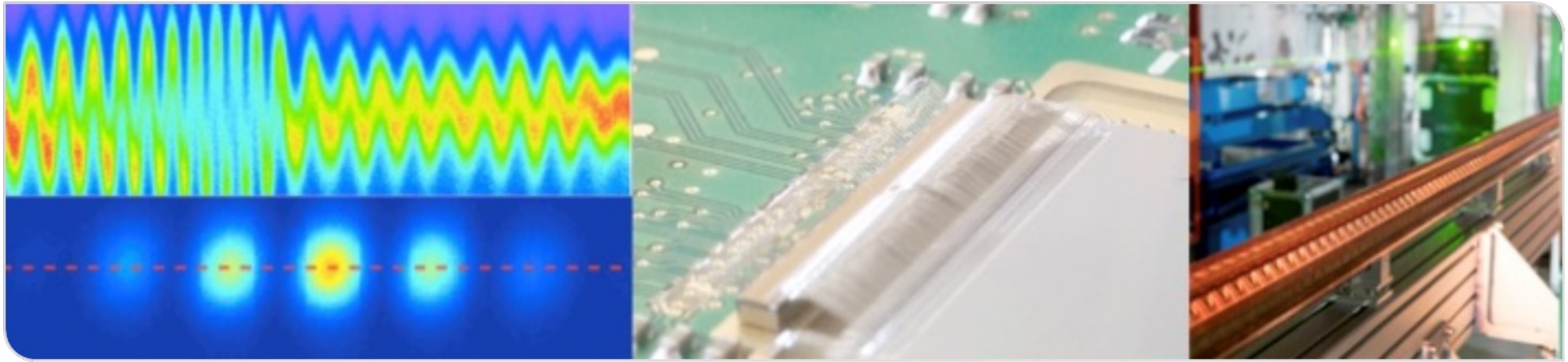
Karlsruhe Institute of Technology

KIT accelerators and research highlights - an overview

Bastian Härer on behalf of the KIT team



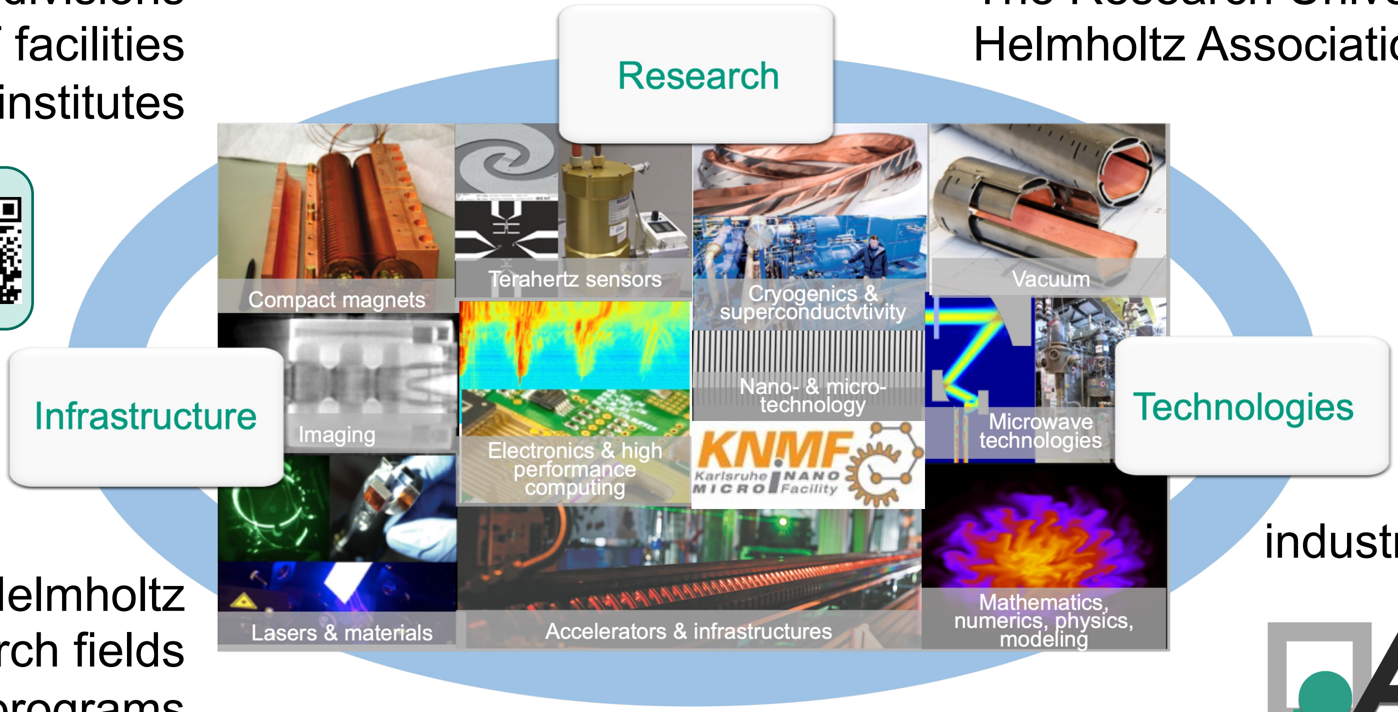
The Accelerator Technology Platform @KIT (ATP)

Karlsruhe Institute of Technology

5 divisions
6 KIT facilities
14 institutes

The Research University in the Helmholtz Association

ATP in lookKIT (German)



Helmholtz
3 research fields
6 programs

+ strong industrial partners

ATP
Accelerator Technology Platform @ KIT

Test facilities & technologies - examples

Karlsruhe Institute of Technology

Pulse power technology   *Gyrotrons*

Winding technologies

Magnet test facilities

Accelerator Technology Platform @ KIT

Cable technologies   *High temperature superconductors*

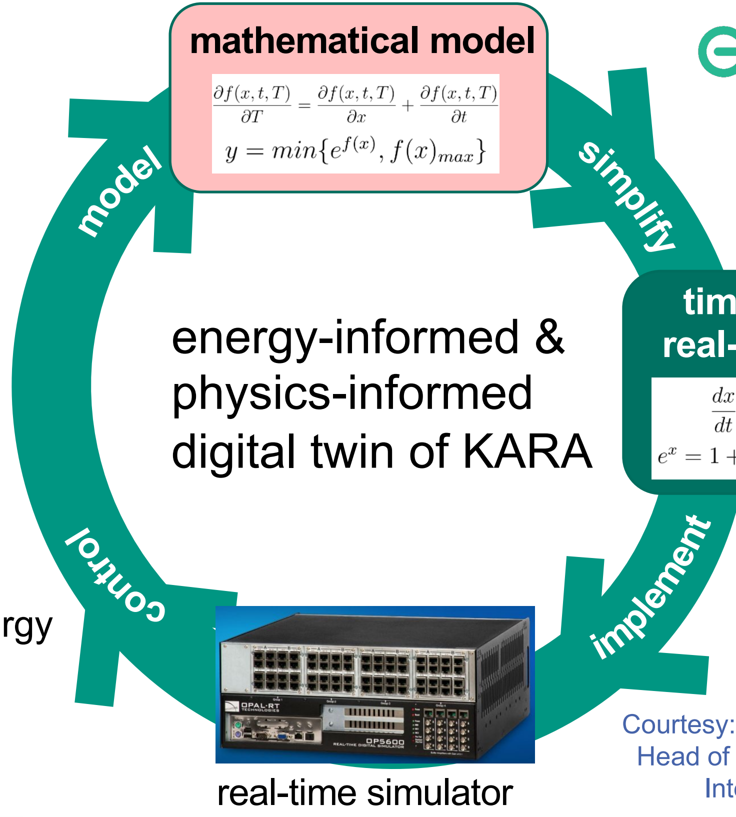
Accelerator & energy systems
Test field KITTEN

