HELMHOLTZ

Research for grand challenges.

Scientific Highlights & Future Strategy ST3

Advanced beam control, diagnostics & dynamics

The ARD test facilities - Essential drivers for timely advances in ST3-topics ARES, cSTART, FLUTE, KARA, PITZ, SEALab, …

Erik Bründermann, KIT (Spokesperson ST3)

Holger Schlarb, DESY (Spokesperson ST3)

Center contacts: Thorsten Kamps (HZB); Michael Kuntzsch, Pavel Evtushenko (HZDR); Peter Forck(GSI)

10.10.2023

9th MT Days, KIT / Karlsruhe

MT ARD ST3 – Advanced beam control, diagnostics & dynamics

Covering today

- **Our vision for PoF IV** – 2021-2027
- **Essential drivers for timely advances in ST3-topics: the ARD test facilities**
  - Advanced accelerator development to explore novel use cases: Radiotherapy & UED

- **Beam dynamics**: Structures and photons to manipulate beams, seeding
- **Beam diagnostics**: Phase space tomography, coherent transition radiation, earthquakes
- **Control systems**: Standardization, reaching the low single-digit fs range
- **Machine learning, reinforcement learning, Bayesian optimization**
  - Reinforcement learning on hardware

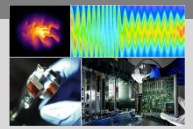
- **Attosecond realm**
- **Future strategy for PoF V**
- **ARD ST3 annual meetings**

ST3 – ADVANCED BEAM CONTROL, DIAGNOSTICS & DYNAMICS

Heart beat of Matter – Faster, more throughput, at highest precision

ARD subtopic 3, MT programme, POF-4: 2021-2027

Control of extreme beams at the forefront of technology



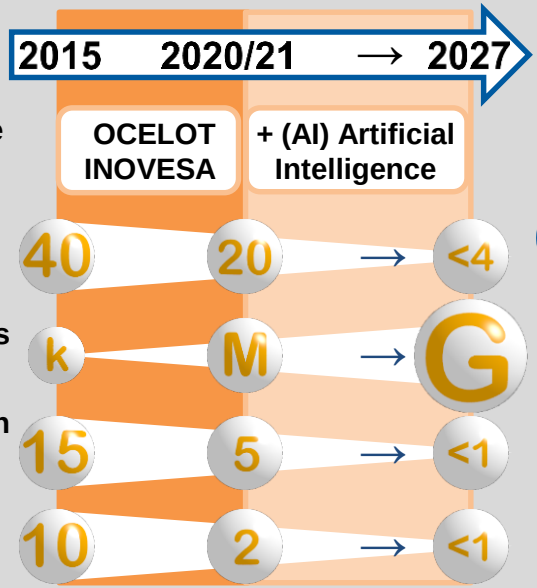
Dynamics code
micro-bunching instabilities

XUV seeding
nm

Diagnostic rates
Frames/second

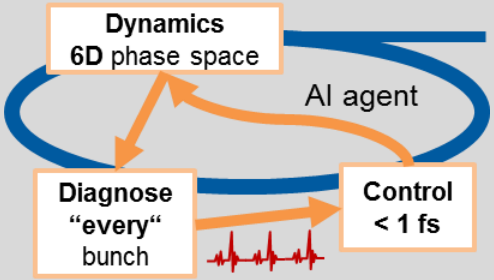
Synchronization
in accelerators
fs

Time-resolved
fs



Custom & Extreme Beams

Extreme dynamic range



Advanced beam control

Attosecond metrology

Connecting Sub-Topics and being a hub to DTS and DMA

VISION

ARD ST3 – Advanced beam control, diagnostics & dynamics

Essential drivers for timely advances in ST3-topics: the ARD test facilities

Transfer new methods and technologies during - limited - access time to user facilities

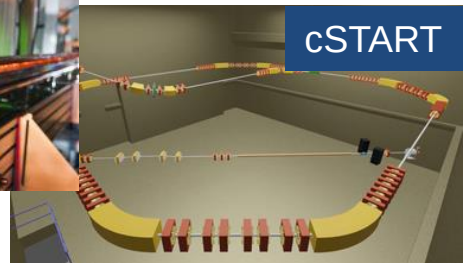
ARES / DESY

Energy	20 – 160 MeV
Charge	0.001 – 280 pC
Rep.rate	Up to 50 Hz
Length	Few fs / sub-fs

