Karlsruhe Institute of Technology

Introduction to accelerator research at KIT-IBPT

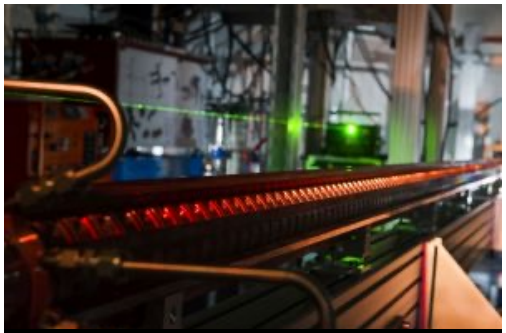
Bastian Härer on behalf of the KIT accelerator team

3 July 2024

KARA

Karlsruhe Research Accelerator

FLUTE



FIR/THz short-bunch linac

cSTART

compact STorage ring for Acc. Res. & Tech.

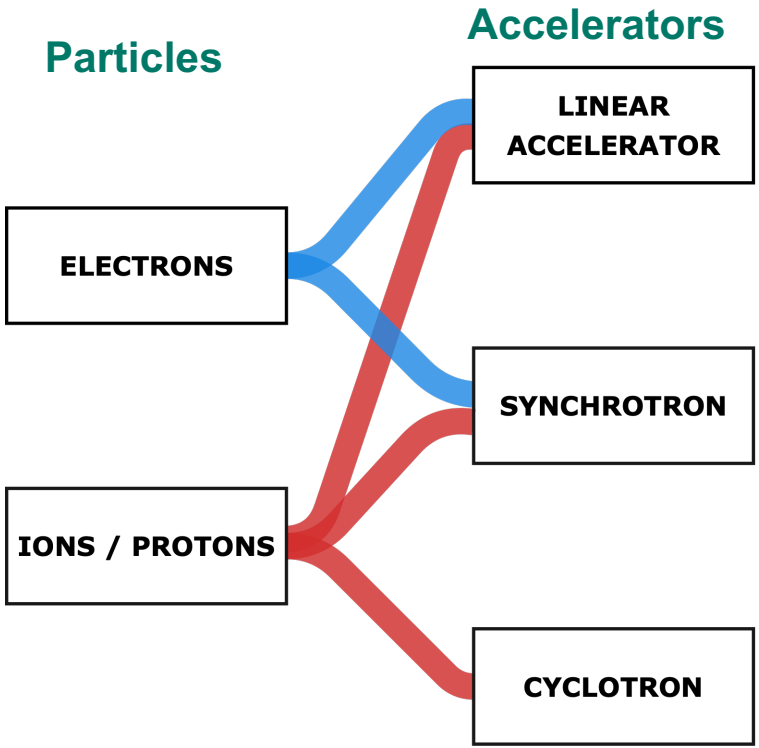
Types of Accelerators

Particles

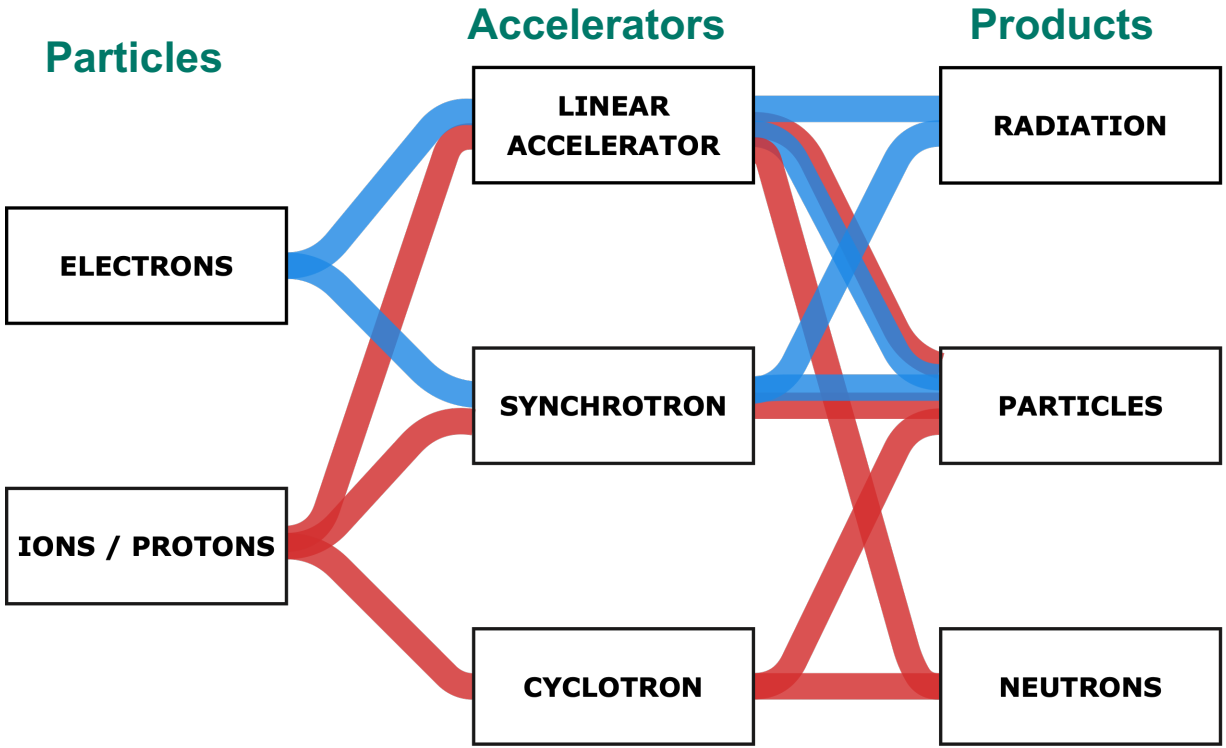
ELECTRONS

IONS / PROTONS

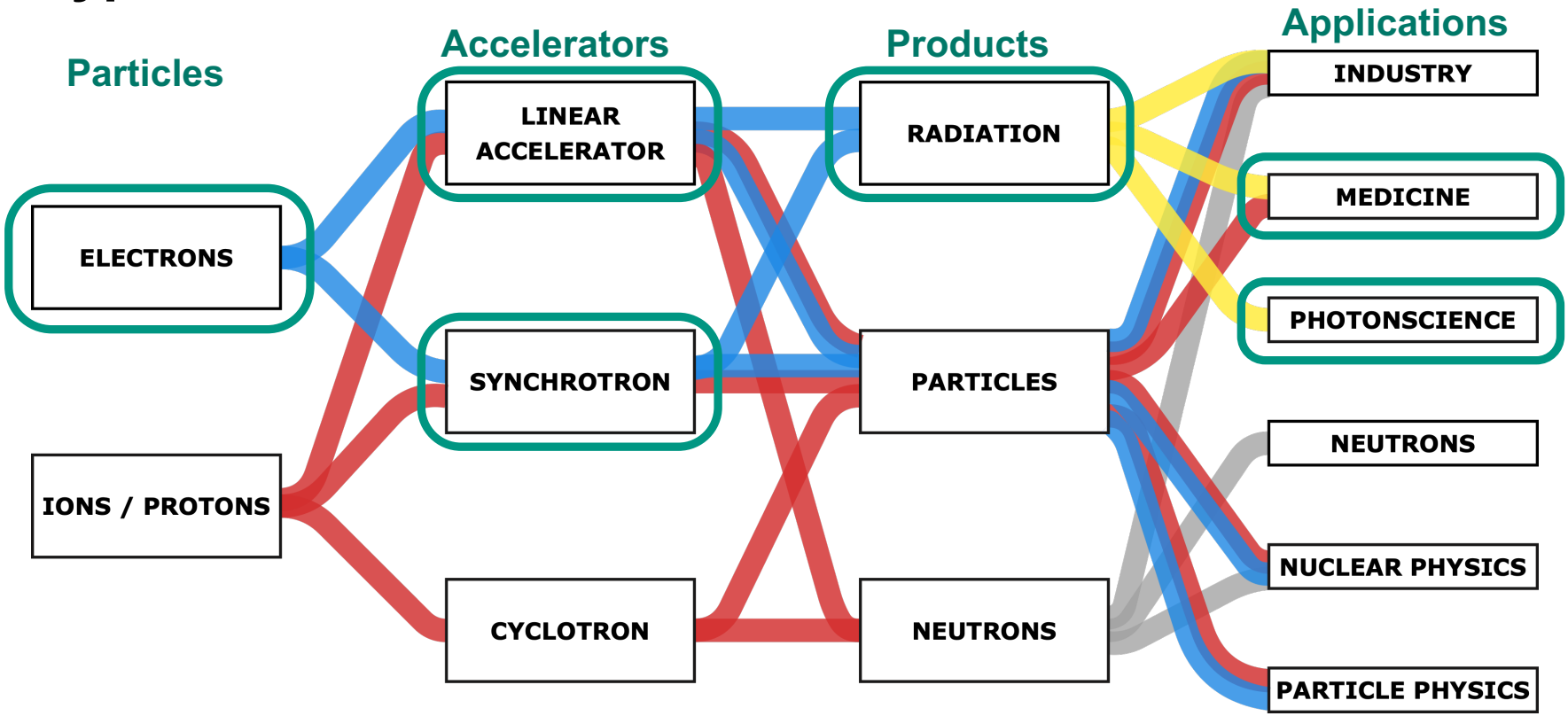
Types of Accelerators



Types of Accelerators



Types of Accelerators