Accelerator Technology Platform @ KIT

Karlsruhe Institute of Technology

ENERGY LAB 2.0

- Digital twin of KARA
  - Analyzing, developing and testing future energy solutions for research infrastructures
- InnovEEA
  - Load management (grid stability)

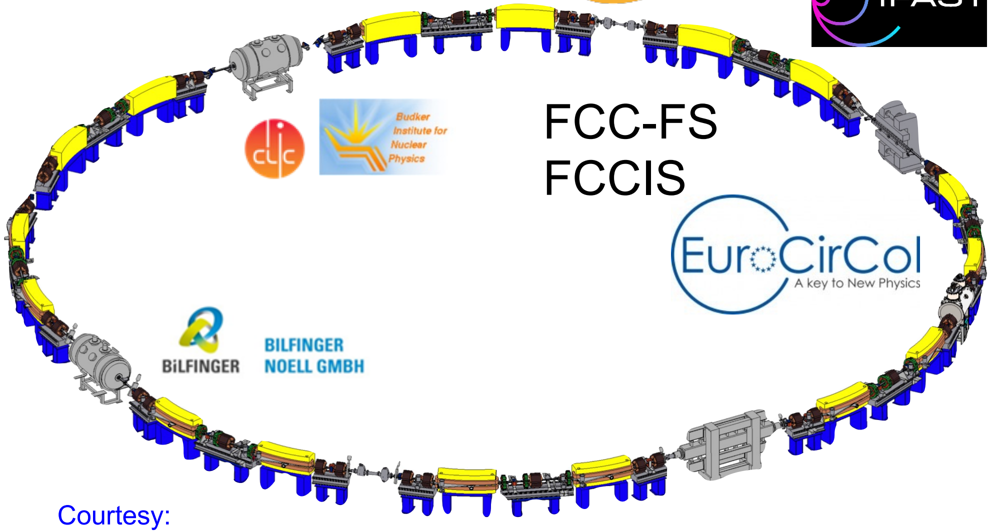


Courtesy: Giovanni De Carne, Head of „Real Time System Integration“, KIT

Karlsruhe Research Accelerator (KARA)

- KIT synchrotron light-source & accelerator test facility

Parameters	Values
Circumference	110.4 m
Energy range	0.5 – 2.5 GeV
RF frequency / period	500 MHz / 2 ns
Revolution frequency / period	2.715 MHz / 368 ns
Beam current	up to 200 mA
RMS bunch length	45 ps (2.5 GeV) a few ps (1.3 GeV)



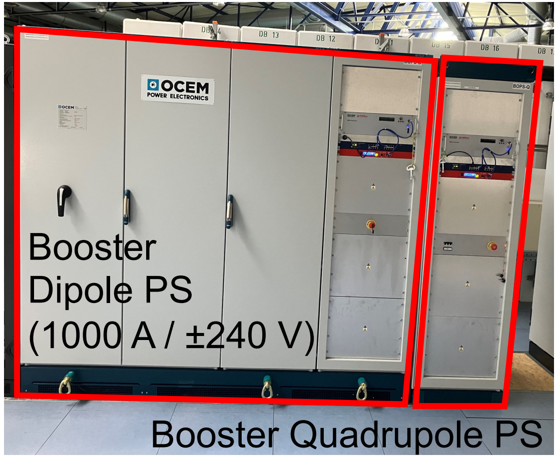
Courtesy:
U. Herberger

www.ibpt.kit.edu/kara

KARA Operation Status

- Operation modes in 2022:
  - 0.5/2.3/2.5 GeV user optics, 0.5/1.3 GeV low-alpha, 0.5/1.3 GeV negative alpha
- Power supply refurbishment program
  - Replaced Booster main power supplies
    - Direct EPICS control interface on device
    - Continuous operation at all energies (50 – 500 MeV)
  - Replaced KARA dipole power supply (800 A / 520 V)
    - Direct EPICS control interface on device
    - Enable new operation modes like down ramping
  - New KARA quadrupole power supplies in the ordering process
    - Start with family powering
    - Test individual powered quadrupole magnets
  - Installed new PS for KARA sextupole magnets and split them from two into tree families

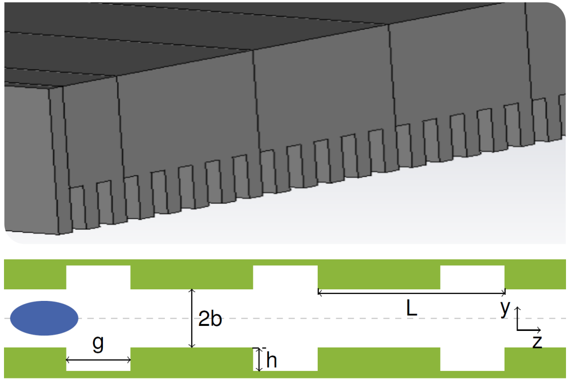
Picture: H. Hoteit

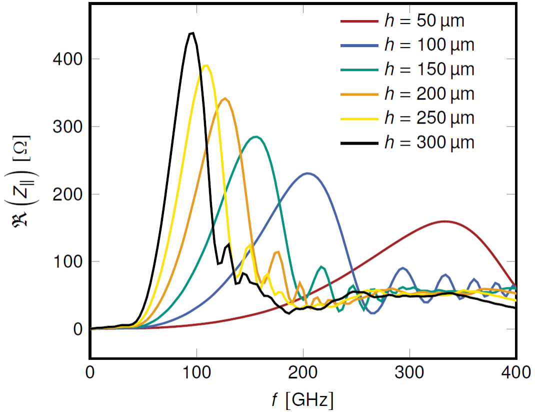


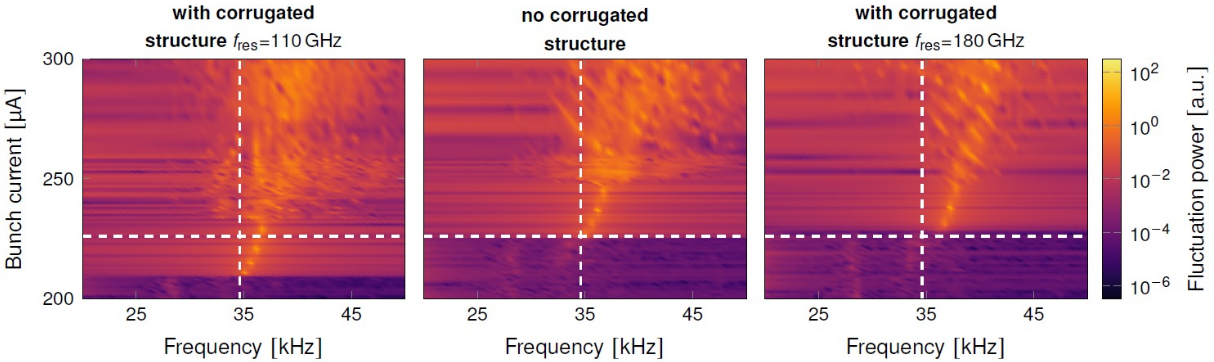
(120 A / ±108 V)

