Developing and testing beam diagnostics for FCC-ee

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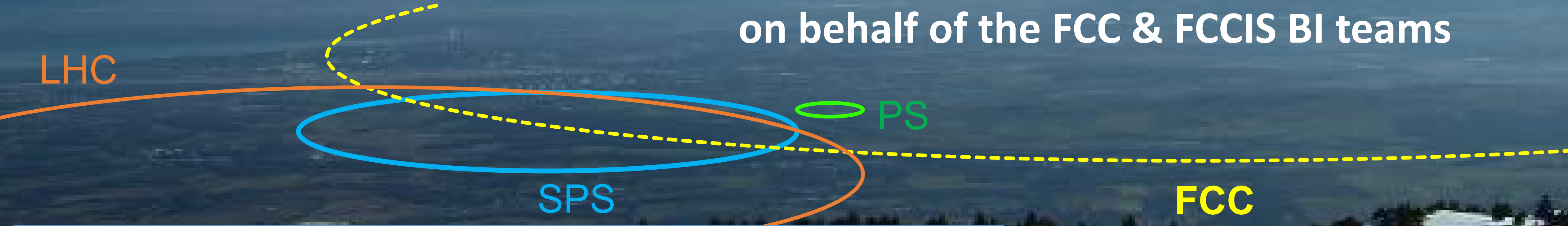
1) *Karlsruhe Institute of Technology (KIT), Institute for Beam Physics and Technology (IBPT)*
2) *CERN*

on behalf of the FCC & FCCIS BI teams



http://cern.ch/fcc

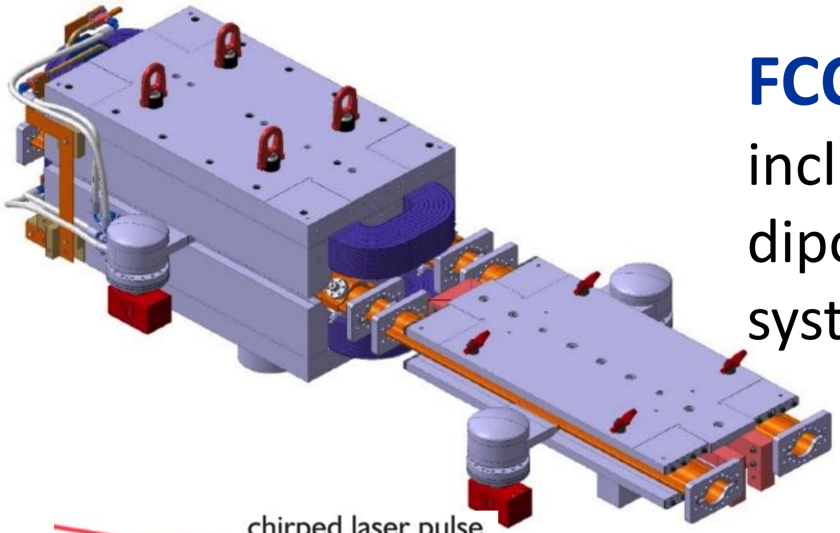
Karlsruhe Institute of Technology

*The **Future Circular Collider Innovation Study (FCCIS)** project has received funding from the **European Union's Horizon 2020 research and innovation programme** under grant No 951754.*
*Additional Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain,** grant agreement no. 764879; **ARIES**, grant agreement 730871; and **E-JADE,** contract no. 645479*

European Commission | Horizon 2020 European Union funding for Research & Innovation

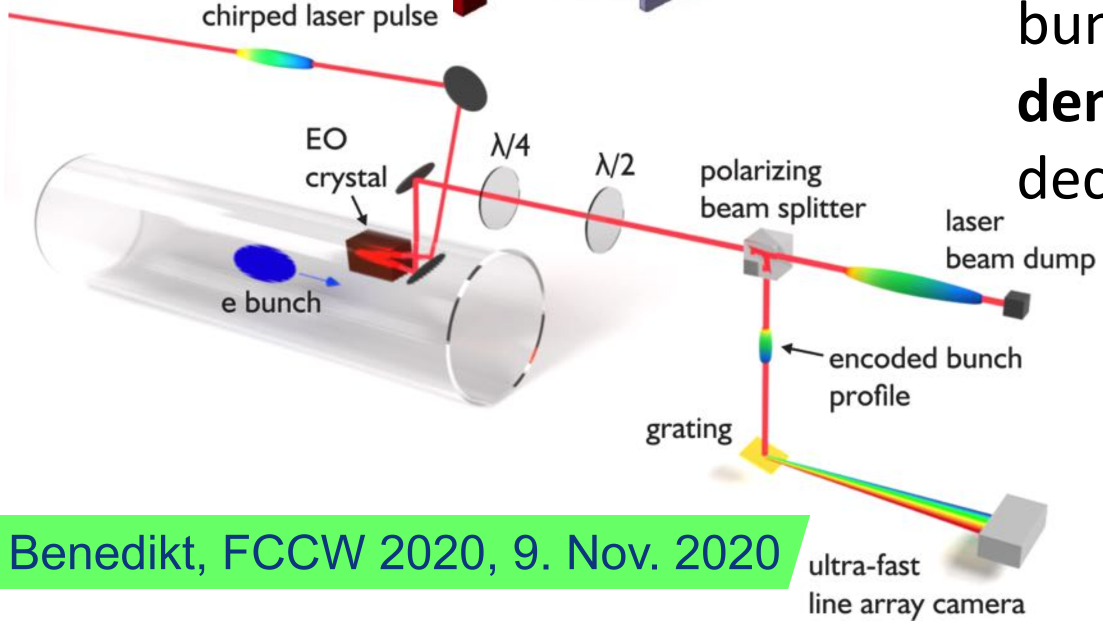
photo: J. Wenninger

FCC key deliverables: prototypes by 2025



FCC-ee complete arc half-cell mock up

including girder, vacuum system with antechamber + pumps, dipole, quadrupole + sext. magnets, BPMs, cooling + alignment systems, technical infrastructure interfaces.



key beam diagnostics elements

bunch-by-bunch turn-by-turn **longitudinal charge density profiles** based on electro-optical spectral decoding (beam tests at KIT/KARA) ;

ultra-low emittance measurement (X-ray interferometer tests at SuperKEKB, ALBA) ;
beam-loss monitors (IJCLab/KEK?) ;
beamstrahlung monitor (KEK);
polarimeter ; **luminometer**

→ M. Benedikt, FCCW 2020, 9. Nov. 2020

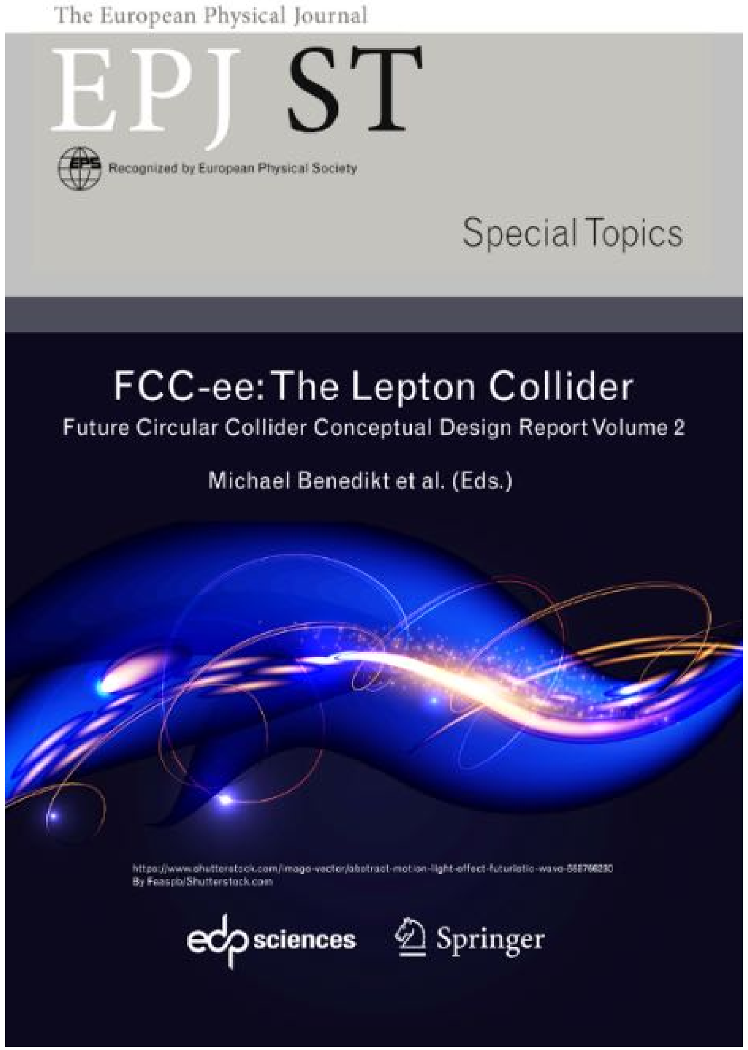
Sincere thanks to all who have contributed!

Particular thanks go to

- T. Mitsuhashi (KEK)
- U. Iriso (ALBA)
- S. Mazzoni (CERN)
- I. Chaikovska (IJCLab/IN2P3-CNRS)
- A. Santamaria, E. Bründermann (KIT)

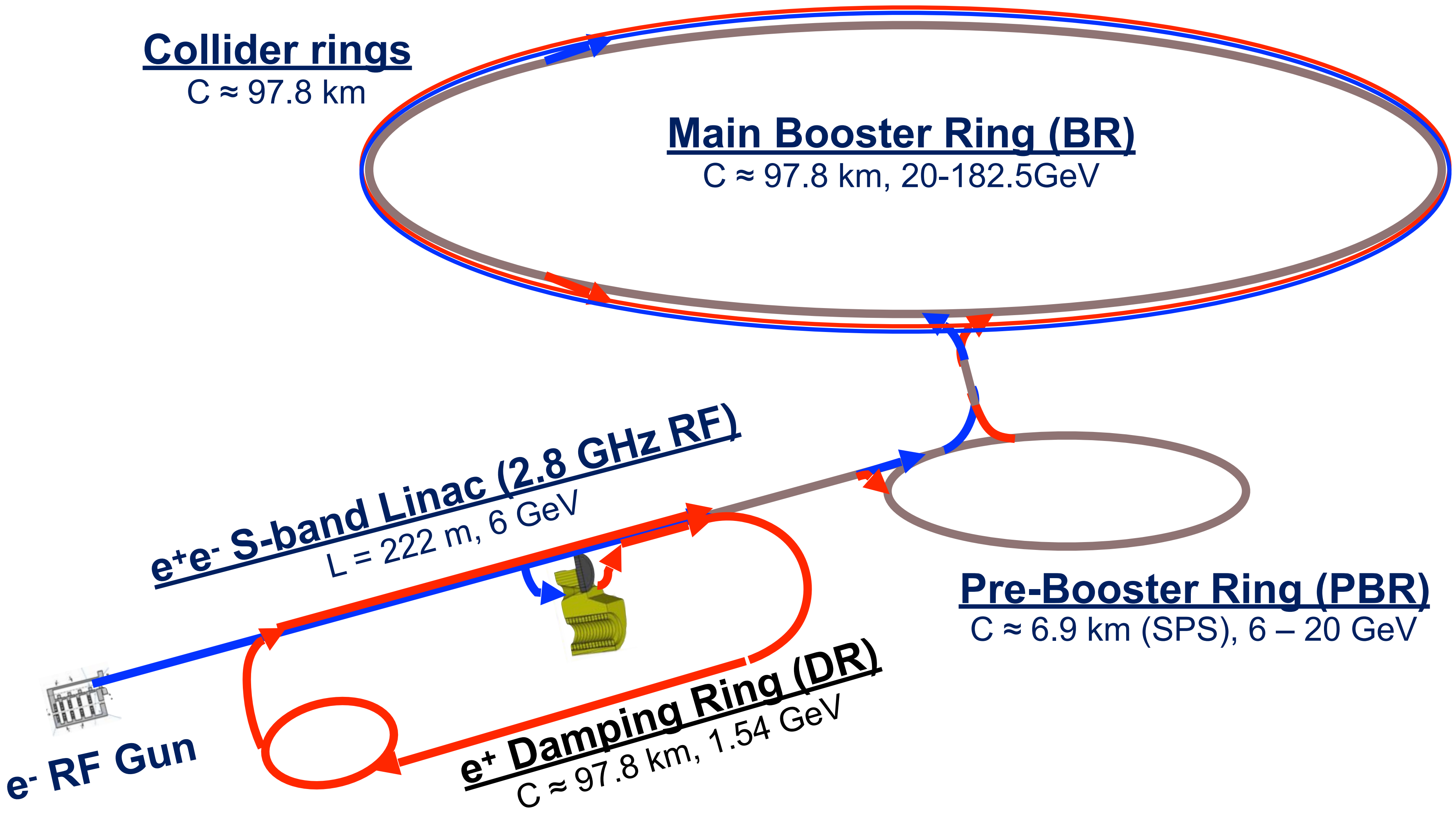
Beam diagnostics for the FCC-ee

- A first conceptual design of the FCC-ee BI has been performed for the CDR ✔
- No feasibility issues ✔
- Long list of technological challenges ahead of us 💪
- Benefitting from the R&D for low-emittance ring / linear colliders / FEL communities 🤝