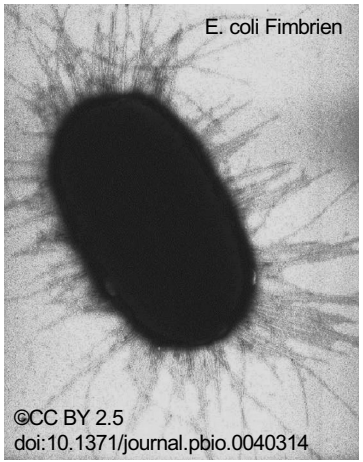
More than 50 light sources around the world

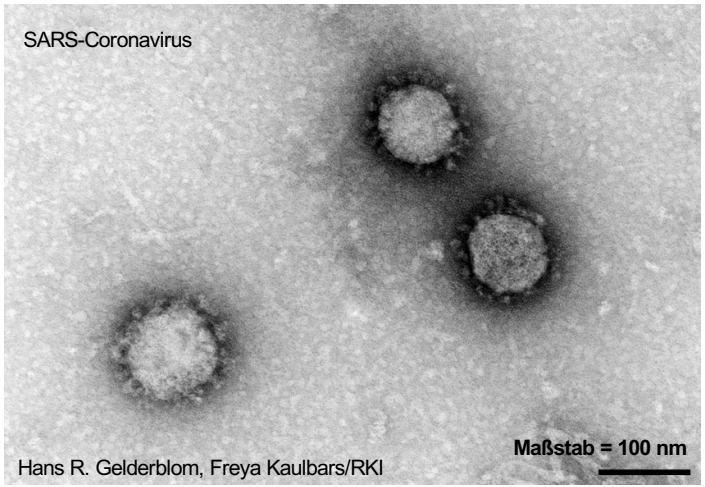
An Accelerator “just” to make Light?

- Synchrotron radiation is special light with unique properties
- About 50 of these facilities worldwide
- One important point: structures smaller than half the wavelength become blurred
- Smallest wavelengths (X-rays) needed

An Accelerator “just” to make Light?

- Optical light microscopes can resolve bacteria (about 1000 nm) but not viruses (about 10 nm)
- Bacteria detected 1675 (light microscope), viruses 1940 (electron microscope).