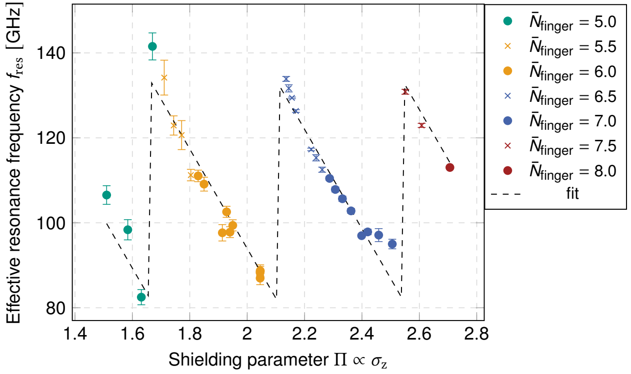
Impedance manipulation at KARA

- **Goal:** Observe, understand, and control the microbunching instability
- **Corrugated plates** will be installed at KARA
- Affecting threshold current and/or bursting frequency with additional impedance









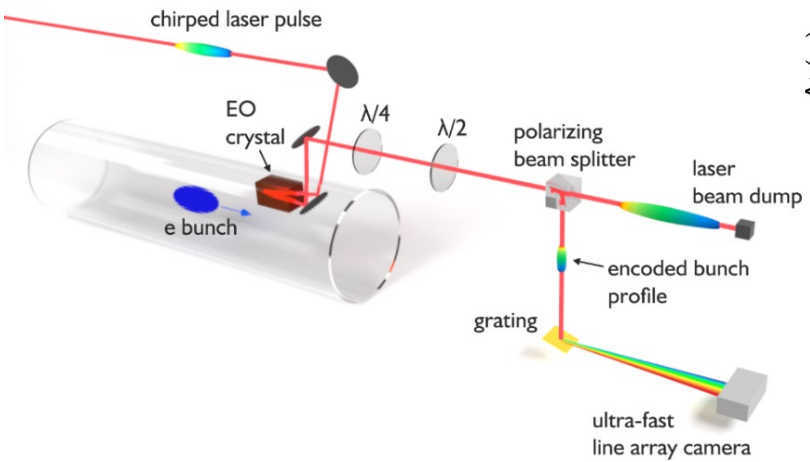
S. Maier et al. https://doi.org/10.18429/JACoW-IPAC-23-WEPL189

EO Near-Field @ KARA: Phase Space Tomography

Federal Ministry of Education and Research
05K22VKB
05K19VKD

KARA Karlsruhe Research Accelerator

KIT Karlsruhe Institute of Technology

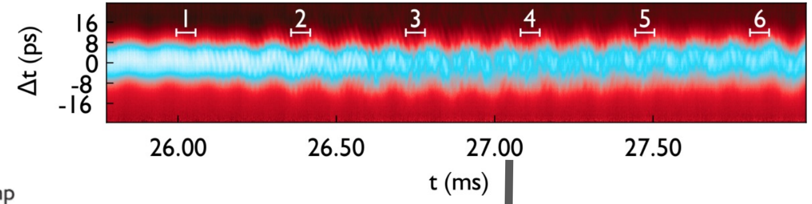


S. Funkner et al., Sci Rep, March 2023, Vol. 13.1, pp. 1-11. doi:10.1038/s41598-023-31196-5

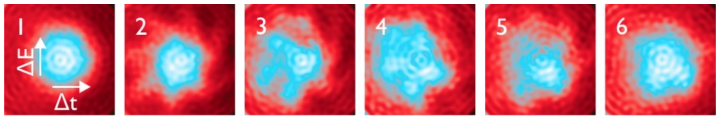
single-bunch @ 2.7 MHz

S. Funker et al., *Sci. Rep.* 4618 (2023)
https://doi.org/10.1038/s41598-023-31196-5

revolution plots/ sinograms

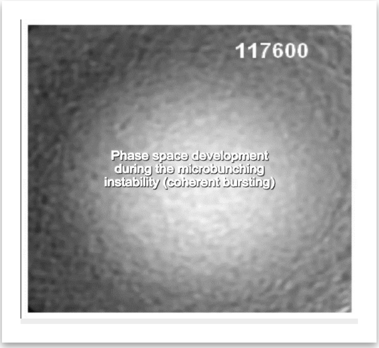


phase space density

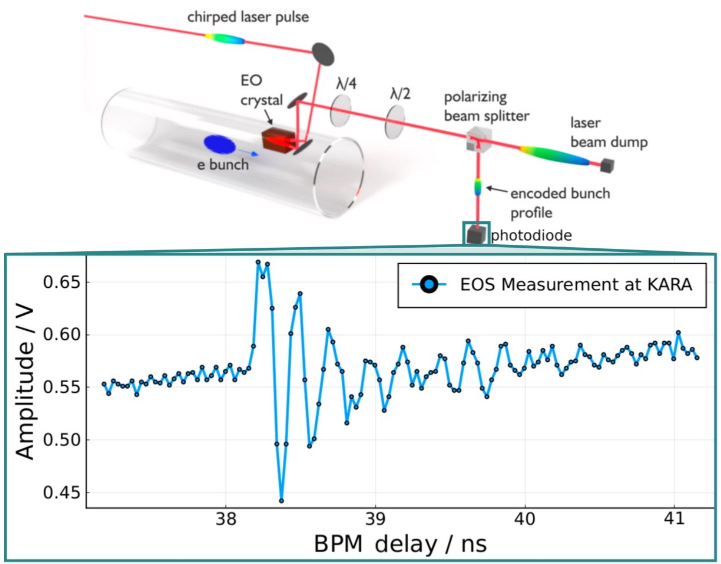


Phase space tomography

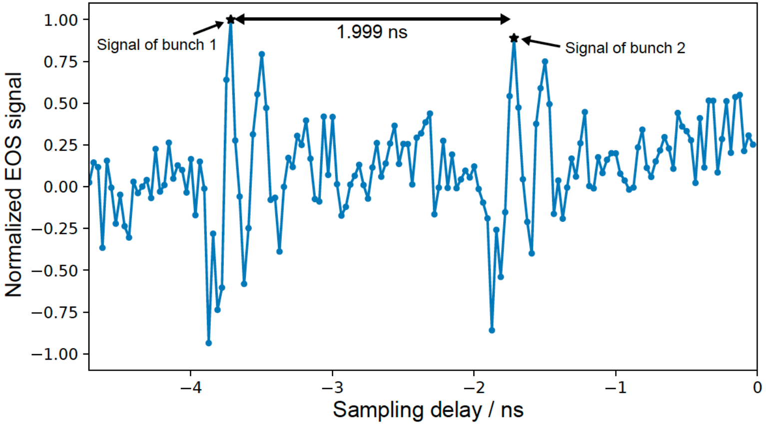
- Complete phase space image reconstructed from time interval of 61 µs
- “Randon morphing“ between independent measurements