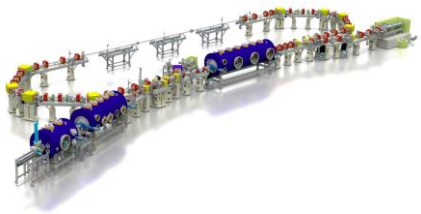
PITZ

FLUTE / KIT

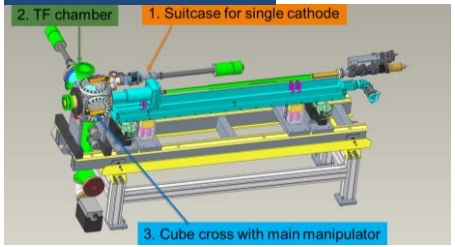
cSTART



SEALab / HZB



ELBE / HZDR



KARA / KIT

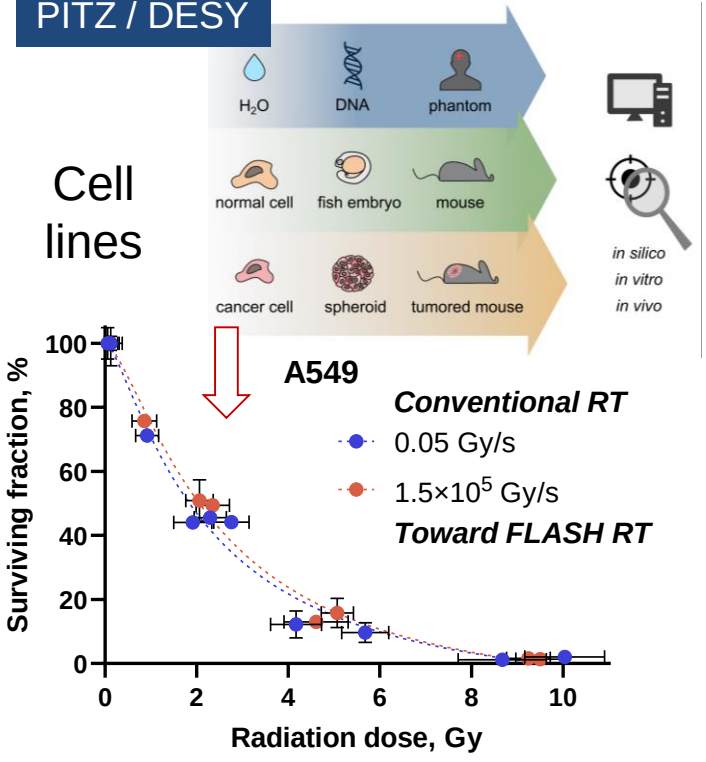
Images from and more at indico.desy.de/e/2023-st3

Advanced accelerator development to explore novel use cases

Radiotherapy (RT) – partner with medical community

Accelerator and Medical Physics (joint session AKBP/ST), DPG 2023

PITZ / DESY

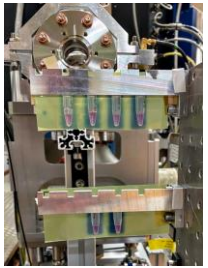


See more in PITZ facility talk

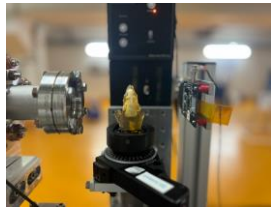
ARES / DESY

Courtesy: Florian Burkart (DESY)

- **Medical imaging** (e- CT)
- **Cancer cell studies** towards RT
- Modalities
  - Very high electron energy (VHEE)
  - FLASH



Mouse phantom

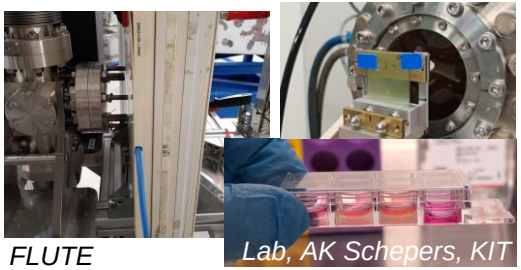


Cancer cells in beam (UKE, U Manchester)

FLUTE & KARA / KIT

- Toward FLASH RT

IMAGE BL @ KARA



FLUTE

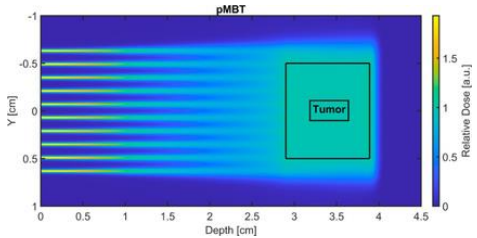
Lab, AK Schepers, KIT

Cells in hydrogel

See more in KIT facility talk

BerlinProtonen / HZB

- Protons for eye tumor therapy



Dose for proton mini-beams

See more in HZB facility talk

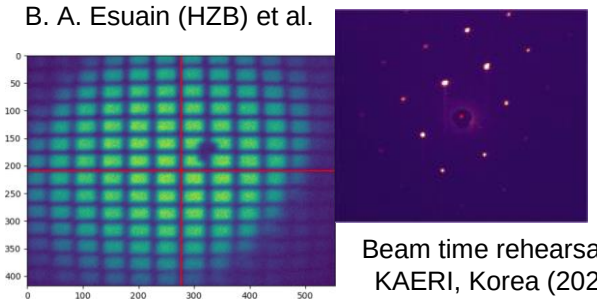
Images from and more at indico.desy.de/e/2023-st3

Advanced accelerator development to explore novel use cases

UED

- Ultrafast electron diffraction/scattering/…
  - Reveal sub-ps to fs e- motions in atomic nuclei within molecules – applications in materials science, chemistry and biology.