- X-rays needed for many scientific investigations

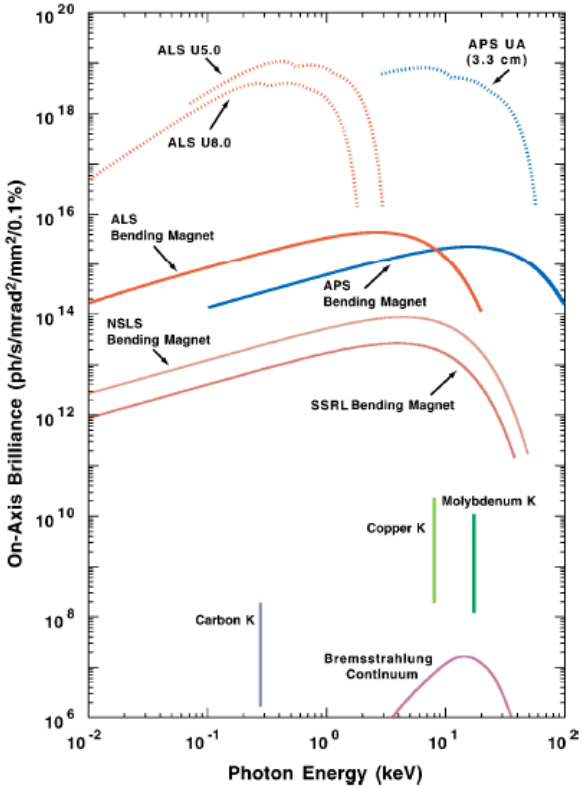
Brilliance

Low brilliance

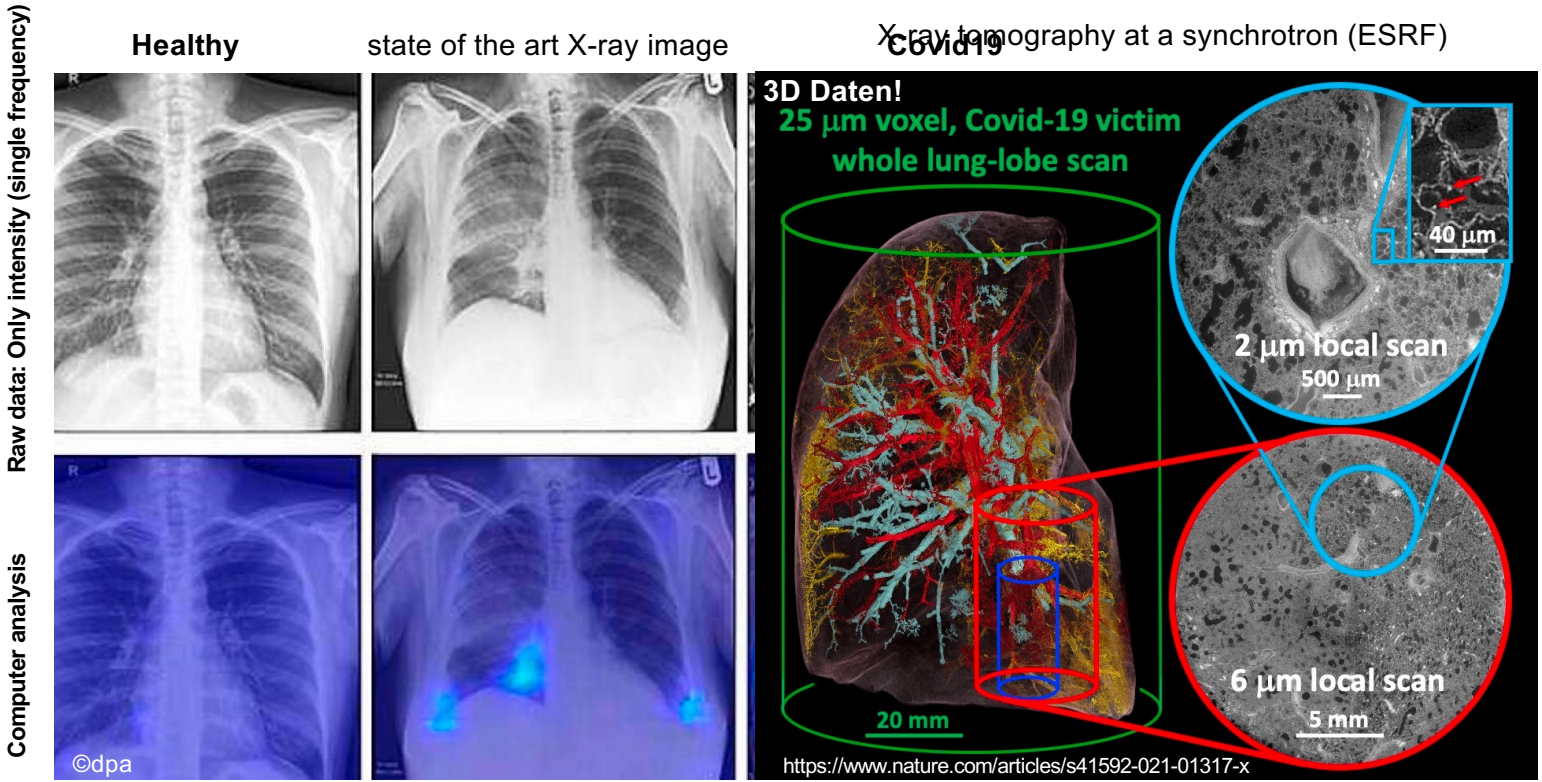
high brilliance

- Property of the source
- Measure of light quality
- Light intensity per time, area, solid angle, bandwidth

$$B = \frac{\Delta N}{t \cdot A \cdot \Delta\Omega \cdot \frac{\Delta\lambda}{\lambda}}$$



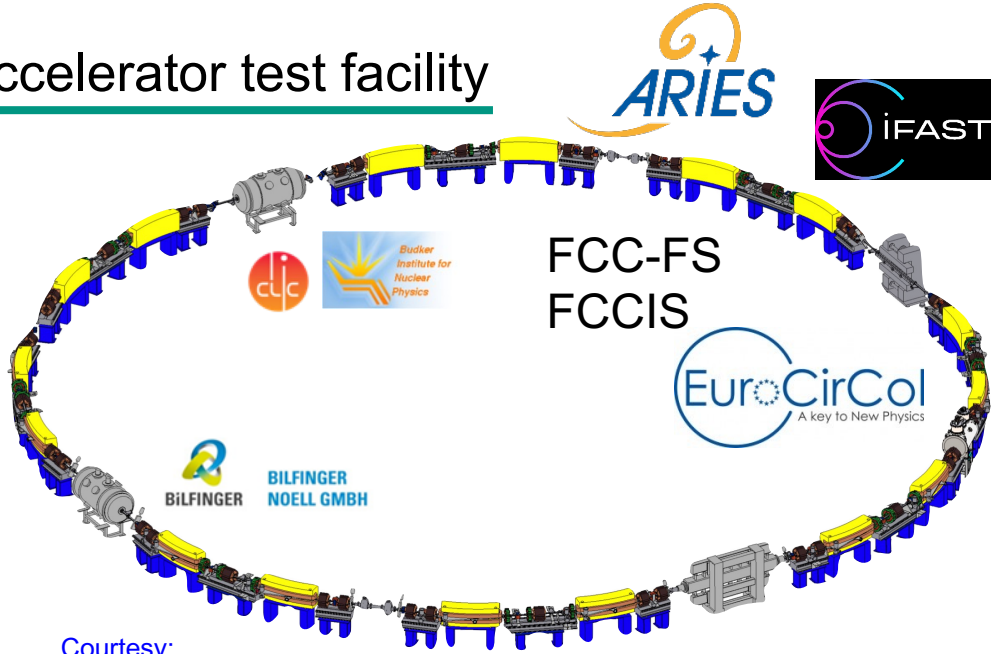
Impact of Brilliance



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

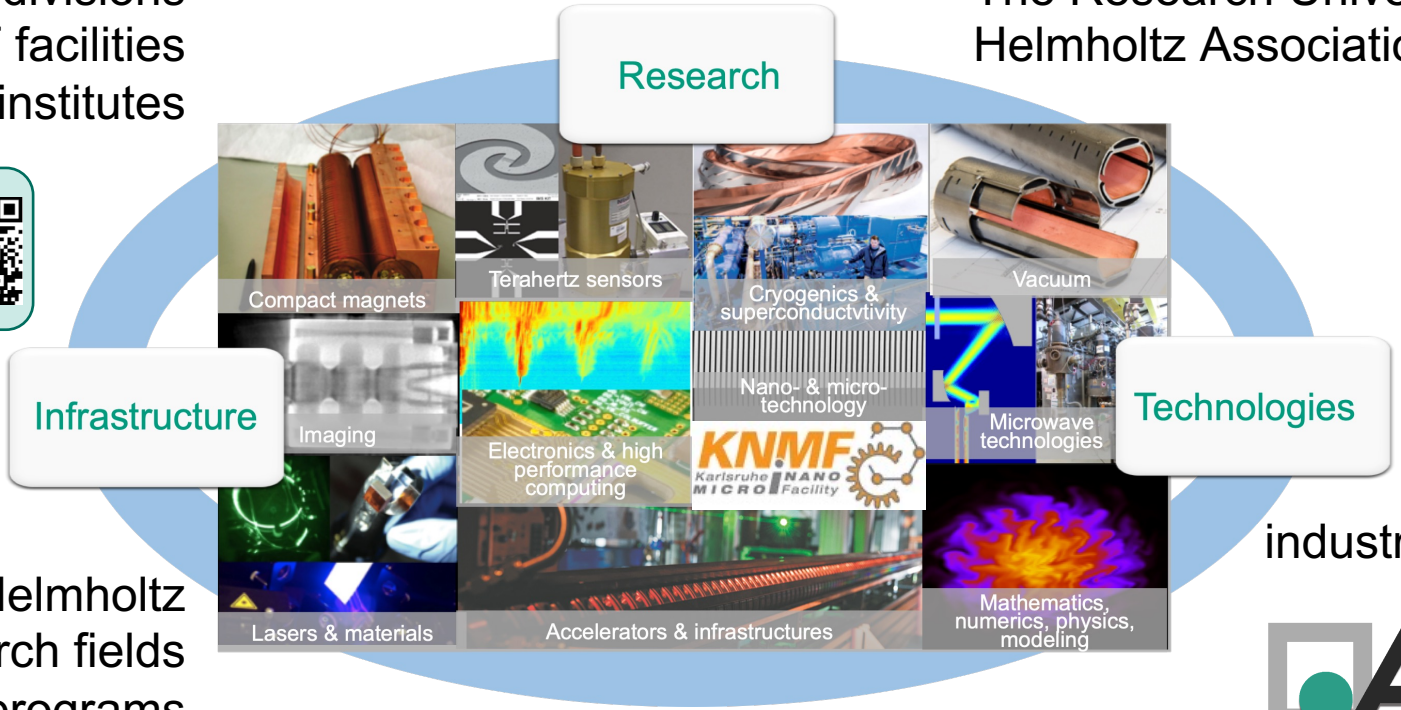
www.ibpt.kit.edu/kara

The Accelerator Technology Platform @KIT (ATP)