→ T. Lefevre, FCCW 2019, 27 June 2019, Brussels
→ T. Lefevre, FCCW 2020, 12 November 2020

FCC-ee Layout



FCC-ee beam parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5

- **High beam intensity and large dynamic range**

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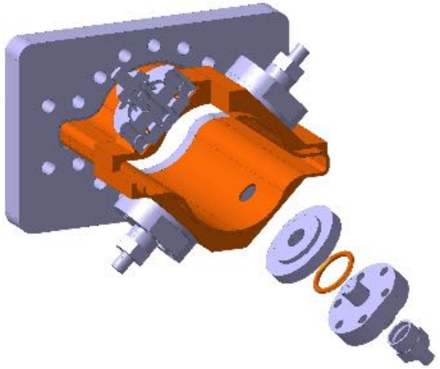
- High beam intensity and large dynamic range
- **Small Emittances**

FCC-ee specifics

BPM & BLM: radiation hard electronic design

- **High luminosity regions**
  - High radiation level close IP's



— 6000 BPMs —
up to 400 W dissipated
➜ active cooling

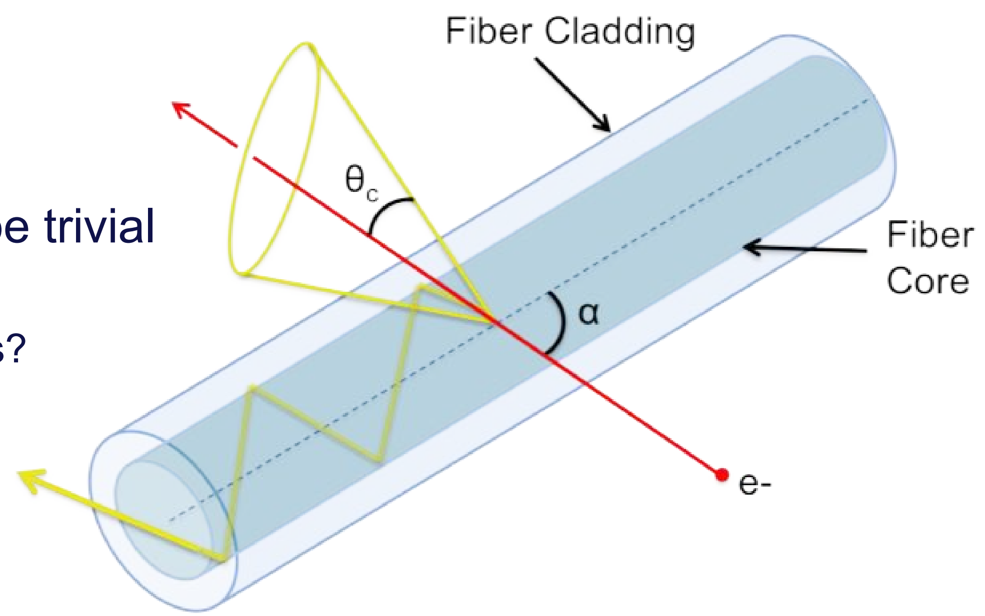
- **High beam intensity**
  - Wakefield effects inducing heat load

- **High SR power in the arcs** would produce high X-ray dose requiring
  - Shielding (design dependent on beam energy, i.e. SR critical energy)
  - Radiation hard electronic design

BEAM-LOSS MONITORING

Beam loss monitoring

- Large energy stored in both Main and Booster beams
  - BLM in the arcs should not be sensitive to X-ray
  - Identifying beam losses from all different beam lines may not be trivial
    - Main rings: Detectors sensitive to beam propagation
    - Main vs booster ring: Possibly having quadrupoles at different locations?

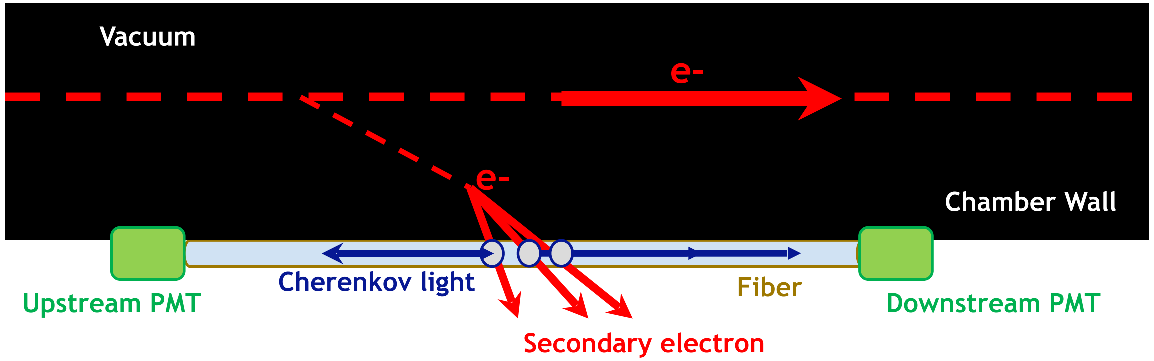


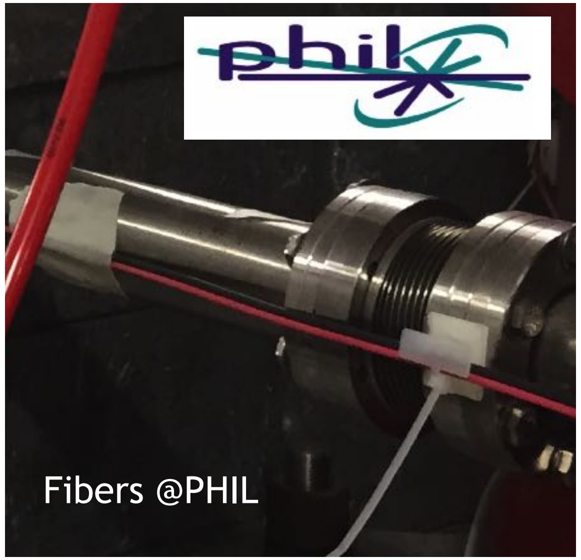
- Optical BLM system based on Cherenkov fibres
  - High directivity
  - Only measures charged particles

Many experimental investigations initiated within Linear collider study

- Crosstalk between beam losses from CLIC Drive and Main beams: *M. Kastriotou et al, "BLM crosstalk studies on the CLIC two-beam module", IBIC, Melbourne, Australia (2015) pp. 148*
- Position resolution of a distributed oBLM system : *E. Nebot del busto et al, "Position resolution of optical fibre-based beam loss monitors using long electron pulses", IBIC, Melbourne, Australia (2015) pp. 580*
- RF studies (Breakdown and Dark current): *M. Kastriotou et al., "A versatile beam loss monitoring system for CLIC", IPAC, Busan, Korea, 2016, pp. 286*

A Fiber Beam Loss Monitor (FBLM)





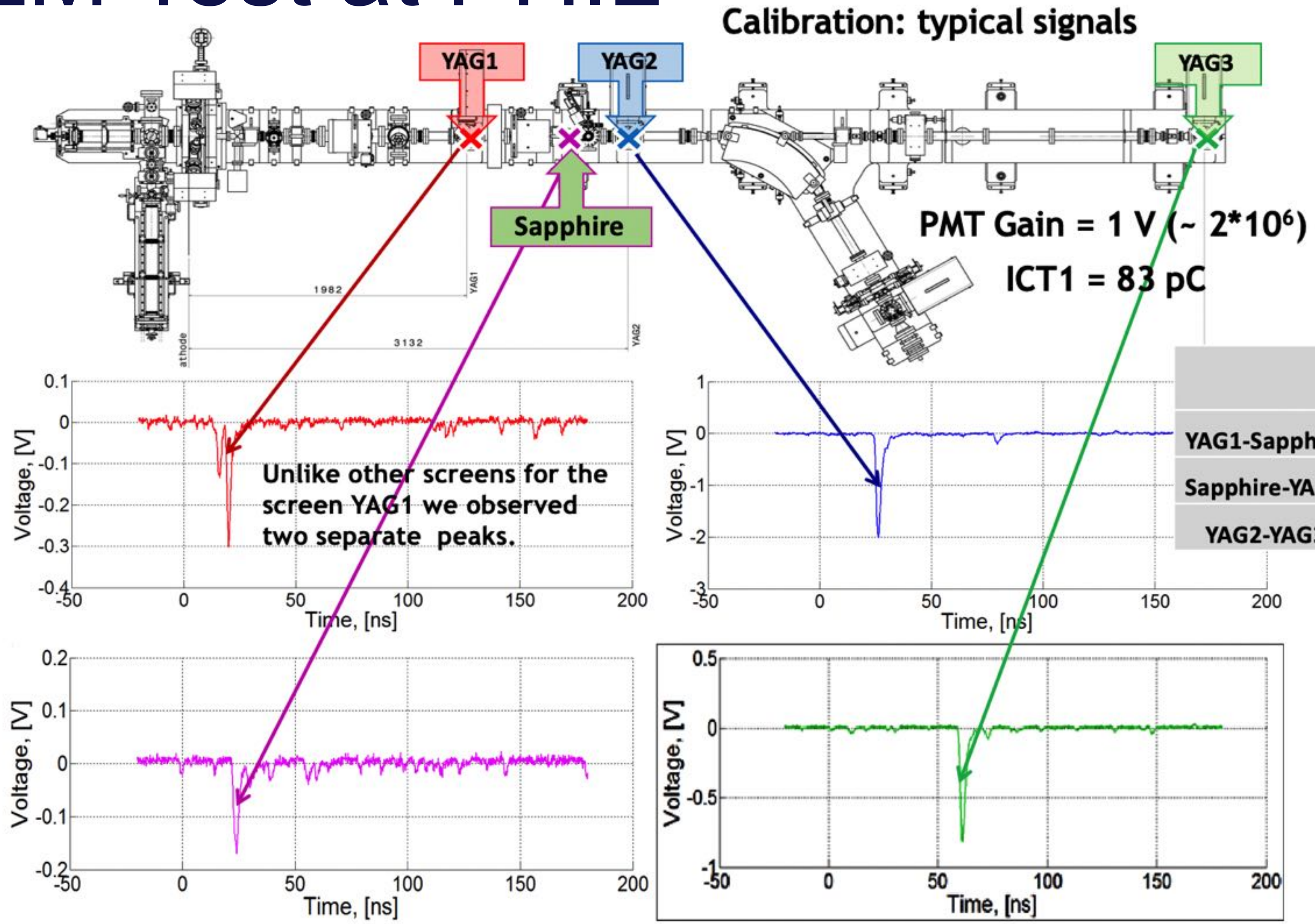
- Optical fiber attached to the vacuum chamber.
- Electromagnetic shower generated when the main beam hits the vacuum chamber or any obstacle.
- Cherenkov radiation produced in the optical fiber by the electromagnetic shower.
- The fiber ends are coupled to the PMTs.
- Cherenkov light converted to an electrical signal containing the information about the position and intensity of the beam losses.

