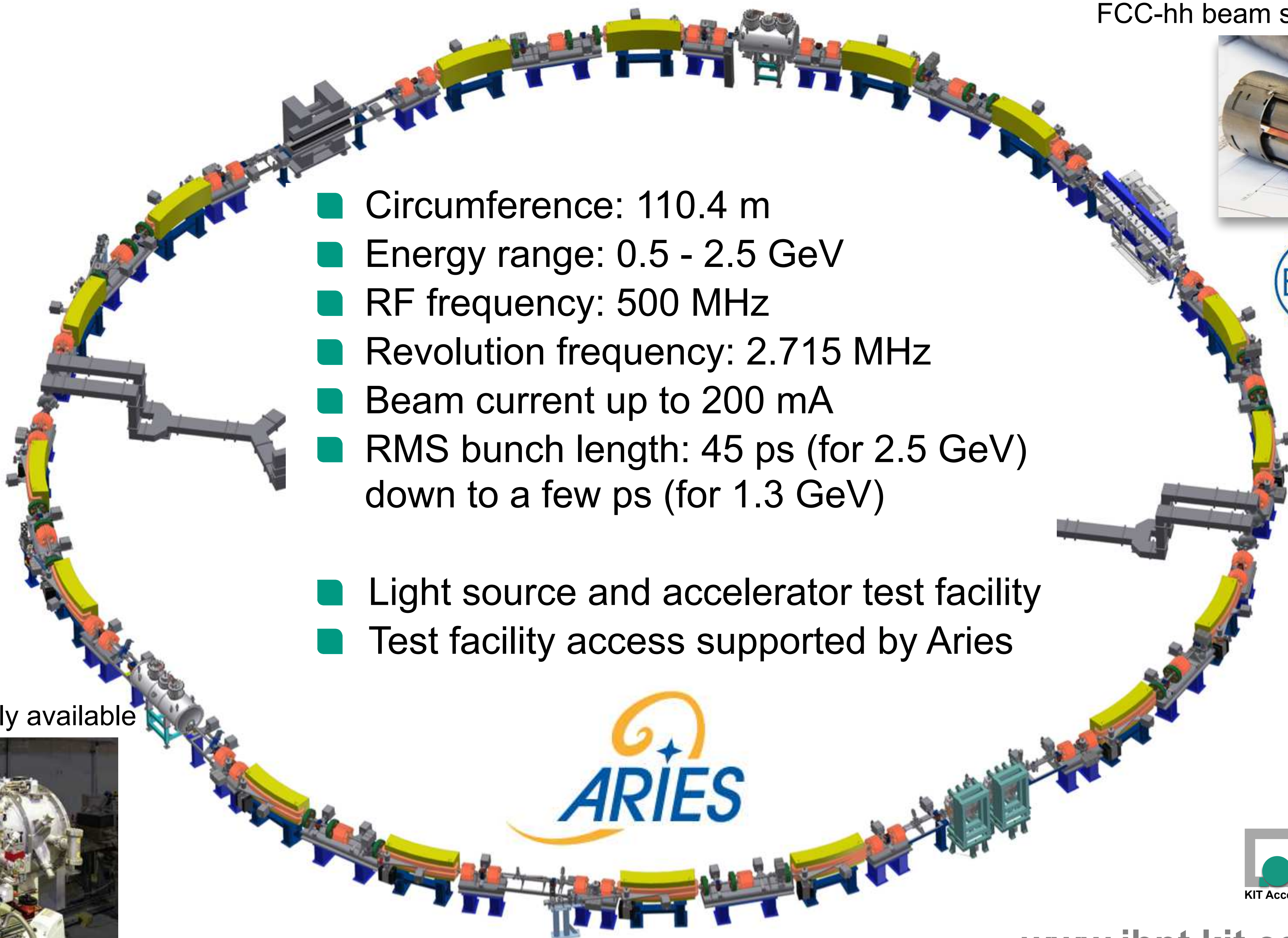
Karlsruhe Institute of Technology

- Located in south-west Germany
- The **Research** University in the **Helmholtz** Association
- Operating 2.5 GeV storage ring KARA
- Close collaboration between physics / various engineering departments
- Development of novel diagnostics



Karlsruhe Research Accelerator (KARA)

FCC-hh beam screen prototype



- Circumference: 110.4 m
- Energy range: 0.5 - 2.5 GeV
- RF frequency: 500 MHz
- Revolution frequency: 2.715 MHz
- Beam current up to 200 mA
- RMS bunch length: 45 ps (for 2.5 GeV) down to a few ps (for 1.3 GeV)

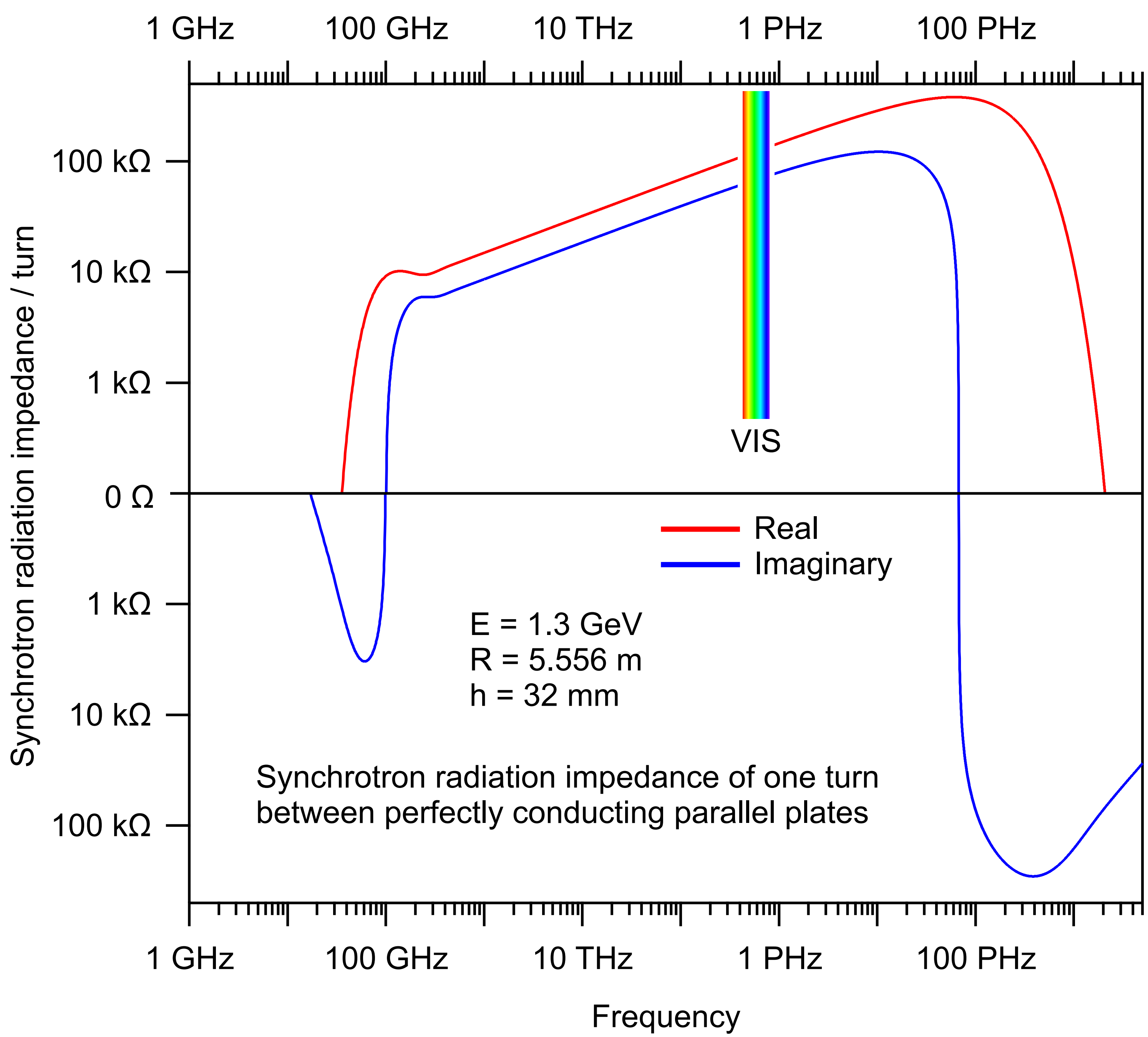
- Light source and accelerator test facility
- Test facility access supported by Aries

SCU20 commercially available

www.ibpt.kit.edu/kara

Micro-bunching instability

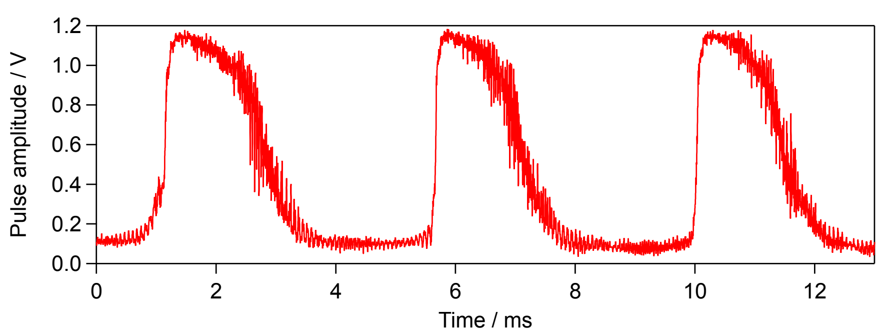
- Longitudinal instability
- CSR self-interaction
- PP-Impedance

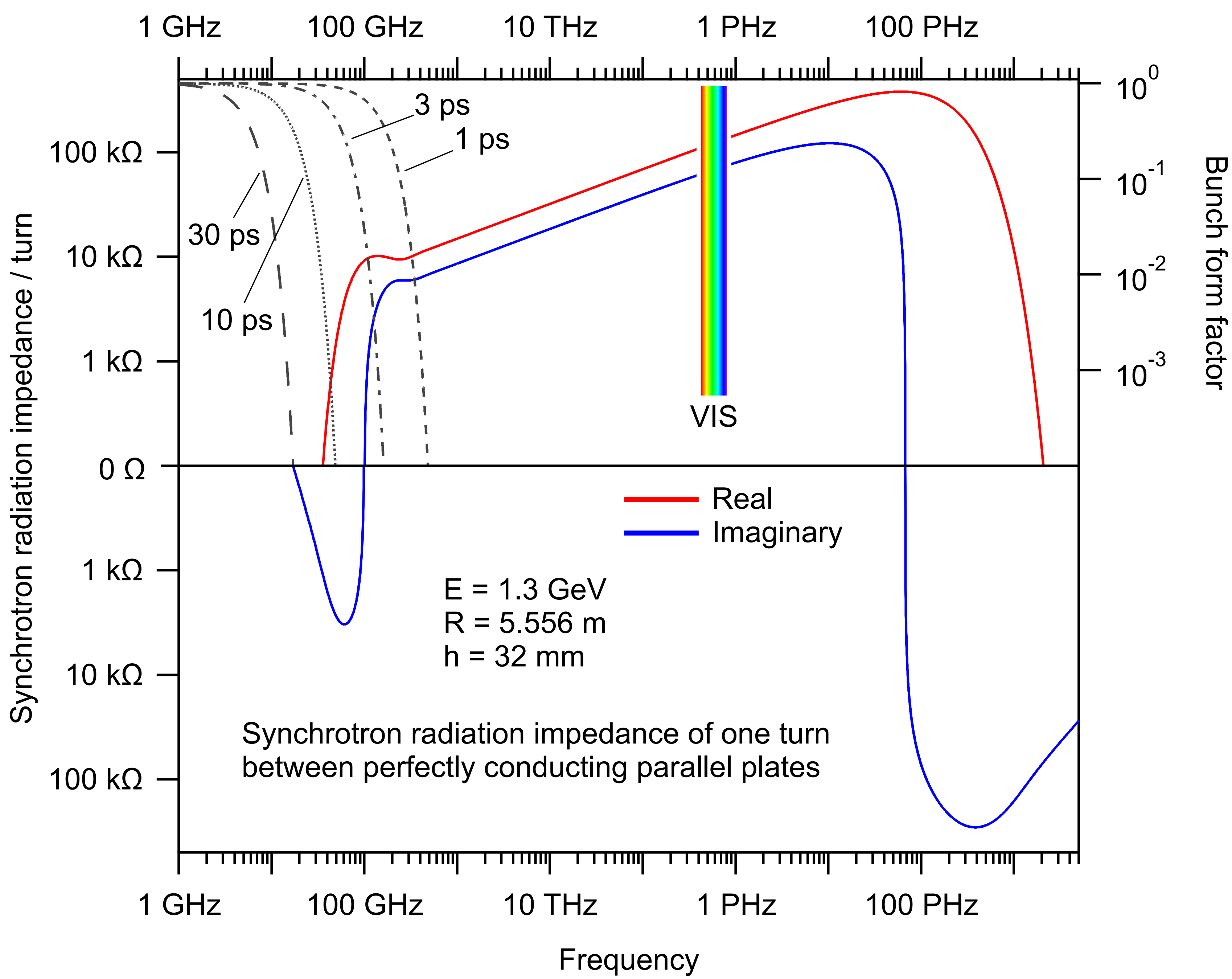


Low frequencies: T. Agoh. „Steady fields of coherent synchrotron radiation in a rectangular pipe“. In: Phys. Rev. ST Accel. Beams 12 DOI: 10.1103/PhysRevSTAB.12.094402
High frequencies: R. Li and C.-Y. Tsai. „CSR Impedance for Non-Ultrarelativistic Beams“, IPAC 2015: http://jacow.org/IPAC2015/papers/mopmn004.pdf

Micro-bunching instability

- Longitudinal instability
- CSR self-interaction
- PP-Impedance
- Effects picosecond short bunches
- Strong instability
- Sawtooth behaviour





Low frequencies: T. Agoh. „Steady fields of coherent synchrotron radiation in a rectangular pipe“. In: Phys. Rev. ST Accel. Beams 12 DOI: 10.1103/PhysRevSTAB.12.094402
High frequencies: R. Li and C.-Y. Tsai. „CSR Impedance for Non-Ultrarelativistic Beams“, IPAC 2015: http://jacow.org/IPAC2015/papers/mopmn004.pdf

Diagnostic requirements

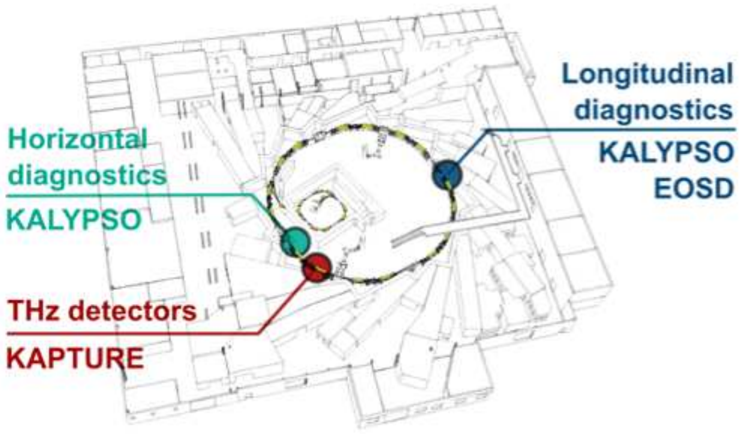
- We want to observe the longitudinal phase space
  - Emitted coherent radiation (THz range) [“indirect”]
  - Longitudinal bunch profile (< ps resolution) [“direct”]
  - Energy spread profile [“direct”]

- Relevant time scales

Size of sub-structures	(sub-)ps
Bunch spacing / turns	2 ns / 368 ns
Rise of micro-bunching instability	~ 100 µs
Repetition rate between outbursts	~ ms
Current dependent changes	~ seconds/hours

- Diagnostic requirements:
  - High resolution (ps)
  - High repetition rate (500 MHz / 2.7 MHz)
  - Long term observation (secs - hr)