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

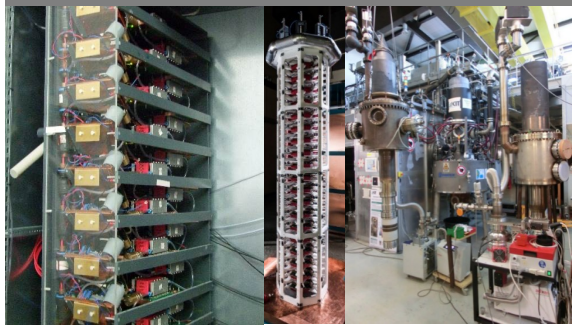
ATP
Accelerator Technology Platform @ KIT

Test facilities & technologies - examples

Karlsruhe Institute of Technology

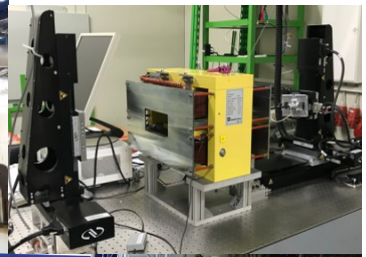
ATP
Accelerator Technology Platform @ KIT

Pulse power technology *Gyrotrons*

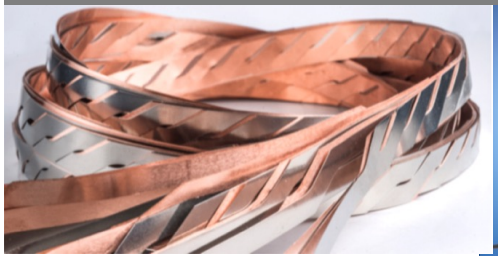


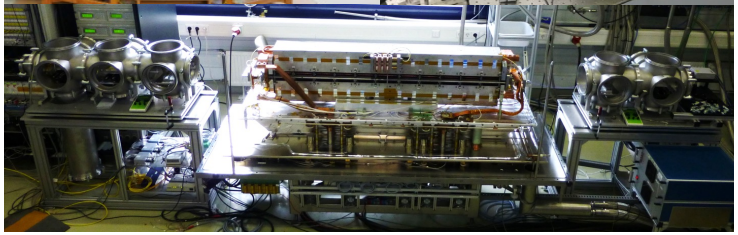
Winding technologies

Magnet test facilities



Cable technologies *High temperature superconductors*

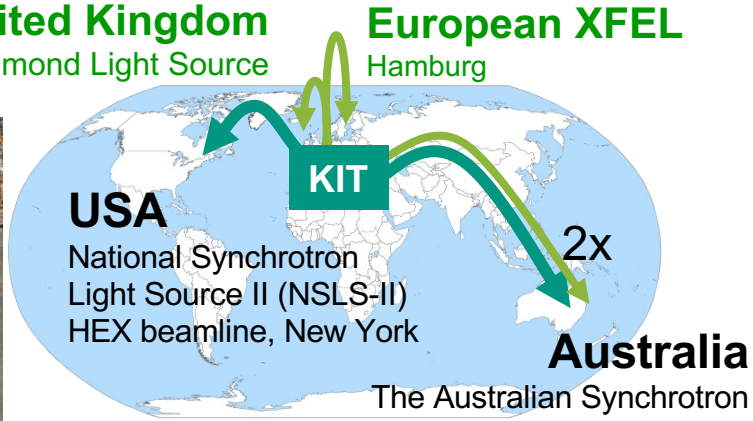




Superconducting undulators (SCU)

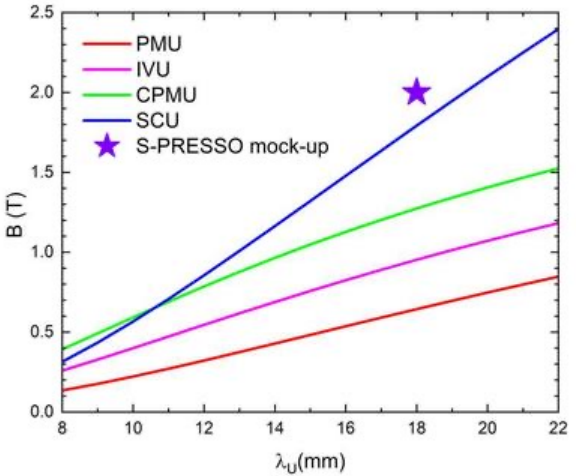
“Superconducing undulators … most powerful light source for any experiment”

SCW installed in
3-GeV storage ring



First light (2022) & orders (2022/23)

- **EuXFEL** & **KIT** team tested SCU pre-series module at **KIT** MCF
- S-PRESSO designed for **EuXFEL** upgrade
- **World record magnetic field reached**



News at EuXFEL 24. Jan 2024 - Link

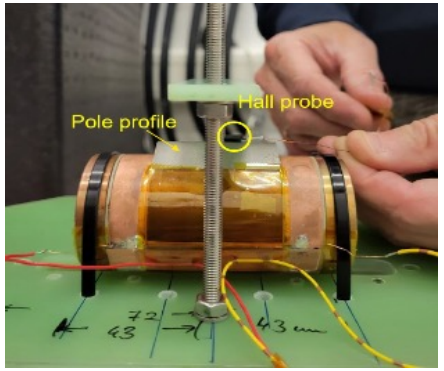
High-temperature superconductors (HTS) magnets

HTS offers for magnets

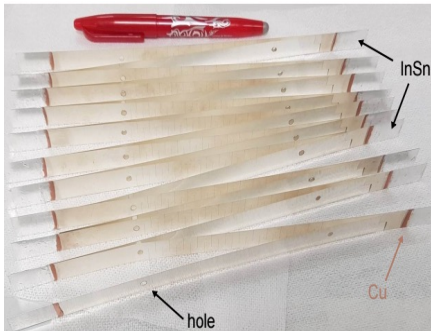
Compact magnets

- **Energy savings & higher performance for all accelerators**
  - Same field at higher temperature
  - Higher field at low temperature
- **Enables new technologies & modalities for magnet systems**
  - Transition from wires (1D) to tapes (2D)
    - **Folding instead of winding!**
  - Materials savings for magnets & undulators by novel designs
  - BMBF project HTS-ES started July 2024
    - KIT coordinator, partners: TU Darmstadt, PSI, CERN
    - ibpt.kit.edu/project_HTS_ES.php

75% less material



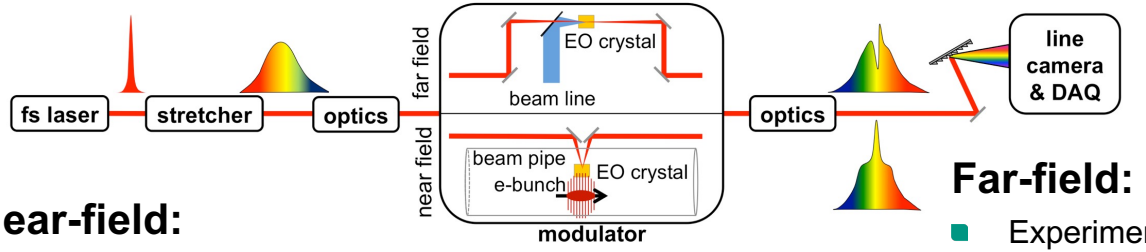
S. Fatehi, et al., KIT



B. Krasch, et al., KIT

Novel undulator design

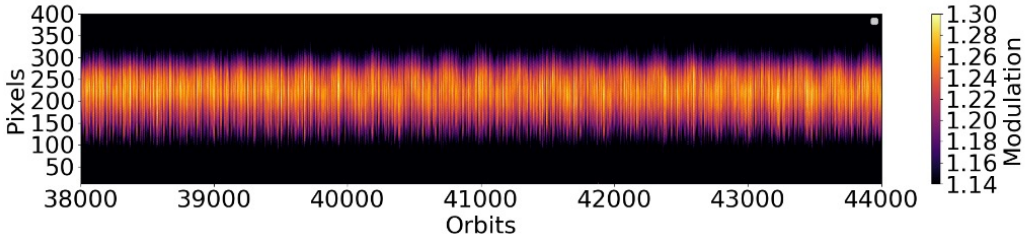
EO diagnostics at IBPT



Near-field:

- Resolving electron bunch profile in every turn @ 2.7 MHz
- Capable of uninterrupted data acquisition for up to several millions of turns
- First measurements with two bunches

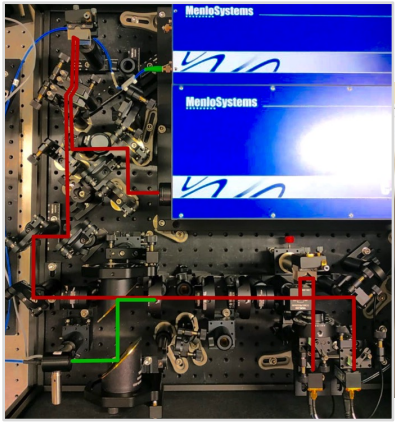
Section of a measurement dataset of 100000 turns

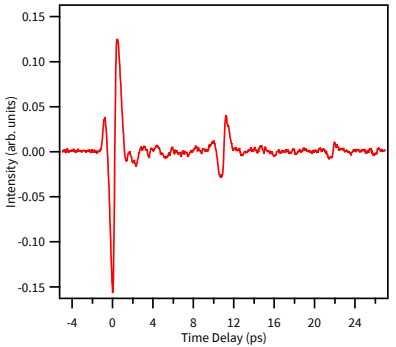


Turn-by-turn data

Far-field:

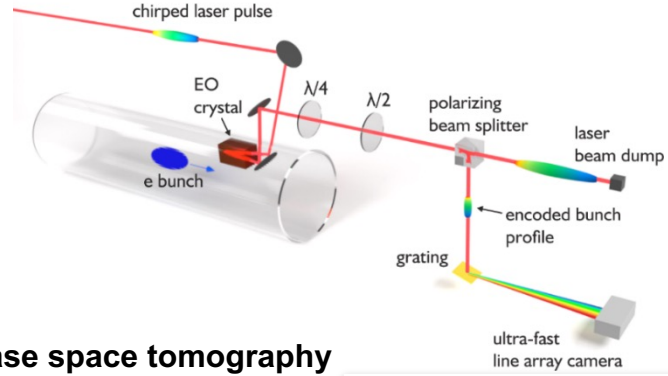
- Experiment under commission, status: successful EOS demonstration with off-line demonstrator using balanced detection
- Aiming to measure the complete THz pulse in single-shot





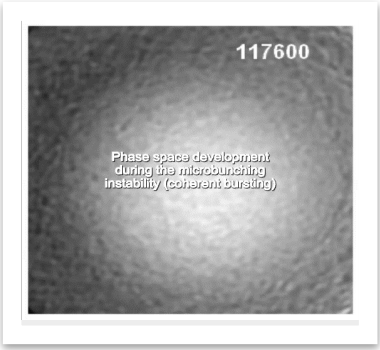
EO Diagnostics at IBPT

Near-field:



Phase space tomography

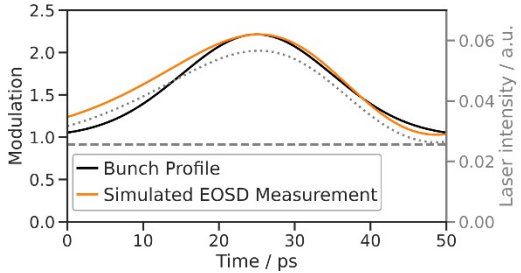
- Complete phase space image reconstructed from time interval of 61 µs
- "Randon morphing" between independent measurement



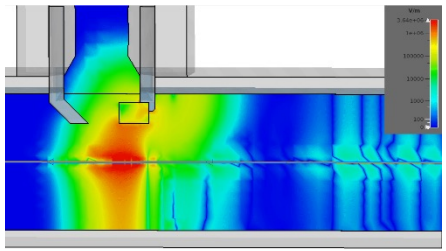
Development of an EO Bunch Profile Monitor for FCC-ee

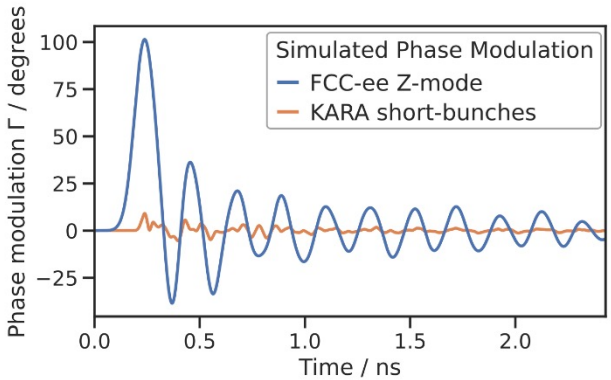
Simulations of the EO near-field measurements at KARA

FUTURE CIRCULAR COLLIDER
Innovation Study

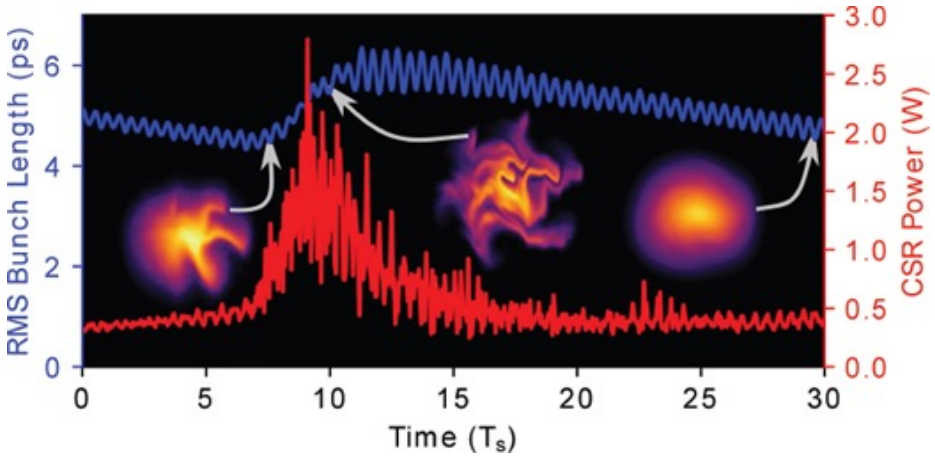


Simulations of EO near-field monitor at KARA



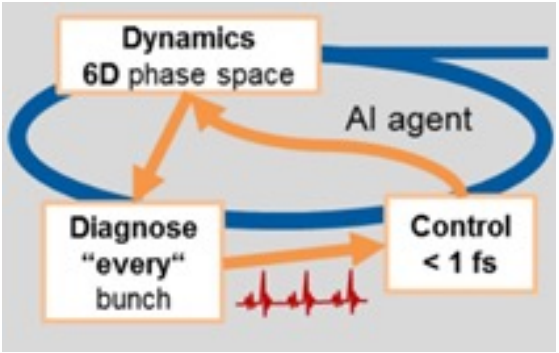


Closing the loop: "every" bunch diagnostics, longitudinal beam dynamics, real-time advanced beam control



