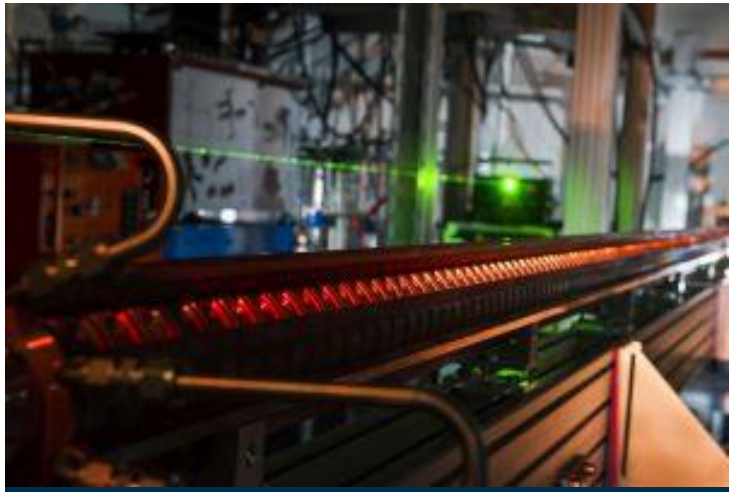
Karlsruhe Research Accelerator



FIR/THz short-bunch linac

compact STorage ring for Acc. Res. & Tech.

KIT Status Report ESLS 2025

Johannes Steinmann on behalf of the KIT accelerator team
2025-10-31

Accelerator Technology Platform (ATP) at KIT

The accelerator test facilities…

KARA^{neo} storage ring	
Energy range	0.5 – 2.5 GeV
Beam current	Up to 200 mA
Bunch length	45 ps down to 1 ps
Circumference	110.4 m
Revolution freq.	2.715 MHz
Lattice structure	DBA

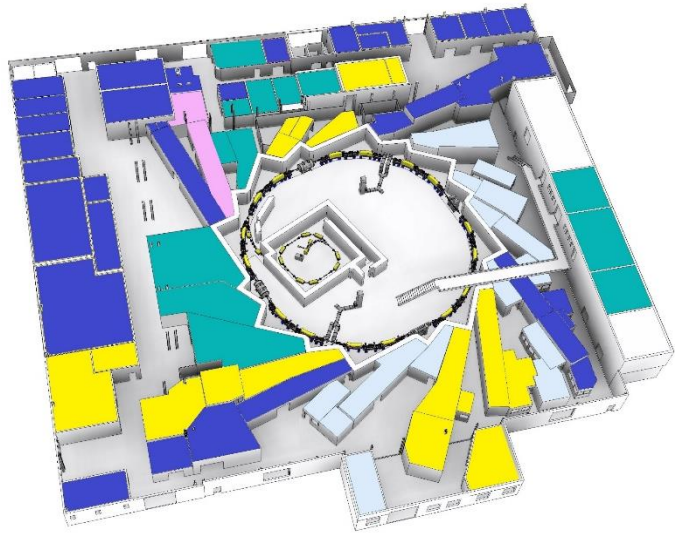
FLUTE linear accelerator	
Energy range	Up to 90 MeV
Bunch charge	Up to 1 nC
Bunch length	Down to 1 fs
Repetition rate	Up to 50 Hz
THz E-field strength	Up to 1 GV/m
Spectral band coverage	Up to 30 THz

Key parameters

Laser-plasma accelerator (typ.)	
Energy range	Up to 500 MeV
Bunch charge	Up to 200 pC
Bunch length	Down to 3 fs
Repetition rate	Up to 10 Hz
Energy spread	Few %
Accelerating field gradient	50 GV/m

cSTART storage ring (under construction)	
Energy range	Up to 90 MeV
Bunch length	< 100 fs
Circumference	43 m
Revolution freq.	6.9 MHz
THz E-field strength	> 1 GV/m
High energy x-rays (Compton scattering)	5 – 200 keV

Karlsruhe Research Accelerator KARA



KARA^{neo}

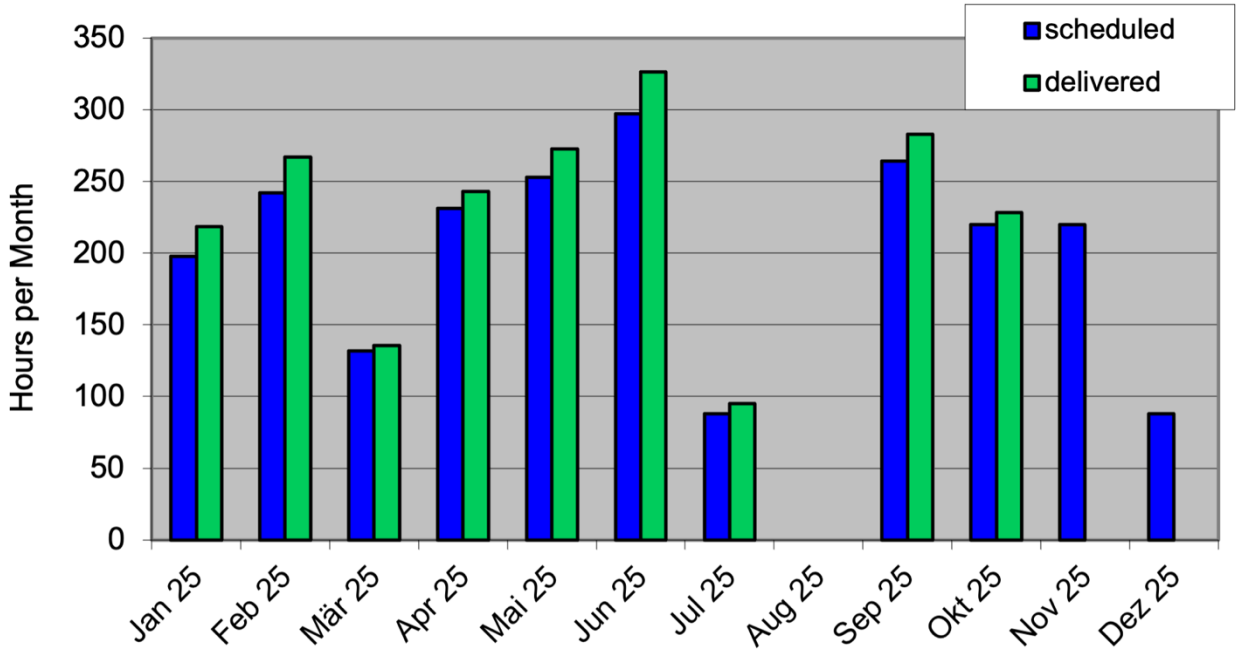
Change on 1.1.2025 for KARA operations

Accelerator Physics and R&D in Accelerator Technologies are our priority

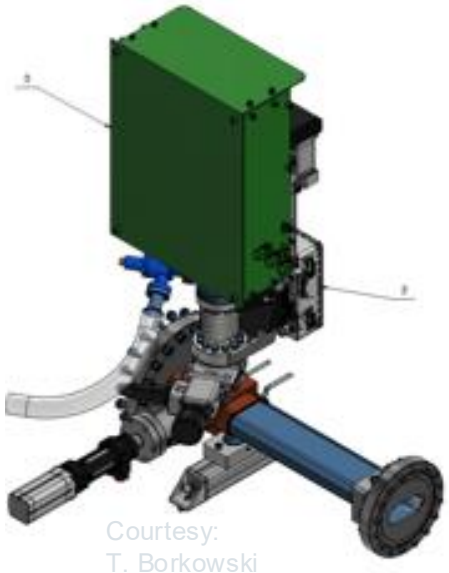
KARA Operation 2025

KARA Operation 2025

- 100 days synchrotron light + 50 days machine physics
- Service on Monday morning
- Operating from Monday afternoon to Saturday morning
- Planned long shutdown in July/August to avoid heat
  (Cooling capacity limit at ~32°C outside temperature)



- Operational Issues
  - First operation of ground water cooling (more later)
  - Water flow alarms and interlocks due to clogging in pipes
    (some in operation for 25 years)
  - Several power glitches - most caused by issues on site
  - Main vacuum PLC stopped (closure of all vacuum valves)
  - New EO chamber: Insertable RF shielding stuck



Courtesy:
T. Borkowski

20 kV Campus Grid Renewal

- Many cables at KIT date back to the 1960s and 1980s
- 20 kV grid consists partly of old, fault-prone (water tree) or paper-insulated cables
- Renovation underway, but incidents are increasing