Ultrafast electron scattering applications at SEALab
B. A. Esuain (HZB) et al.



Beam time rehearsal at KAERI, Korea (2022)

- Interest of several centers and universities
  - High-repetition rates
  - Superconducting RF
  - High-speed, wide dynamic range, low charge, non-invasive diagnostics

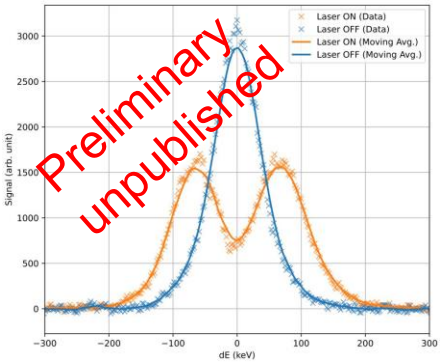
Talk (Wed) Klaus Flöttmann, DESY

Images from and more at indico.desy.de/e/2023-st3

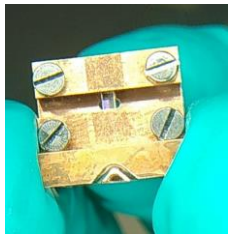
Highlight ST3 – Advanced beam control, diagnostics & dynamics

Beam dynamics, structures and photons to manipulate beams, seeding

Dielectric laser accelerator at ARES
First momentum modulation
W. Kuropka (DESY) et al.

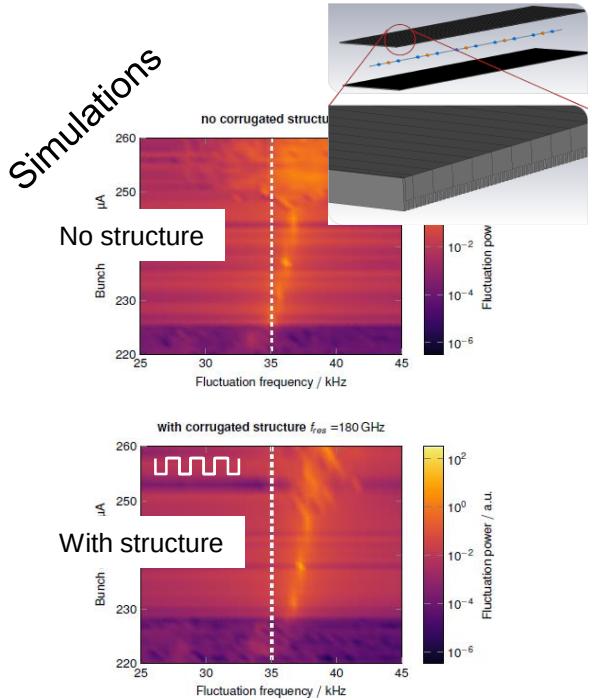


Aperture: 1 µm x 1 mm



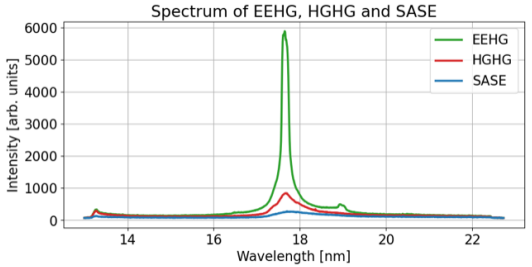
Accelerator on a chip (ACHIP)

Corrugated structure impedance at KARA
S. Maier (KIT) et al.

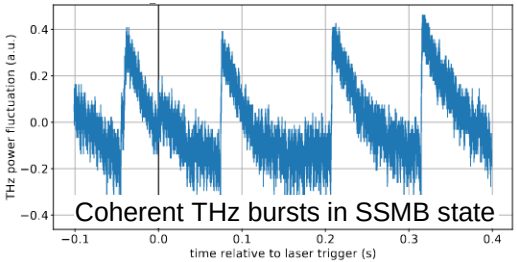


First EEHG seeding at FLASH (echo-enabled harmonic generation)
G. Paraskaki (DESY) et al.

Talk (Tue) Eugenio Ferrari, DESY



Steady-state micro-bunching (SSMB) at MLS
A. Kruschinski (HZB) et al.



Images from and more at indico.desy.de/e/2023-st3

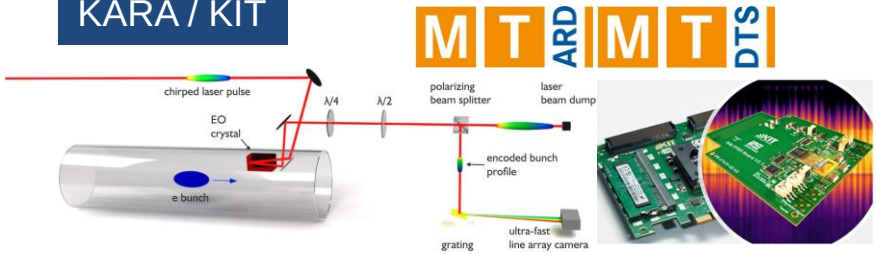
Highlight ST3 – Advanced beam control, diagnostics & dynamics