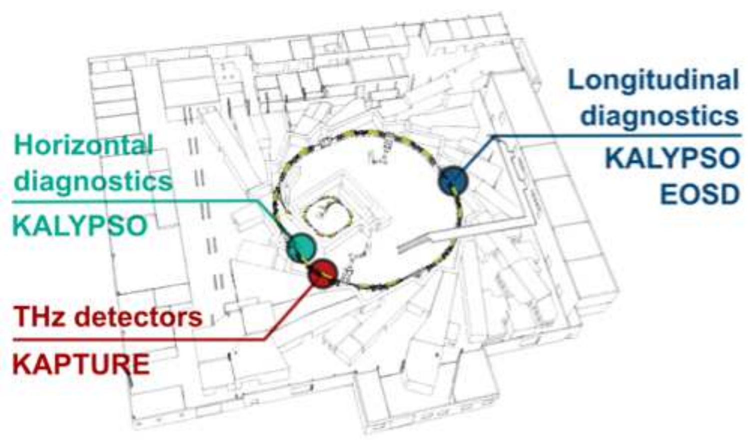
KARA distributed sensor network



Analyze Longitudinal Phase Space

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

KARA distributed sensor network



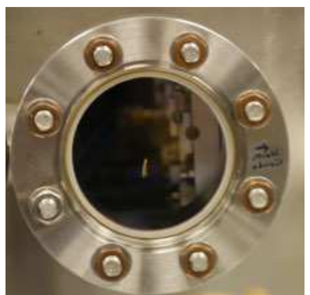
Analyze Longitudinal Phase Space

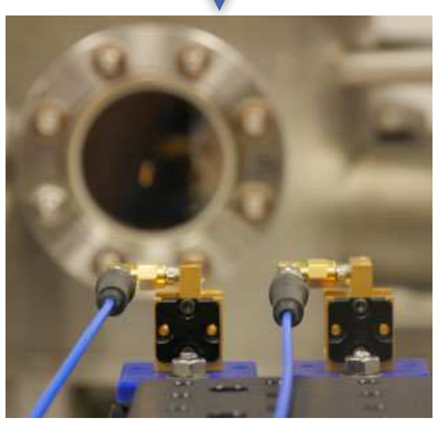
- **Emitted CSR**
  - THz Detector
  - KAPTURE
- **Energy Spread**
  - Horizontal bunch profile in dispersive section
  - FGC: fast gated camera
- **Bunch Profile**
  - Electro-optical spectral decoding
  - KALYPSO

KAPTURE

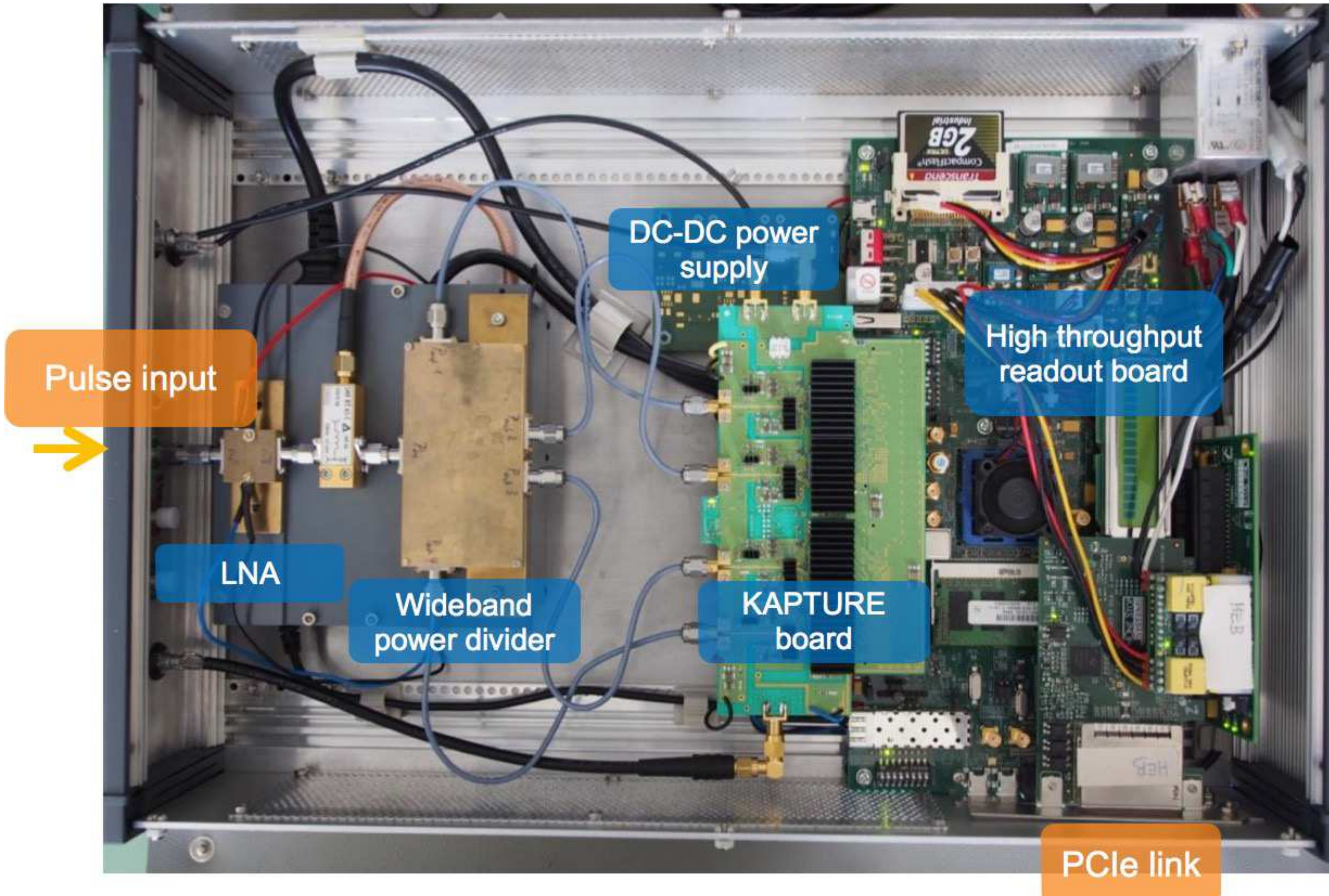
KArlsruhe Pulse Taking Ultra-fast Readout Electronics

IR Beamline
(edge radiation)



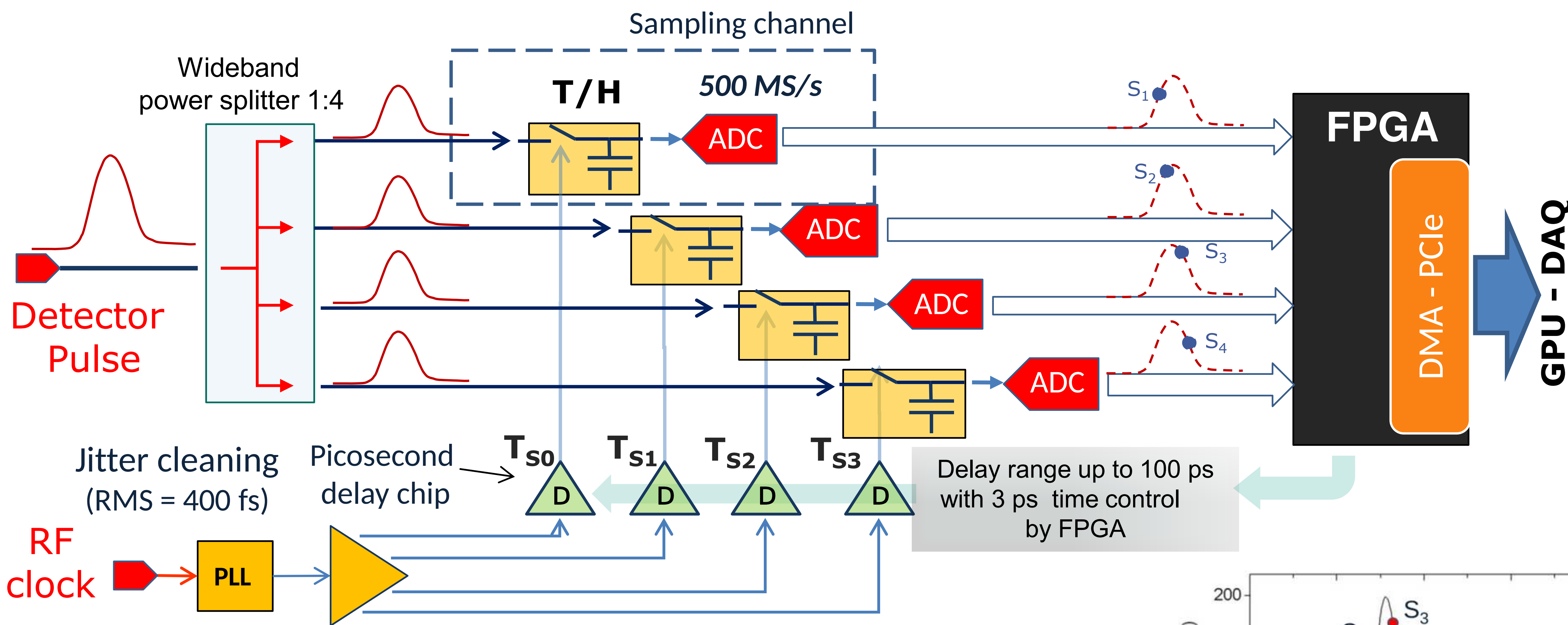


THz Detector

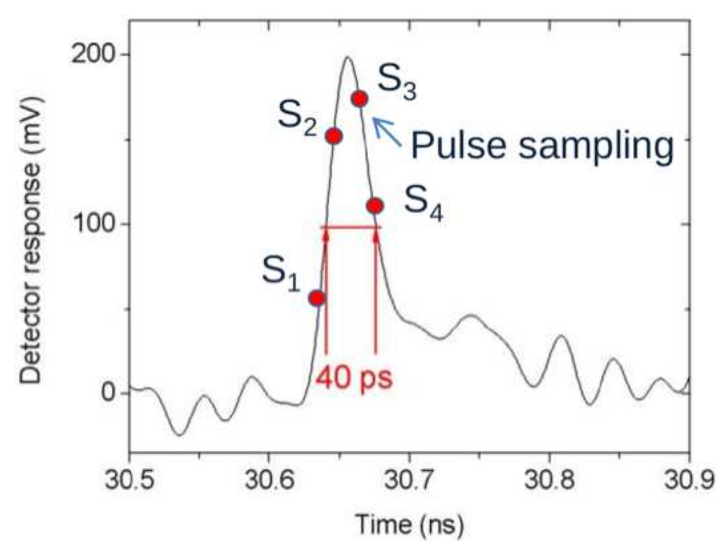


M. Caselle et. al., IPAC14: DOI: JACoW-IPAC2014-THPME113
M. Caselle et. al., IBIC14: URL: http://jacow.org/IBIC2014/papers/moczb1.pdf

KAPTURE sampling stage

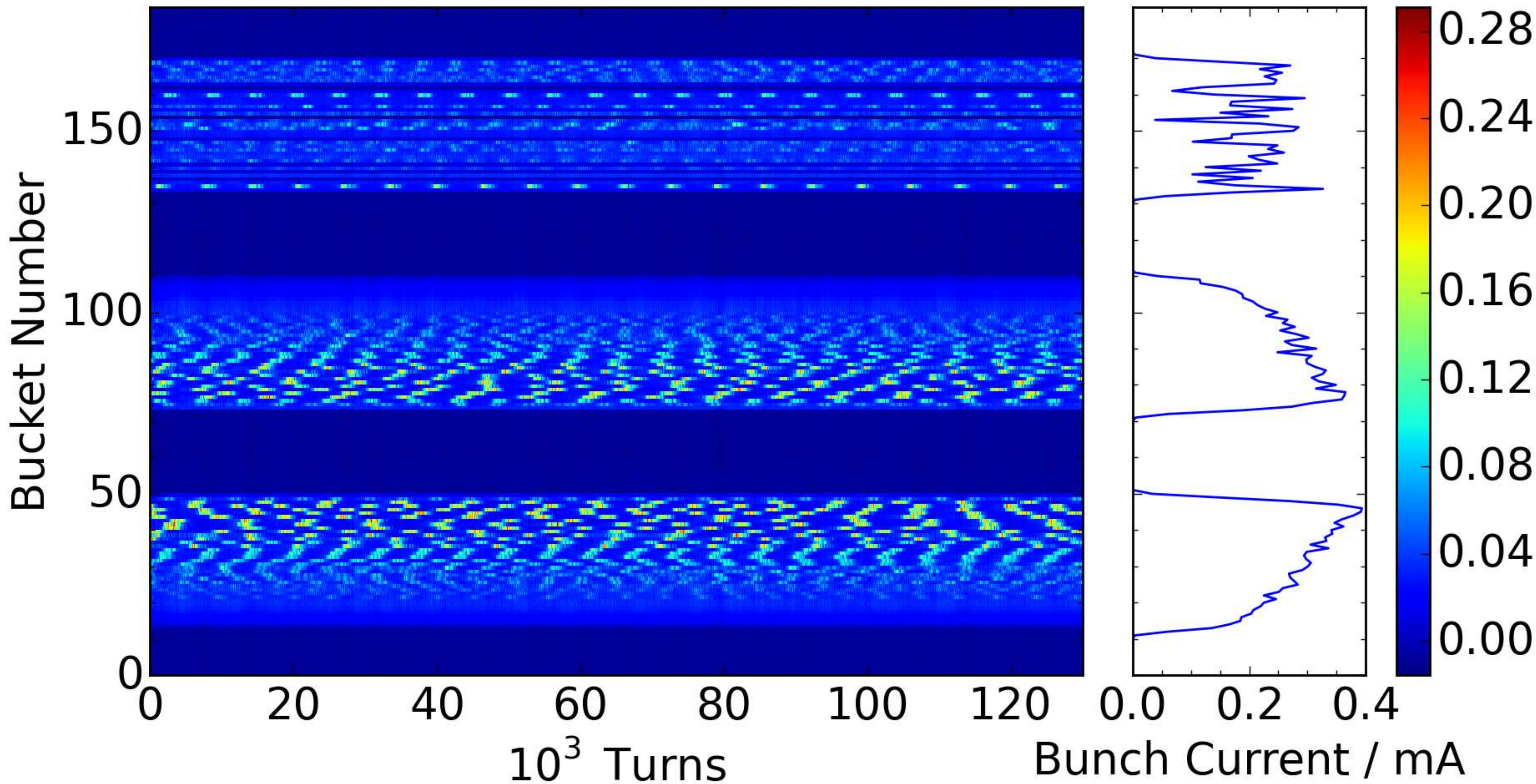


- Steps of 3 ps
- Each channel individually adjustable
- Ability to measure arrival time, width and amplitude



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), http://stacks.iop.org/1748-0221/12/i=01/a=C01040.