Cooling at KARA

Conventional cooling with 1 to 2 cooling machines:
EER 3-5 (à 1 MW per machine)

Electricity consumed by cooling machines

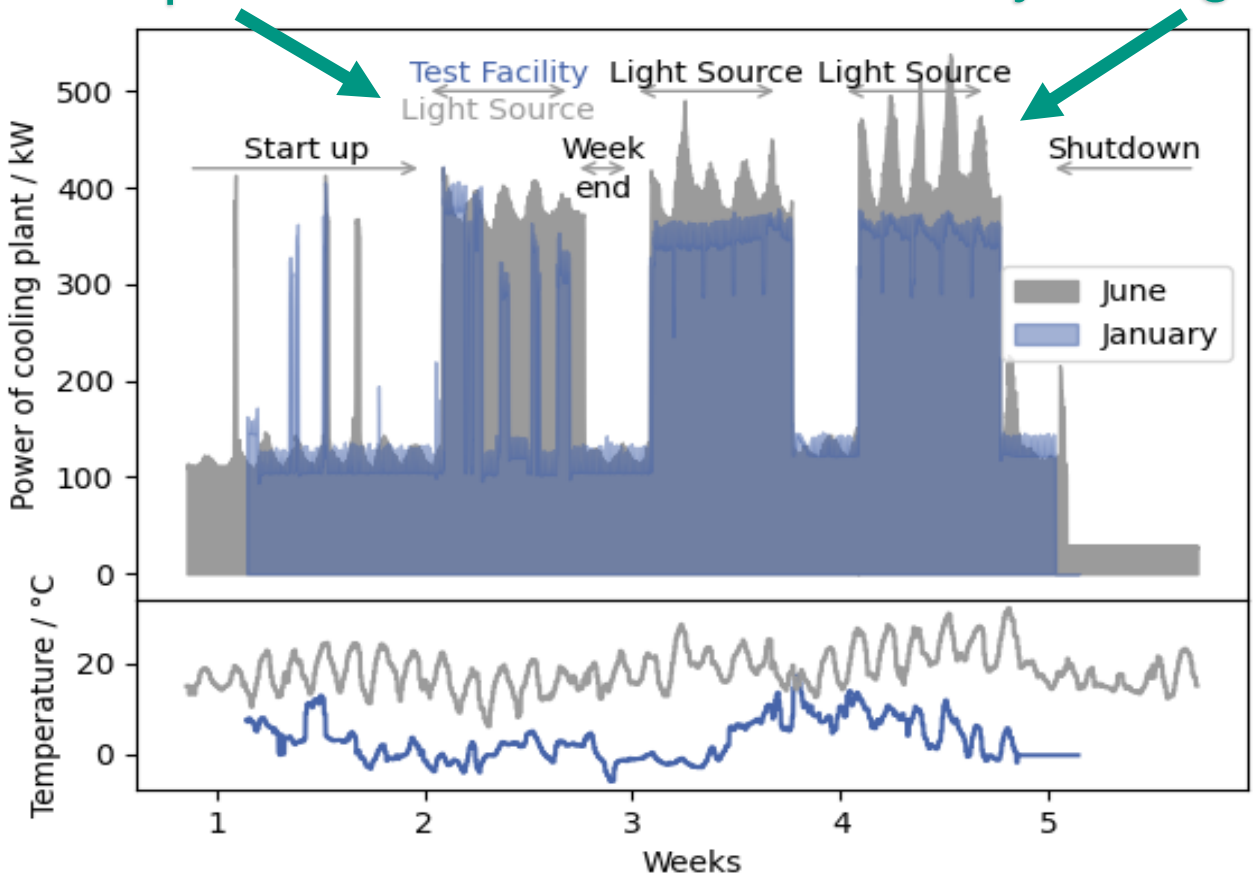
KARA stand-by	120 kW_{el}
KARA operation	400 kW_{el}
Summer heat (extra)	+100 kW_{el}
current capacity up to	550 kW_{el}

Goal: Cut consumption by half = - 275 kW_{el}

Not possible only by our 540 kWp photovoltaics plant
(or other RF2.0 or KITTEN measures, yet