Beam diagnostics: phase space tomography

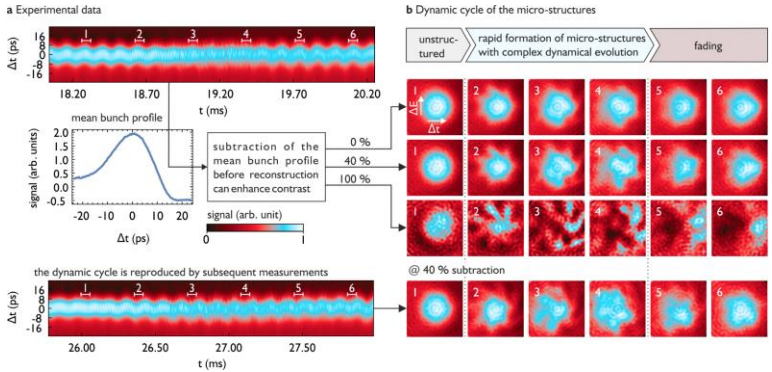
12th Workshop on Longitudinal Electron Bunch Diagnostics, Jun 12-14, 2023, KCETA, KIT (39 participants) - indico.scc.kit.edu/e/cwld12

Revealing the dynamics of ultrarelativistic non-equilibrium many-electron systems with phase space tomography
S. Funkner (KIT) et al., see also *nature* – Sci. Rep. 13, 4618 (2023)

KARA / KIT



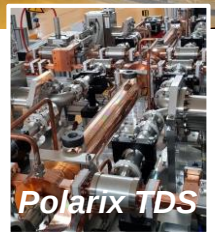
Transfer: European XFEL, DELTA, FLASH, and SOLEIL use **KALYPSO**.



ARES / DESY

Courtesy: Florian Burkart (DESY)

- ARD test facility for novel acceleration techniques and diagnostics (DLA) & medical applications.
- S-band electron linac with world record stability.
- **5D beam tomography** (in commissioning).
  - **PolariX X-Band TDS** (CERN, PSI, DESY).



FLUTE / KIT

M. Nabinger (KIT) et al.

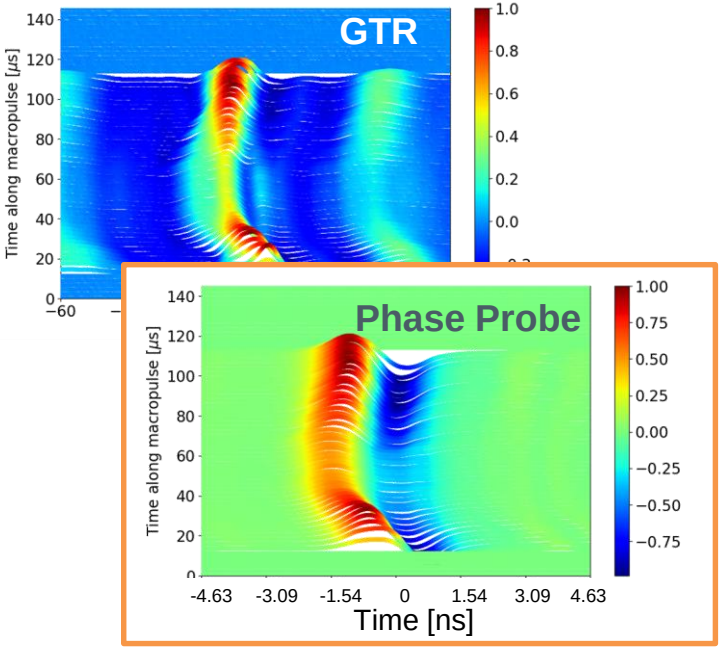
- **Compact TDS** (transverse-deflecting system).
- **THz streaking** with split-ring resonator.

Images from and more at indico.desy.de/e/2023-st3

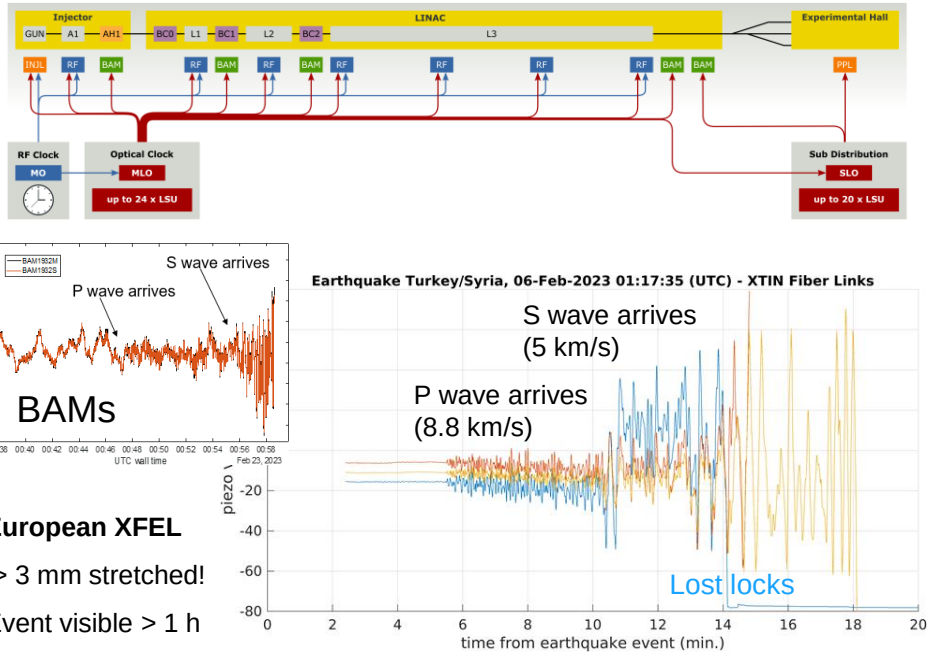
Highlight ST3 – Advanced beam control, diagnostics & dynamics