KAPTURE raw data of pulse amplitude

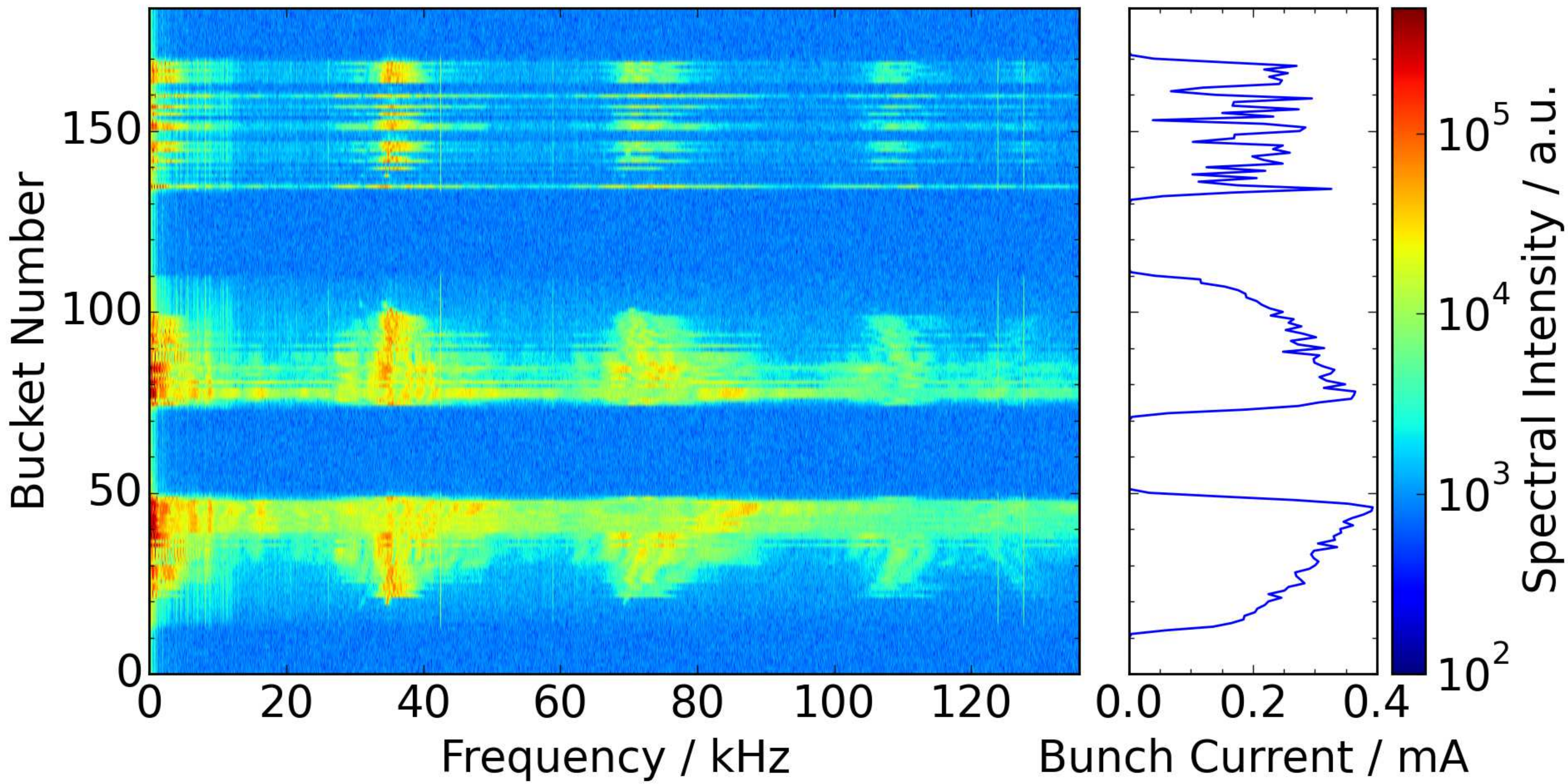


Current dependent effects can be studied with a tailored filling pattern

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

KAPTURE data - Fourier transformation

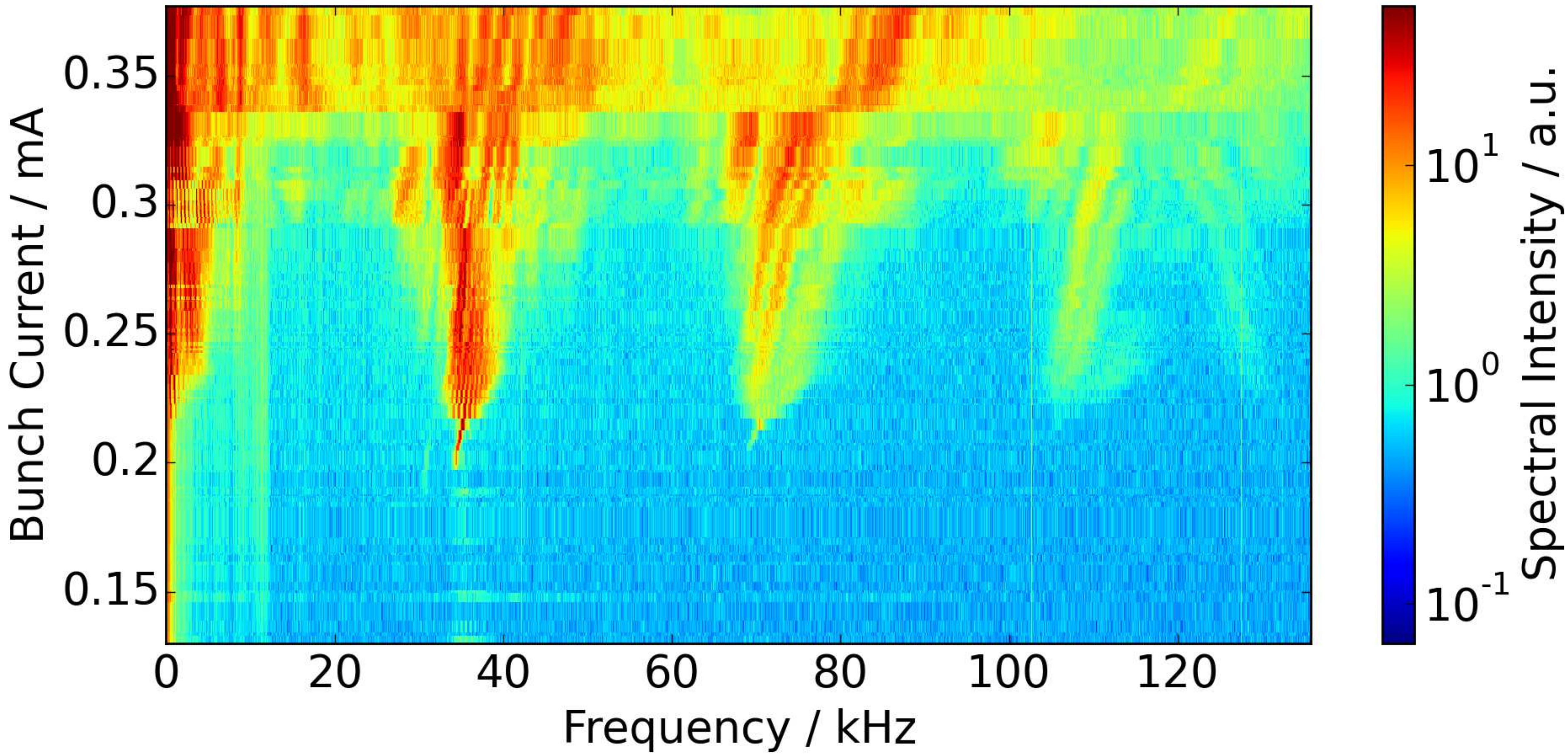
Karlsruher Institut für Technologie



Current dependent effects can be studied with a tailored filling pattern

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

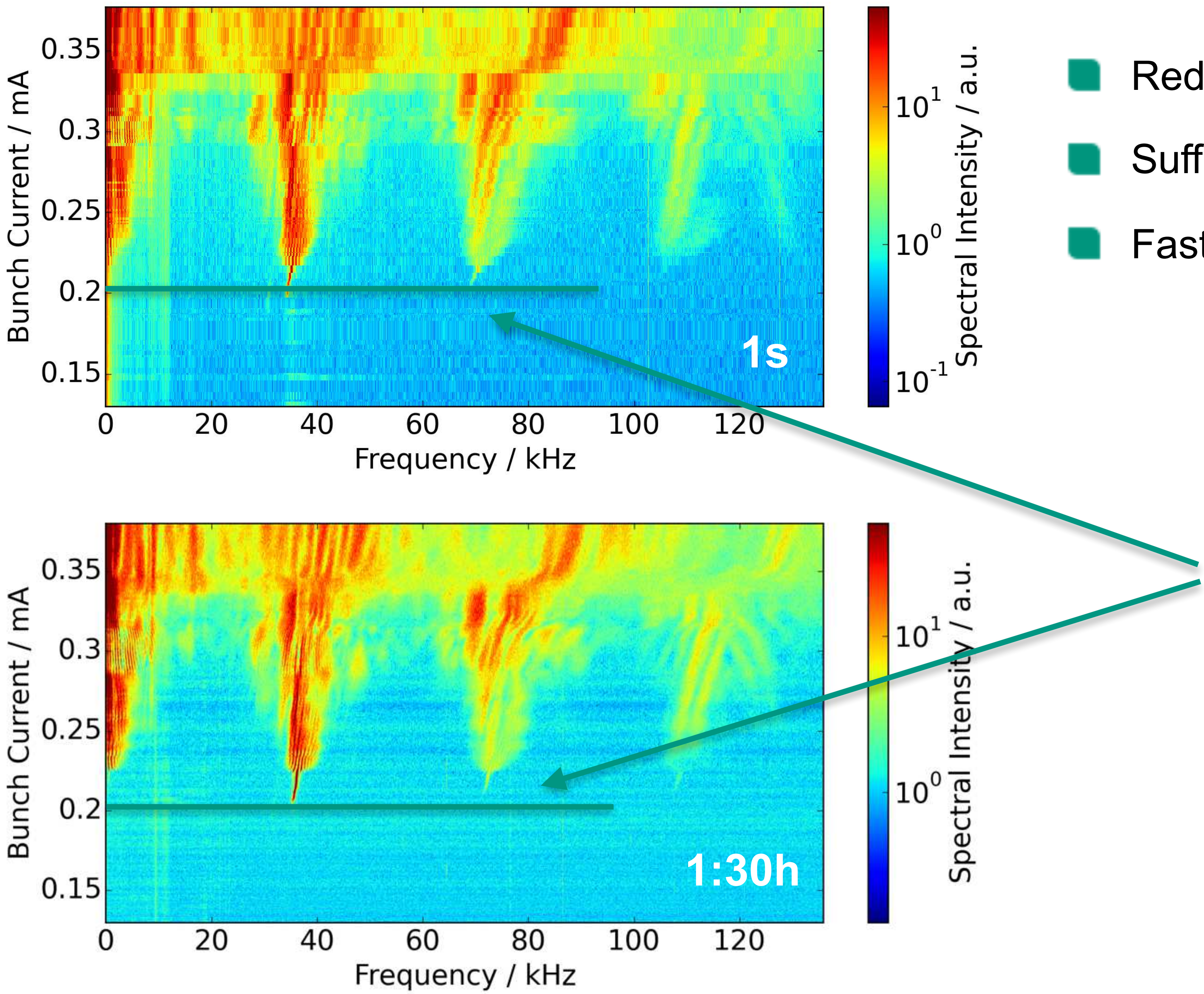
Snapshot method



Full spectrogram recorded in a single second with KAPTURE

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

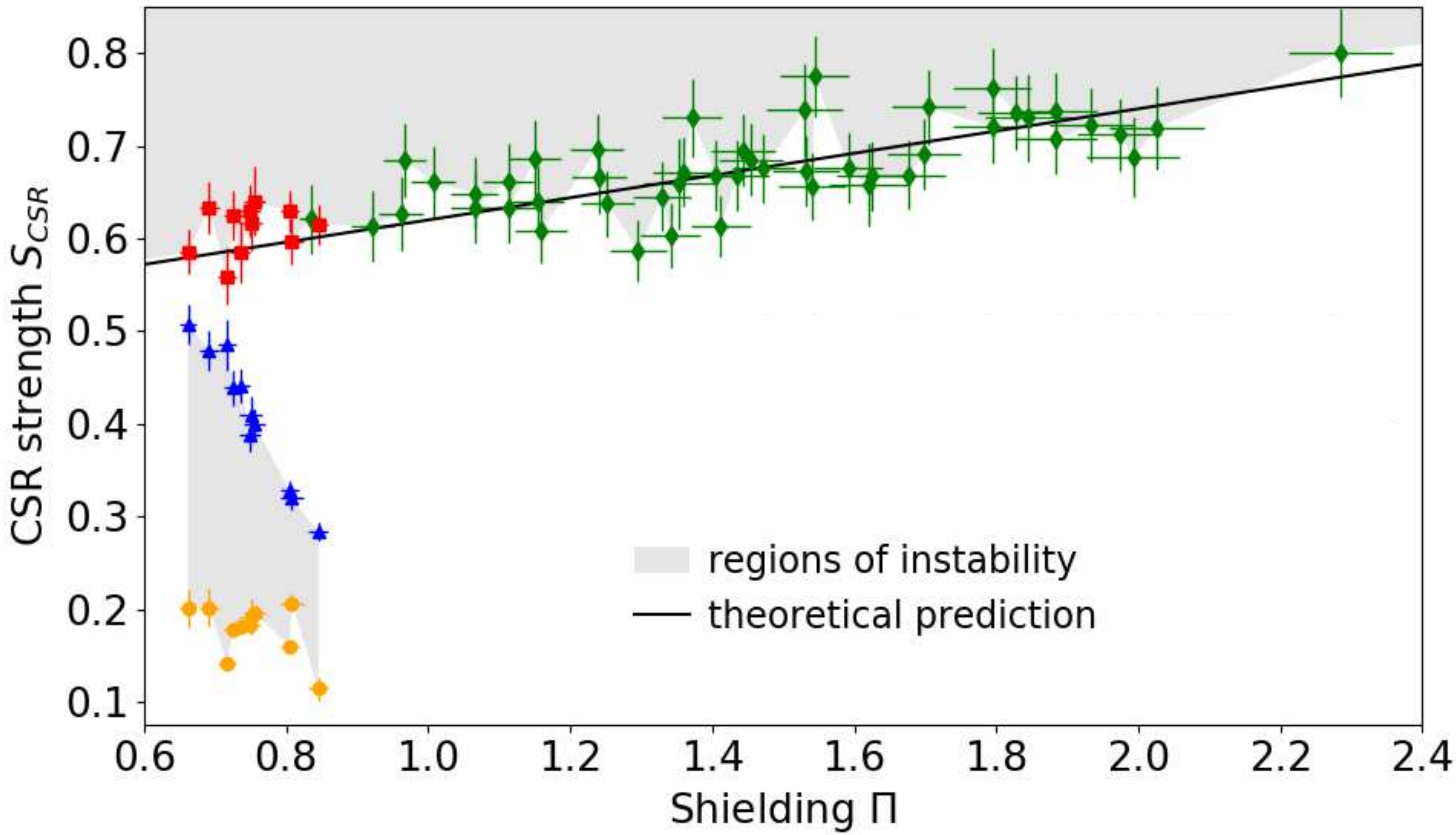
Snapshot method



- Reduced measurement time
- Sufficient current resolution
- Fast scan of machine settings

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

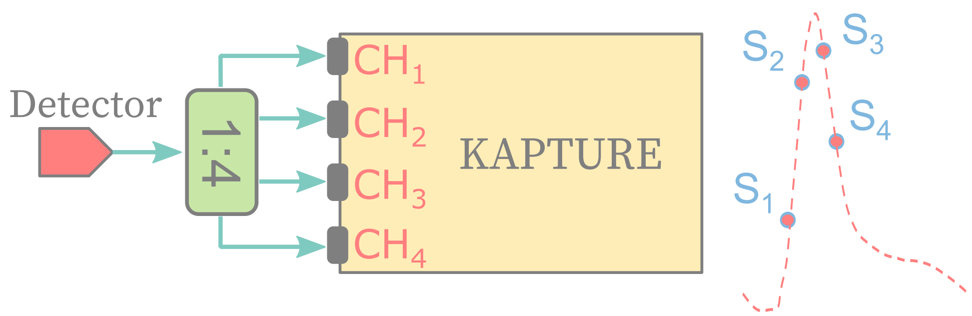
Parameter scan to determine MBI threshold



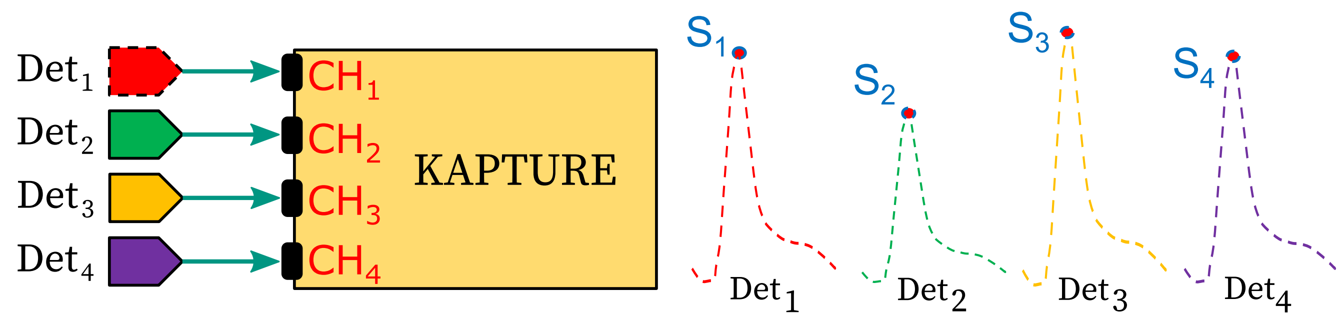
For conventions of S_{CSR} and ∏, see: K.L.F. Bane, Y. Cai and G. Stupakov, *Phys. Rev. ST Accel. Beams*, vol. 13, 2010, doi: 10.1103/PhysRevSTAB.13.104402.

M. Brosi, et. al., „Systematic Studies of Short Bunch-Length Bursting at ANKA“, *IPAC 2016,* DOI: 10.18429/JACoW-IPAC2016-TUPOR006.