Various operation modi

T intra-day changes



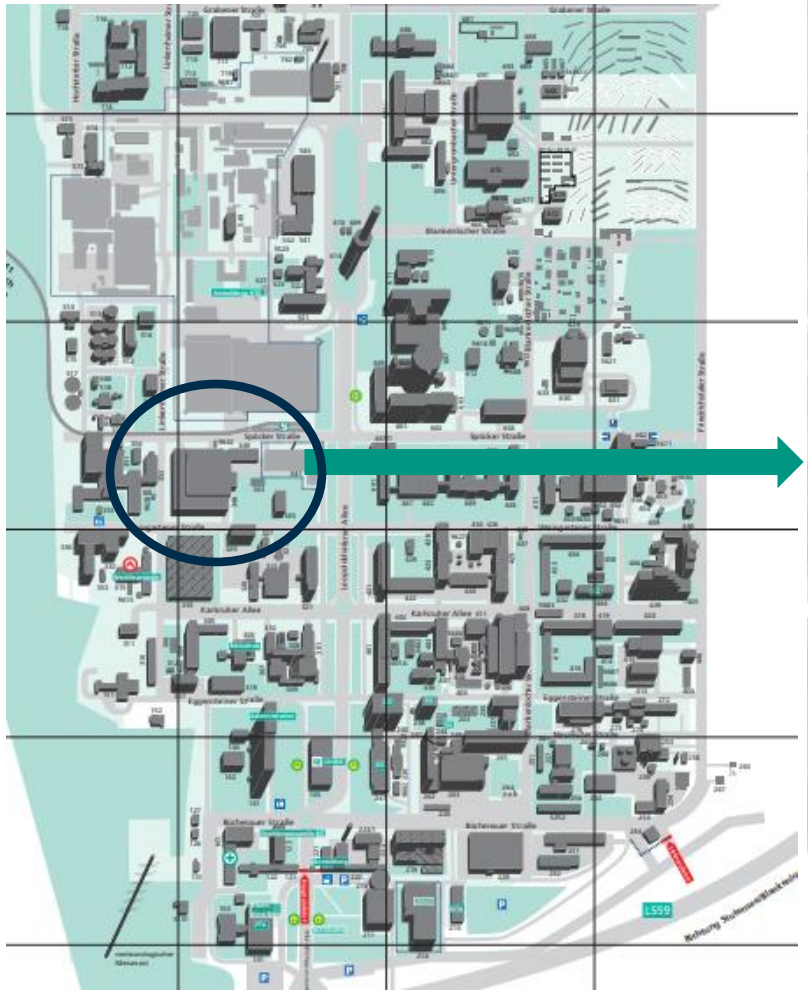
10.18429/JACoW-IPAC2025-THPB096

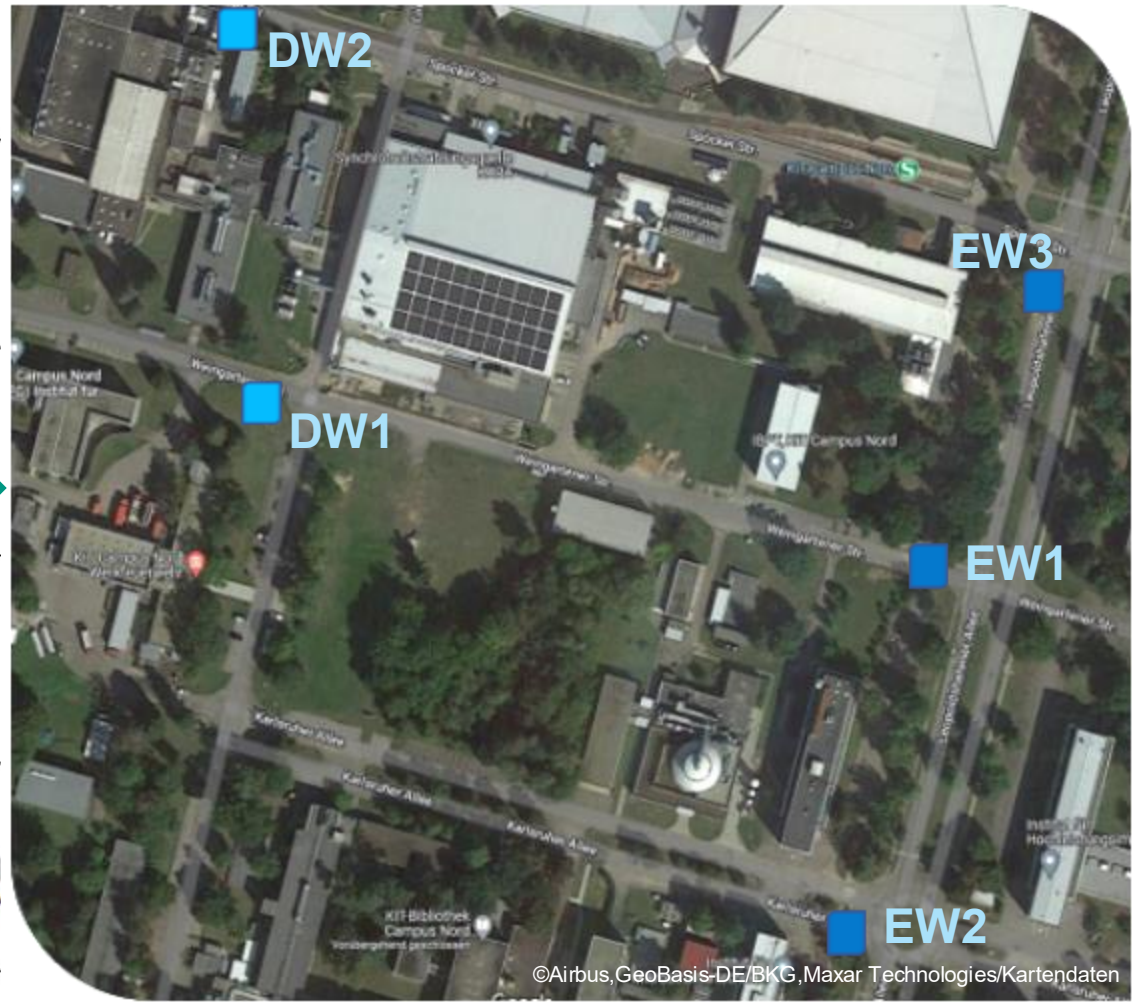
RF2.0 RESEARCH FACILITY
TOWARDS A MORE ENERGY-EFFICIENT AND SUSTAINABLE PATH

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

$$EER = \frac{\textit{cooling}\ \text{capacity (output)}}{\text{electrical energie (input)}}$$

Thermal Wells at KARA





extraction wells = EW with pumps

dissipative wells = DW

Thermal Wells at KARA

Compents that have to be cooled ➔

Magnets

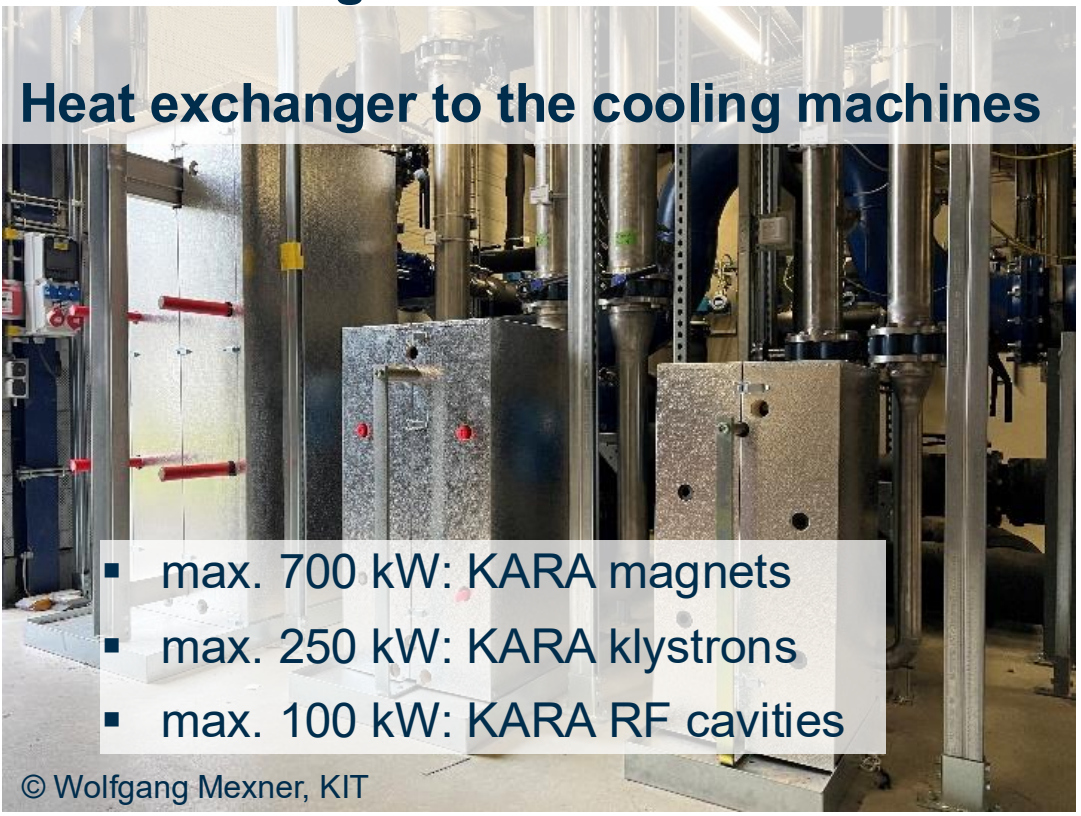
Klystron

RF cavity

Air condition

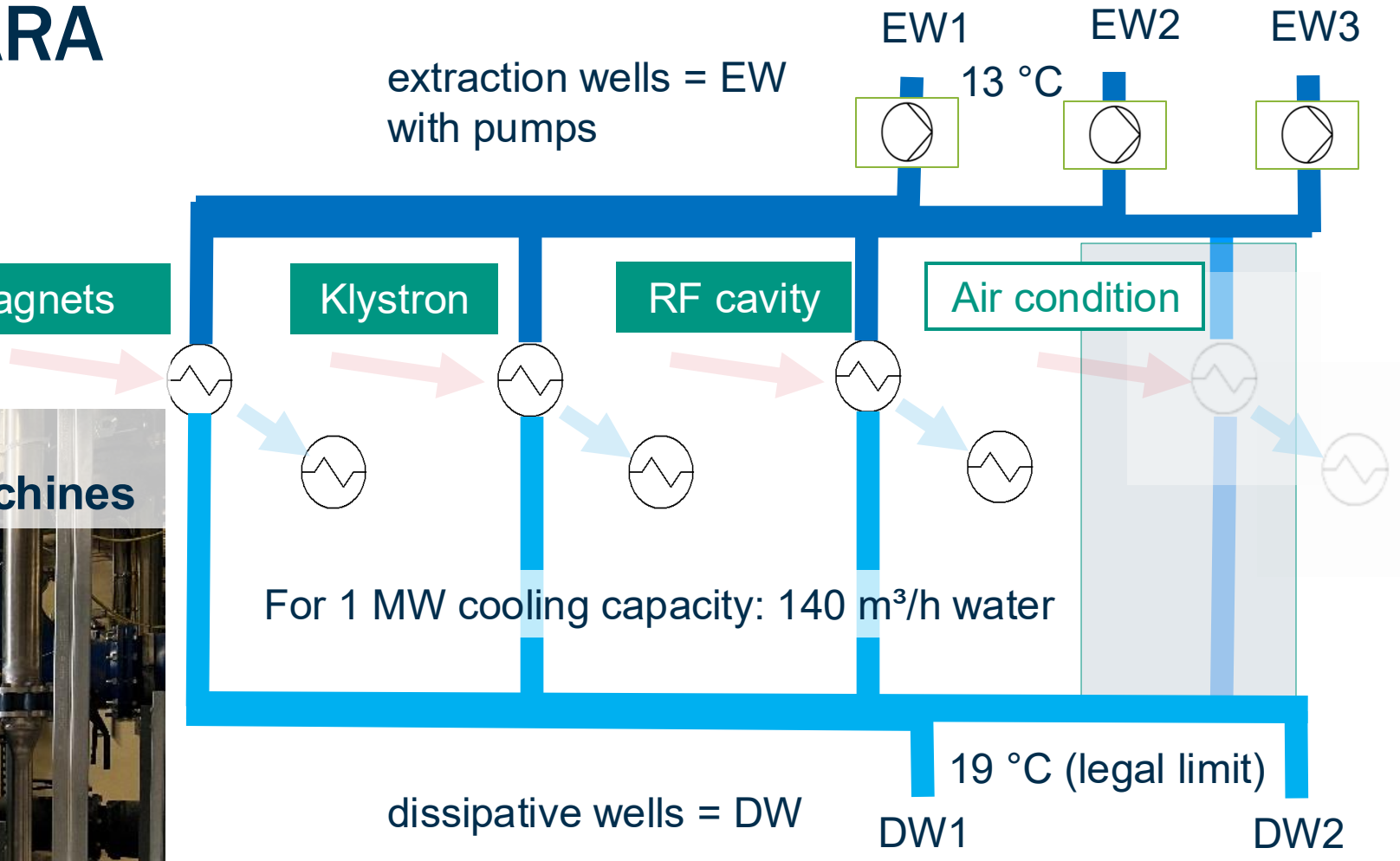
Heat exchanger to the wells ➔

Heat exchanger to the cooling machines



- max. 700 kW: KARA magnets
- max. 250 kW: KARA klystrons
- max. 100 kW: KARA RF cavities

© Wolfgang Mexner, KIT



Additionally we must condition our water (FERMANOX®) to avoid clogging.