EO Near-Field @ KARA: Towards Multi-Bunch Measurements

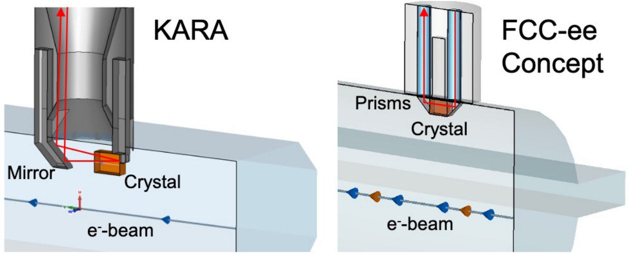


First 2 bunch EOS measurements at KARA:



- Compensation for signal drift (heating?)
- Two bunches are clearly visible in the measurement

Prototype for an EO Bunch Profile Monitor for FCC-ee:

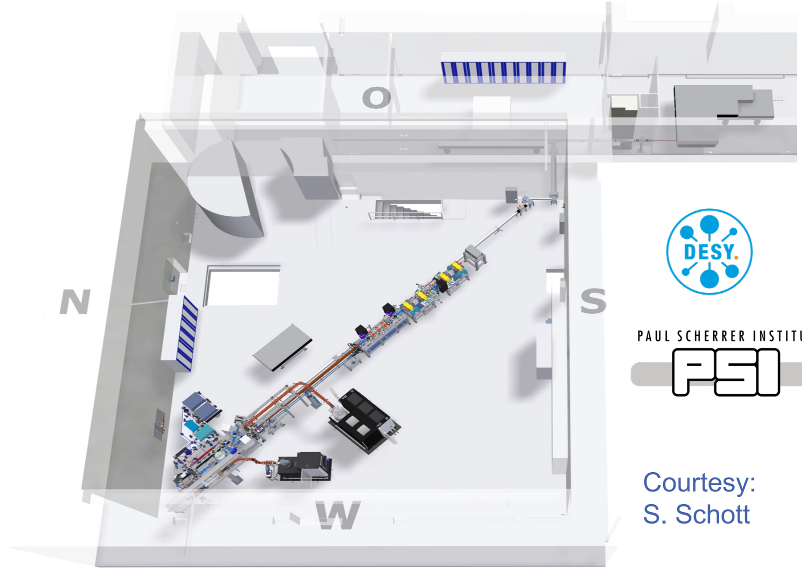


M. Reißig et al. https://doi.org/10.18429/JACoW-IPAC2023-THPL121

FLUTE: Accelerator Test Facility at KIT

- FLUTE (Ferninfrarot Linac- Und Test-Experiment)
  - Test facility for accelerator physics within ARD
  - Experiments with THz radiation

Final electron energy	~ 41	MeV
Electron bunch charge	0.001 - 1	nC
Electron bunch length	1 - 300	fs
Pulse repetition rate	5	Hz
THz E-Field strength	up to 1.2	GV/m



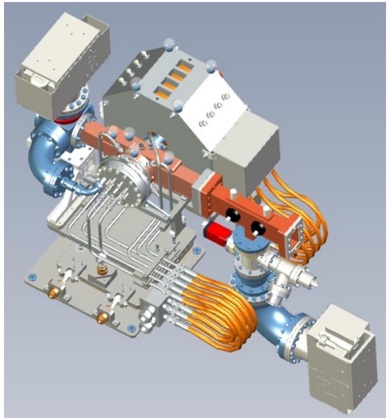
Courtesy:
S. Schott

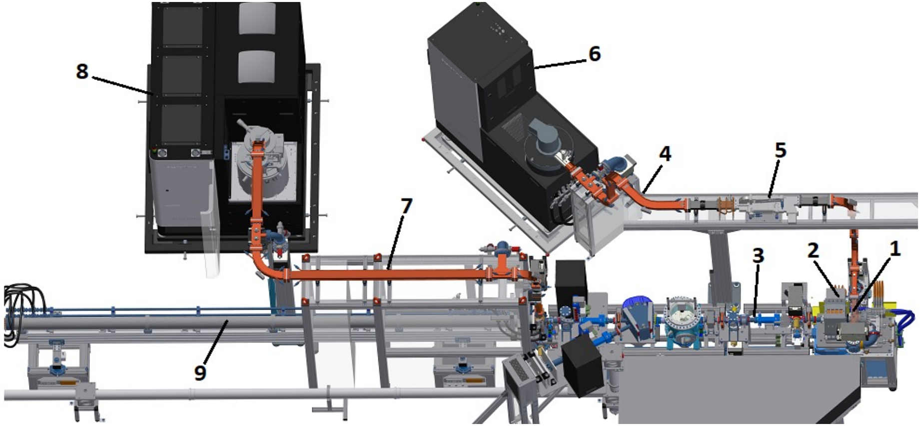
- R&D topics
  - Serve as a test bench for new beam diagnostic methods and tools
  - Systematic bunch compression and THz generation studies
  - Develop single shot fs diagnostics
  - Synchronization on a femtosecond level

www.ibpt.kit.edu/flute

FLUTE : upgrade status

- Dedicated RF units for RF photo-injector and linac have been installed and commissioned
- New RF photo-injector with low dark current has been delivered, installation and commissioning is under way
- Installation of the RF waveguide for the linac and its conditioning will follow
- UV laser beam aligned and referenced





Courtesy: S. Schott

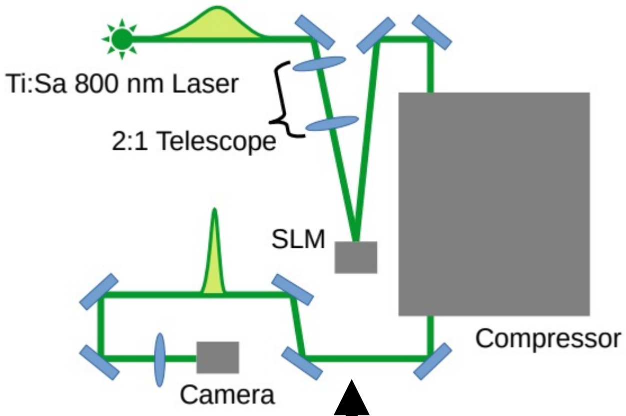
1. RF photo-injector
2. Solenoid
3. Diagnostic section
4. K100 waveguide
5. Circulator
6. K100 RF unit (10 MW)
7. K300 waveguide
8. K300 RF unit (37 MW)
9. Linac

Parameter	Value
Input RF power	9.5 MW
Output Energy	5.5 MeV
Operating Frequency	2.998 GHz
Repetition rate	50 Hz
Peak cathode field	120 MV/m
Bunch charge (max)	1 nC

Controlling the Transverse Beam Shape of the Photoinjector Laser via an SLM

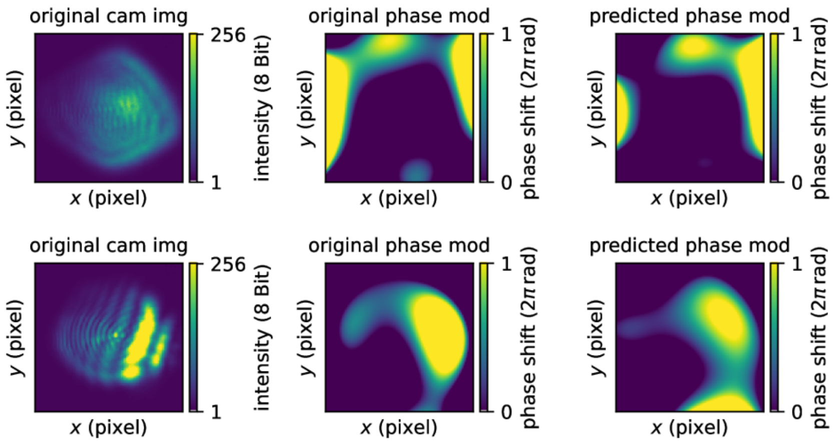
- Evolve last year's test setup and approach by ...
  - Using the Ti:Sa 800 nm photoinjector laser system
  - Including a compressor in the optical path
  - Mapping the camera intensity directly to the phase modulation via a deep neural network