Single-shot 4-channel spectrometer



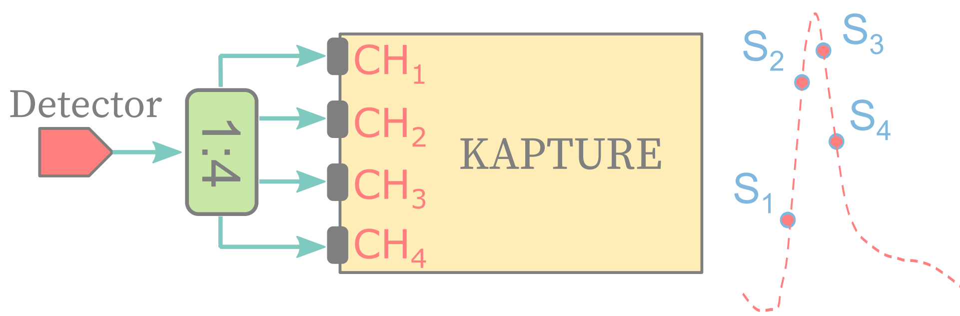
Configuration 1



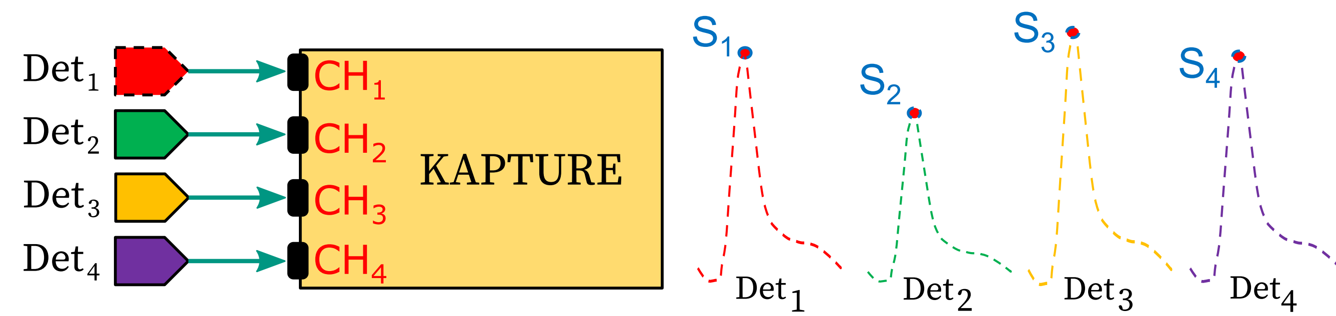
Configuration 2

J. L. Steinmann et. al., IPAC17, DOI: 10.18429/JACoW-IPAC2017-MOPAB056.

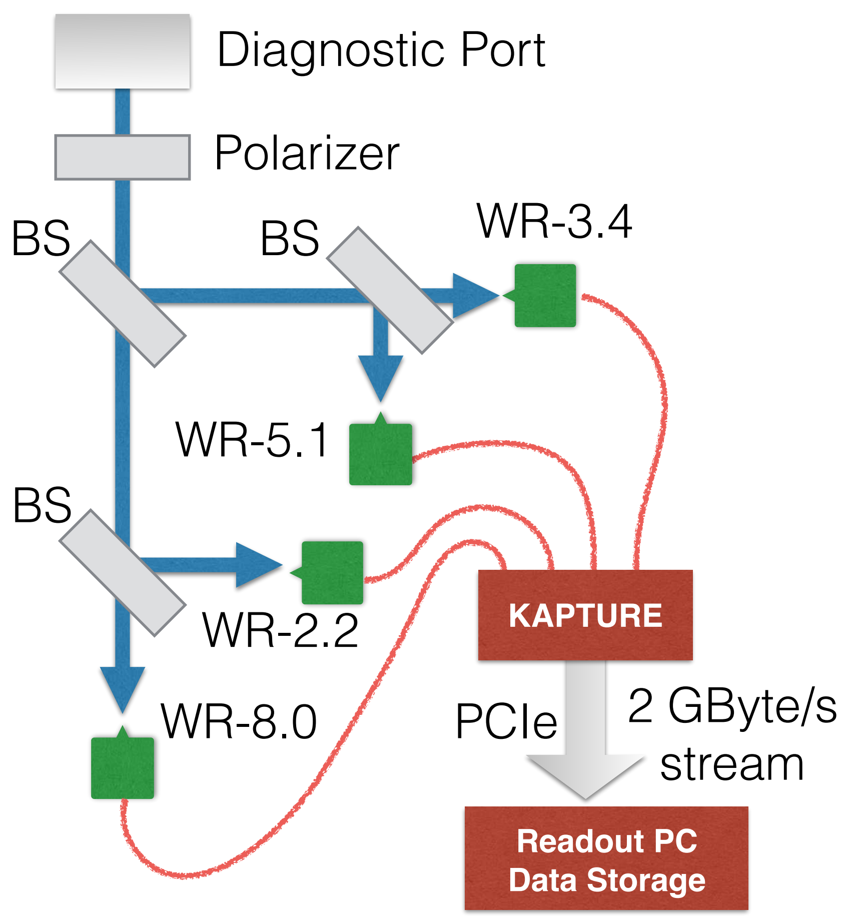
Single-shot 4-channel spectrometer

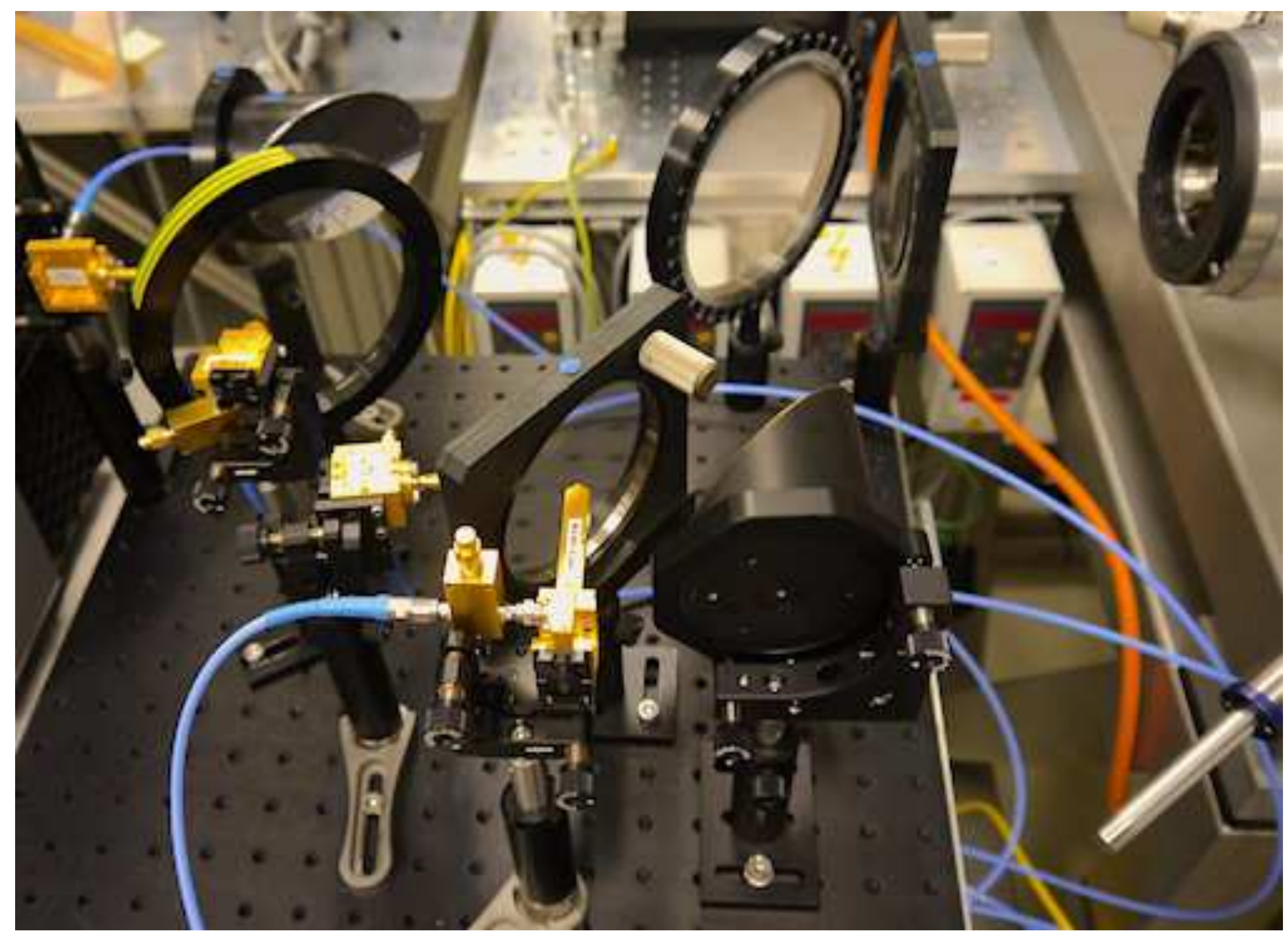


Configuration 1



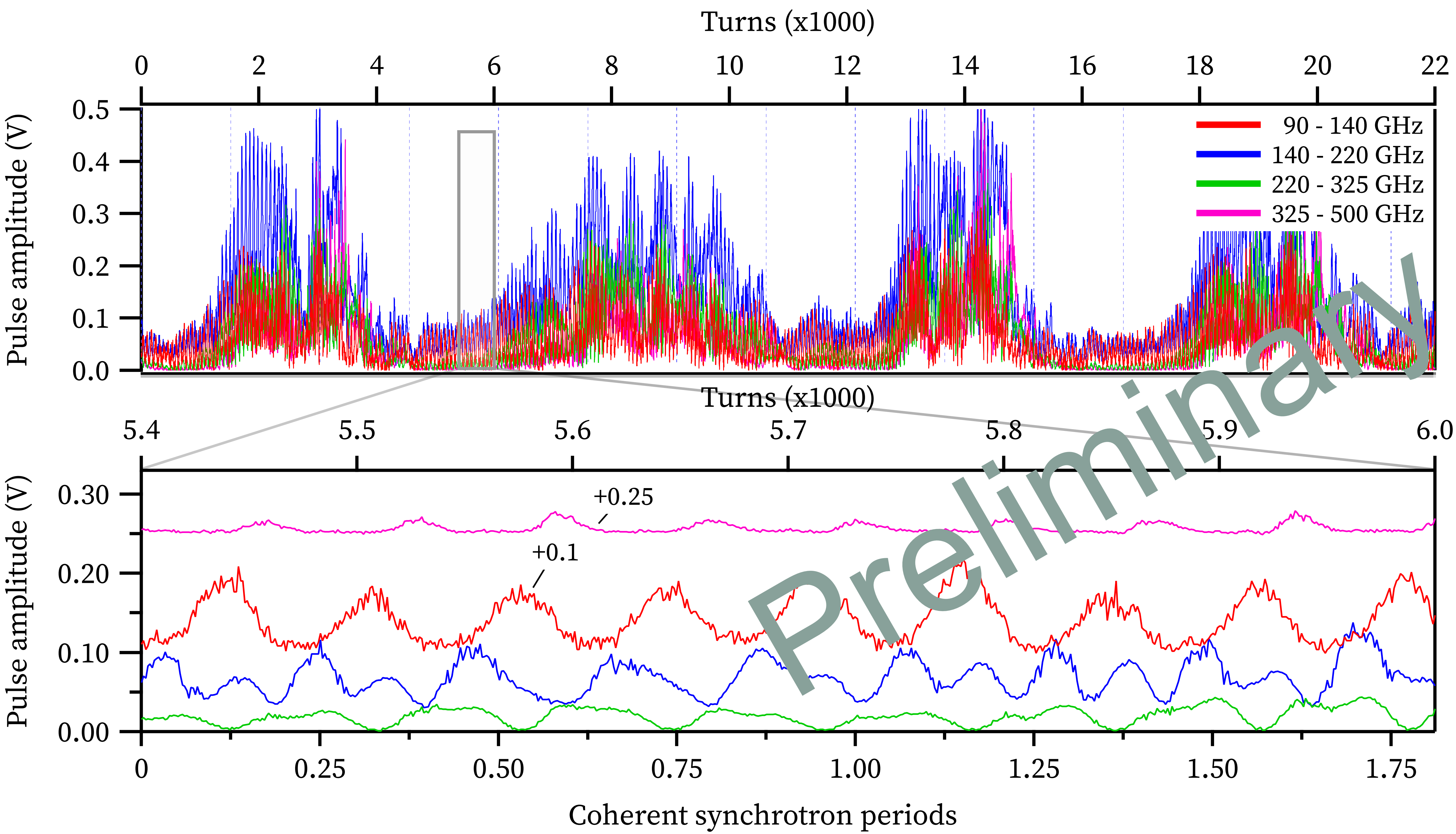
Configuration 2





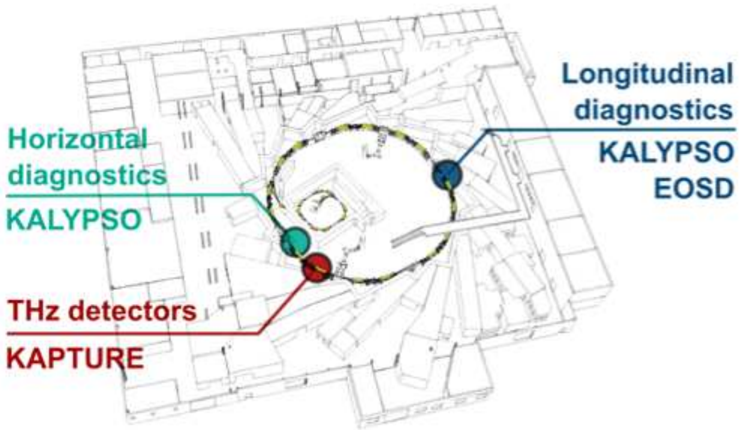
J. L. Steinmann et. al., IPAC17, DOI: 10.18429/JACoW-IPAC2017-MOPAB056.

Single-shot 4-channel spectrometer



J. L. Steinmann, to be published

KARA distributed sensor network

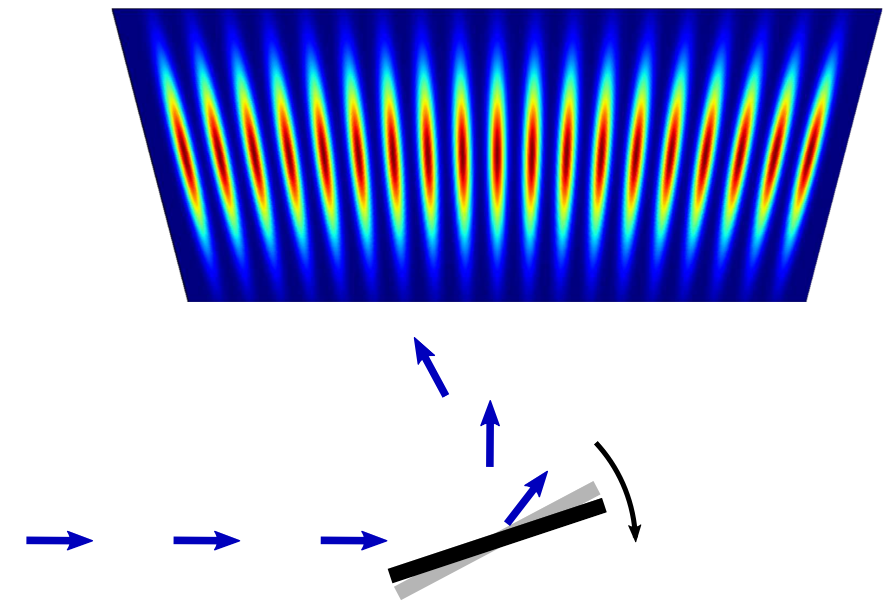


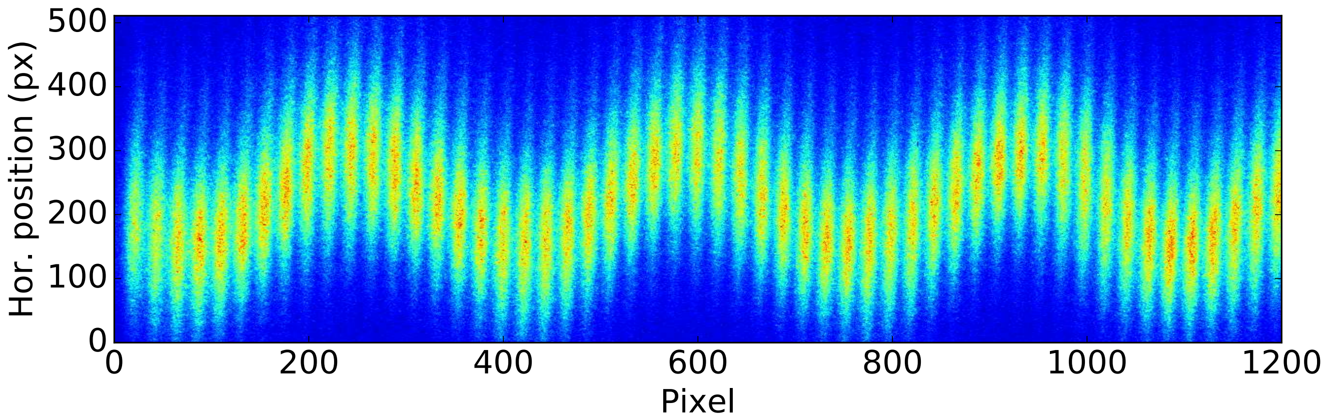
Analyze Longitudinal Phase Space

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

Time-resolved energy spread studies

- Horizontal bunch size in a dispersive section correlates with the energy spread
- Fast-gated camera + rotating mirror
- Image intensifier as pulse picker
- Single-turn images of single bunch