Requirements for the fibers:

- High photon yield (large core fibers)
- No scintillation in the fiber (long decay time => worse BL position resolution)
- High optical transmission
- Radiation hardness.

Courtesy I. Chaikovska (IJCLab/IN2P3-CNRS)

FBLM Test at PHIL



	FBLM	According to the drawing
YAG1-Sapphire	0.96 m	0.87 m
Sapphire-YAG2	0.2 m	0.28 m
YAG2-YAG3	4.22 m	4.11 m

The FBLM system has been installed at PHIL and its functionality has been proven.

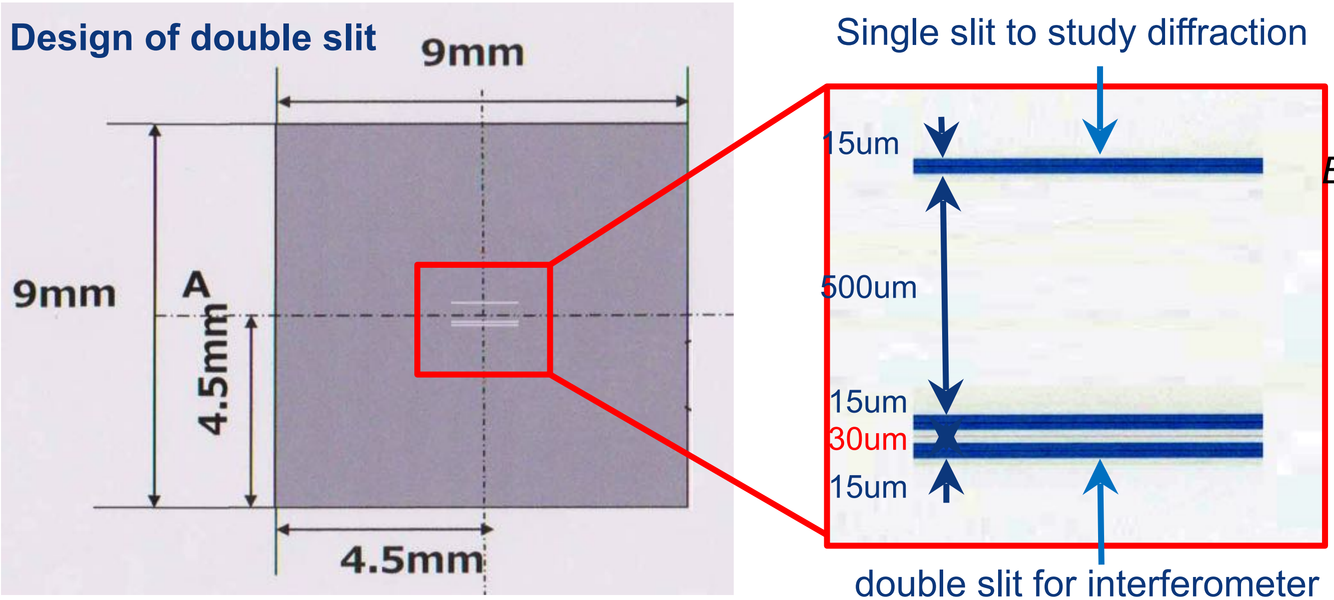
The measured position accuracy allows **resolving the beam losses occurring as close as 30 – 40 cm** with the 25 m fiber along the vacuum chamber.

Courtesy I. Chaikovska (IJCLab/IN2P3-CNRS)

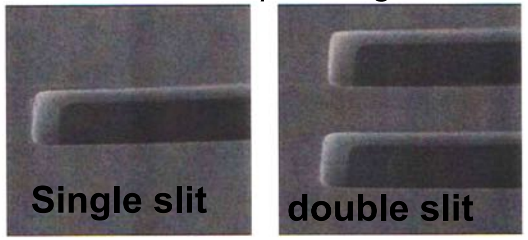
ULTRA-LOW EMITTANCE MEASUREMENT

transverse beam size and profile

Beam Size: Prototype X-ray interferometer at KEK



Electron microscope image of slits



Vacuum Chamber and Linear Stage - received

Plan to install the full system on an X-ray beam line at SuperKEKB in next spring shutdown

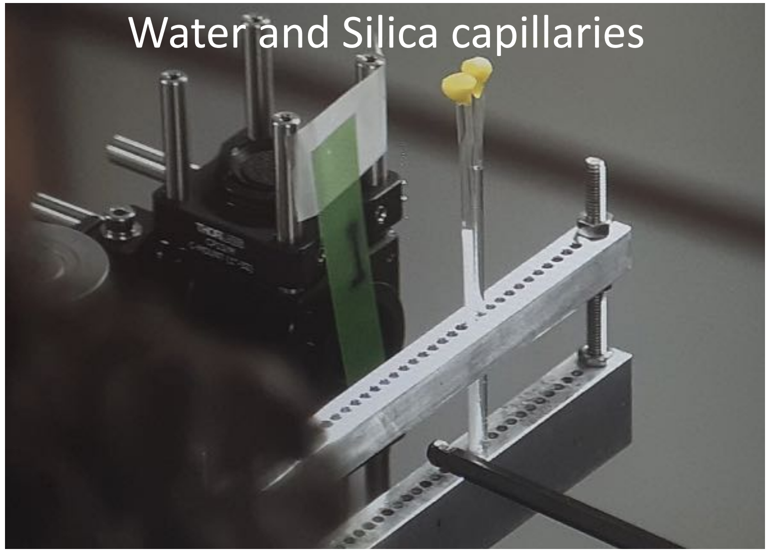
T. Mitsuhashi (KEK)

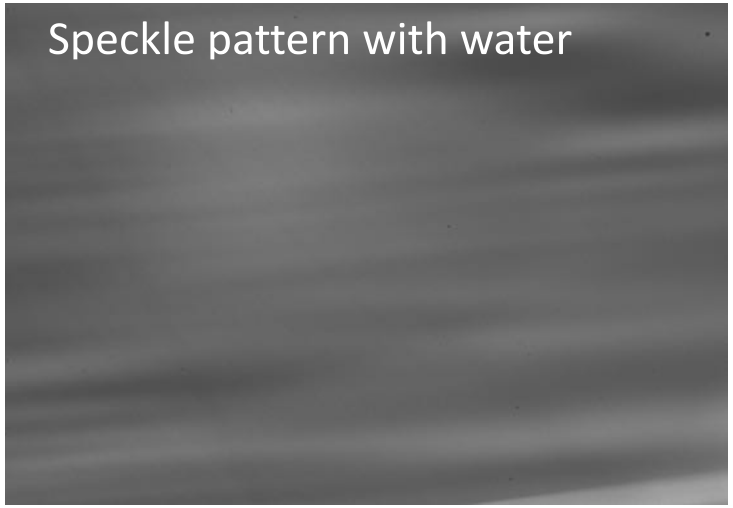
Beam Size: Heterodyne Near Field Speckles

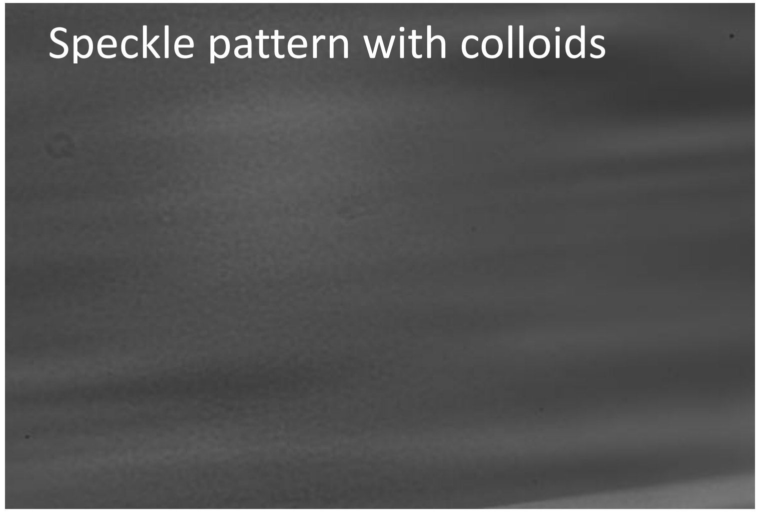
FCC-Collaboration between CERN, Univ. Of Milano and ALBA

GOAL: Alternative way to measure the beam size

- Procedure: analyze the interference of the photon beam with Silica nanospheres suspended in water
- From this interfence pattern (called speckles), we obtain the photon beam coherence, and from it, we derive the beam size







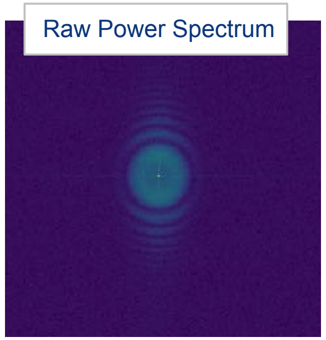
M. Siano et al., **Phys. Rev. Accel. Beams 20**, 110702 (2017)

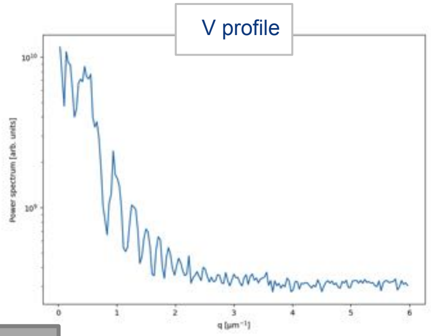
Courtesy U. Iriso (ALBA)

Test of Heterodyne Near Field Speckles at ALBA

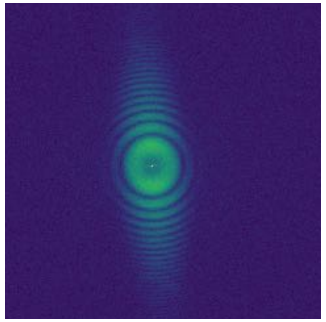
Many lessons learned, setup and signal visibly improved over the years