EER wells: 35
Theoretical EER w/o extra conditioning: 41

KARA as Test Facility

2

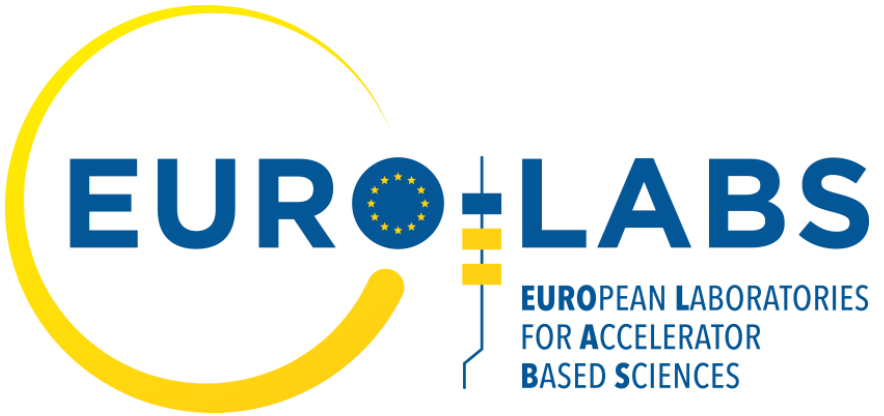
KIT Accelerators as Test Facility

50 Days / year of dedicated beam physics operation at KARA

- Used by KIT students and collaborators
- Lab courses, hands on training
- Device testing in real accelerator environment

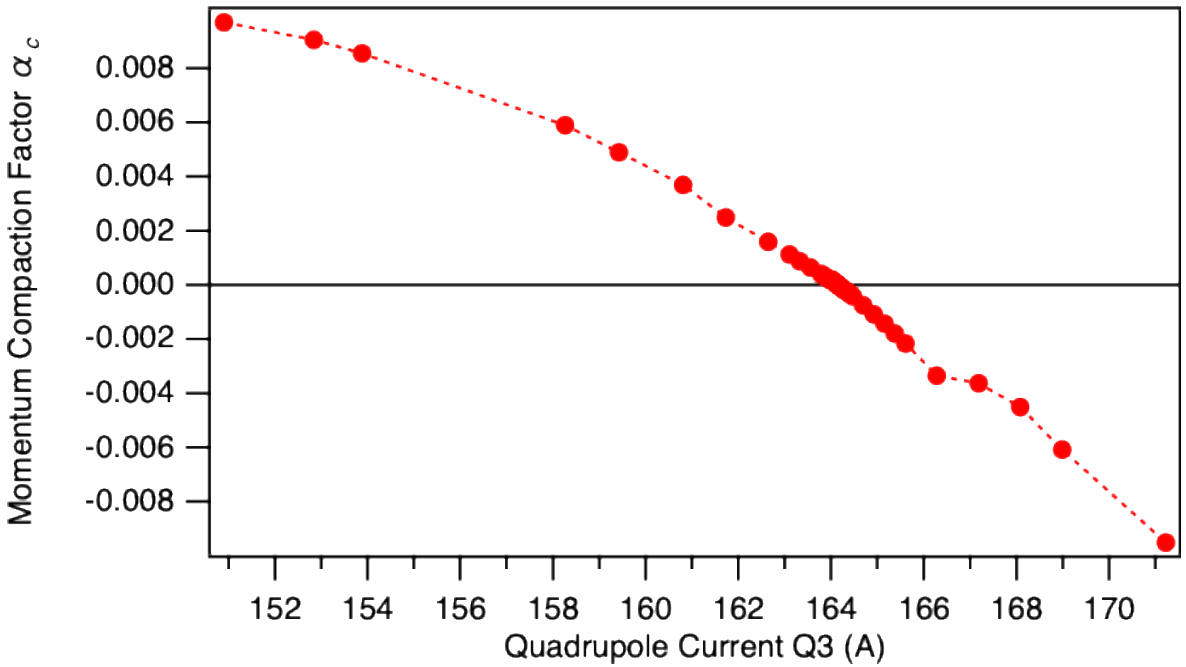
FLUTE & KARA test facilities are part of Euro-Labs

- Support for travel & accommodation costs for experiments
- Relatively simple application process
- Open for proposals (for EU and EEC labs)!
- Contact: Robert Ruprecht (KIT, IBPT): robert.ruprecht@kit.edu

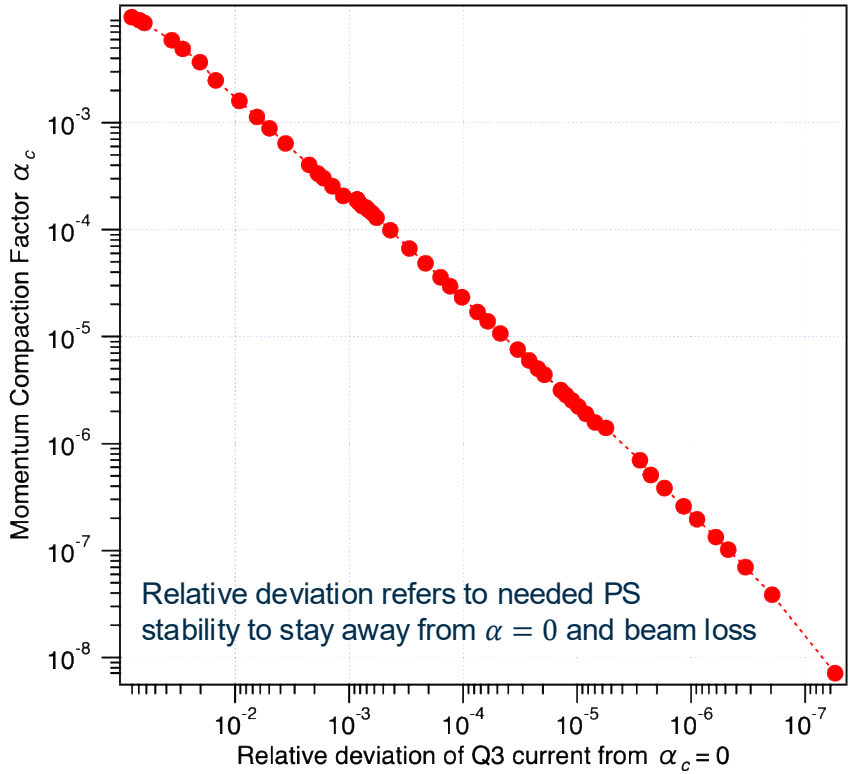


Low-Alpha Improvements at KARA

- Short-bunch operation mode (low-alpha) implemented since 2003
- Limited by optics (no octupoles, only 2 sextupole families) and power supply stability to ~2 ps zero-current bunch length
- Quadrupole power supply upgrade improved stability to < 5 ppm