Every 50th turn

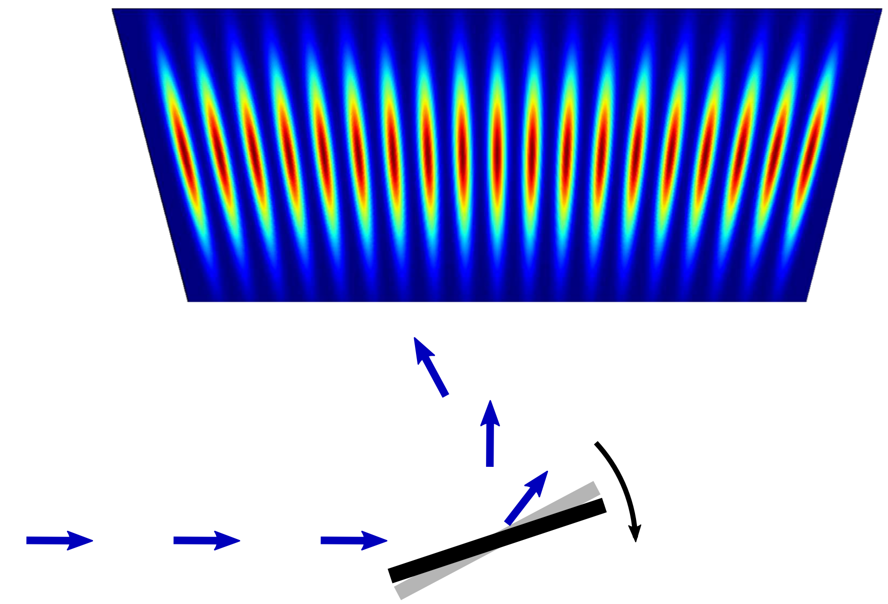
- Minimum separation: 6 turns
- Maximum number of spots: ~60

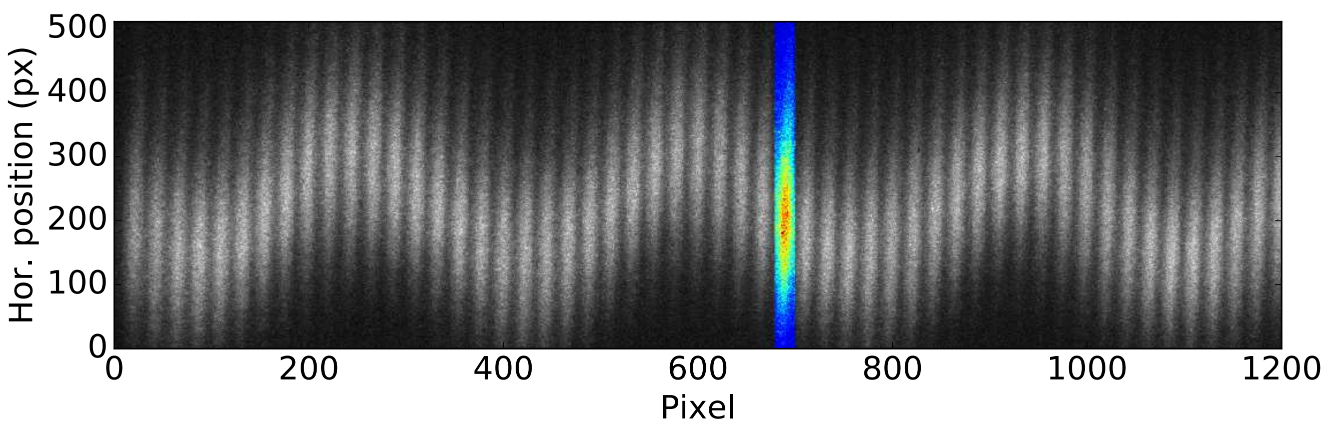
B. Kehrer *et al.*, “Visible Light Diagnostics at the ANKA Storage Ring,”, *IPAC’15*,
P. Schütze “Transversale Stahldynamik bei der Erzeugung kohärenter Synchrotronstrahlung”. Springer, 2017, isbn: 978- 3-658-20385-6.

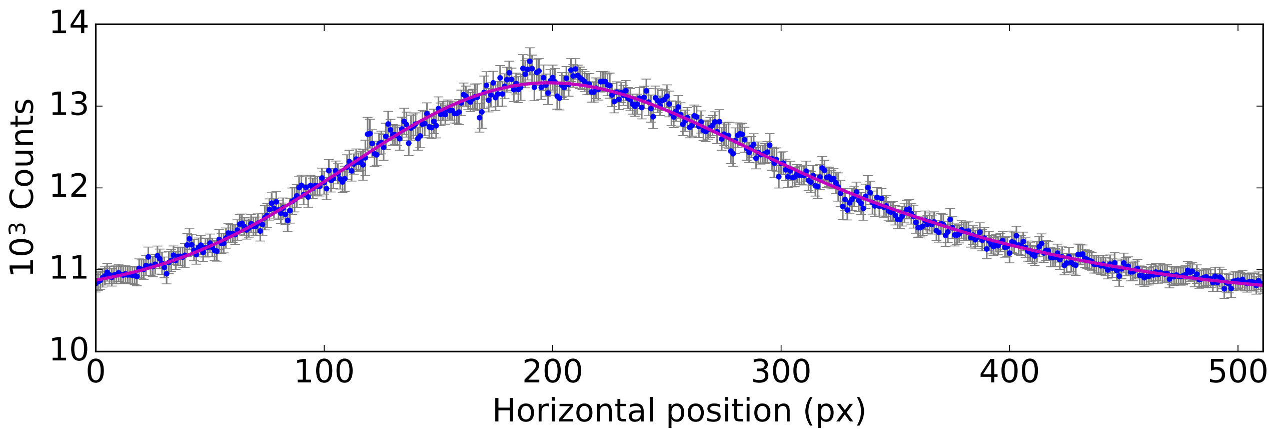
Time-resolved energy spread studies

Karlsruher Institut für Technologie

- Horizontal bunch size in a dispersive section correlates with the energy spread
- Fast-gated camera + rotating mirror
- Image intensifier as pulse picker
- Single-turn images of single bunch



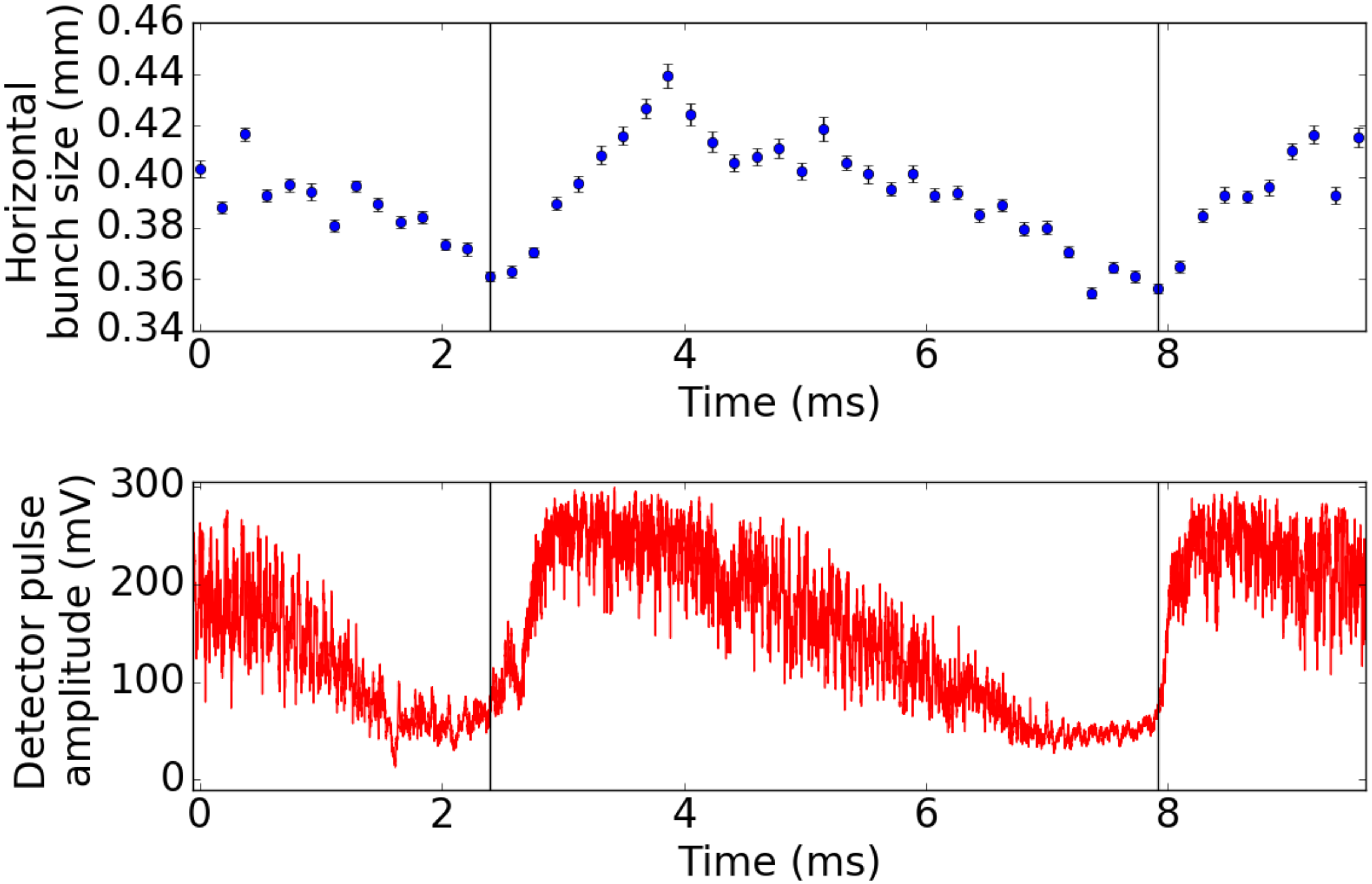




- Minimum separation: 6 turns
- Maximum number of spots: ~60
- Determine horizontal spot size

B. Kehrer *et al.*, “Visible Light Diagnostics at the ANKA Storage Ring,”, *IPAC’15*,
P. Schütze “Transversale Stahldynamik bei der Erzeugung kohärenter Synchrotronstrahlung”. Springer, 2017, isbn: 978- 3-658-20385-6.

Synchronized measurements



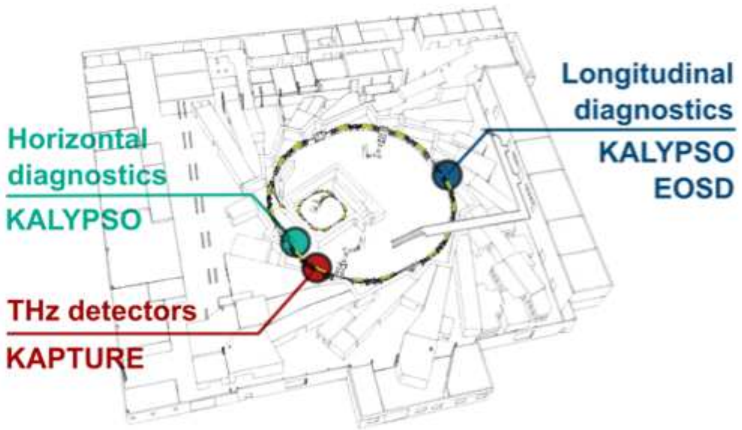
Horizontal bunch size as measure for the energy spread

THz intensity measured by KAPTURE

- Same modulation period length
- Onset of burst correlates to minimum energy spread

B. Kehrer *et al*., "Simultaneous Detection of Longitudinal and Transverse Bunch Signals at ANKA," *IPAC 2016)* doi:10.18429/JACoW-IPAC2016-MOPMB014

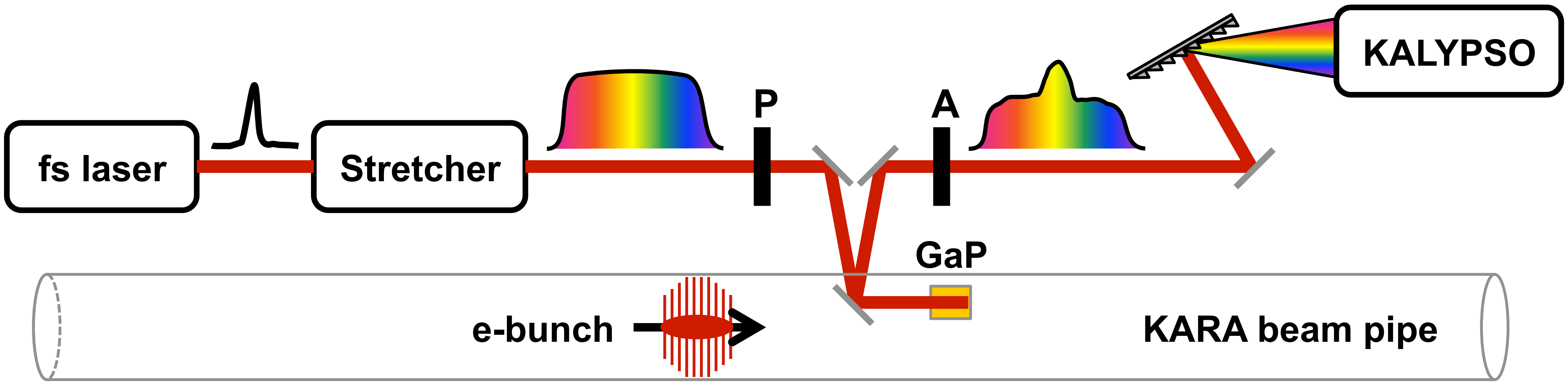
KARA distributed sensor network



Analyze Longitudinal Phase Space

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

Electro-Optical Spectral Decoding (EOSD)

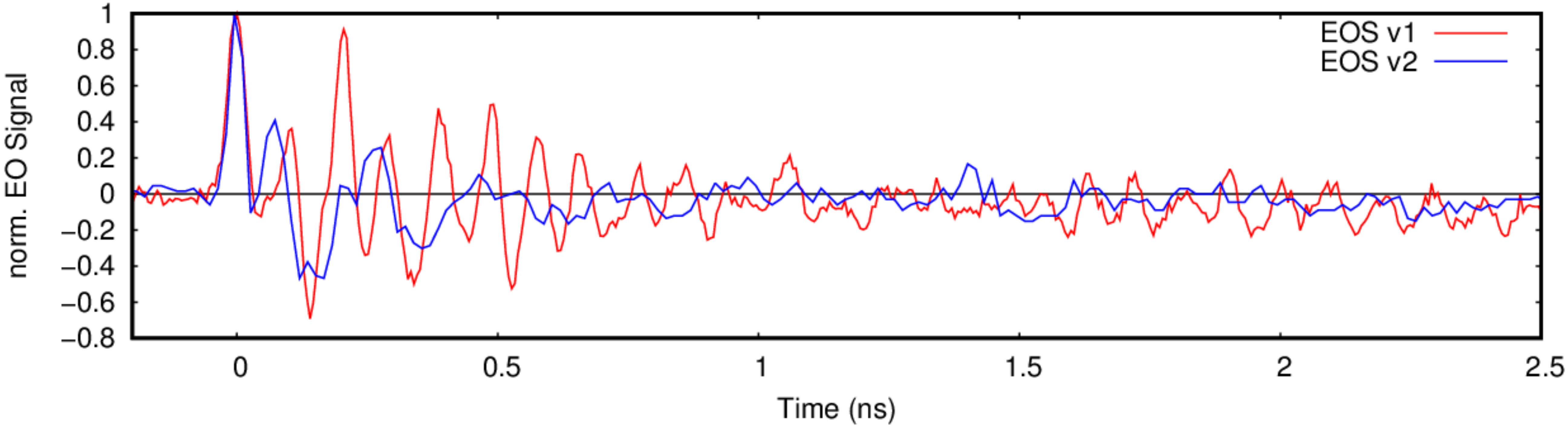


- Developed for single-pass linear accelerators
- Permanently installed in the KARA storage ring
- Improvements done to increase sensitivity and reduce heat load

Optimized setup for reduced heat load

- Version 1 arm (EOS v1)
- LINAC design
- By DESY & PSI

- Version 2 New arm (EOS v2)
- First design for rings by KIT
- **Reduced wake fields** at 2 ns (500 MHz)
- **Improved sensitivity**