Beam diagnostics

Bunch shape detection by GHz coherent transition radiation at the ion LINAC
S. Klaproth et al. (GSI)



Impact of earthquakes on fs-synchronization
Failed link length compensation
S. Schulz (DESY) et al.



European XFEL

> 3 mm stretched!

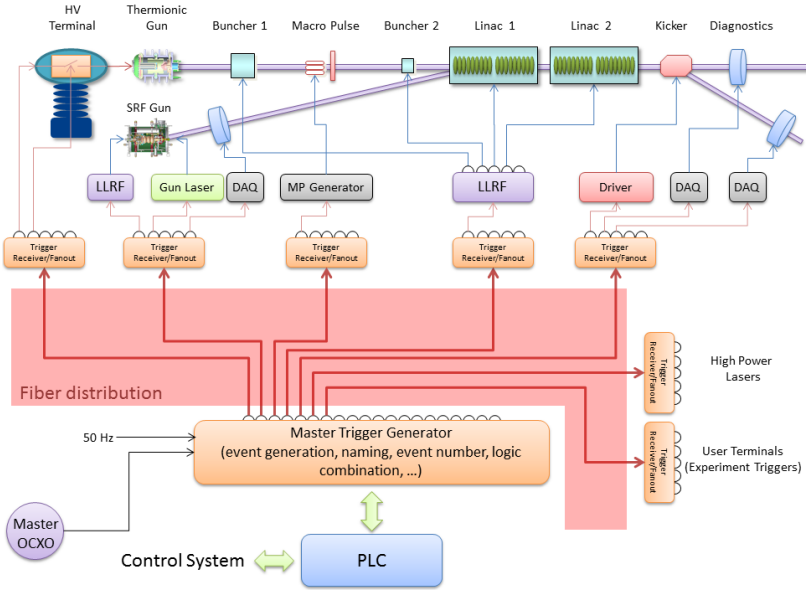
Event visible > 1 h

Images from and more at indico.desy.de/e/2023-st3

ARD ST3 – Advanced beam control, diagnostics & dynamics

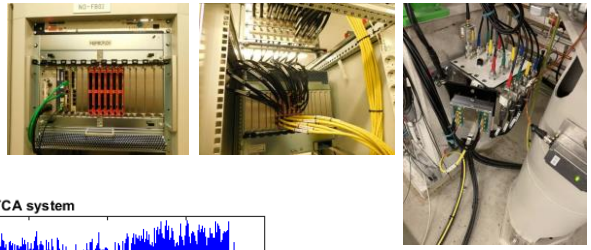
Control systems – standardization

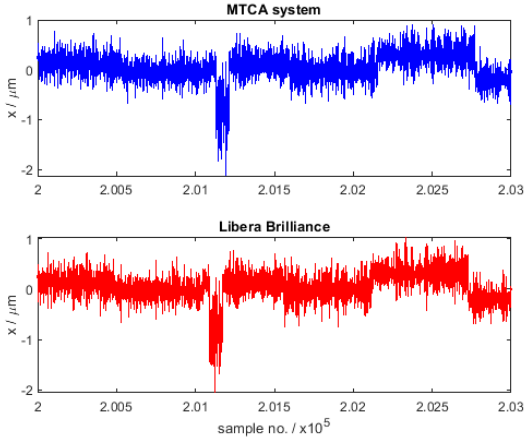
New Picosecond Timing System for ELBE
M. Kuntzsch (HZDR) et al.
see also Improving Beam-Based Regulation
A. Maalberg (HZDR) et al.