loglog

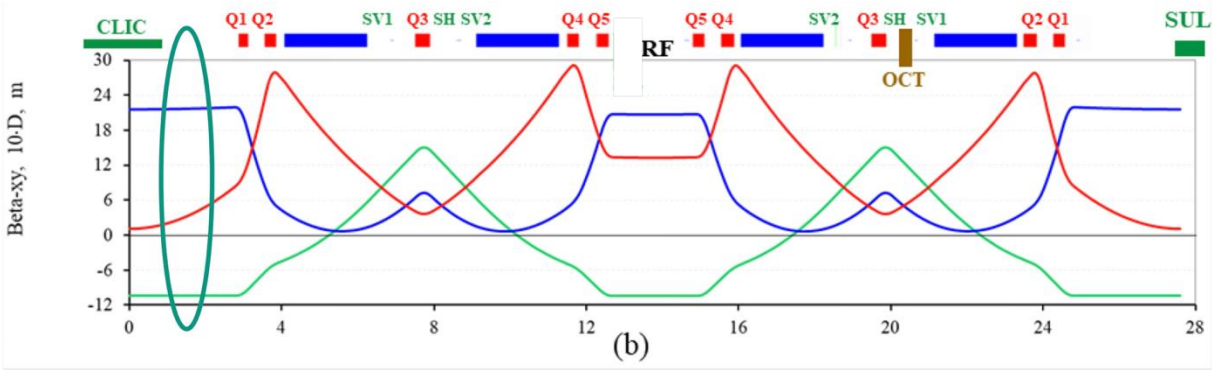


Low-Alpha Improvements at KARA

- Second order momentum compaction factor depends scales with sextupole strength to third power of dispersion

$$\Delta\alpha_2 = -\frac{1}{2L_0}\oint \frac{\Delta D_1(s)}{\rho(s)}\,ds = -\frac{1}{2L_0}\oint D_0^3 \cdot \Delta K_{SXT}\,ds$$

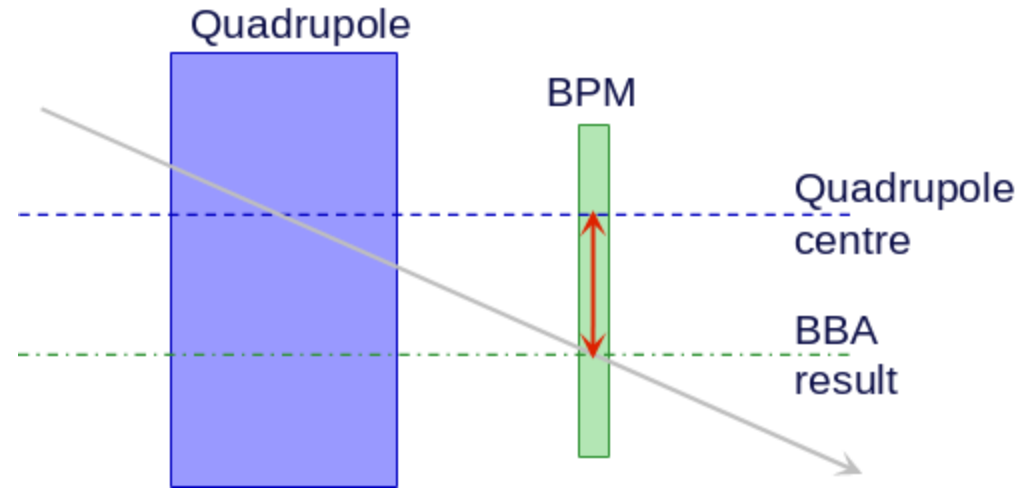
- Dispersion is stretched in low-alpha operation, leading to region with very high dispersion
- Install single additional sextupole at position with high dispersion

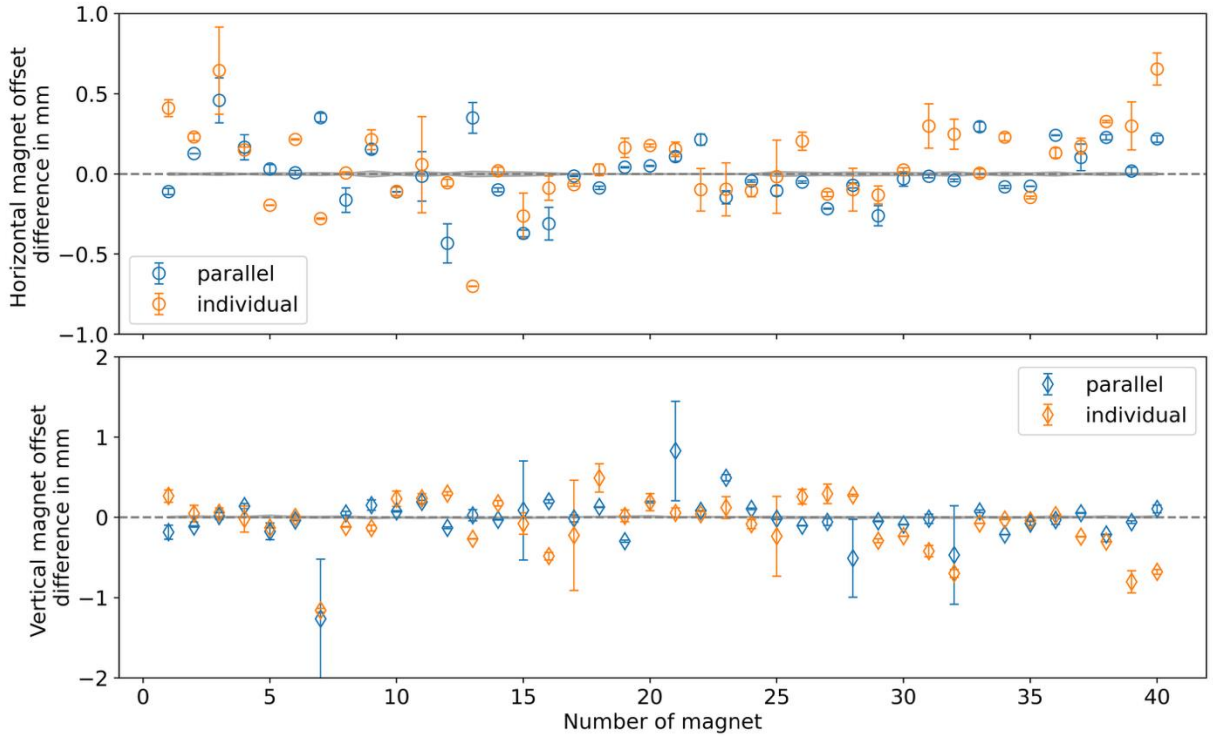


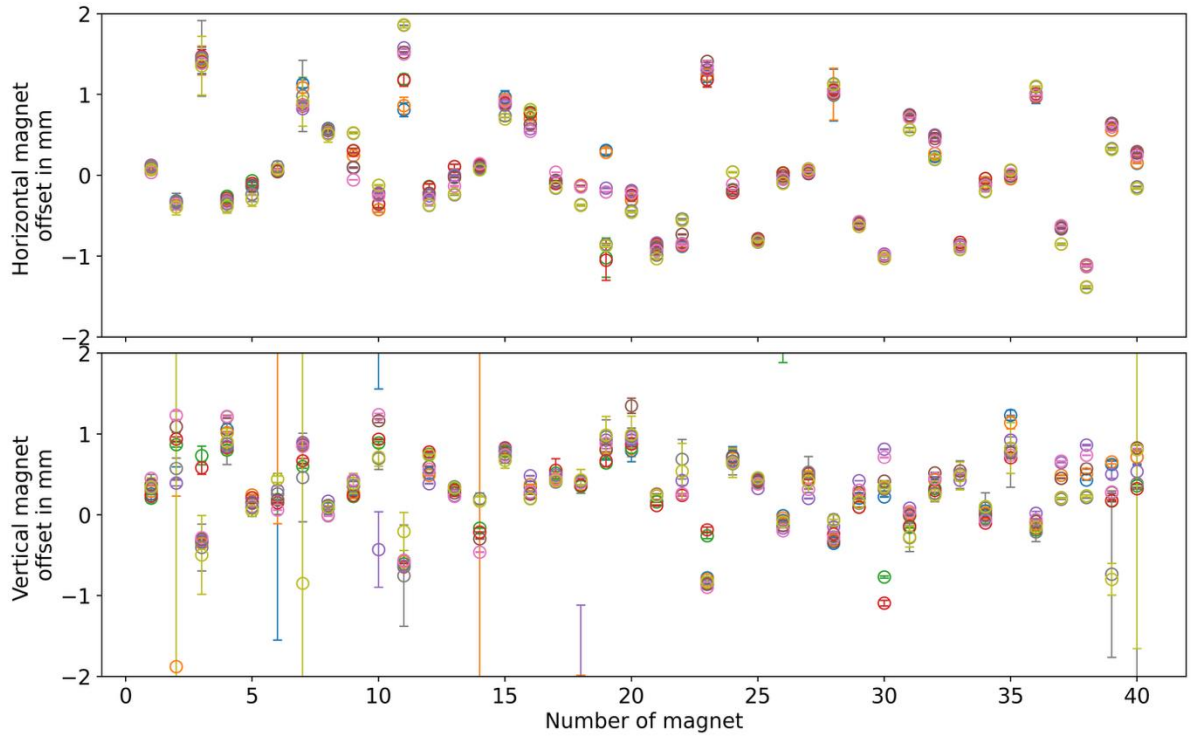
- Just one KARA spare sextupole powered at only 12 A is enough to sufficiently reduce α_2
- Reached $\alpha = 4x10^{-5}$ which corresponds to a zero-current bunch length of 920 fs
  - No octupoles, 2 families of sextupoles and a single “longitudinal” sextupole