Neural network architecture

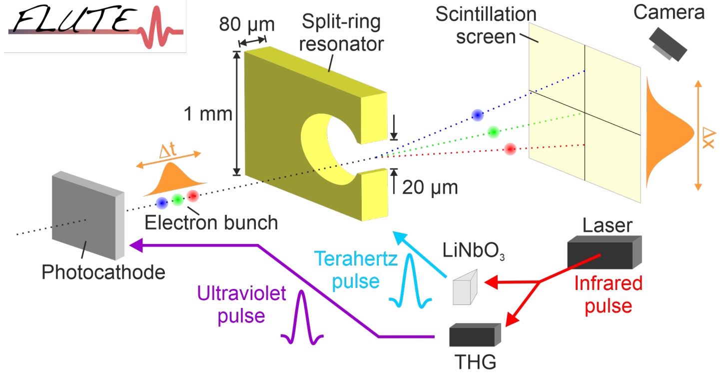


Schematic setup

Test results

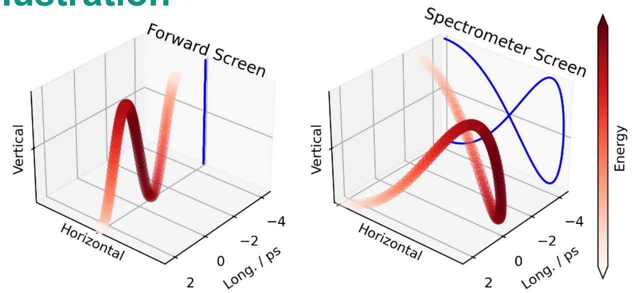


Split-ring resonator

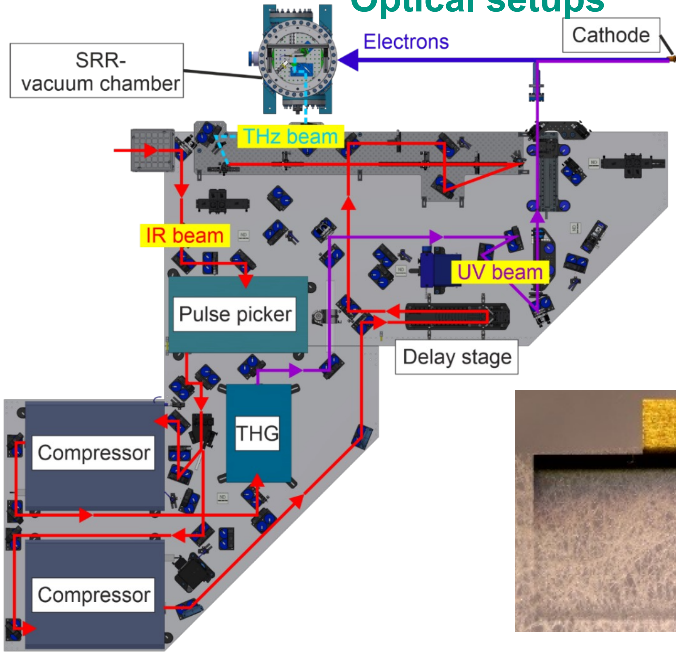


- Streaking with THz radiation and amplifying the electric field with a 20 µm gap **split-ring resonator**

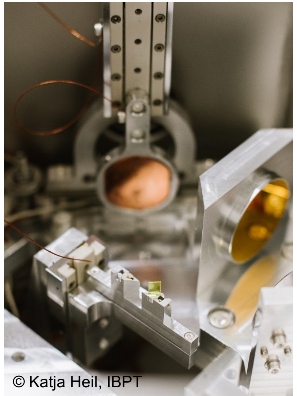
Illustration



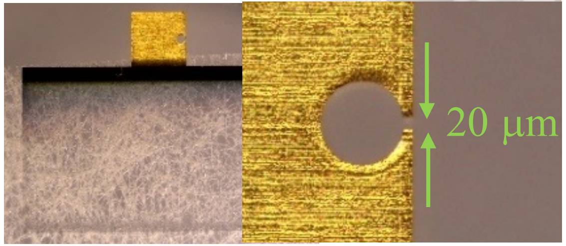
Optical setups



Courtesy: S. Schott



© Katja Heil, IBPT



- Setup of the split-ring resonator measurement in low energy section at FLUTE
- Experimental setup in vacuum chamber **installed and in commissioning**

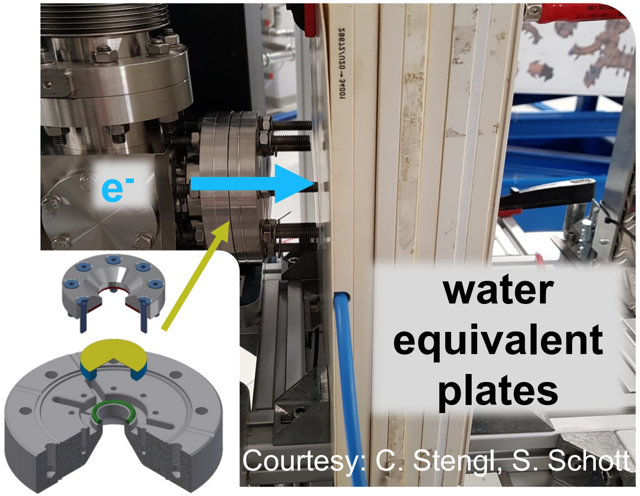
J. Schäfer et al. https://doi.org/10.18429/JACoW-IPAC-23-THPL122
M. Nabinger et al. https://doi.org/10.18429/JACoW-IPAC-23-THPA079

Accelerator technology for precision medicine

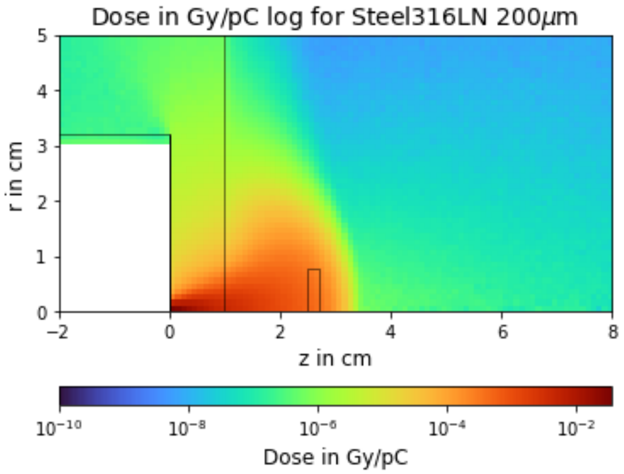
KIT Center HealthTech https://www.healthtech.kit.edu/

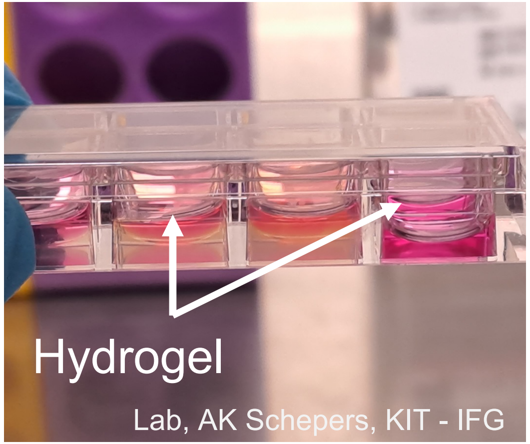
Development and implementation of innovative technologies leading to the transformation of health technologies into future healthcare.