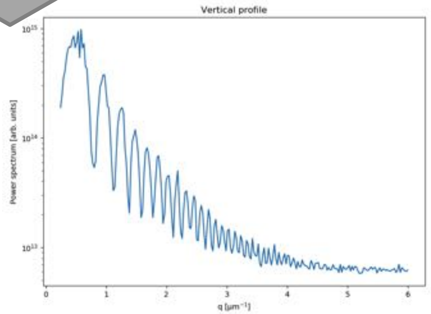
Oct 2018

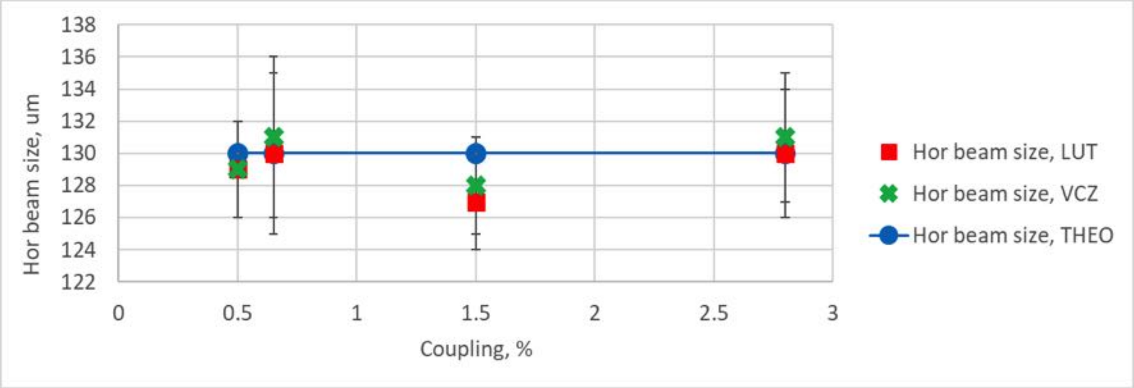


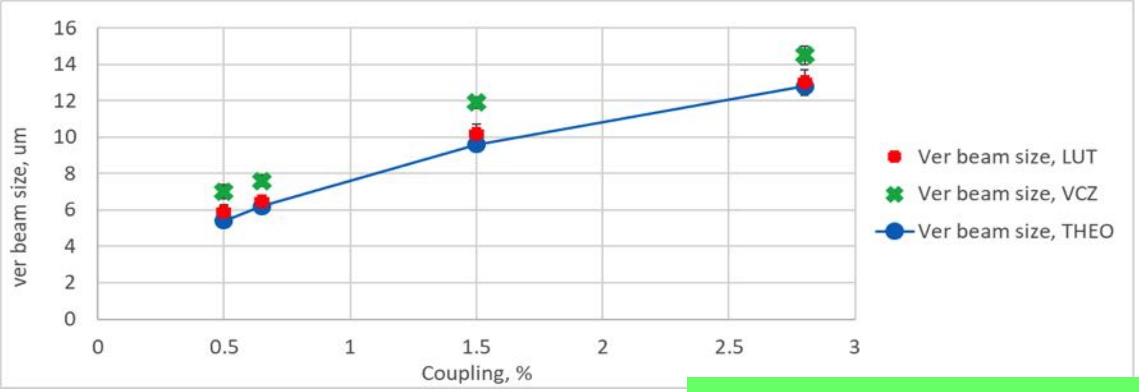


Sept 2020







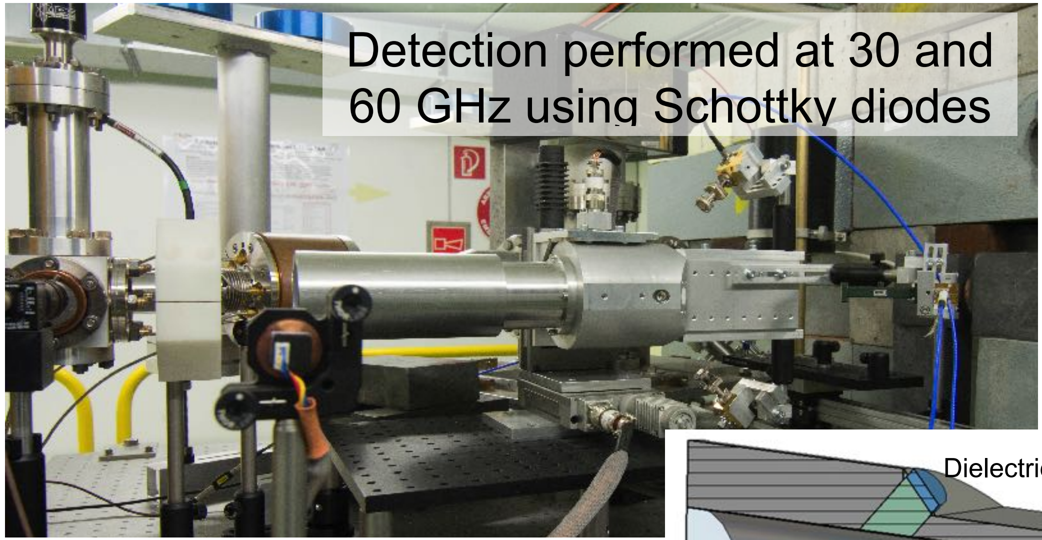


Courtesy U. Iriso (ALBA)

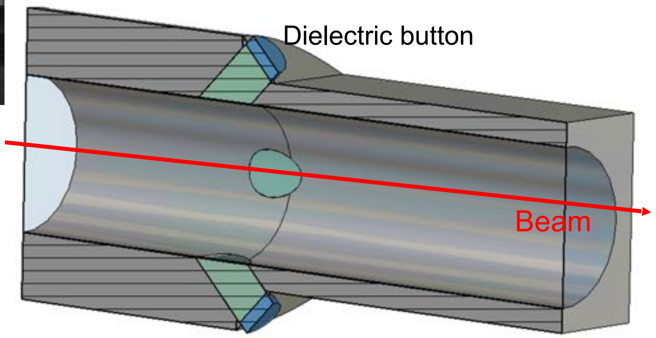
LONGITUDINAL CHARGE DENSITY PROFILES

bunch length, shape, and structures

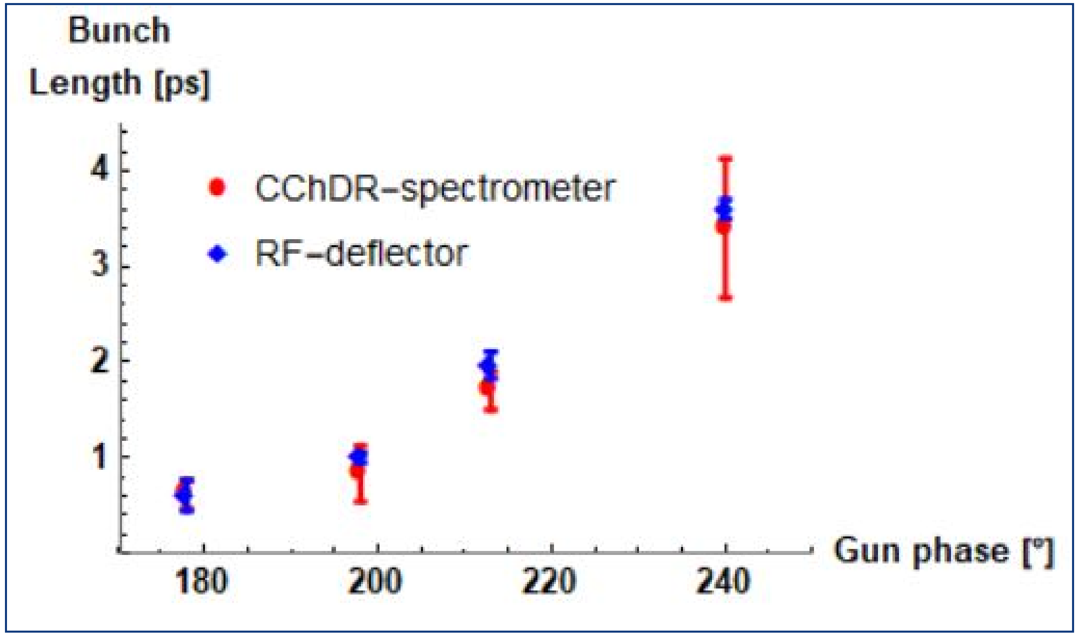
Bunch length: dielectric buttons at CLEAR



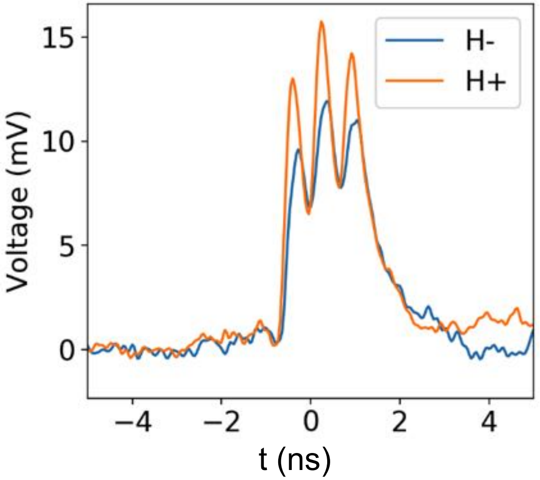
Using Dielectric buttons producing Cherenkov Diffraction radiation as a source of radiation



Measured Bunch length using RF spectrometry



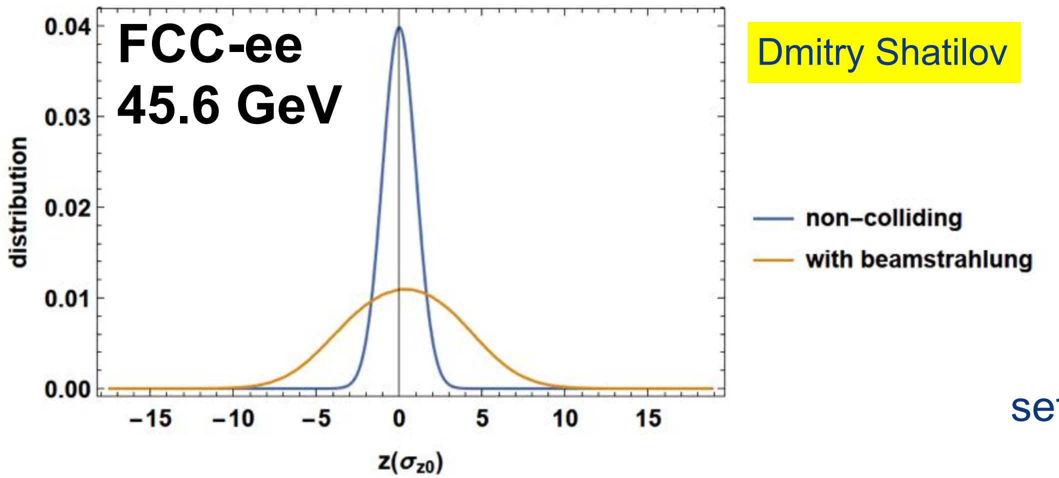
Temporal response of detector



Bunch by bunch resolution possible

*Curcio et al, "Non-invasive bunch length measurements exploiting Cherenkov diffraction radiation, **Phys. Rev. Accel. Beams 23**, 022802 (2020)*
Senes et al, "A dielectric beam position monitor for short bunches of charged particles", to be submitted

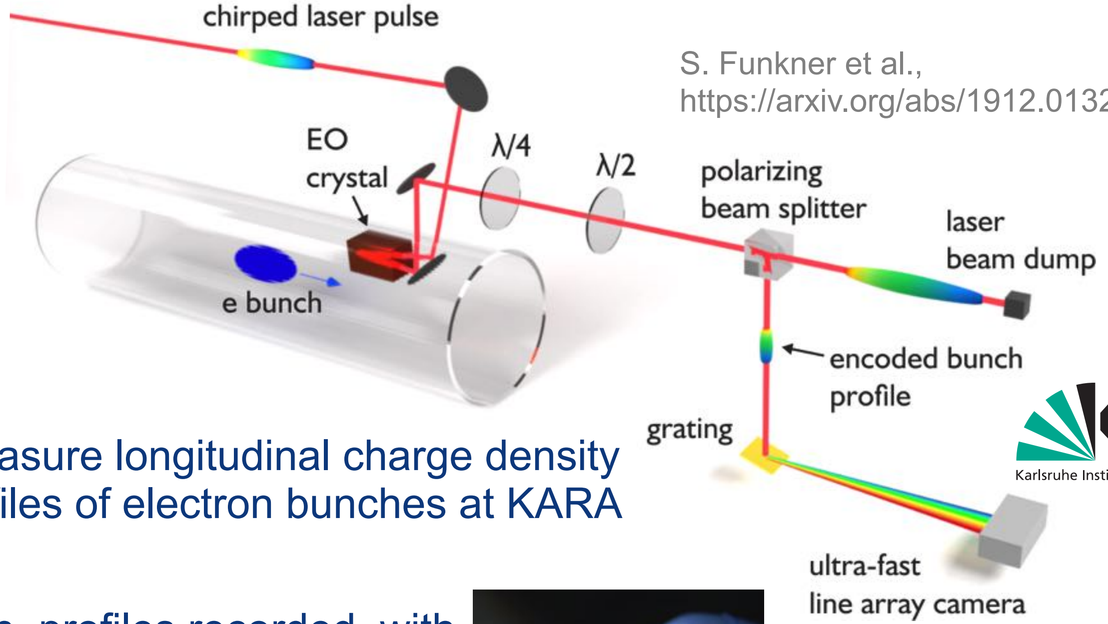
Bunch-by-bunch longitudinal profiles



Dmitry Shatilov

FCC-ee bunch profiles are strongly affected by beamstrahlung in collision

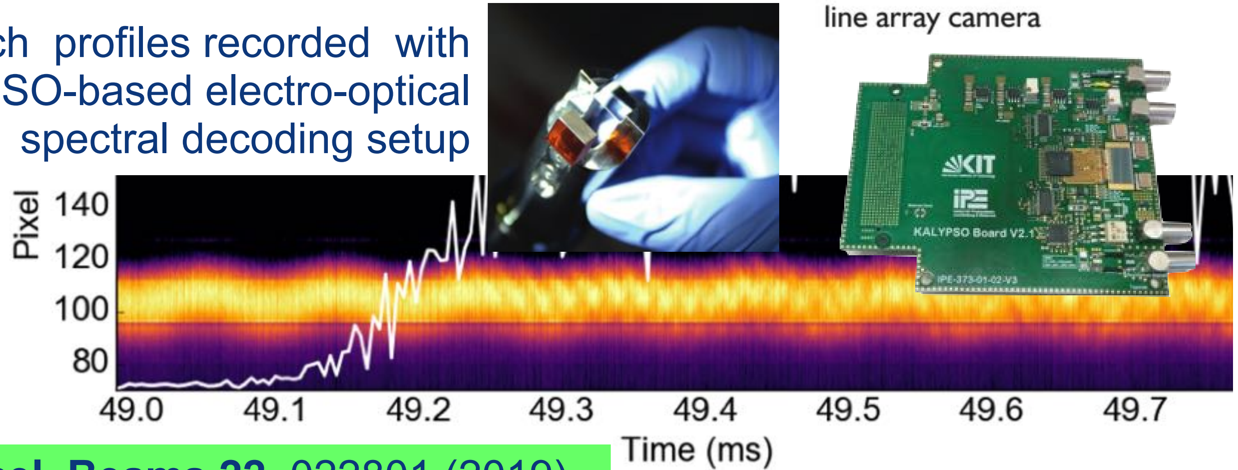
high-throughput electro-optical single-shot diagnostics developed at KIT