Beam-based alignment (BBA)
Individual and parallel

- Relevant impact of beam angles
- Different BBA approaches and corrector settings for orbit variations lead to different BBA results
- Difference of up 350 µm rms between BBA results







I.FAST Workshop on Stability of Storage Ring Based Light Sources

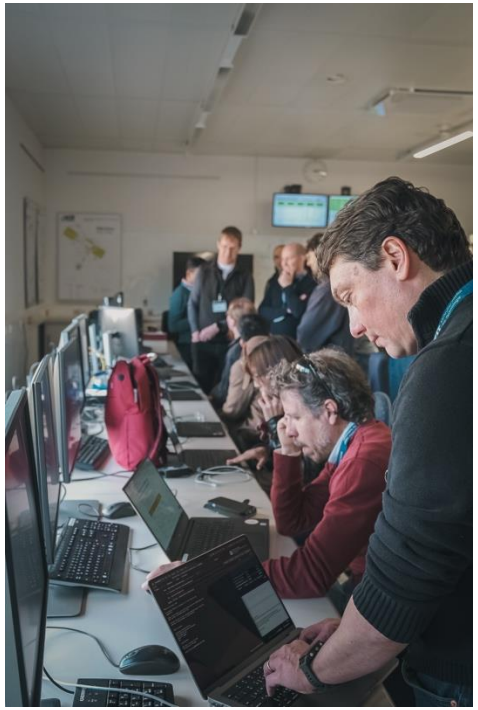
All presentation slides and abstracts are available on the Indico website:

https://indico.scc.kit.edu/event/4809/

- 17-19 March 2025: **Workshop**
- 20-21 March 2025: **Joint Experiment** (as the EURO-LABS Project activity)
- Joint organization with SOLEIL and KIT
- Venue: KARA large seminar hall

- Session blocks:
  - Source position stability
  - Resistive and permanent magnets
  - Infrastructure
  - Challenging issues
- Participants:
  - Onsite **52** + Online **34** = **86** (registered)
  - From research and industrial areas
  - From Europe, Asia Pacific, America
- Number of talks: 26

Joint Experiment at KARA



20-21 March 2025: Joint experiment (1.5 days) as a EURO-LABS project activity

- Experimental topics: source position stability with beam-based alignment
- Comparison between normal and parallel beam based alignment
- Beam based alignment in different operation energies (2.2, 2.3 and 2.5 GeV) and different beam current conditions
- Workshop participants and I.FAST-WP7 members joined the experiment
- Systematic measurements ... The data analysis is ongoing, and the data are being shared with the participants.

Insertion Device Activities

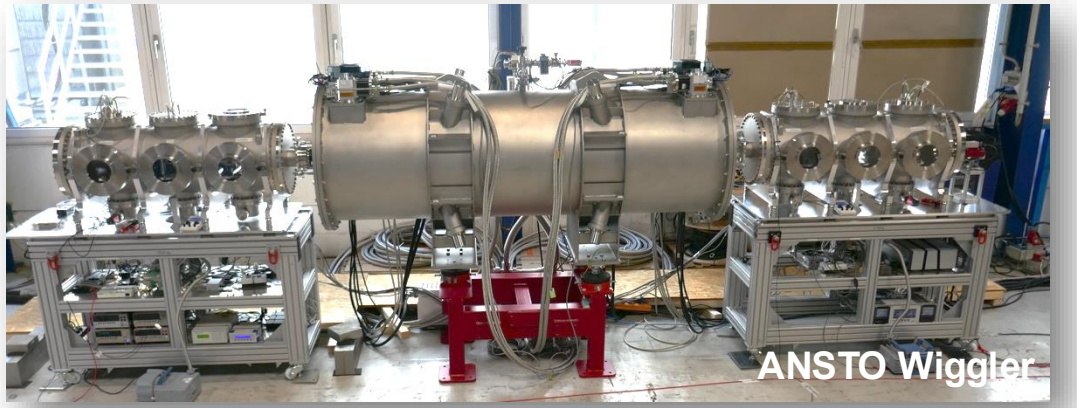
Superconducting Insertion Device Activities

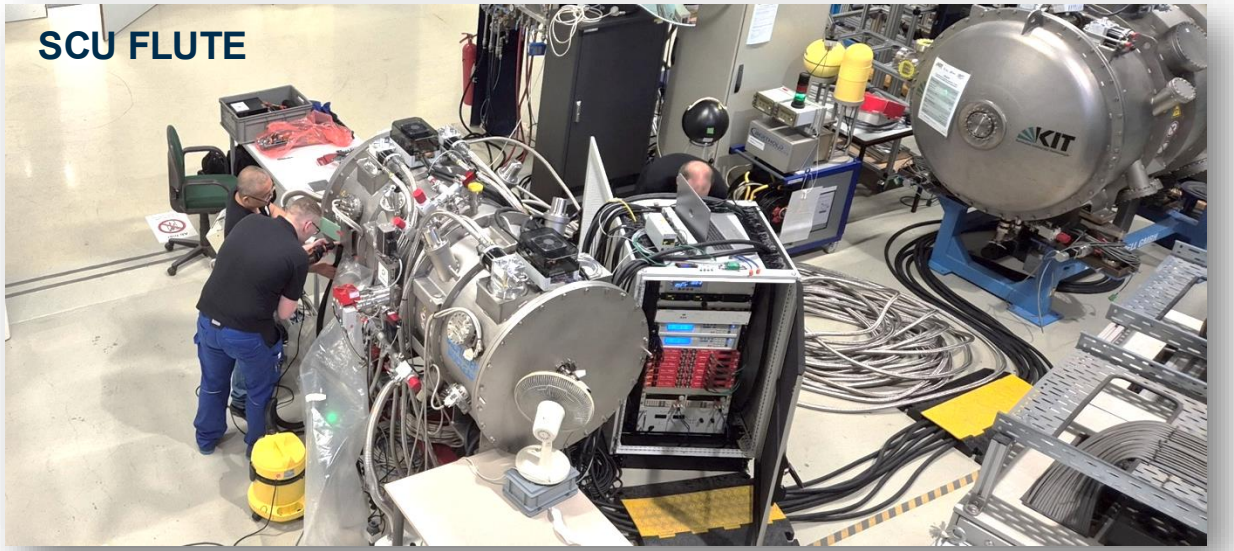
SCU for FLUTE

- Coils delivered to KIT, cooled down and are working ✓
- Delivery of SCU-F to KIT July 2025 ✓
- Ongoing SAT scheduled to be finished end of the year

Mobile Measurement Setup

- System to characterize **local field** distribution & **field integrals** of undulators in final cryostat (for FATs and SATs)
- At Bilfinger, first field operation for FATs





ID-Group
A. Grau,
D. Saez de Jauregui,
B. Krasch
et al.