- KARA → photon irradiation
- FLUTE → electron irradiation
- First tests in cooperation with DKFZ



K. Mayer, Master thesis 2023

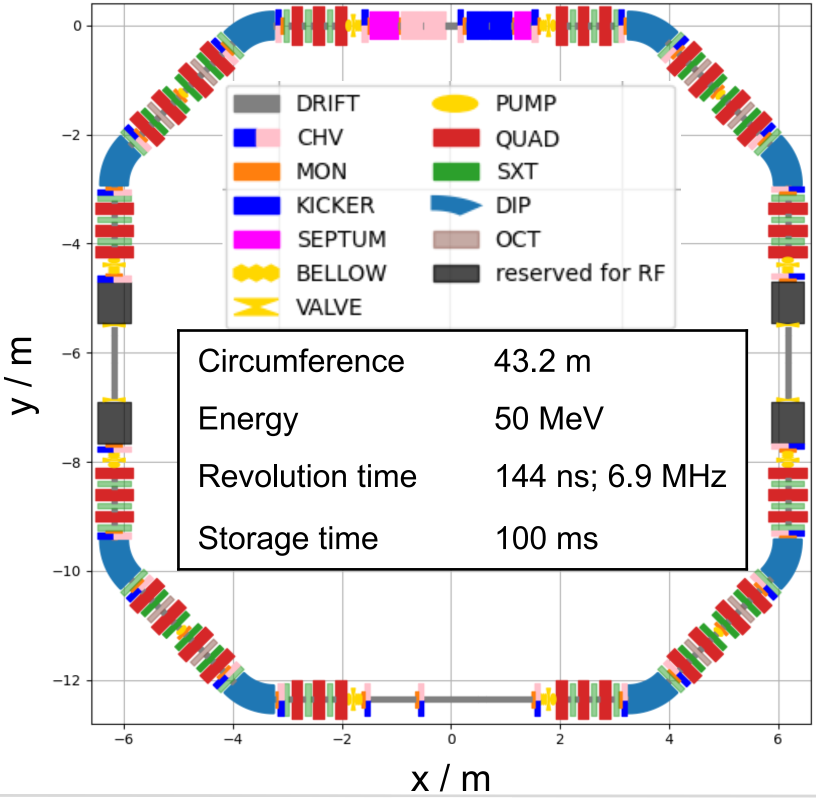




cSTART Project

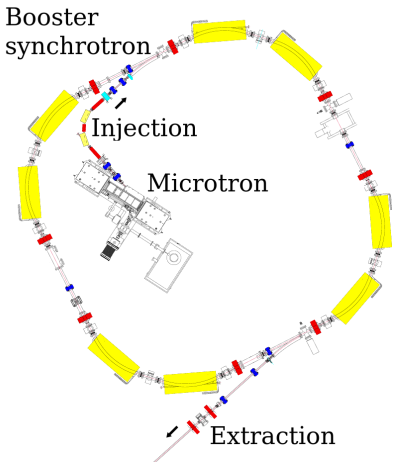
- **Motivation:** Storage of ultra-short (fs) electron bunches with high repetition rate
- Compact storage ring with very large momentum acceptance and dynamic aperture
- FLUTE with new transfer line as injector
- Status:
  - Conceptual design and specification: finished
  - Transfer line magnets: first magnets delivered
  - Test diagnostics at KARA booster: ongoing

A. Papash et al. https://doi.org/10.18429/JACoW-IPAC2022-THPOPT023
M. Schwarz et al. https://doi.org/10.18429/JACoW-IPAC-23-WEPL167
D. El Khechen et al. https://doi.org/10.18429/JACoW-IPAC2022-MOPOPT026
J. Schäfer et al. https://doi.org/10.18429/JACoW-IPAC2022-MOPOST041
B. Härer et al. https://doi.org/ 10.18429/JACoW-IPAC2022-THPOPT059



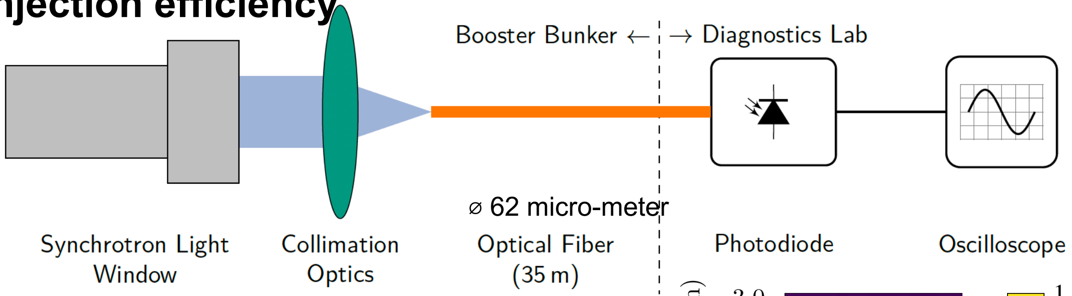
Circumference	43.2 m
Energy	50 MeV
Revolution time	144 ns; 6.9 MHz
Storage time	100 ms

KARA Booster Diagnostics

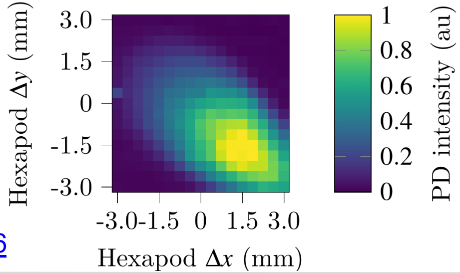


- Injection facility for KARA
- Components:
  - 53 MeV racetrack microtron
  - Injection line
  - 26 m circumference booster synchrotron
    (53 MeV → 500 MeV, RMS bunch length: 200 ps...1000 ps)
  - Extraction line

- Diagnostic Devices:
  - Button/Stripline beam position monitors
  - Two synchrotron radiation ports
- **Implement longitudinal diagnostics to improve storage ring injection efficiency**



Preliminary results, scan using hexapod system:



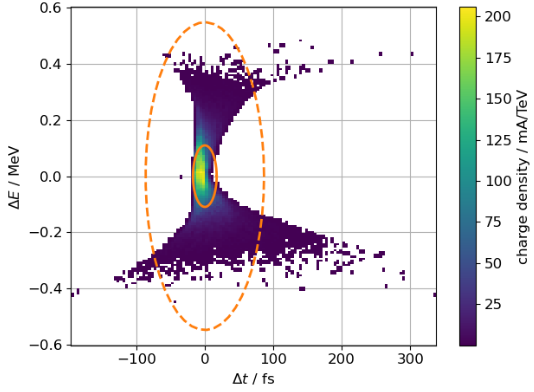
M.-D. Noll et al. https://doi.org/10.18429/JACoW-IPAC2023-THPL126