Microbunching instability (MBI)
Phase space, bunch length, CSR

Beam Diagnostics towards **Beam Control**

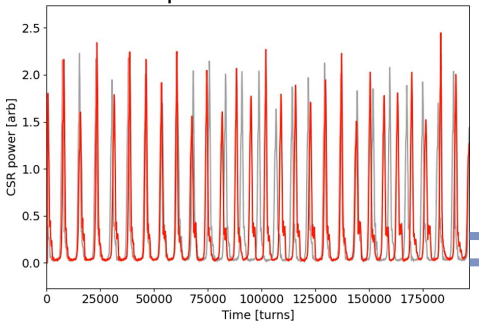


Real-time Reinforcement Learning on FPGA with Online Training for Autonomous Accelerators

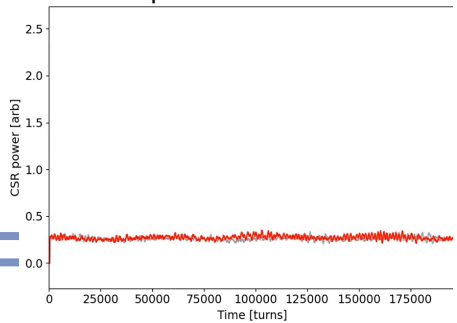
World's first AI real-time control of the microbunching instability at KIT

Close collaboration & rapid prototyping at KIT

CSR power - **random state**

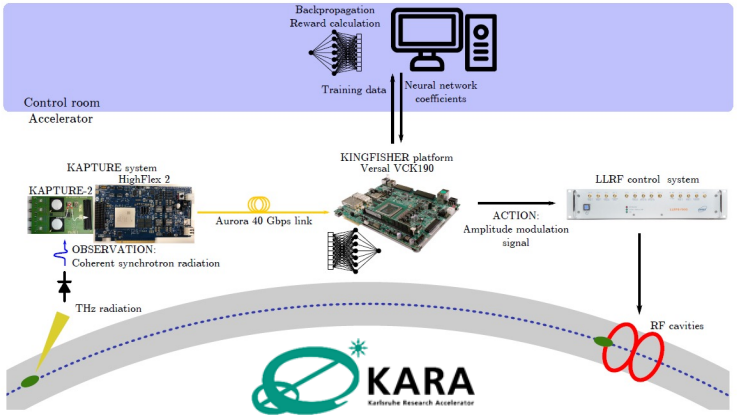


CSR power – **AI controlled**



AI control of coherent synchrotron radiation (CSR) with online-training – and without pre-training – on hardware.

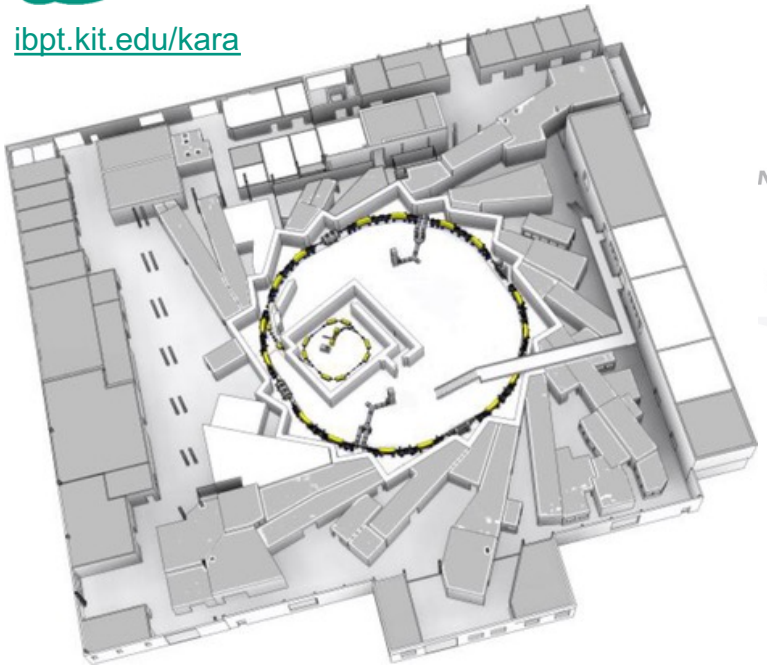
Setup at Karlsruhe Research Accelerator KARA



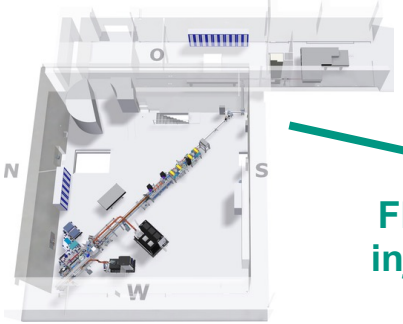
Accelerator facilities for non-equilibrium systems
Rings, linac, non-eq. storage ring, laser plasma acc.

KARA ○ 110 m ○ 26 m

ibpt.kit.edu/kara



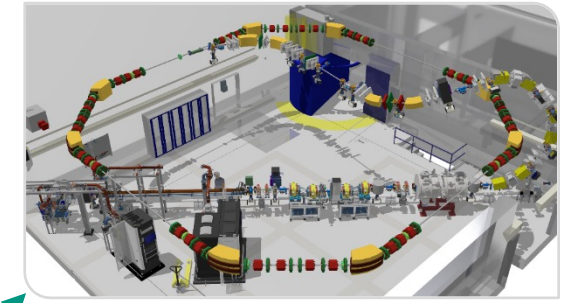
/ 20 m FLUTE



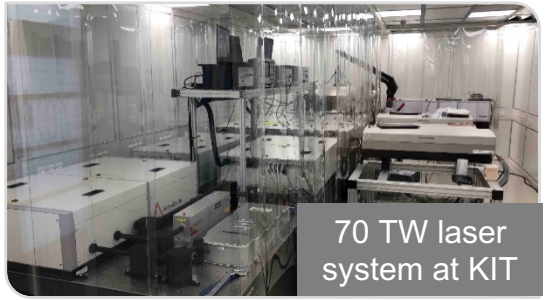
ibpt.kit.edu/flute

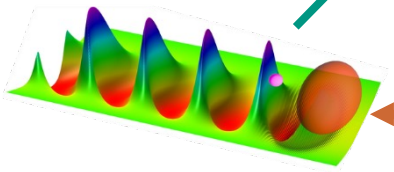
FLUTE injector

cSTART ○ 43 m



LPA injector

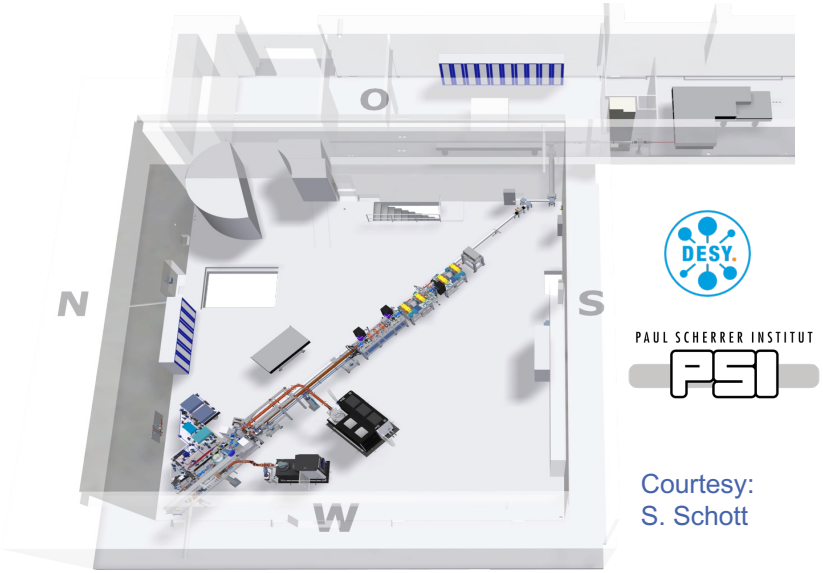




Laser plasma accelerator (LPA)