FLUTE as Test Facility

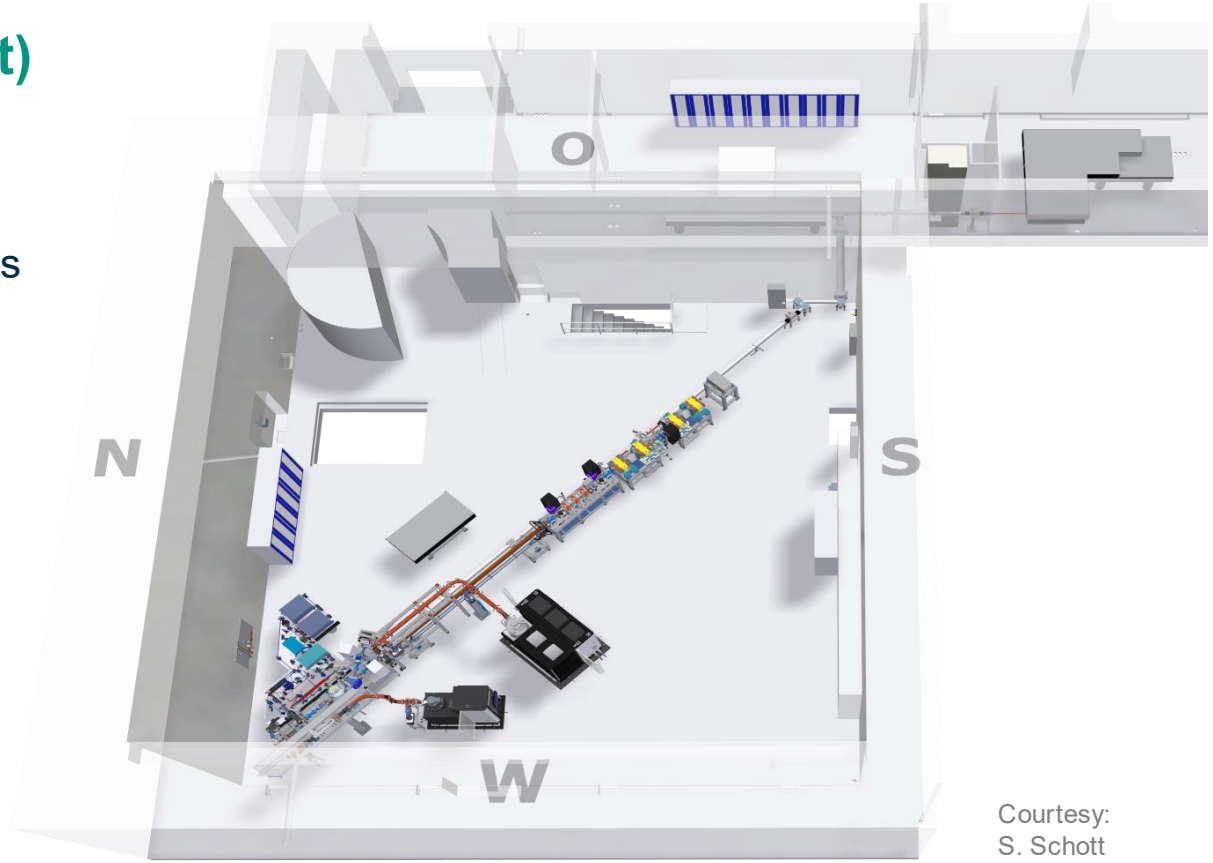
4

Status of FLUTE
Accelerator Test Facility at KIT

FLUTE (Ferninfrarot Linac- Und Test-Experiment)

- Test bench for **new beam diagnostic** methods and tools
- **In-air electron** experiments
- Systematic **bunch compression** and **THz generation** studies

Optimal electron energy	~ 41	MeV
Electron bunch charge	0.001 - 1	nC
Electron bunch length	1 - 300	fs
Pulse repetition rate	up to 50	Hz
THz E-Field strength	up to 1.2	GV/m



Courtesy:
S. Schott

www.ibpt.kit.edu/flute

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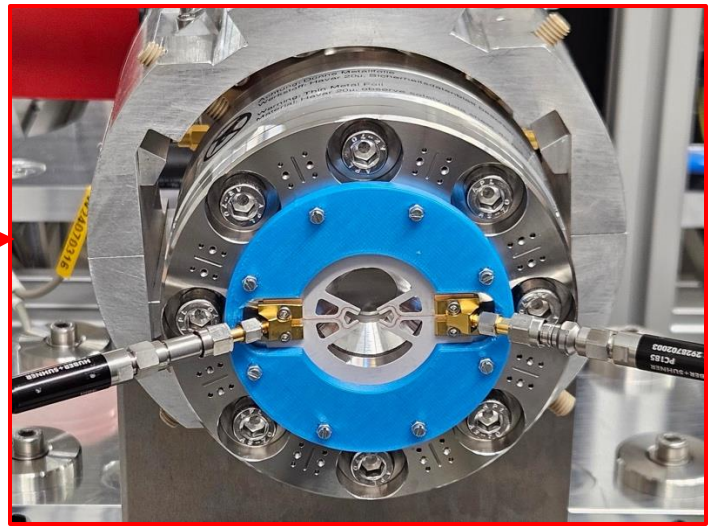
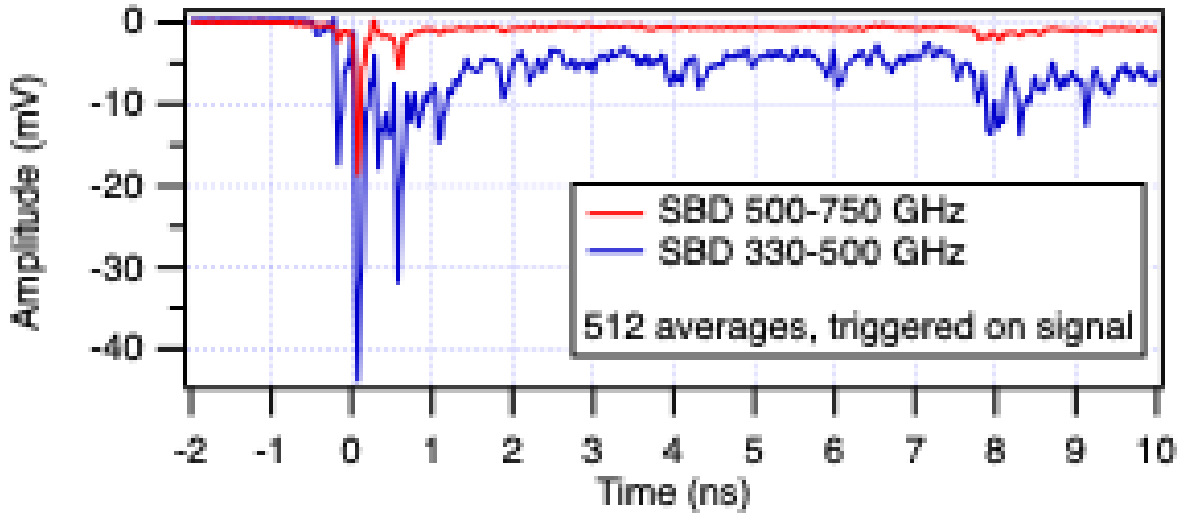
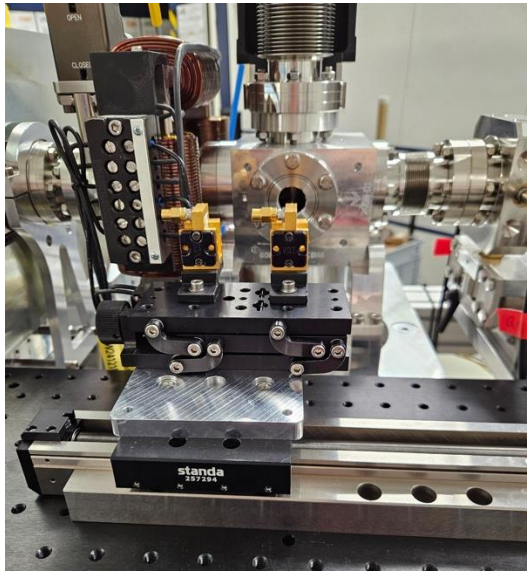
www.ibpt.kit.edu/flute

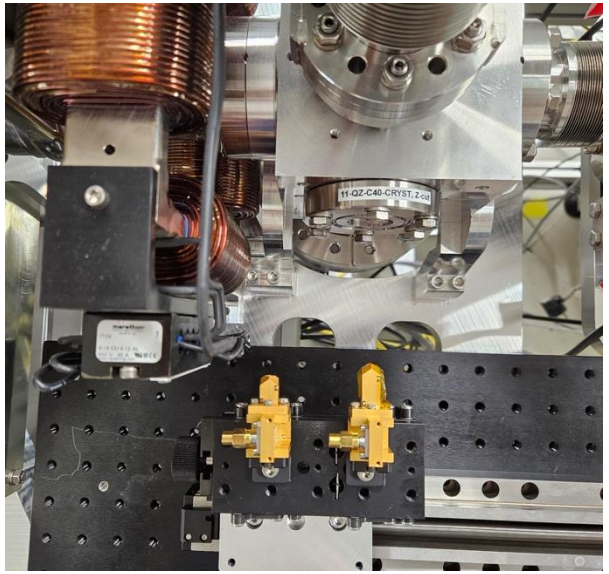
- Test bench for **new beam diagnostic** methods and tools
  - Compact transverse deflecting systems (split-ring resonator)
  - Button BPMs, BLMs, BAMs, THz spectrum-based BCMs, etc.
- Versatile experimental platform for **in-air electrons** for…
  - …systematic dosimetry tests towards FLASH effect studies
  - …development of new dosimeters
  - …test of advanced BAMs, new EO sensors etc.