Longitudinal beam dynamics for different initial distributions at cSTART

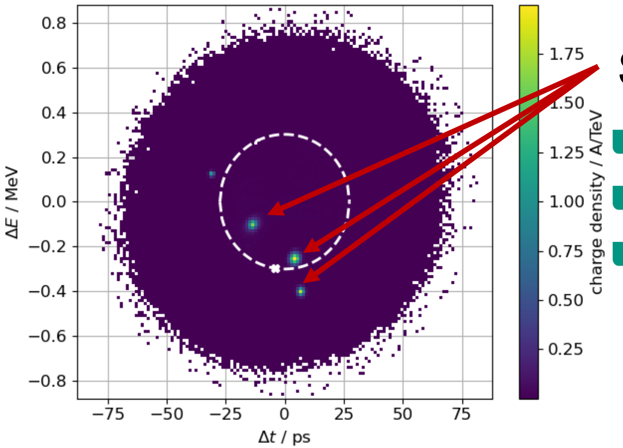
- Storage time ≪ damping time → Non-equilibrium dynamics
- Simulation of 700 k turns with 1 M macro-particles

Initial distribution

- 1 pC
- $\sigma_{\mathrm{RMS}} = 17$ fs; $\delta_{\mathrm{E}} = 0.003$



Distribution after 100 ms



Sub bunches

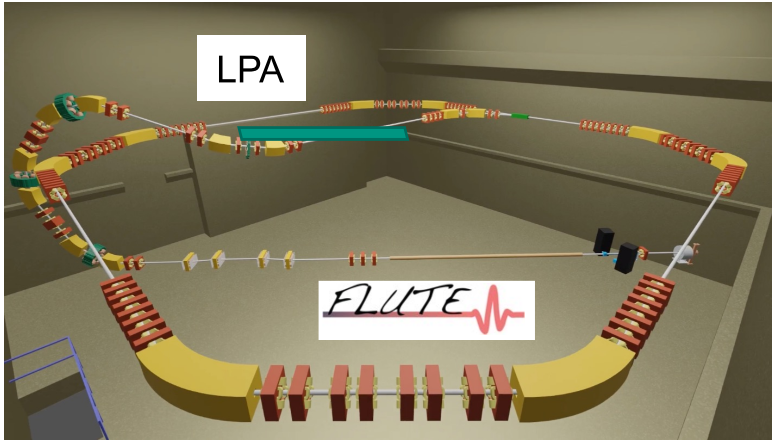
- Contain 40 % of particles
- Survive for 100 ms
- RMS bunch length ≤ 1 ps

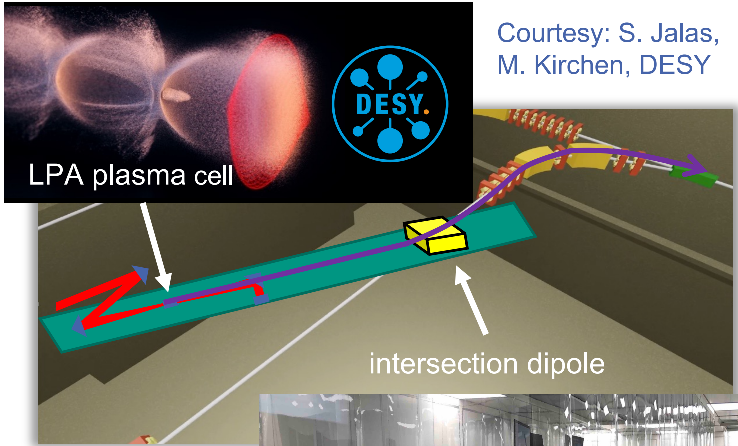
M. Schwarz et al. https://doi.org/10.18429/JACoW-IPAC-23-WEPL167

ATHENA @KIT - Status

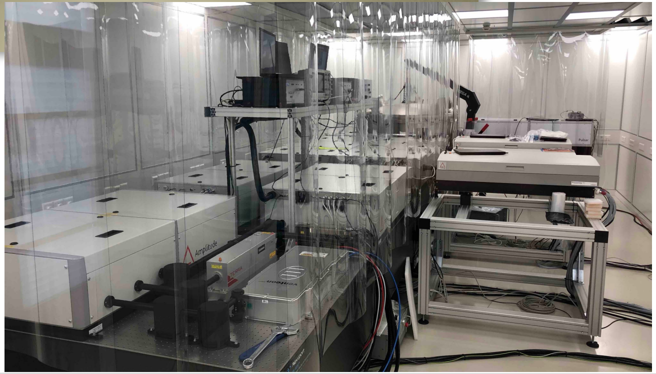
Karlsruhe Institute of Technology

Goal: **injection & storage** of a laser plasma accelerator beam in a storage ring





Courtesy: S. Jalas, M. Kirchen, DESY

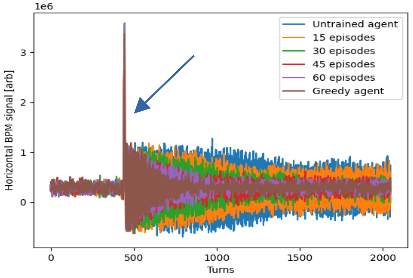


- Clean room for laser system built ✓
- Commercial laser system in commissioning
- Conceptual design of transfer lines including diagnostics finished ✓
- Next step: Fine-tuning of optics and tracking calculations
- Additional professor at KIT in 2023

AI4Accelerators team highlights

Reinforcement Learning

First successful application of RL in an accelerator with **online training** and **running on hardware in the world at KARA**!



Lattice agnostic RL

- Code usable in different accelerators

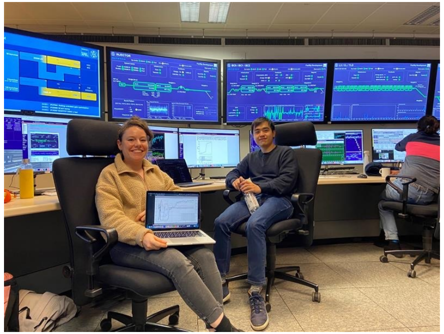
Creation of the Collaboration on Reinforcement Learning for Autonomous Accelerators (RL4AA)!

- Kick-off with workshop organized at KIT
- Proceedings to be published

https://rl4aa.github.io/

Bayesian Optimization

- Time to inject to KARA cut in half with automated tuning by BO algorithm
  https://doi.org/10.1103/PhysRevAccelBeams.26.034601
- Emitted THz radiation at FLUTE optimized with parallel BO in simulation
  https://doi.org/10.18429/JACoW-IPAC2022-WEPOMS023
- Transfer of algorithm to EuXFEL to tune SASE emission https://www.ipac23.org/preproc/pdf/THPL028.pdf



RL vs BO

https://arxiv.org/abs/2306.03739

[Submitted on 6 Jun 2023]

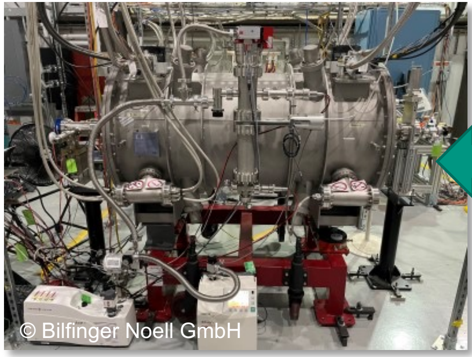
Learning to Do or Learning While Doing: Reinforcement Learning and Bayesian Optimisation for Online Continuous Tuning