P. Schönfeldt et al., IPAC17, MOPAB055

KALYPSO: KArlsruhe Linear arraY detector for MHz-rePetition rate SpectrOscopy

Karlsruher Institut für Technologie

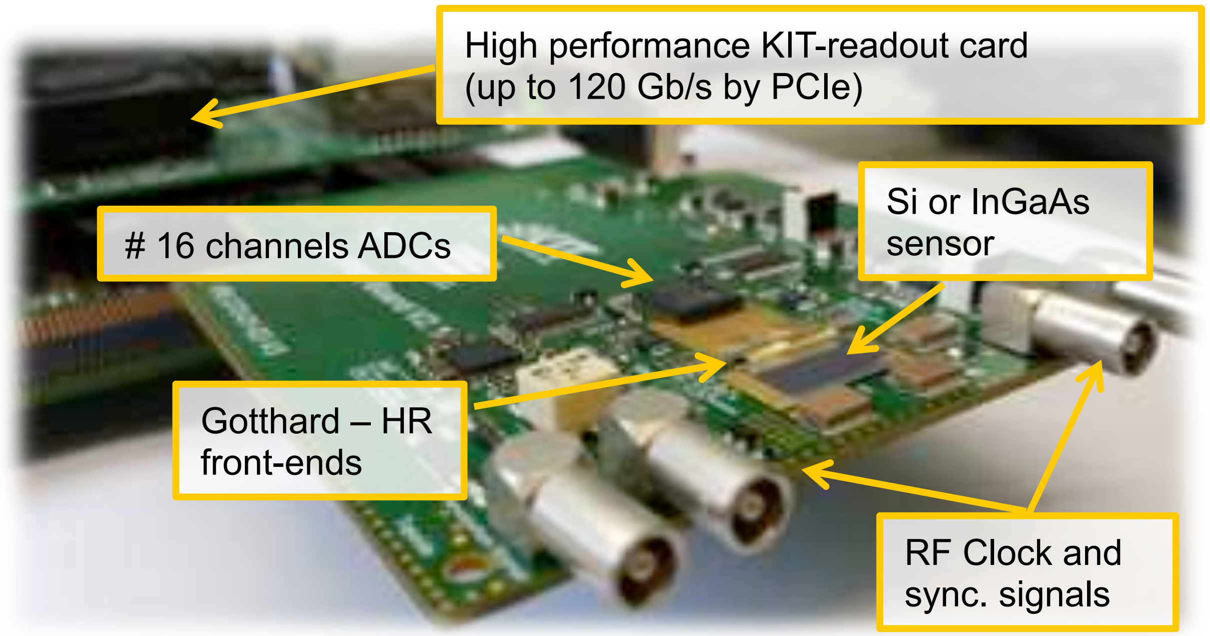
- Scientific goal: develop the “ideal” detector for EOSD measurements:
  - High-repetition rate single-shot resolution
  - Continuous data acquisition ➜ turn-by-turn monitoring over > 10^6 turns
  - Detect radiation in visible & near-infrared spectrum
  - Real-time data analysis ➜ FPGA / GPU heterogeneous DAQ
- Main technological challenges:
  - Fast front-end electronics: GOTTHARD chip
  - High density connections (wire-bondings, transmission lines, etc.)
  - High-throughput DAQ system

L. Rota, IBIC’17, TU2AB3

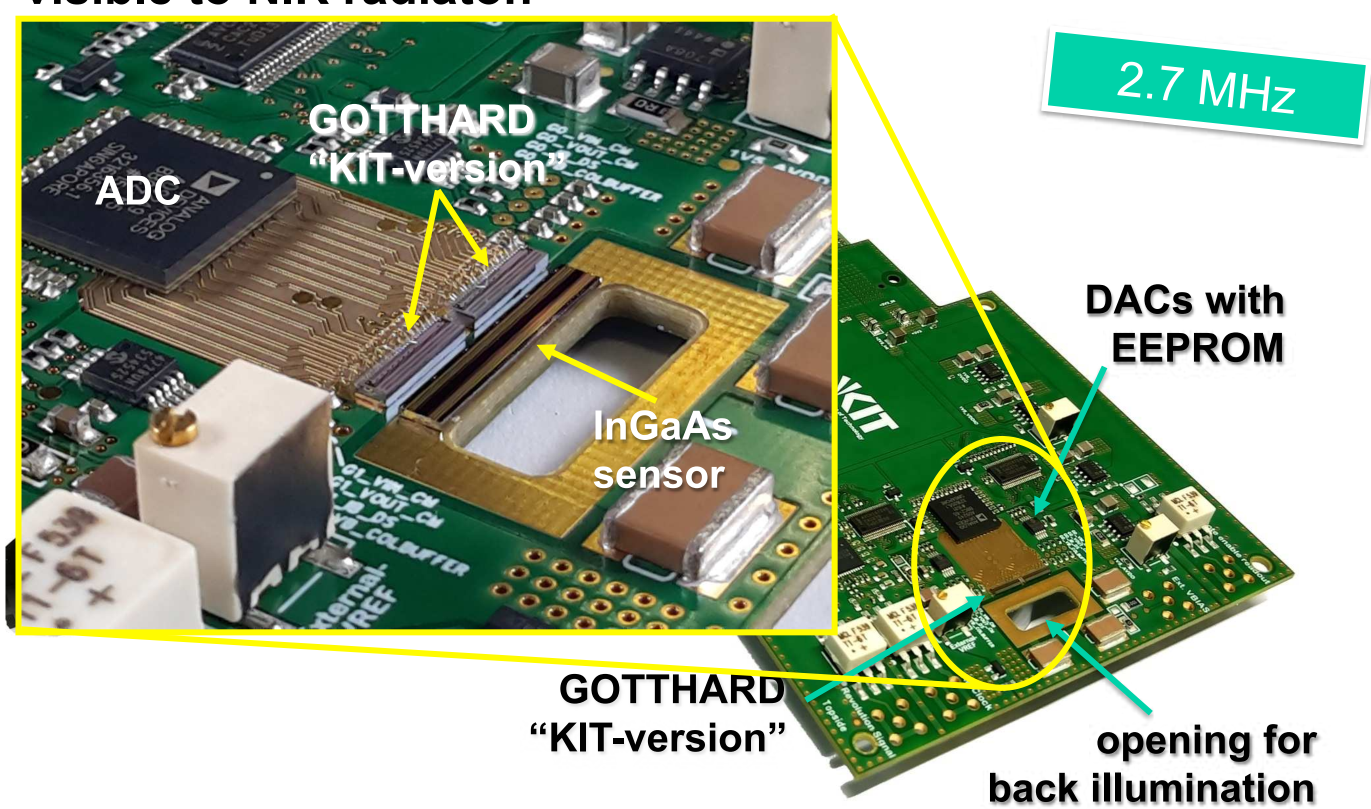
KALYPSO: KArlsruhe Linear arraY detector for MHz-rePetition rate SpectrOscopy

Karlsruher Institut für Technologie

- KALYPSO consists of
  - linear line array
  - GOTTHARD front-end chip
  - 14-bit ADC
  - high-throughput board



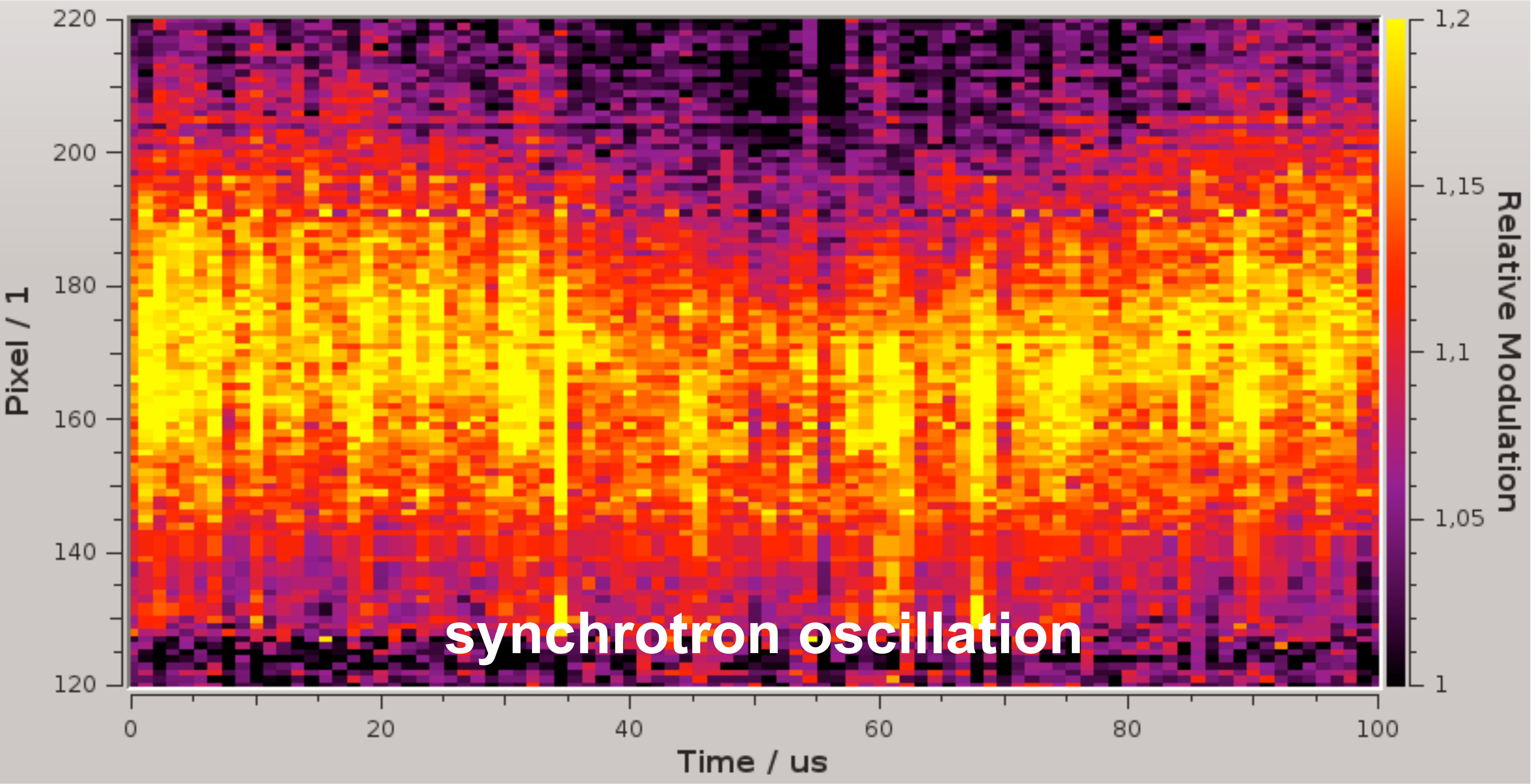
KALYPSO: a 2.7 Mfps linear-array detector for visible to NIR radiaton