12 BPM signals split for study of new MTCA readout electronics parallel operation with existing Libera Brilliance system

Prototype MTCA-based system installed at PETRA III





both electronics see same signal, **but MTCA has higher resolution!**

See more in DESY facility talk

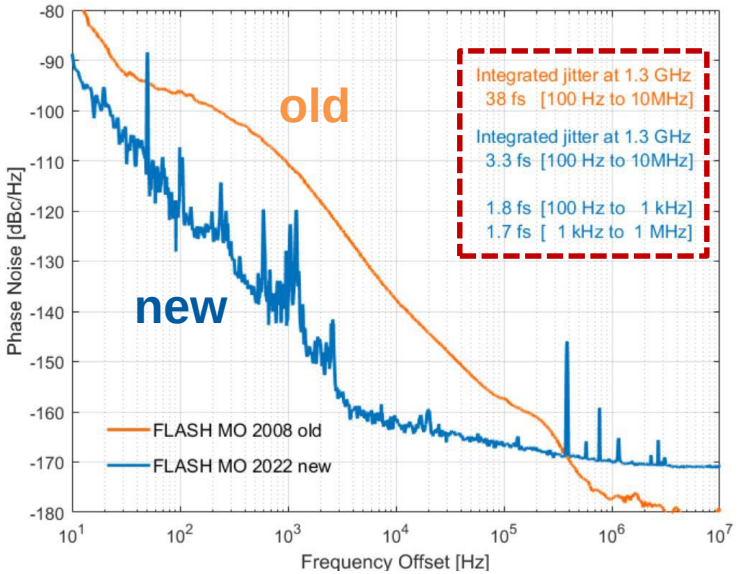
Images from and more at indico.desy.de/e/2023-st3

ARD ST3 – Advanced beam control, diagnostics & dynamics

New master oscillators & optical reference module

Improved machine stability

- FLASH's main oscillator completely redesigned
- Integrated time jitter improved
  - From **38 fs** to **3 fs**
    at high-power RF level of **+47 dBm**
- Master laser oscillator (MLO) synchronized
  - **2 fs** (improvement x5)



See more in DESY facility talk at ST3 meeting by Holger Schlarb on PETRA IV, FLASH2020+, and European XFEL.

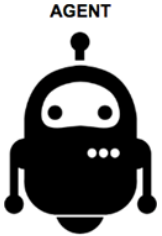
Images from and more at indico.desy.de/e/2023-st3

Highlight ST3 – Advanced beam control, diagnostics & dynamics

Machine learning, reinforcement learning, Bayesian optimization & control

Transfer machine learning methods to European XFEL
Reinforcement Learning Applications at Particle Accelerators

C. Xu (KIT) et al., see also Bayesian Optimization for SASE Tuning at the EuXFEL, IPAC'23, THPL028 (2023)



Check out
RL4AA Collaboration

rl4aa.github.io/ & RL4AA'24
Feb 05-07, 2024, Salzburg

Joined DESY & KIT ST3-publication

arXiv:2306.03739

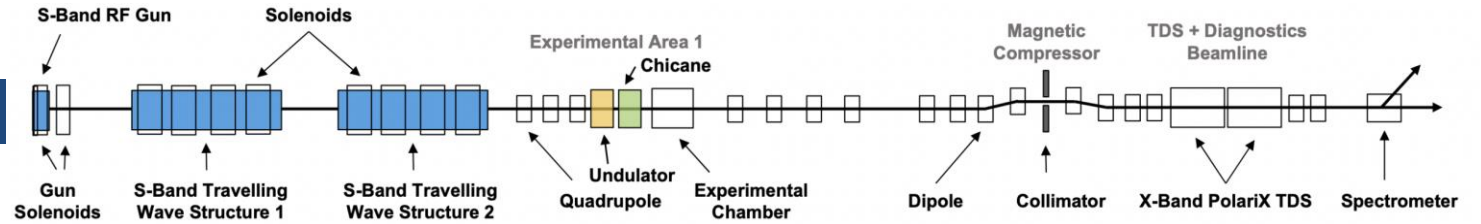
[Submitted on 6 Jun 2023]

Learning to Do or Learning While Doing: Reinforcement Learning and Bayesian Optimisation for Online Continuous Tuning

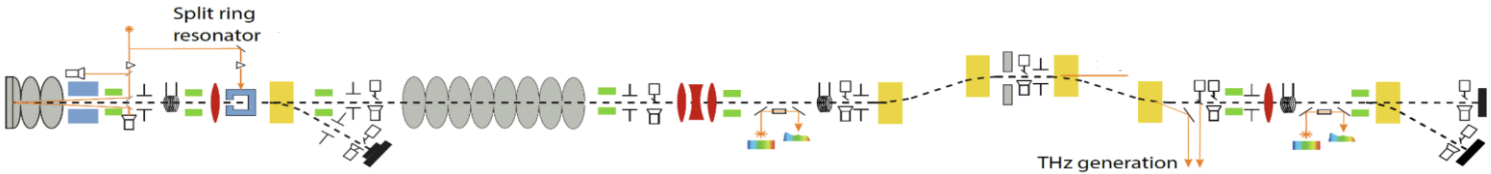
Jan Kaiser, Chenran Xu, Annika Eichler, Andrea Santamaria Garcia, Oliver Stein, Erik Bründermann, Willi Kuropka, Hannes Dinter, Frank Mayet, Thomas Vinatier, Florian Burkart, Holger Schlarb