S. Funkner et al., https://arxiv.org/abs/1912.01323

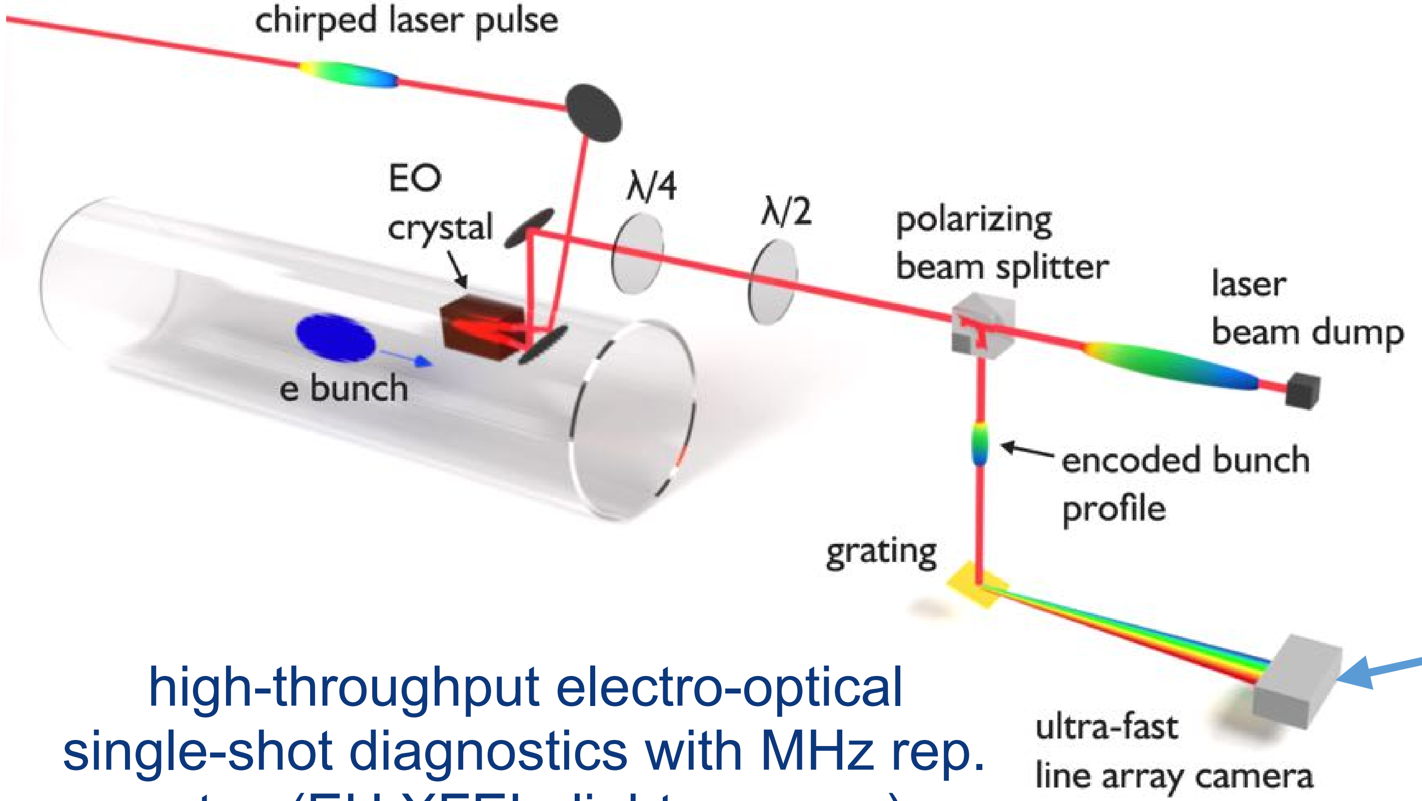
setup to measure longitudinal charge density profiles of electron bunches at KARA

longitudinal bunch profiles recorded with the KALYPSO-based electro-optical spectral decoding setup



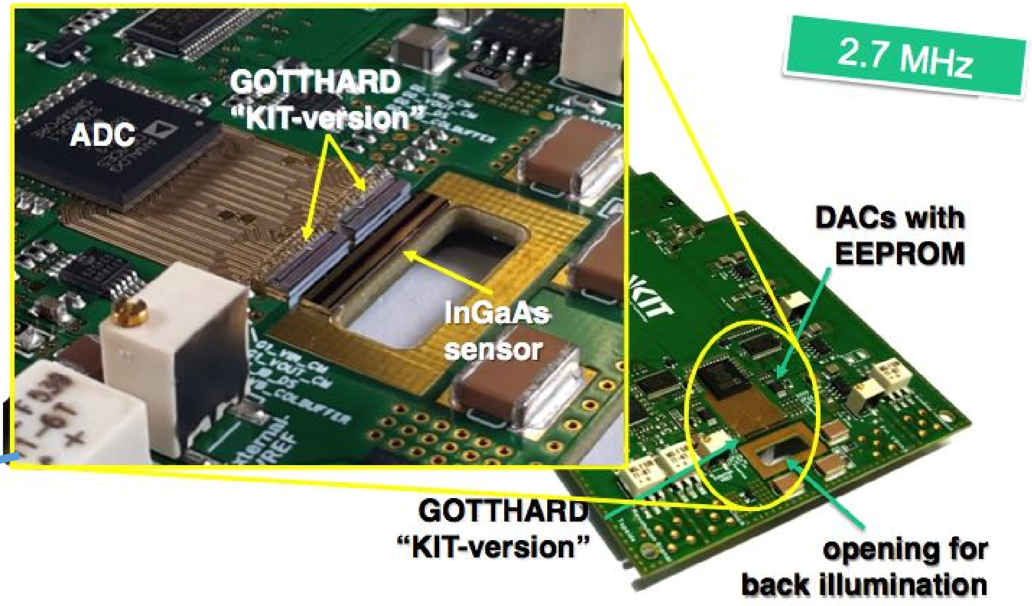
Stefan Funkner et al., **Phys. Rev. Accel. Beams 22**, 022801 (2019)
Benjamin Kehrer et al., **Phys. Rev. Accel. Beams 21**, 102803 (2018)

Near-field electro-optical spectral decoding



high-throughput electro-optical single-shot diagnostics with MHz rep. rates (EU XFEL, light sources)

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

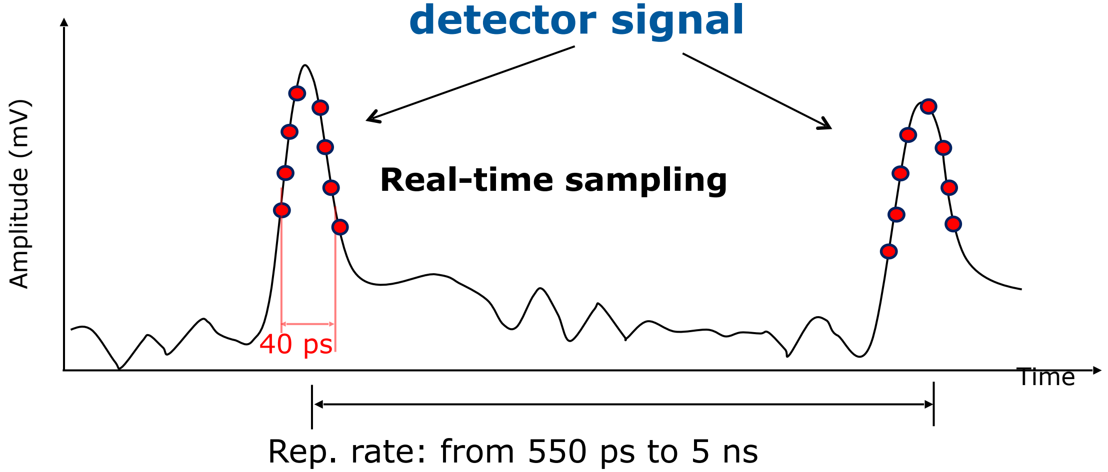


L. Rota et al., **NIM A, 936**, pp. 10-13, 2019
Stefan Funker et al., **Phys. Rev. Accel. Beams 22, 022801 (2019)**

Pulse diagnostics, e.g., for THz signals

- **KAPTURE readout electronics for fast sensors**
  - Picosecond sampling system
  - Up to 1 GHz trigger rate
  - Up to 8 sampling points per detector pulse
  - Readout by PCIe up to 64 Gb/s continuously
  - Real-time data elaboration by GPUs

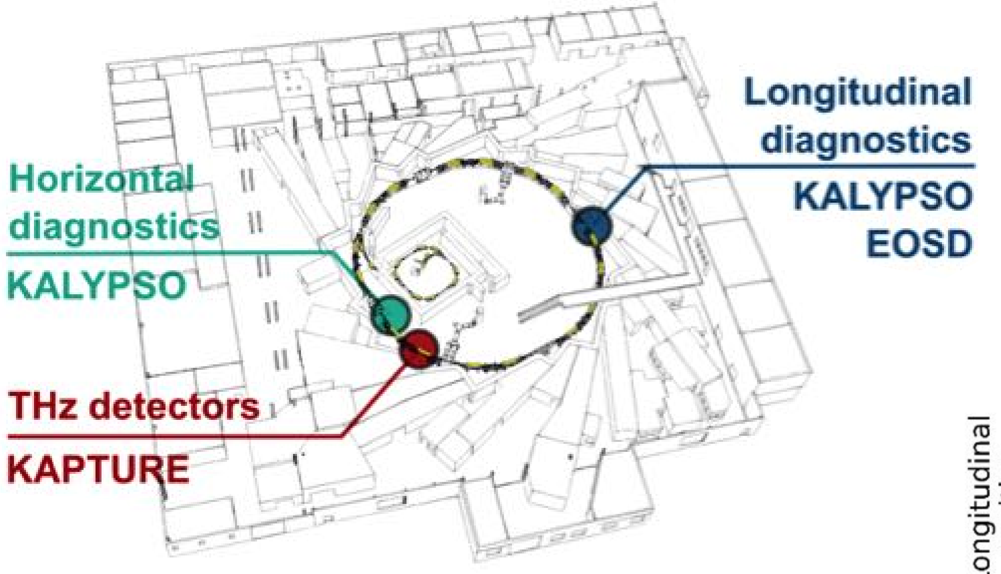
KAPTURE working principle



- **Scalable, multi-purpose, e.g.**
  - Modular setup
  - Simultaneous readout of multiple sensors
  - Online pulse-shape reconstruction