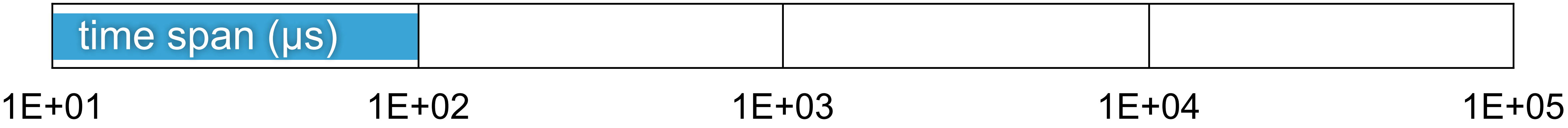


Single-shot bunch profiles with EO & KALYPSO

- Each vertical line corresponds to a single-shot profile measurement

courtesy P. Schönfeldt

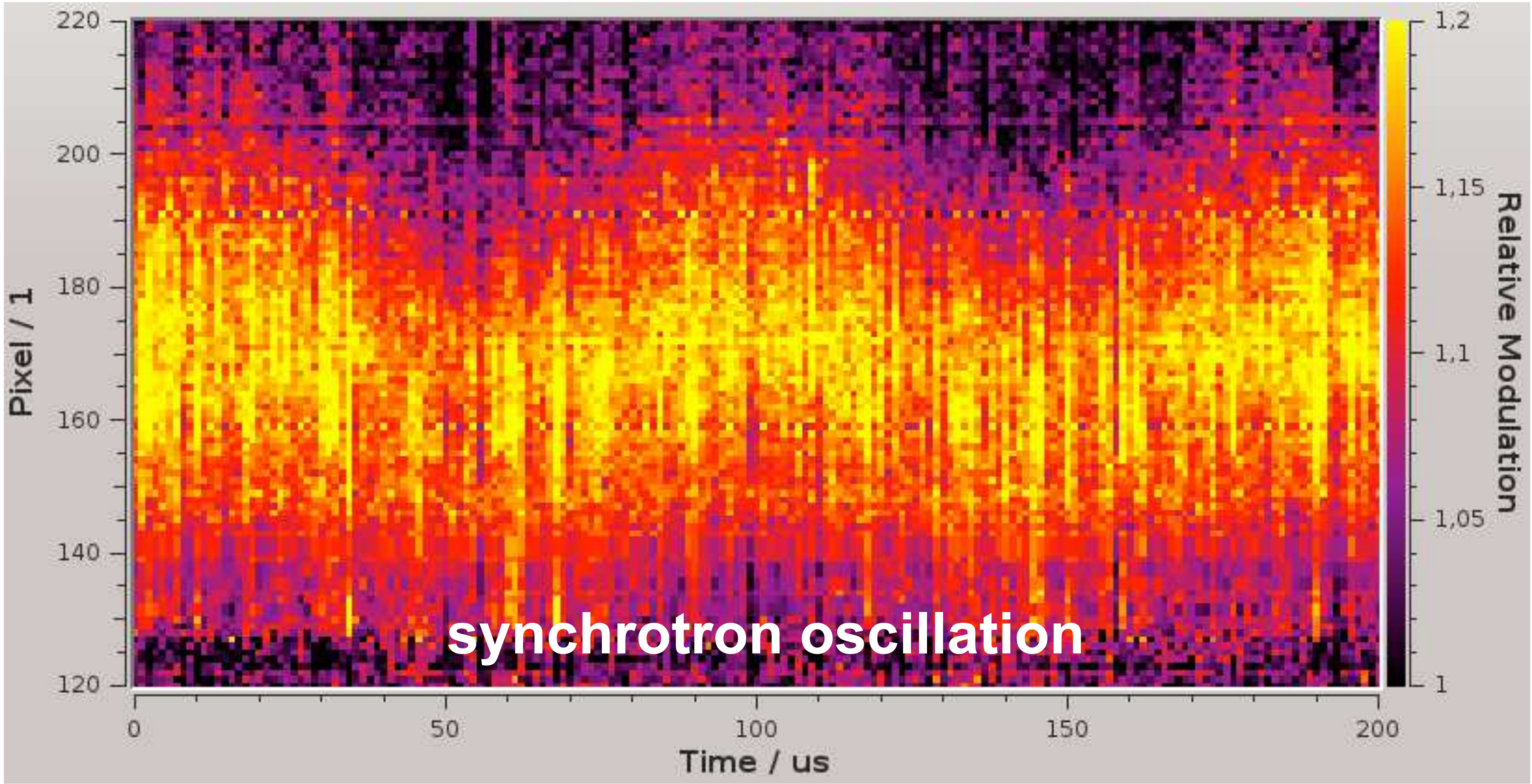


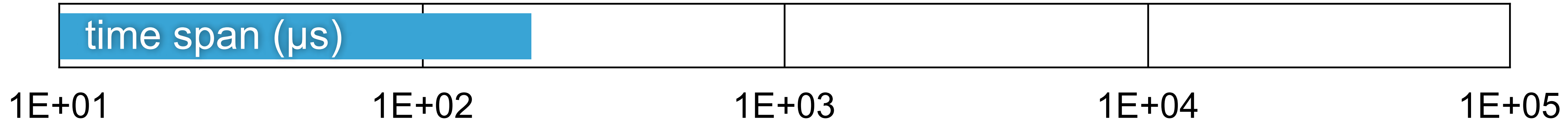


Single-shot bunch profiles with EO & KALYPSO

- Each vertical line corresponds to a single-shot profile measurement

courtesy P. Schönfeldt

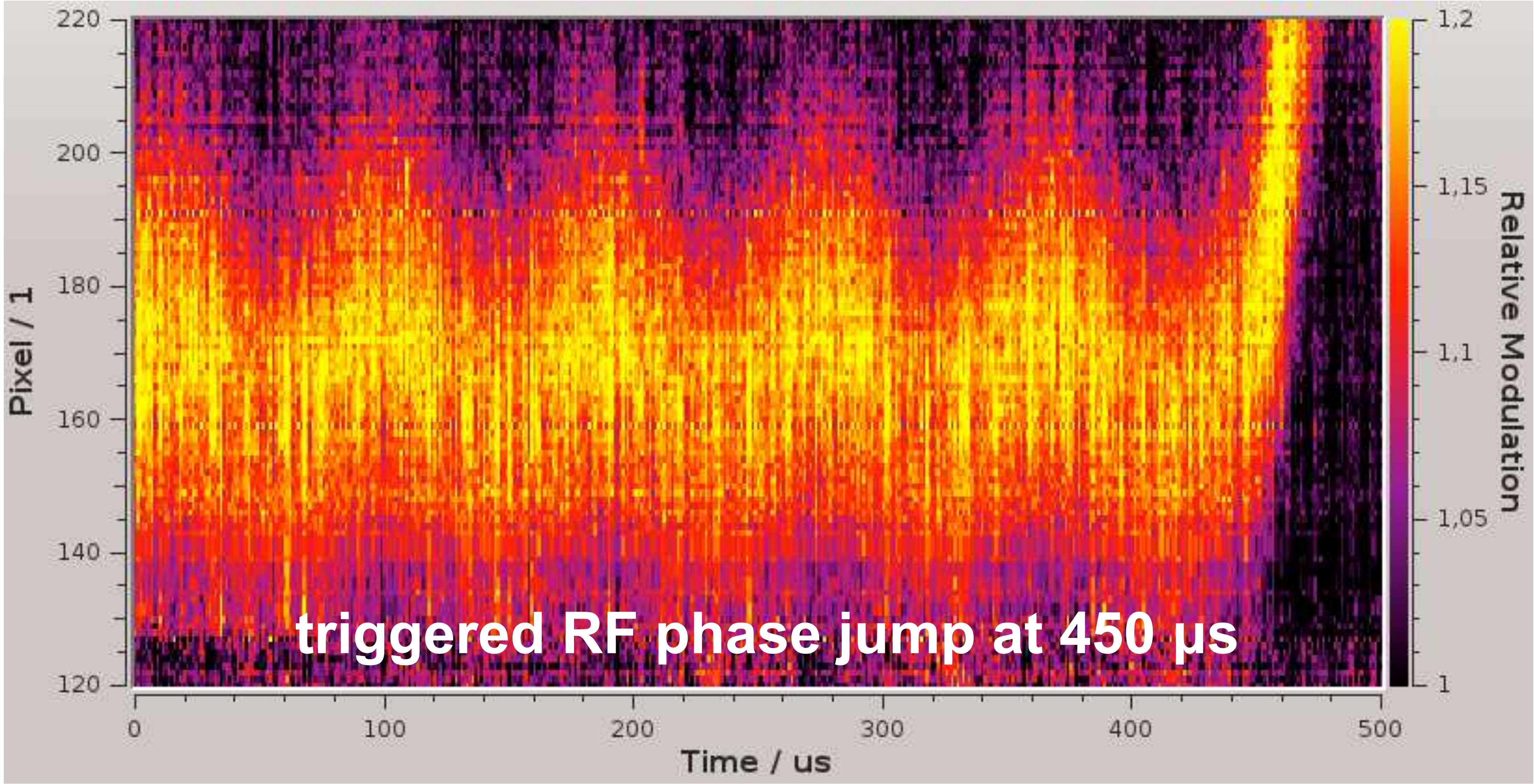


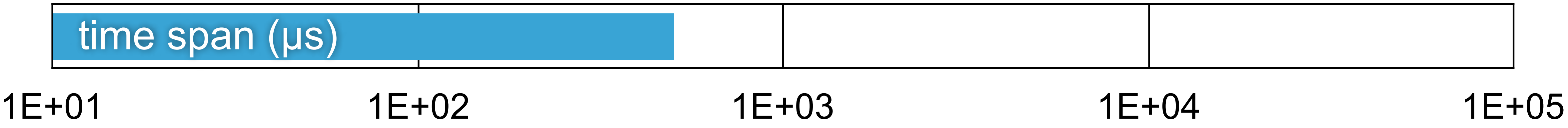


Single-shot bunch profiles with EO & KALYPSO

- Each vertical line corresponds to a single-shot profile measurement

courtesy P. Schönfeldt

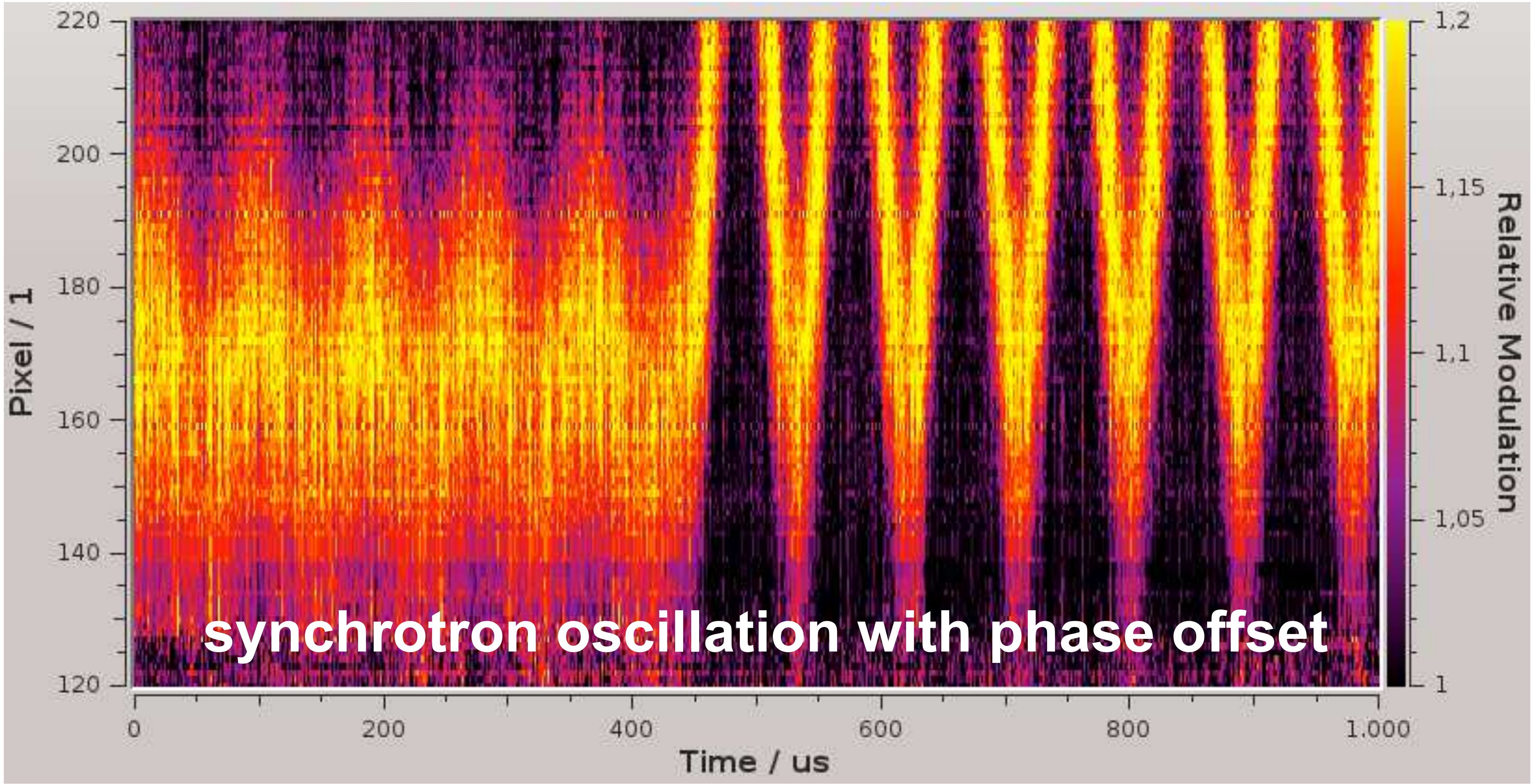


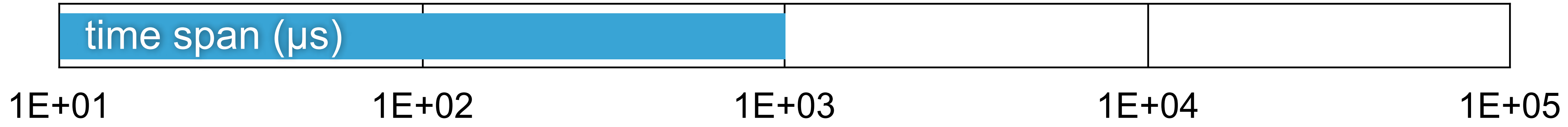


Single-shot bunch profiles with EO & KALYPSO

- Each vertical line corresponds to a single-shot profile measurement

courtesy P. Schönfeldt

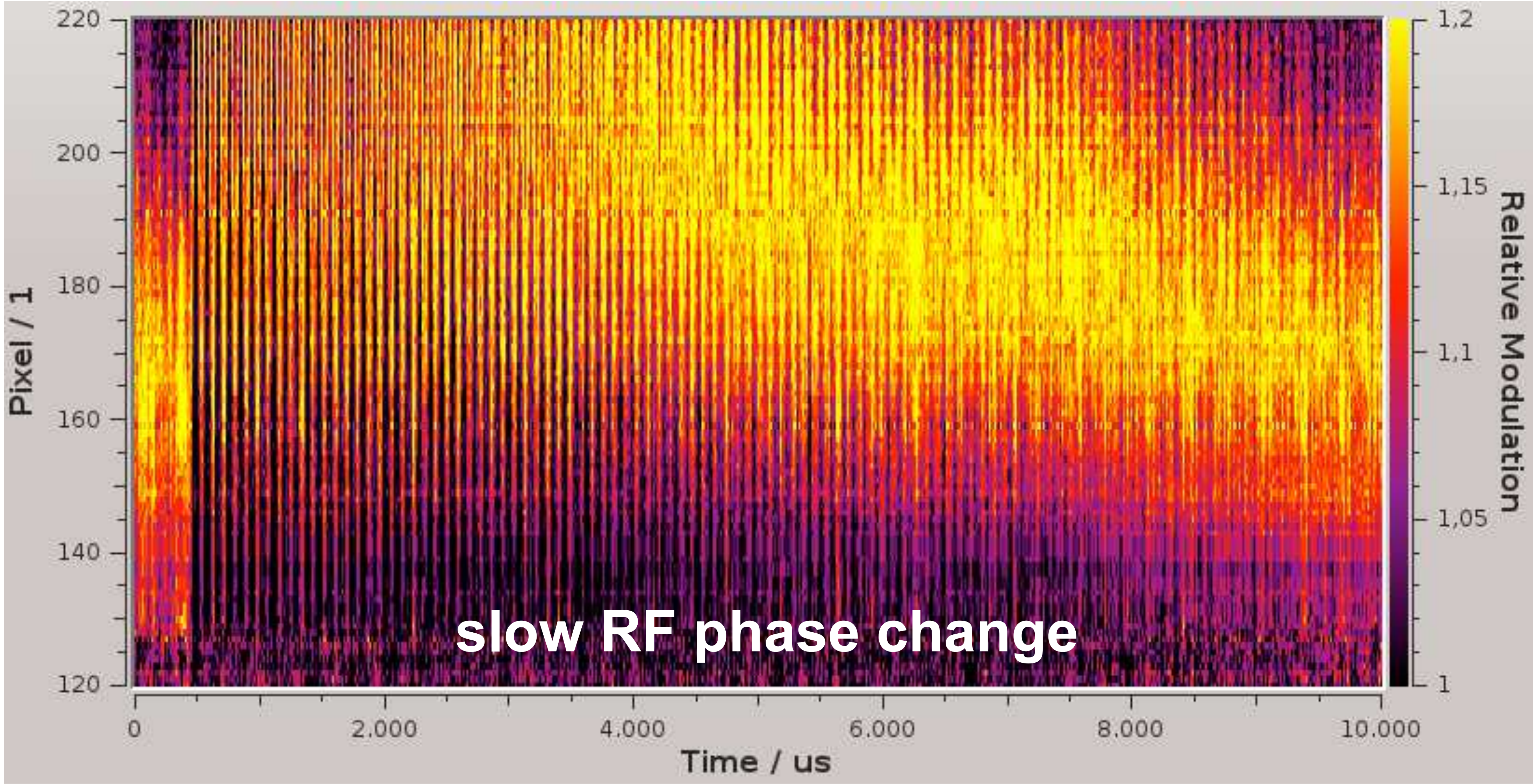




Single-shot bunch profiles with EO & KALYPSO

- Each vertical line corresponds to a single-shot profile measurement

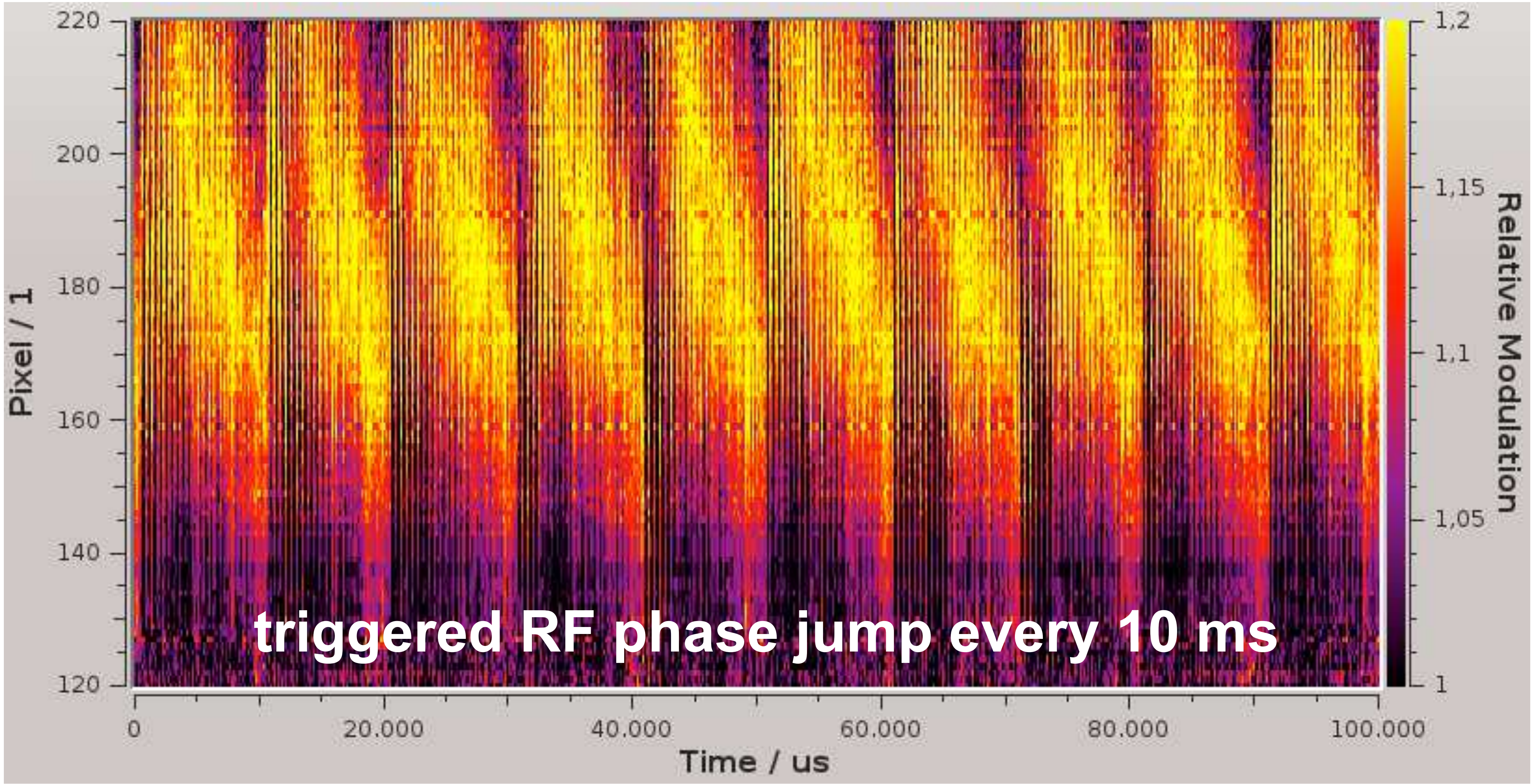
courtesy P. Schönfeldt

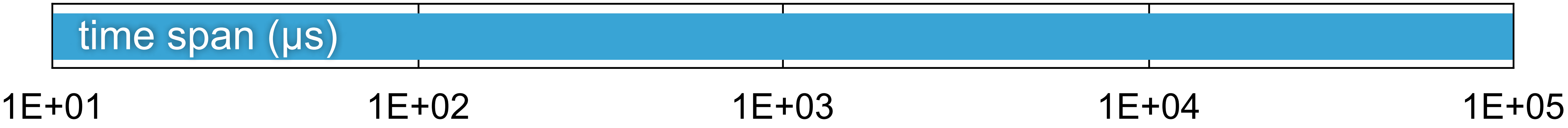


Single-shot bunch profiles with EO & KALYPSO

- Each vertical line corresponds to a single-shot profile measurement

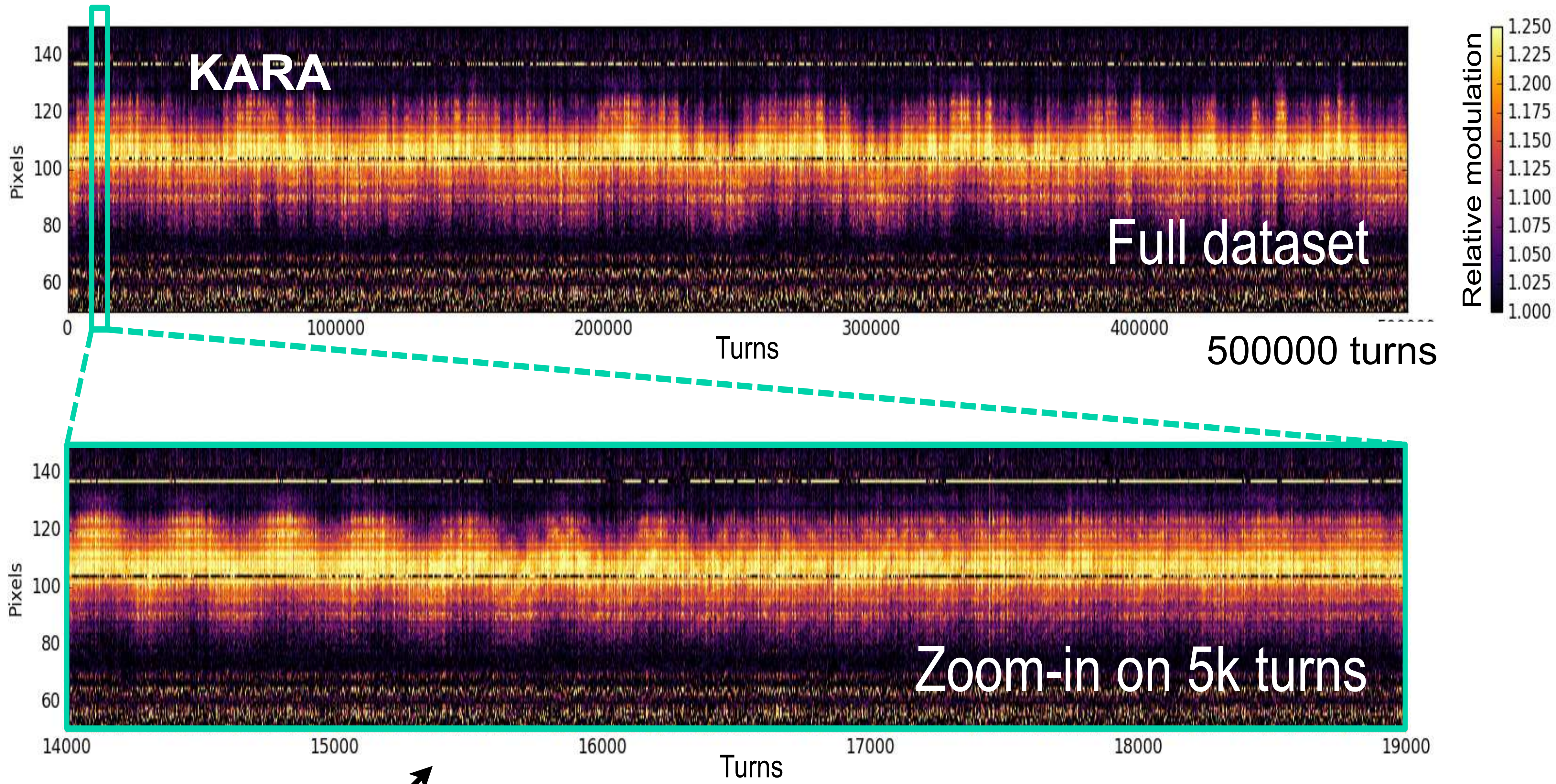
courtesy P. Schönfeldt





Micro-bunching measurements with KALYPSO

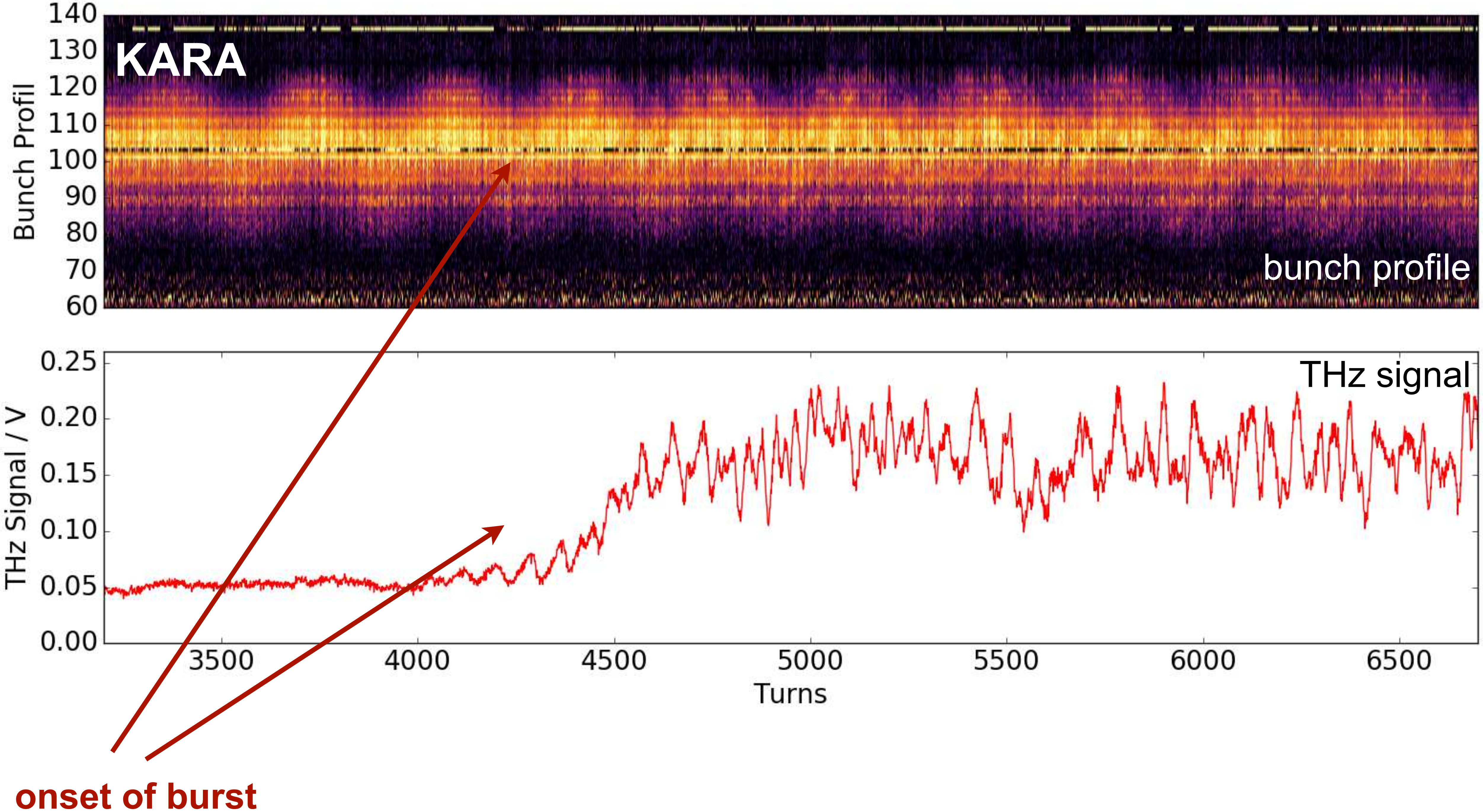
- Each vertical line corresponds to a single-shot profile measurement



detail: development of sub-structures