Autonomous Accelerators supported by Helmholtz AI project

ARES / DESY



FLUTE / KIT



Images from and more at indico.desy.de/e/2023-st3

Highlight ST3 – Advanced beam control, diagnostics & dynamics

Machine learning, reinforcement learning, Bayesian optimization & control

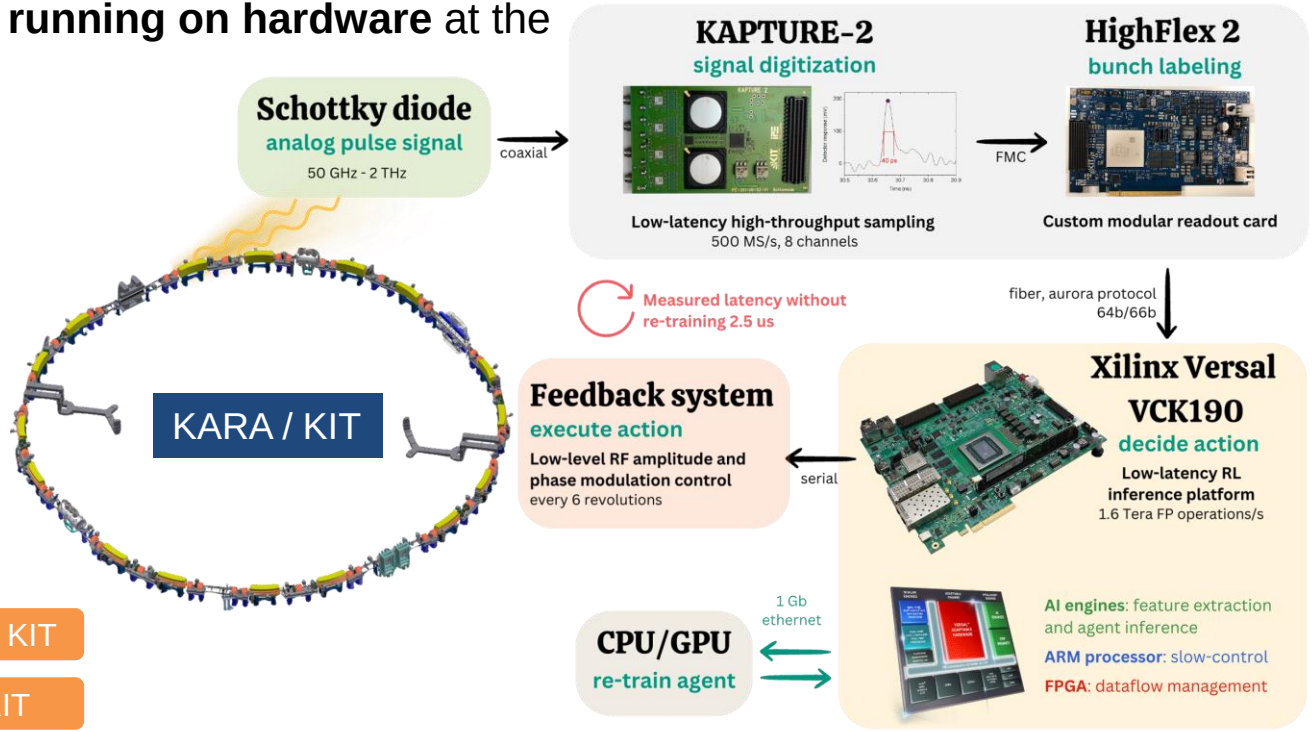
First successful application of RL in an **accelerator with online training** and **running on hardware** at the ARD test facility KARA**.**

Full cycle with latency of only 2.5 µs (!)

Rapid prototyping by close collaboration.

Talk (Wed) Andrea Santamaria, KIT

Talk (Tue) Luca Scomparin, KIT



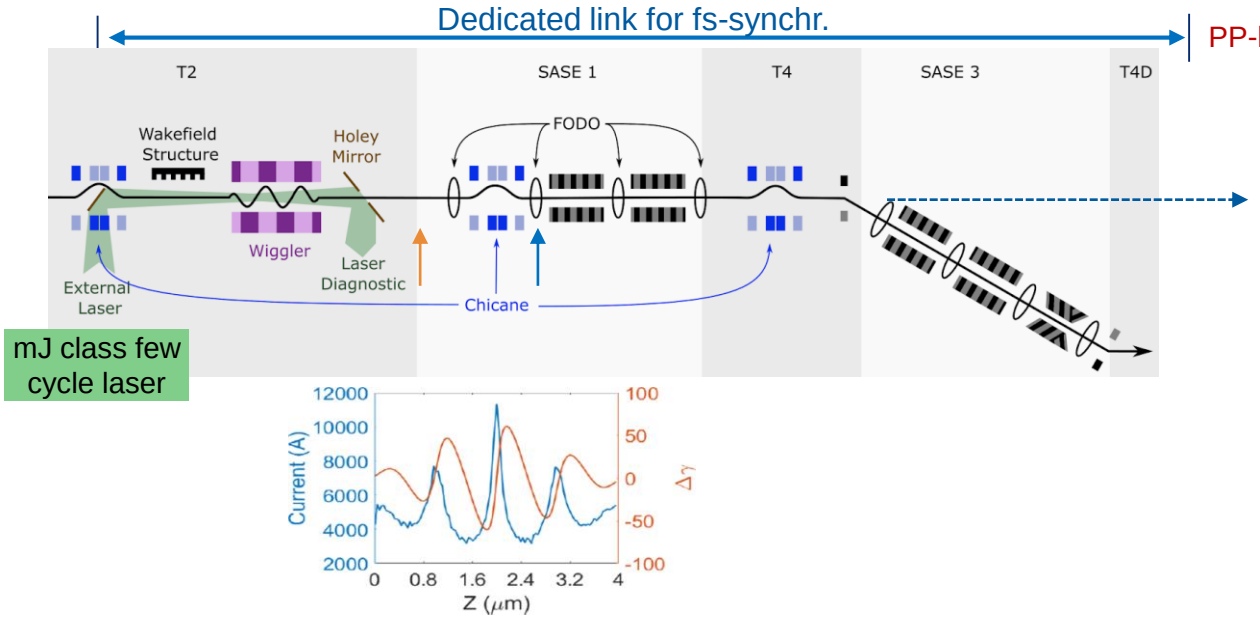
Courtesy: A. Santamaria Garcia (KIT)