FLUTE: Accelerator Test Facility at KIT

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



Courtesy:
S. Schott

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

- 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

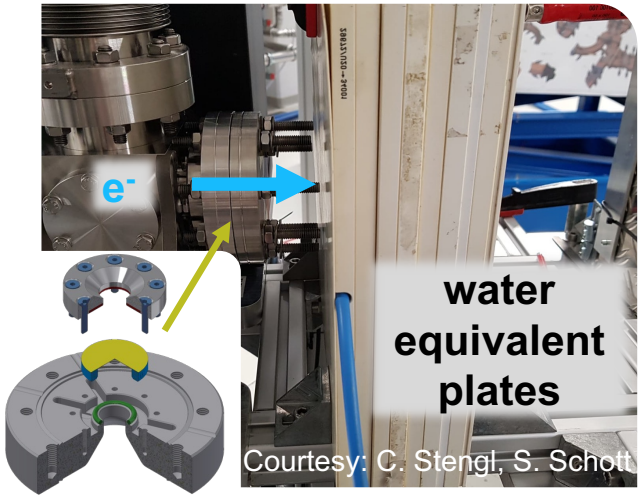
www.ibpt.kit.edu/flute

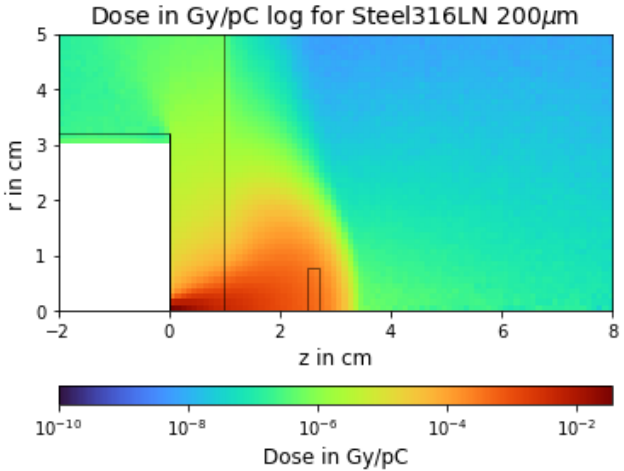
Accelerator technology for precision medicine

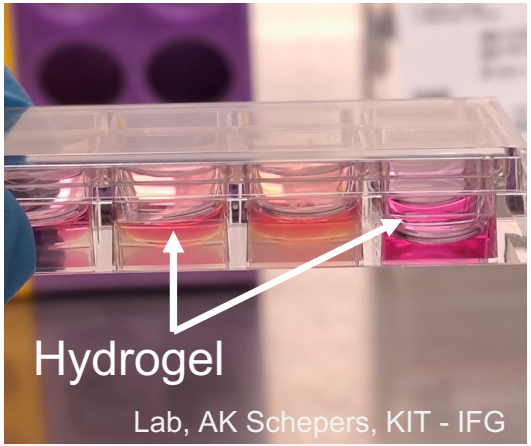
KIT Center HealthTech https://www.healthtech.kit.edu/

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





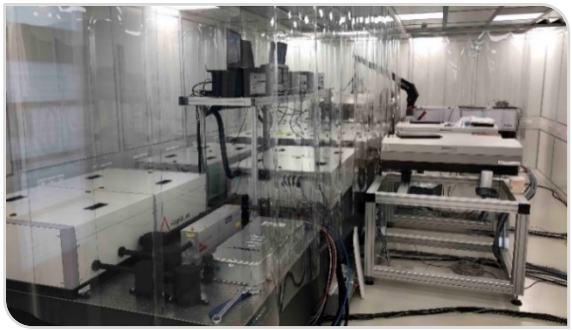


Compact Accelerators

New great additions & opportunities for accelerator R&D
Short-pulse generation and new facilities

Laser plasma accelerator (LPA) & injector

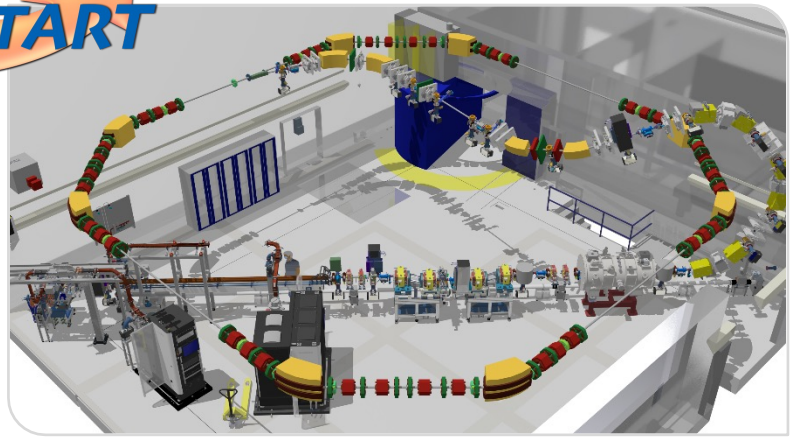
- Terawatt laser system at KIT in operation
  - > 70 TW, < 23 fs, 10 Hz, > 1.5 J
- Transfer line magnets for injector ready
- Diagnostic systems ready
- 09/23: Prof. Dr. M. Fuchs & LPA team arrived at KIT



For further details see: ibpt.kit.edu/project.php

non-equilibrium storage ring

cSTART

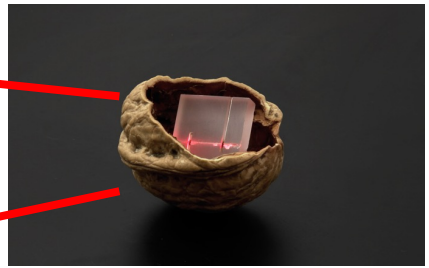


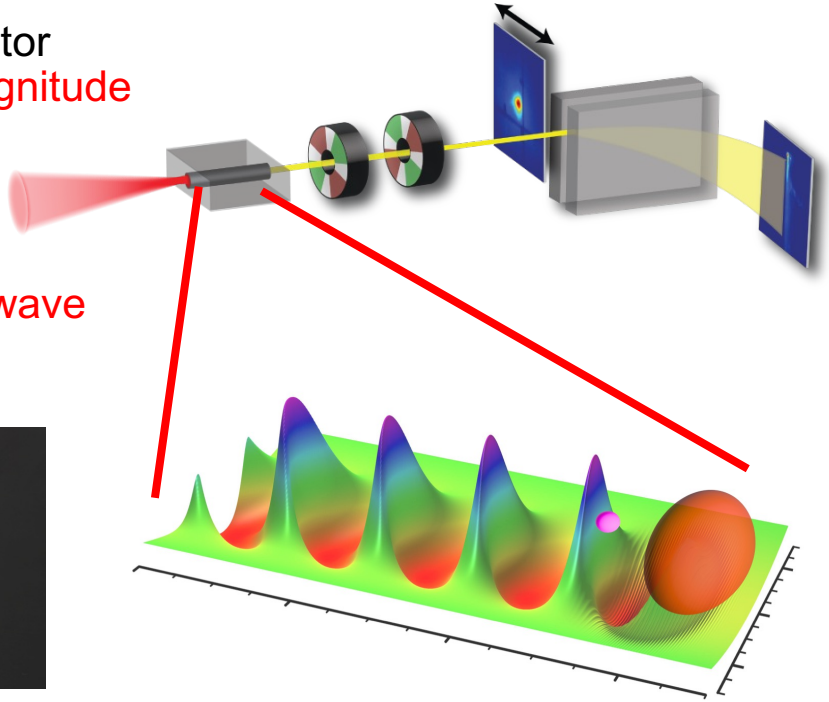
Timeline

- 2024: Technical design report (TDR)
  - KIT & research instruments
- 2026: Assembly