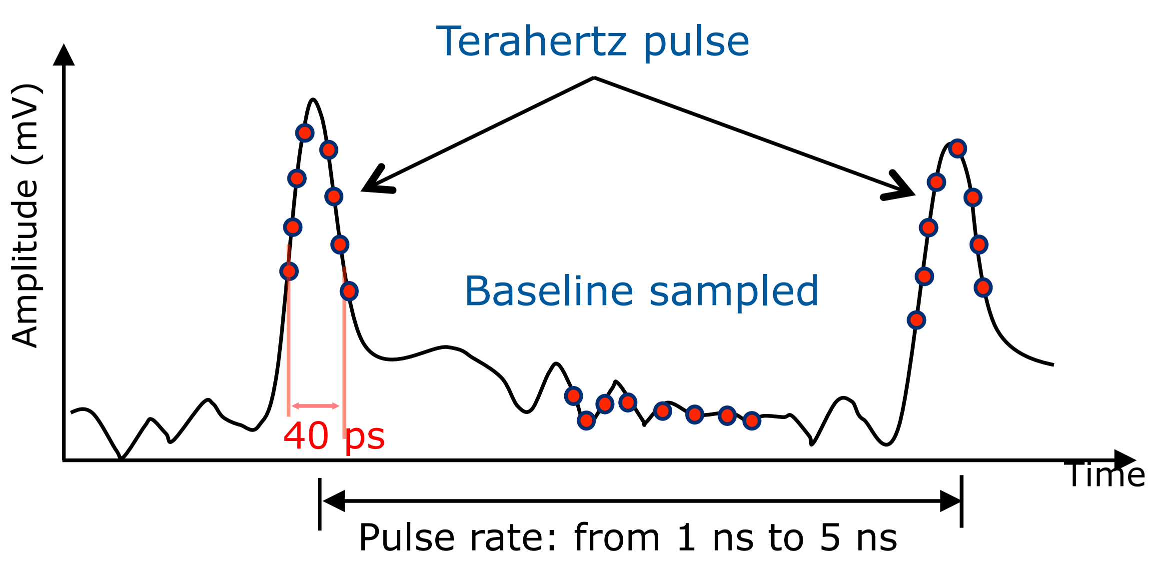
courtesy L. Rota

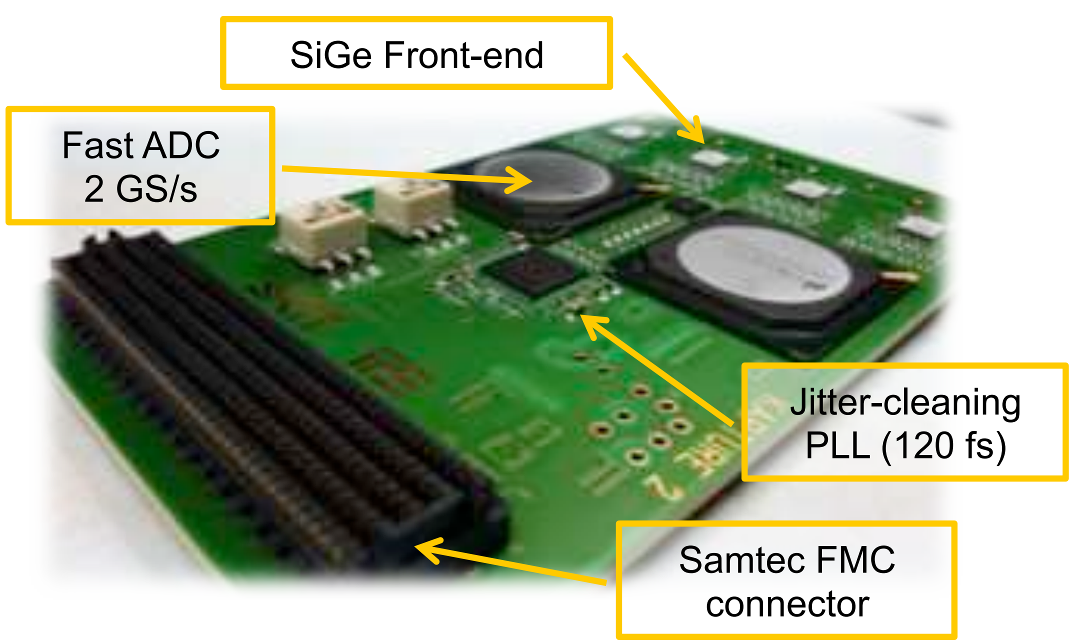
Synchronous measurements with KALYPSO and KAPTURE



KAPTURE II

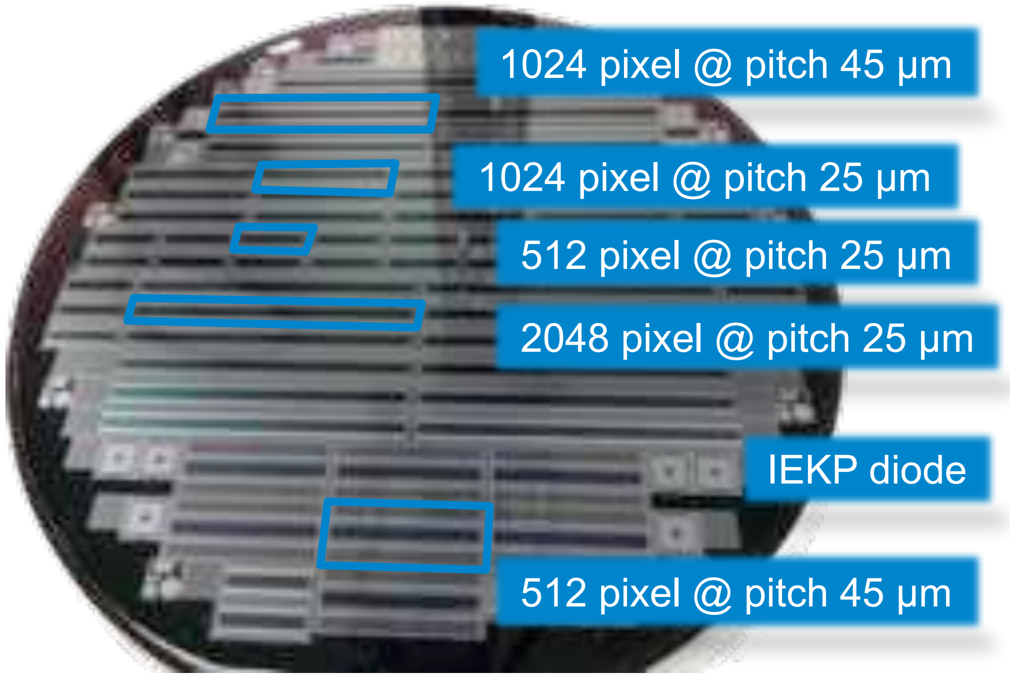
- Up to 1.8 GHz trigger rate
- Up to 8 sampling points
- Continuous readout by PCIe, up to 64 Gb/s
- Real-time data processing by GPUs
- Mechanically and electrically compatible with FMC / µTCA system





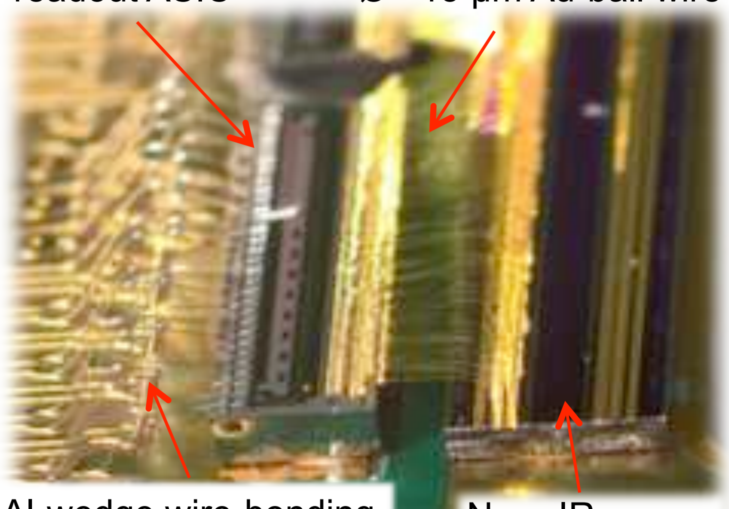
M. Caselle et al, *"KAPTURE-2. A picosecond sampling system for individual THz pulses with high repetition rate"*, JINST 072P_1116, http://dx.doi.org/10.1088/1748-0221/12/01/C01040

KALYPSO III



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

Gotthard-HR-10MHz ASIC - UMC 110 nm technology



M. Caselle, L. Rota et al., IBIC TU2AB3 (2017)

KAPTURE and KALYPSO: International distribution

Already installed at XFEL,
further collaborations planned

- DESY Hamburg / Eu-XFEL
- TU Dortmund / DELTA
- HZDR Dresden / ELBE
- HZB Berlin / BESSY II - VSR
- DESY Hamburg / FLASH
- SOLEIL-Sync. Paris
- PSI / Swiss Light Source

Acknowledgements

Involved KIT Institutes:

Institute for Beam Physics and Technology (IBPT)
Laboratory for Applications of Synchrotron Radiation (LAS)
Institute for Photon Science and Synchrotron Radiation (IPS)
Institute for Data Processing and Electronics (IPE)
Institute of Micro- und Nanoelectronic Systems (IMS)

Beam dynamics and diagnostics students

KIT accelerator technology platform (ATP)