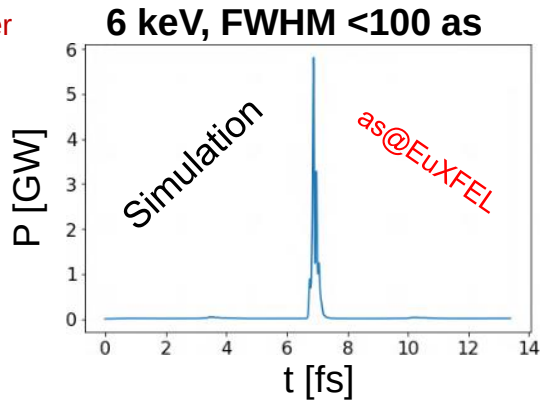
Attosecond physics and technology

One of our ST3 goals for PoF IV until 2027: **Attosecond metrology**

Nobel Prize Physics 2023 “for experimental methods that **generate attosecond pulses of light** for the study of **electron dynamics in matter**”

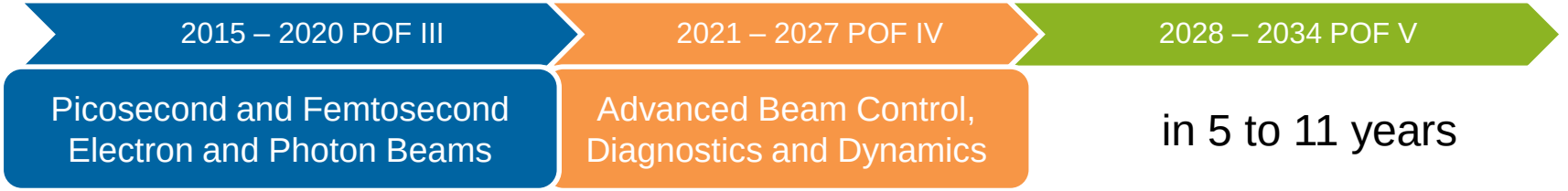
ASPECT: **A**tto-**s**econd **p**ulses with **e**SASE and **c**hirp/**t**aper





Courtesy: M. Guetg (DESY)

Future strategy for ST3



Possible topics

- Important **cross-center topic** (micro-bunching instability (MBI), seeding, SSMB, ...).
- **Structured beams**, **micro-structured beams** for FEL and storage rings/synchrotrons.
- **Non-equilibrium** beam dynamics (e.g. cSTART).
- **UED** at several centers (**fC bunches** at **high repetition rates**, extension of the limits on dynamic range, **source development**, challenges for **non-invasive diagnostics**, …).
- FEL source development and **high brightness** (**CW**) beams (e.g. RF/SRF guns).

- **Beam control**: AI at the most challenging level (e.g. **reinforcement learning on hardware** for **real-time control**). Define interfaces & boundaries with ARD ST2.
- **Beam diagnostics**: Non-invasive diagnostics (e.g. photon detection: **coherent transition radiation**, dynamic range, ARD ST4 topics, ...).
- **Beam dynamics**: Models in general also for ion beams (spilling).

ARD ST3 – Advanced beam control, diagnostics & dynamics

Annual meetings

Next 12th MT-ARD-ST3 at GSI, Darmstadt
indico.desy.de/e/2024-st3

- The 2023 edition of the **11th MT-ARD-ST3 meeting** was held in July at HZDR
  - 68 registered participants
  - Preceding **workshops**: **Open Source Firmware & ChimeraTK** & **UED**
  - 6 facility talks (DESY & PITZ, GSI, HZB, HZDR, KIT)
  - **Tutorials** on laser plasma acceleration and diagnostics
  - **Wealth of online material** at: indico.desy.de/e/2023-st3
    - See also *Annual Meetings (archive)*

Includes visiting the local accelerators

Essential drivers for timely advances in ST3- topics: the ARD test facilities