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

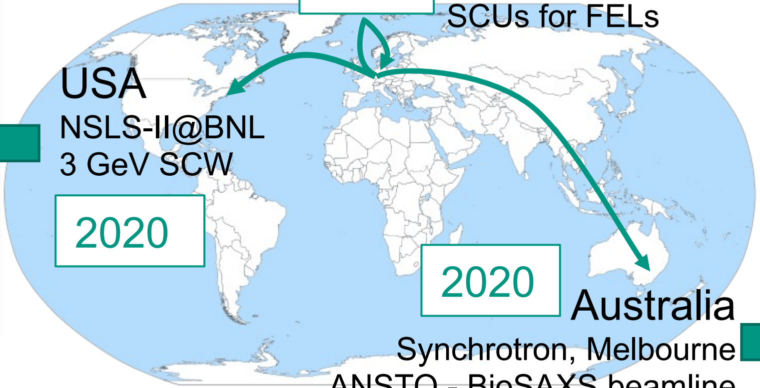
Online tuning of real-world plants is a complex optimisation problem that continues to require manual intervention by experienced human operators. Autonomous tuning is a rapidly expanding field of research, where learning-based methods, such as Reinforcement Learning-trained Optimisation (RLO) and Bayesian optimisation (BO), hold great promise for achieving outstanding plant performance and reducing tuning times.

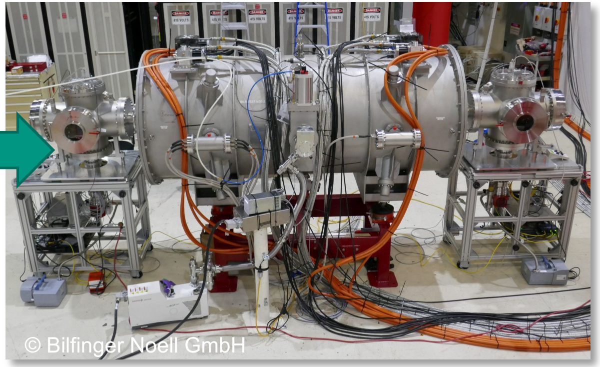
Technology transfer from KARA to the world

Superconducting Undulators – **The future is now**



First light: Nov. 2022





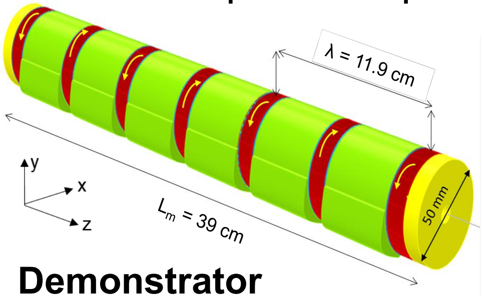
First light: Nov. 2022

Bilfinger Website: "**Superconducting undulators … most powerful light source for any experiment**"

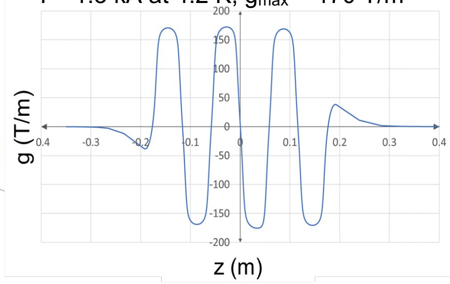
HTS magnet technology

HTS miniature magnets

periodic quadrupole

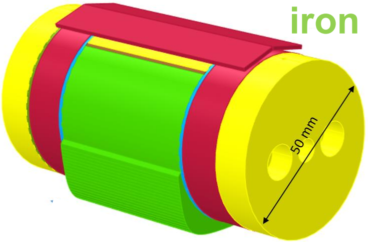


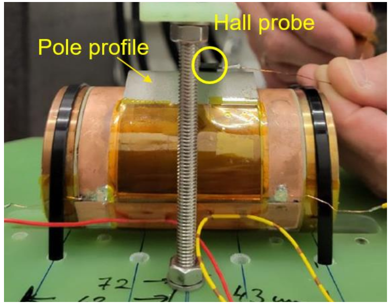
I = 1.3 kA at 4.2 K, g_{max} = 170 T/m



Demonstrator
- HTS windings in 72 turns
- iron core

HTS tape
iron





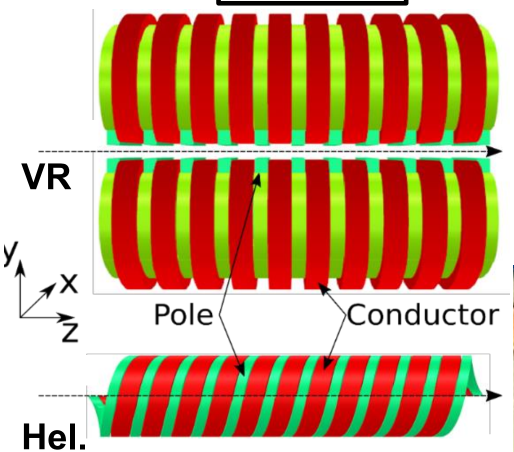
Successfully tested in LN_2 at 77 K

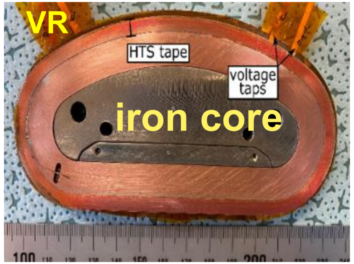
HTS compact undulator

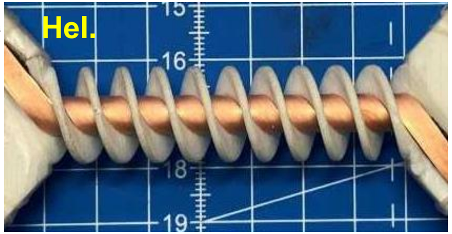
Main challenges: Bending radii < 5 mm

Quench protection

λ = 13 mm







VR and hel. prototype coils were manufactured and successfully tested

Acknowledgements

Thank you for your attention!

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- The accelerator team

Falastine Abusaif, Axel Bernhard, Edmund Blomley, Simon Braner, Erik Bründermann, Hyuk Jin Cha, Kantaphon Damminsek, Dima El Khechen, Samira Fatehi, Stefan Funkner, Julian Gethmann, Christian Goffing, Andreas Grau, Leander Grimm,Steffen Grohmann, Bastian Härer, Michael Hagelstein, Erhard Huttel, Igor Kriznar, Stephan-Robert Kötter, Bennet Krasch, Anton Malygin, Sebastian Maier, Sebastian Marsching, Yves-Laurent Mathis, Katharina Mayer, Wolfgang Mexner, Matthias Nabinger, Michael J. Nasse, Gudrun Niehues, Marvin Noll, Alexander Papash, Meghana Patil, Micha Reißig, Robert Ruprecht, Andrea Santamaria Garcia, Patrick Schreiber, David Seaz de Jauregui, Jens Schäfer, Thiemo Schmelzer, André Schmidt, Marcel Schuh, Markus Schwarz, Nigel John Smale, Johannes L. Steinmann, Pawel Wesolowski, Christina Widmann, Chenran Xu and Anke-Susanne Müller

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