M. Caselle et al., **JINST 072P_1116 (2016)**
M. Brosi et al., **Phys. Rev. Accel. Beams 19, 110701 (2016)**

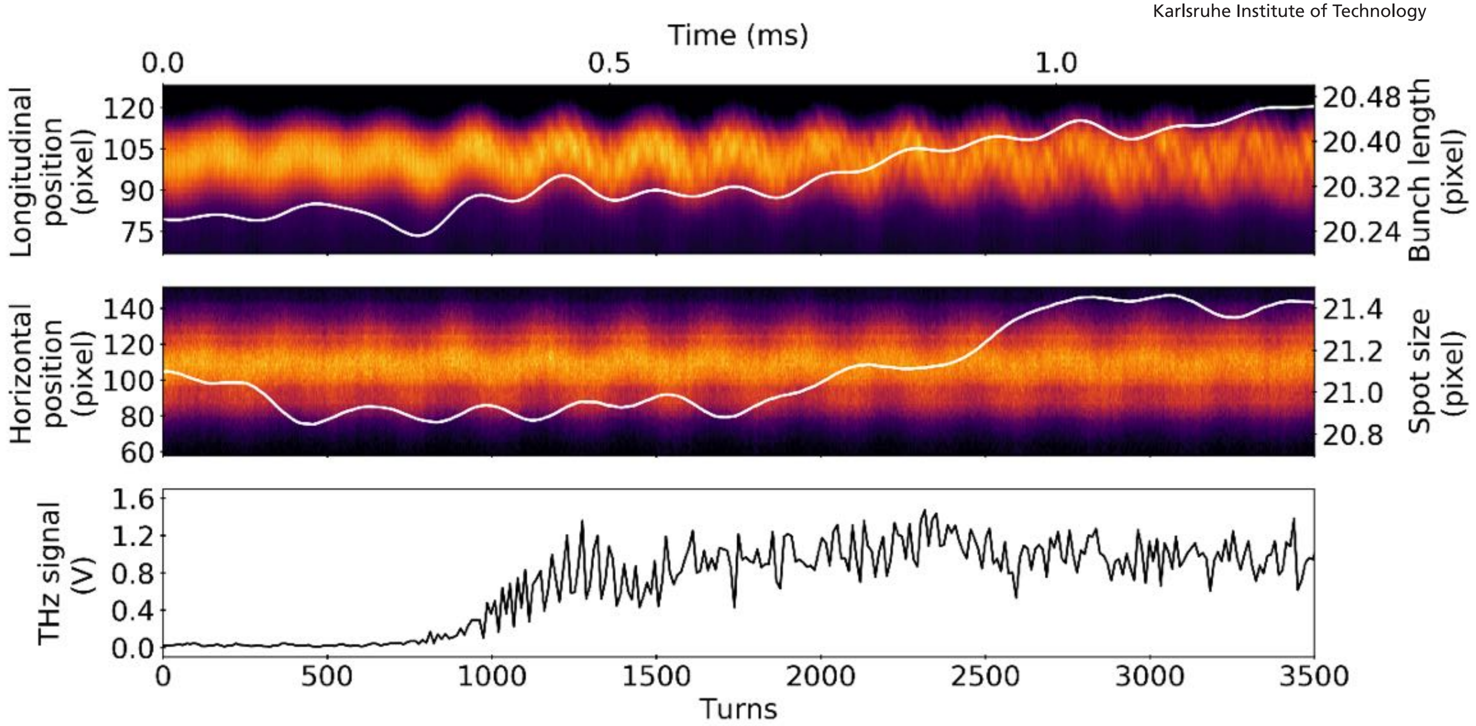
The full picture…. at 2.7 MHz



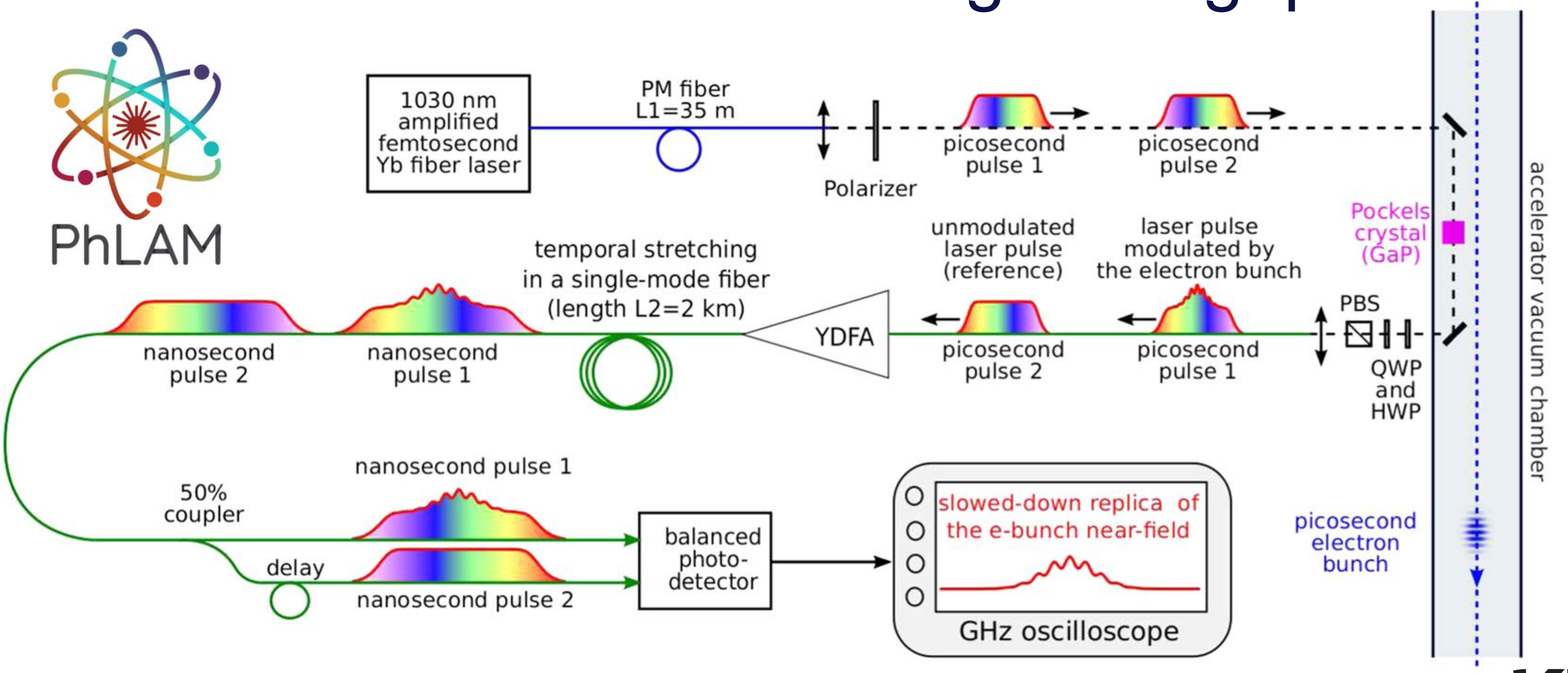
KARA test facility

- Circumference: 110.4 m
- Energy range: 0.5 - 2.5 GeV
- Revolution frequency: 2.715 MHz
- RMS bunch length:
  45 ps (for 2.5 GeV) down to
  a few ps (for 1.3 GeV)

M. Brosi et al.,IPAC19,
https://doi.org/10.18429/JACoW-IPAC2019-WEPTS015



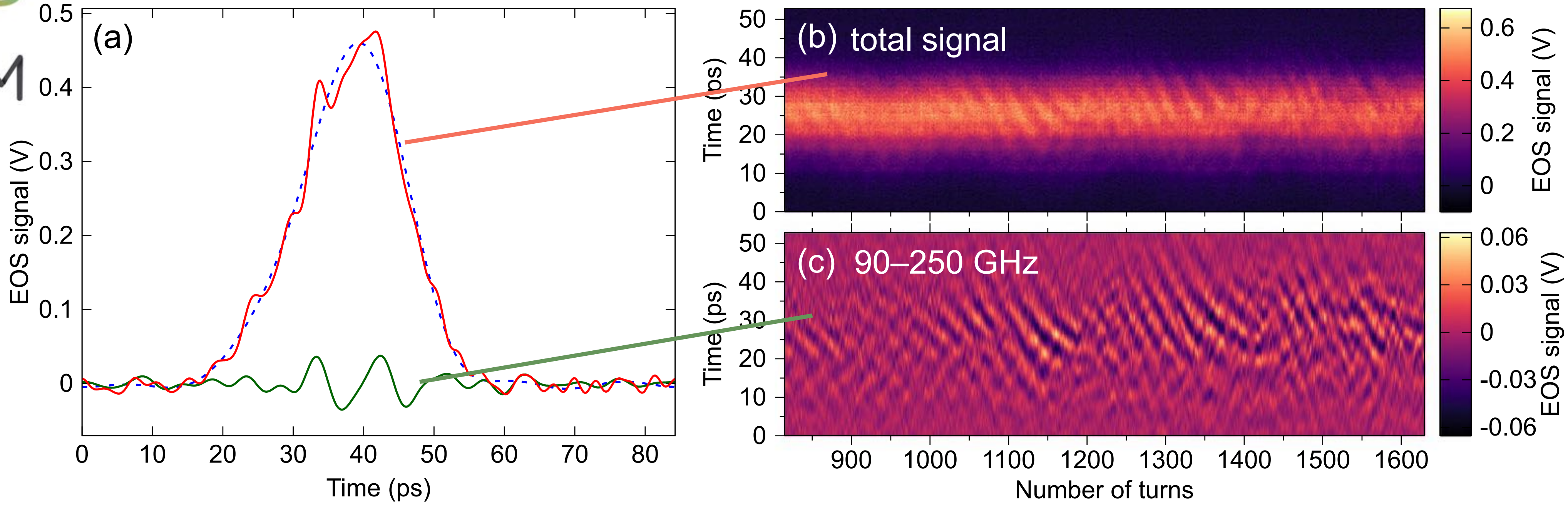
Photonic time-stretch recording of long. profile



Serge Bielawski et al., **Scientific Reports, 9(1):10391**, 2019

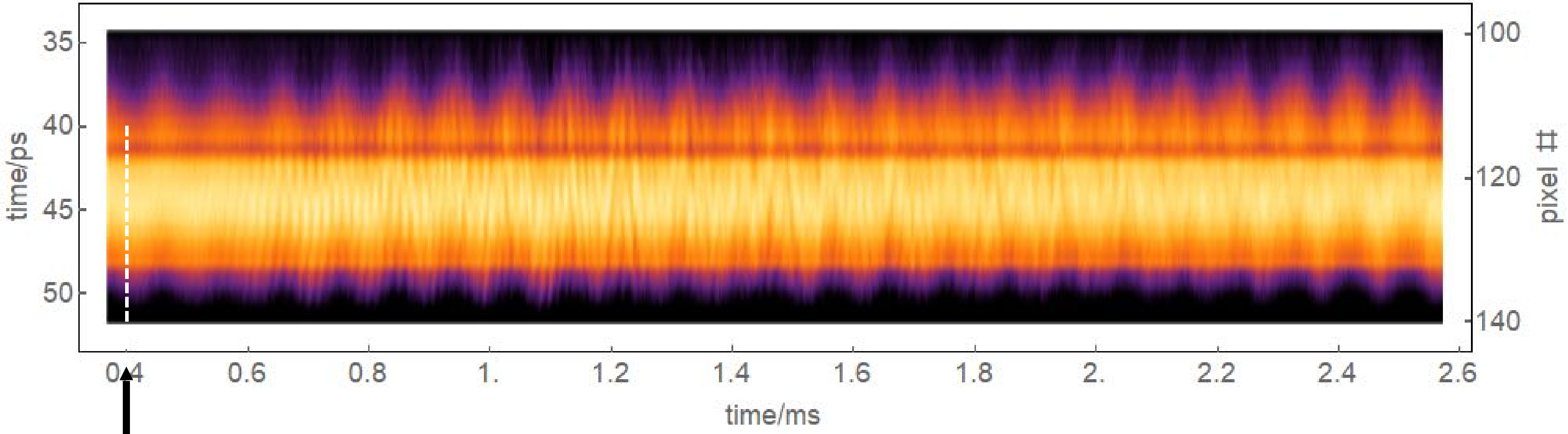
Photonic time-stretch recording of long. profile