Laser-Plasma Accelerators

- Use laser-plasma interactions to reduce accelerator dimensions and cost by more than 3 order of magnitude
- Driver: high-power lasers (PW-class laser, 1 PW = 10^{15} W)
- Laser excites plasma wave
- Electrons get accelerated by surfing the plasma wave





Compact storage ring for non-equilibrium systems/beam dynamics/accelerator physics

Goal 1:

Injection of LPA beam in storage ring

- Efficient charge/bunch transfer
- First paper/thesis on LPA injectors
  - Hillenbrand S. (KIT), et al.
    Study of laser wakefield accelerators as injectors for synchrotron light sources
    NIM A 740, pp. 153-157 (2014).
    doi: 10.1016/j.nima.2013.10.081
- Collaboration with DESY & HIJ (ATHENA)

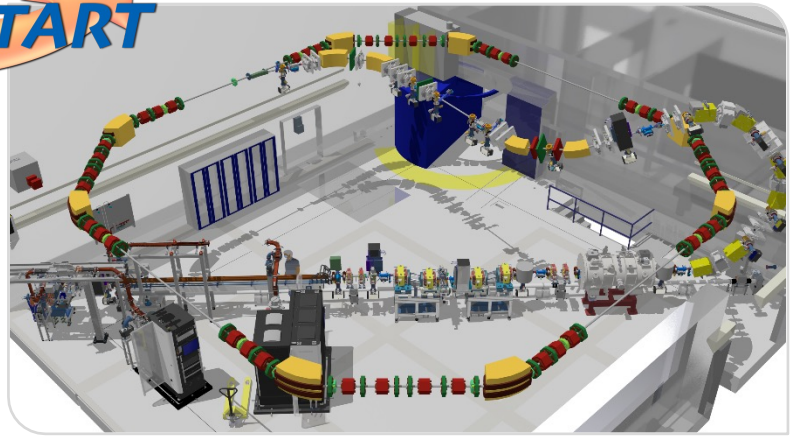
Goal 2:

Storage of sub-ps bunches

- Using FLUTE linear accelerator as injector

cSTART

non-equilibrium storage ring

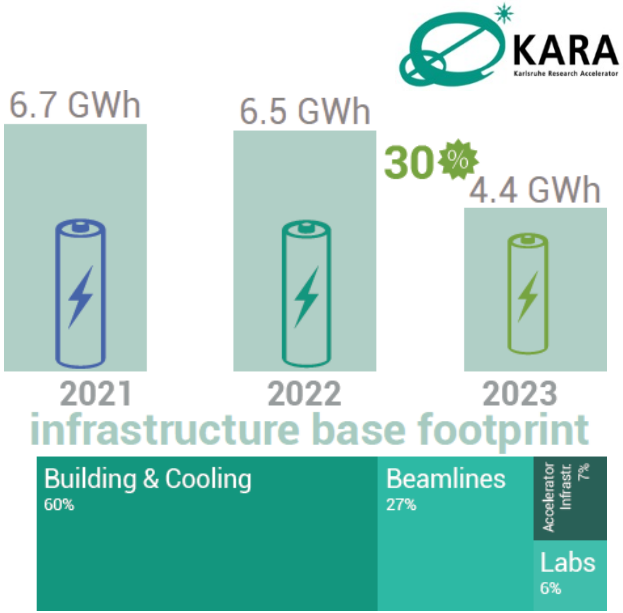


Features

- Compact storage ring
- Large dynamic aperture for LPA beam
- Space for advanced diagnostics & accelerator physics experiments

Energy solutions – Getting results with KITTEN

New KIT-coordinated project: Research Facility 2.0



- **KIT-coordinated** project **Research Facility 2.0** (2024-2026): **Towards a more energy-efficient and sustainable path,** rf20.eu
- **First year of data taking with the electricity meter network for sustainable operation of the KIT accelerator facilities for the KITTEN project**
  J. Gethmann, E. Blomley, E. Bründermann, G. De Carne, H. Hoteit, M. Mohammad Zadeh, A.-S. Müller, M. Schuh, J. L. Steinmann, Proc. IPAC'24 (2024).

Energy solutions – Getting results with KITTEN

Real-time energy-informed & physics-informed digital twin

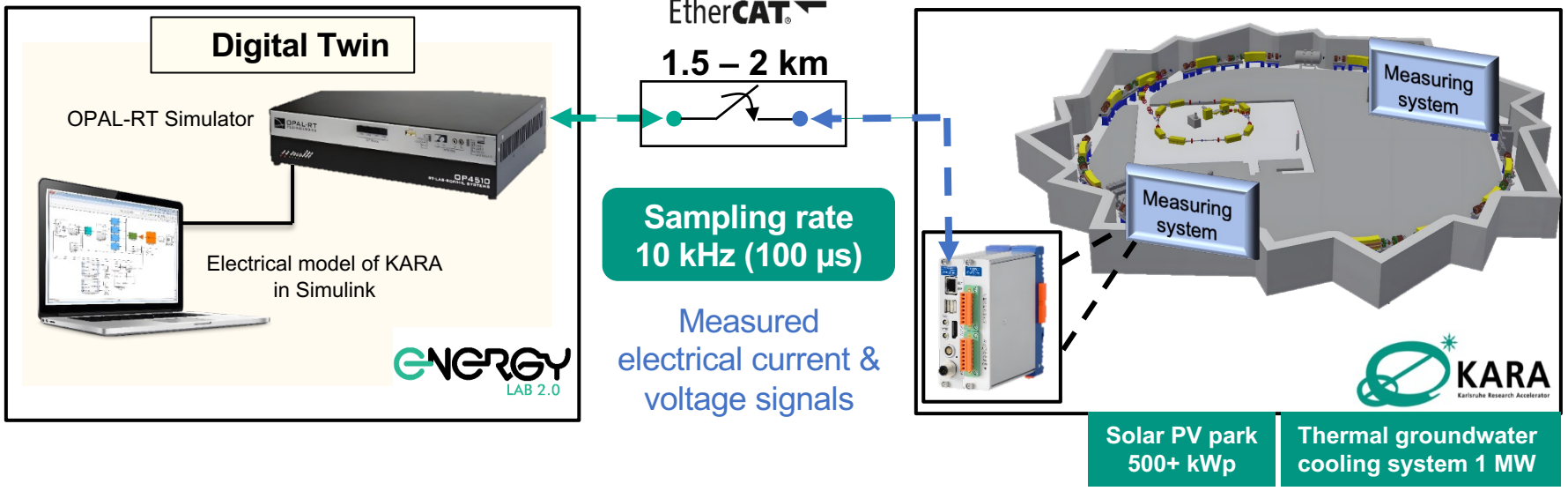
Union of 2 large-scale KIT research infrastructures: EL2.0 & KARA

Karlsruhe Institute of Technology

ATP Accelerator Technology Platform @ KIT

KITTEN KIT test center for energy efficiency & grid stability in large-scale research infrastructures

Communication Infrastructure



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- The accelerator team

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- For a selection of collaborating KIT institutes see: atp.kit.edu/members.php
- For a selection of EU/EC, Helmholtz & university collaboration partners see: ibpt.kit.edu/project.php

Thank you for your attention!