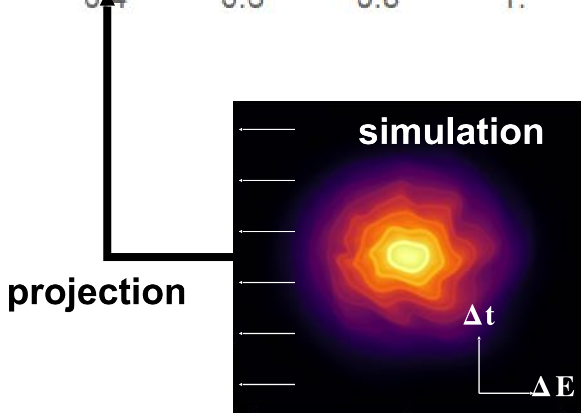
PhLAM



Serge Bielawski et al., **Scientific Reports, 9(1):10391**, 2019

Phase space interpretation of bunch profile measurements

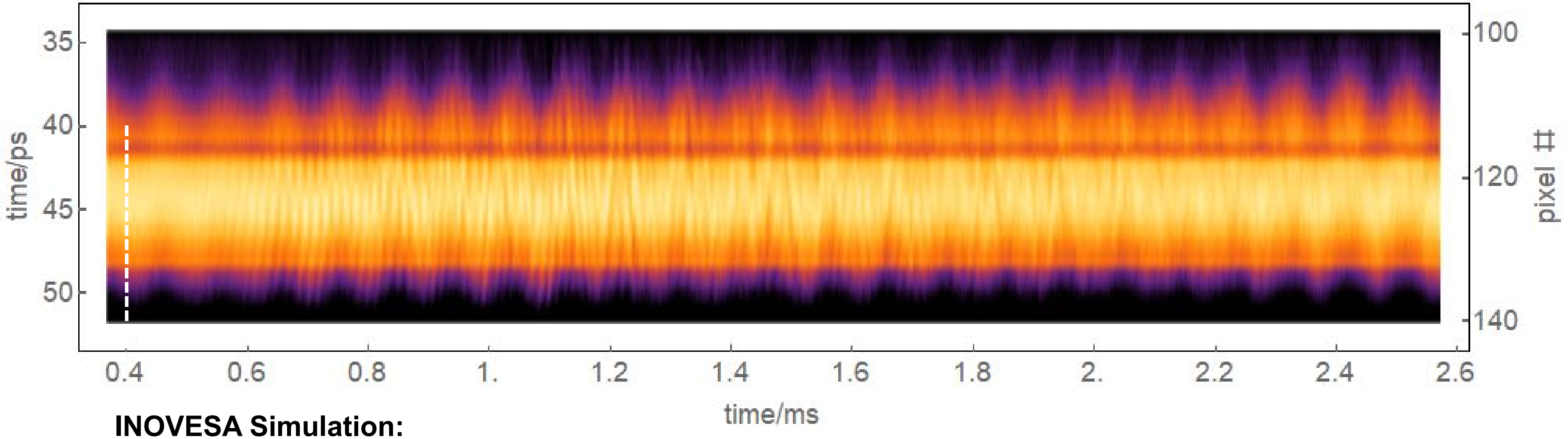




phase space density

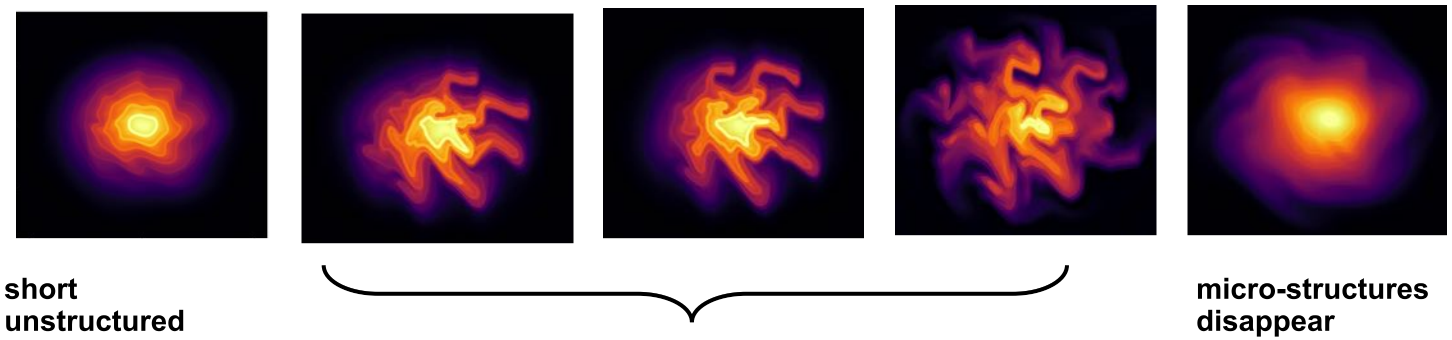
S. Funker et al., **Phys. Rev. Accel. Beams 22, 022801 (2019)**
P. Schönfeldt et al., **Phys. Rev. Accel. Beams 20 (3), 030704, (2017)**

Phase space interpretation of bunch profile measurements



Karlsruhe Institute of Technology

INOVESA Simulation:



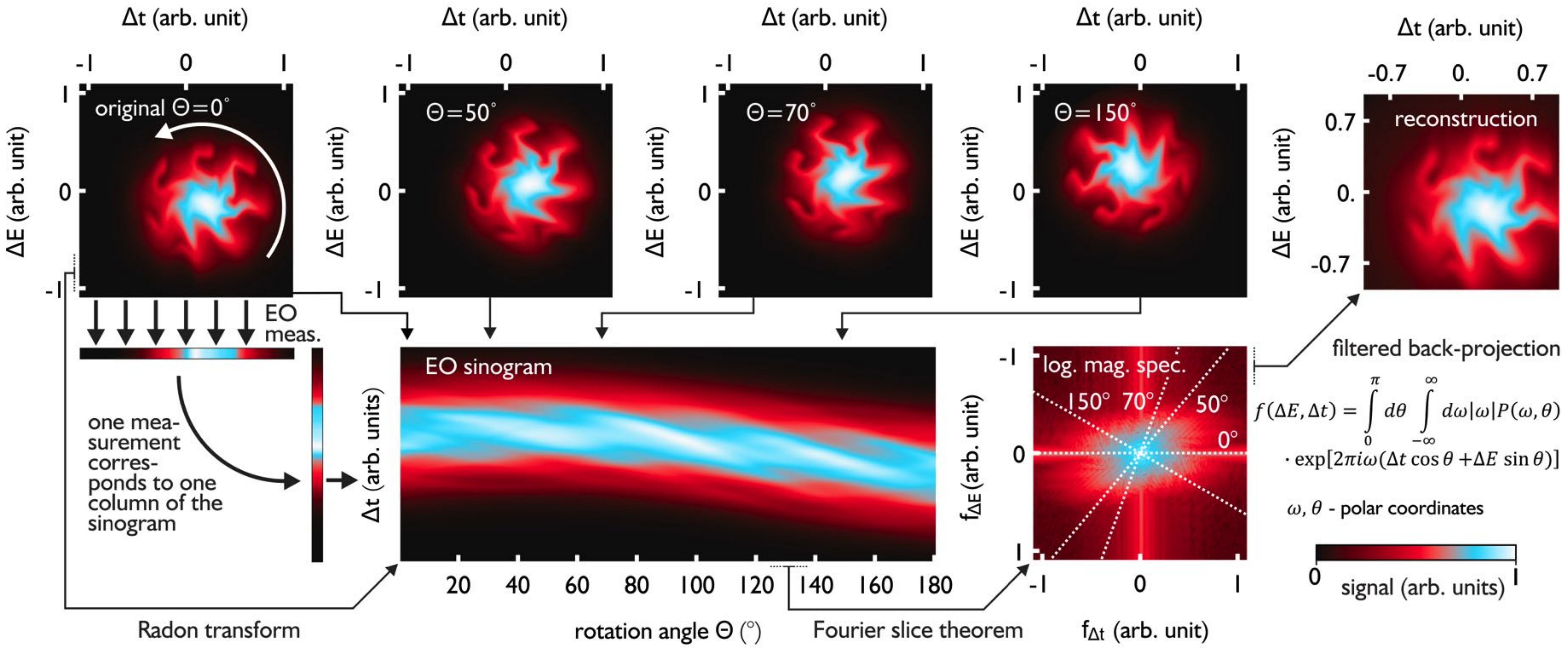
short unstructured bunch

micro-structures appear + increase of bunch size

micro-structures disappear

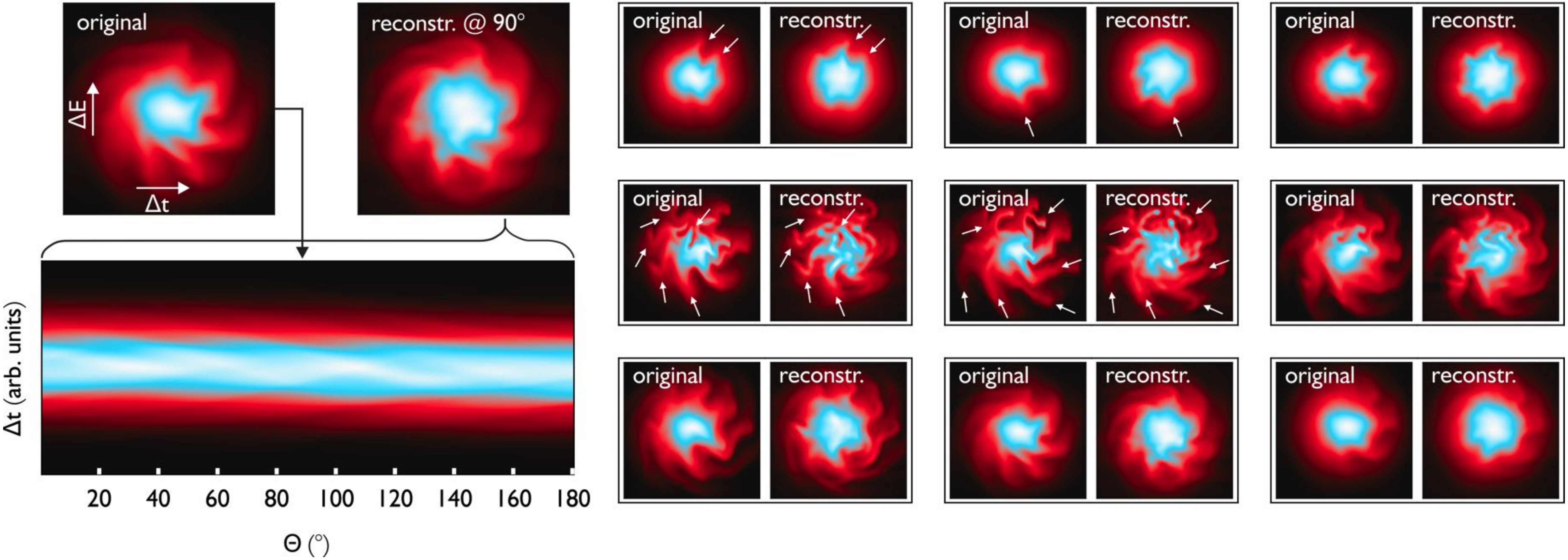
S. Funker et al., **Phys. Rev. Accel. Beams 22, 022801 (2019)**
P. Schönfeldt et al., **Phys. Rev. Accel. Beams 20 (3), 030704, (2017)**

Phase space reconstruction, …



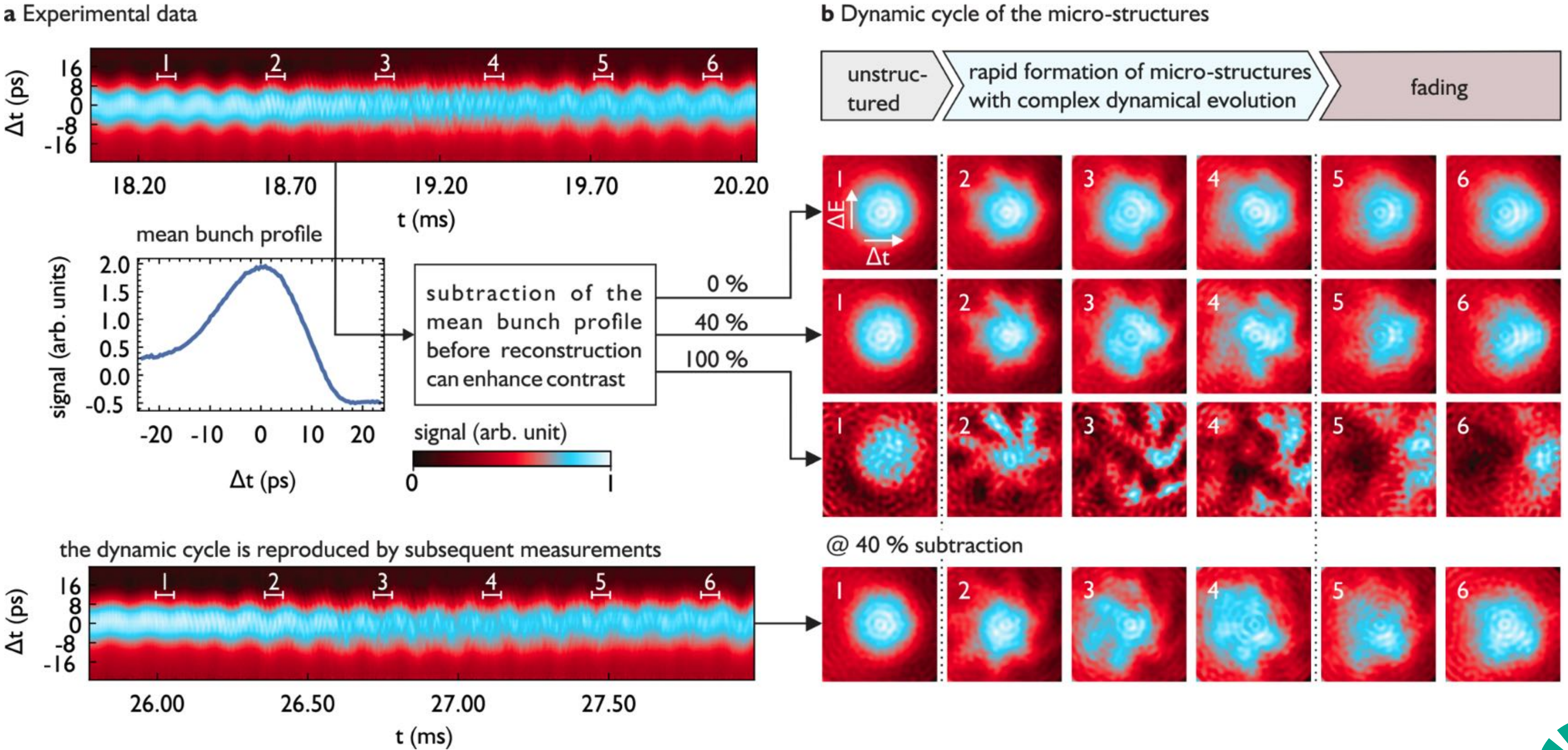
S. Funker et al., https://arxiv.org/abs/1912.01323 (2020)

…validation with simulations, …



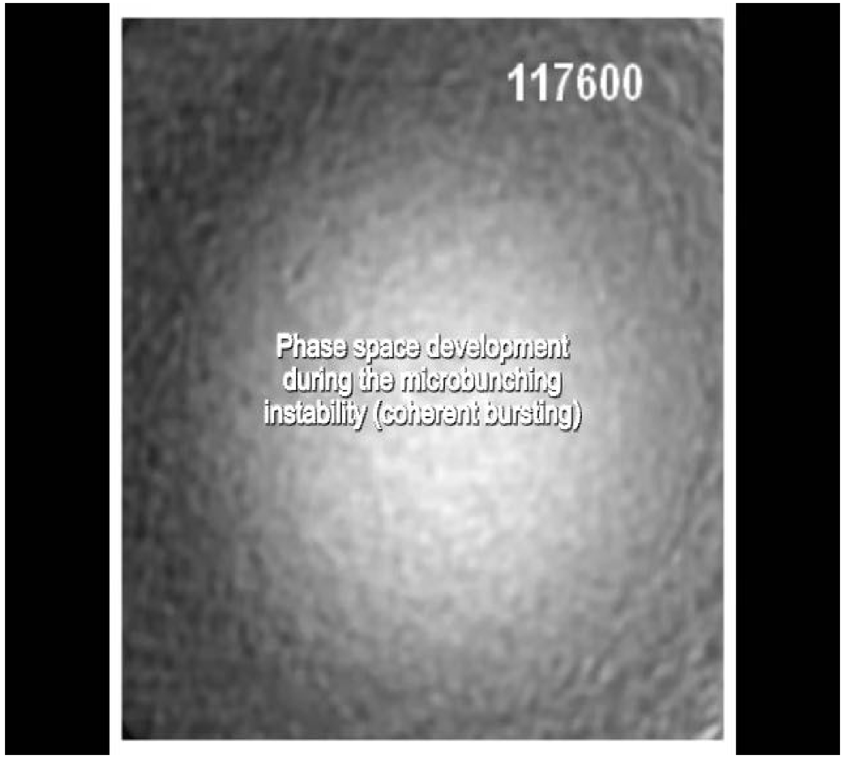
S. Funker et al., https://arxiv.org/abs/1912.01323 (2020)

…and application to beam measurements



S. Funker et al., https://arxiv.org/abs/1912.01323 (2020)

Turn-by-turn dynamics during the microbunching instability

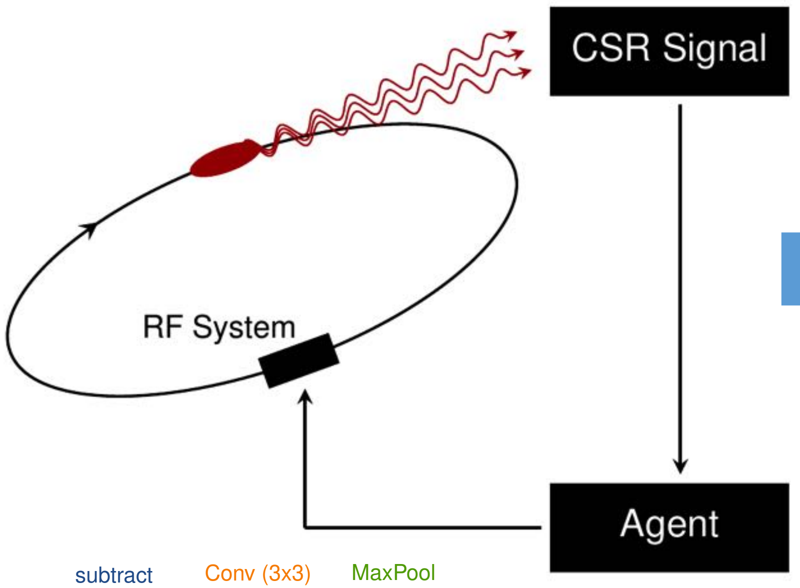


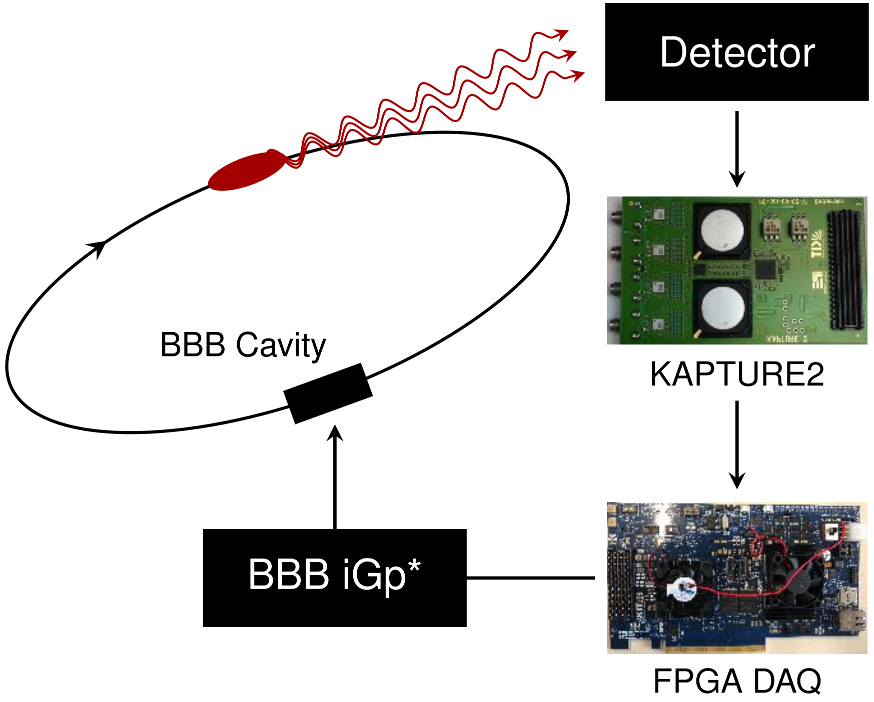
Demonstration at KARA test facility

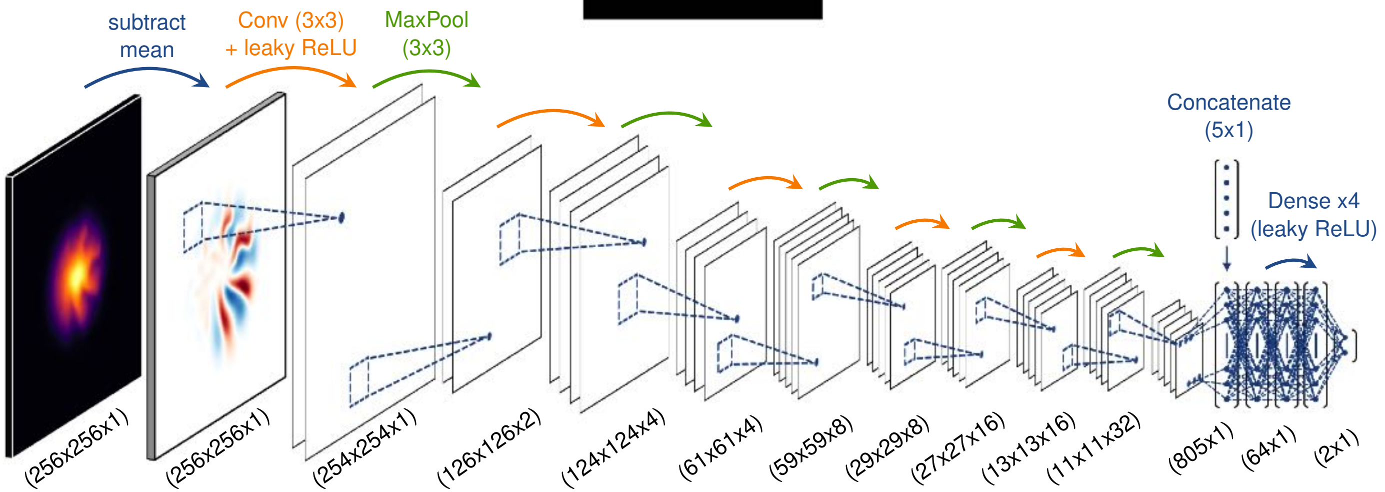
- reconstruction time for complete phase space image: 61 µs
- „Randon morphing“ between independent measurement

S. Funker et al., https://arxiv.org/abs/1912.01323 (2020)

AI: fast detection - fast feedback ?







Vision:
Controlling instabilities in autonomous accelerators

Andrea Santamaria Garcia, et al. (KIT)

Conclusion and next steps

- A first conceptual design of the FCC-ee BI has been performed for the CDR
- No feasibility issues
- Long list of technological challenges ahead of us
- Benefitting from the R&D done in low-emittance ring / linear colliders / FEL communities.
- Next step is to launch the FCC-ee specific R&D work to provide a realistic suite of beam diagnostic with a more precise cost estimation

Thank you for your attention.