Courtesy:
A. Penirschke,
B. Scheible







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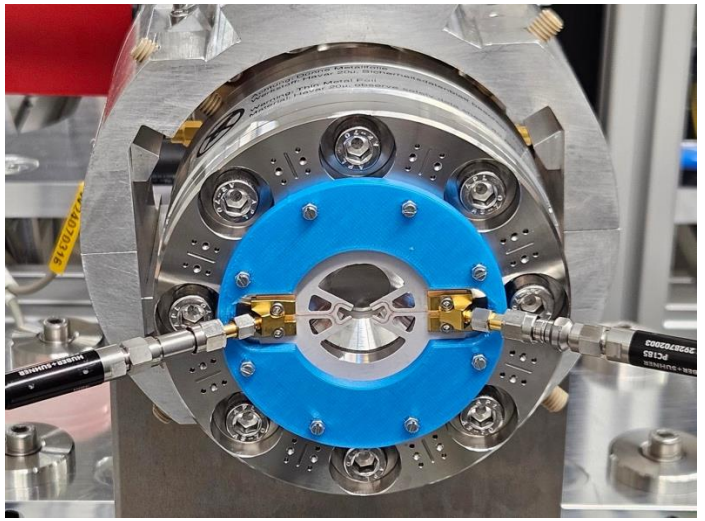

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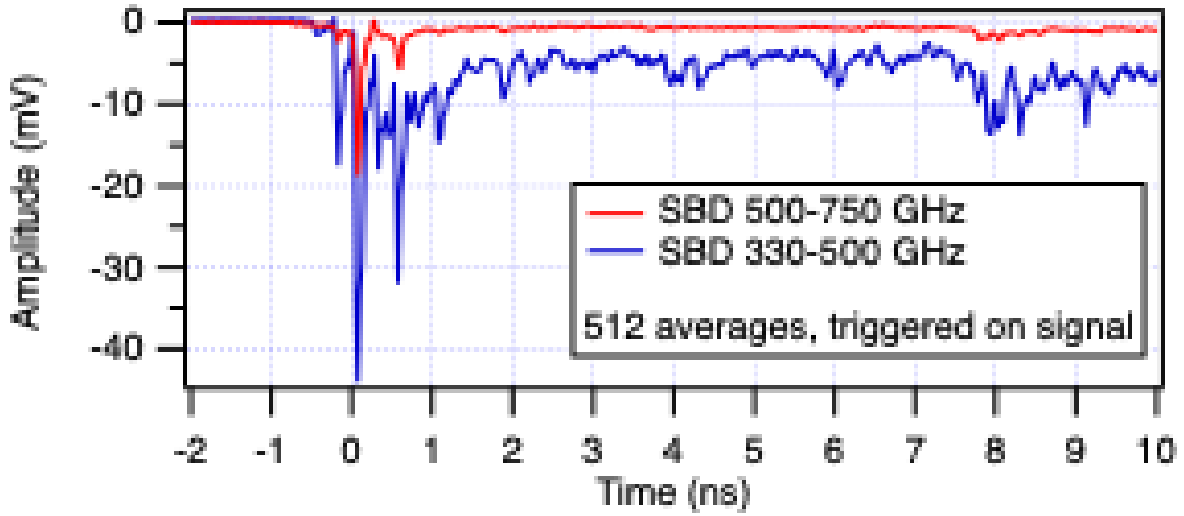

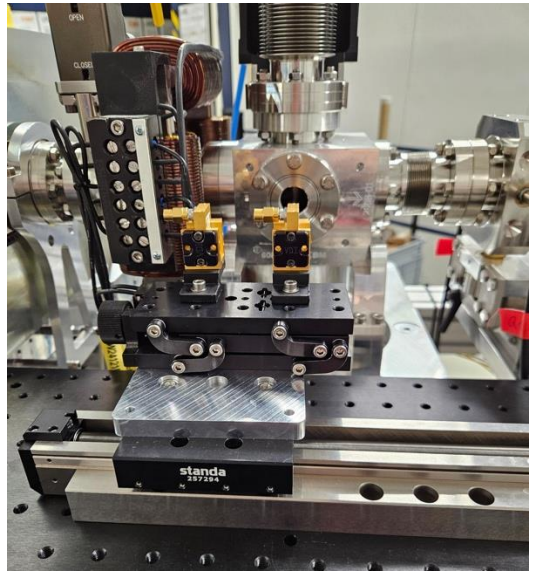

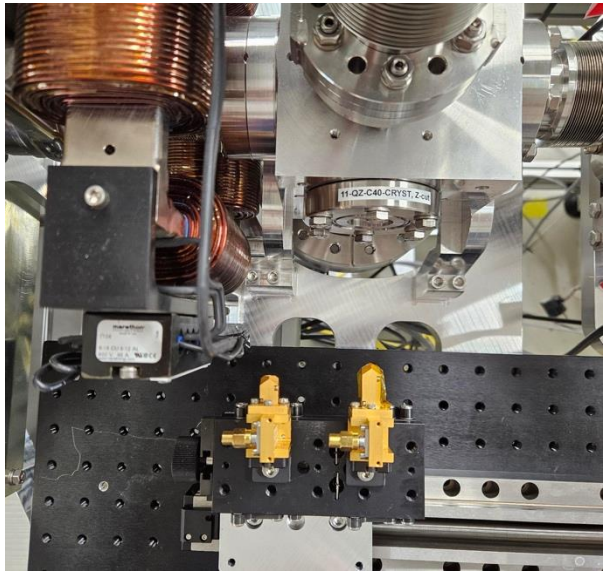

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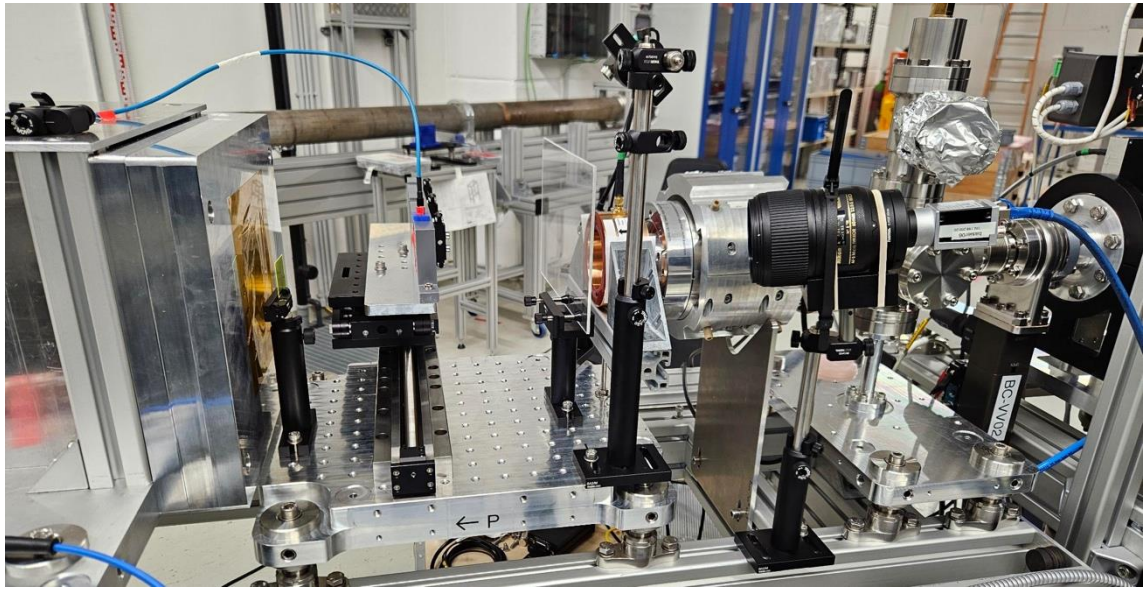
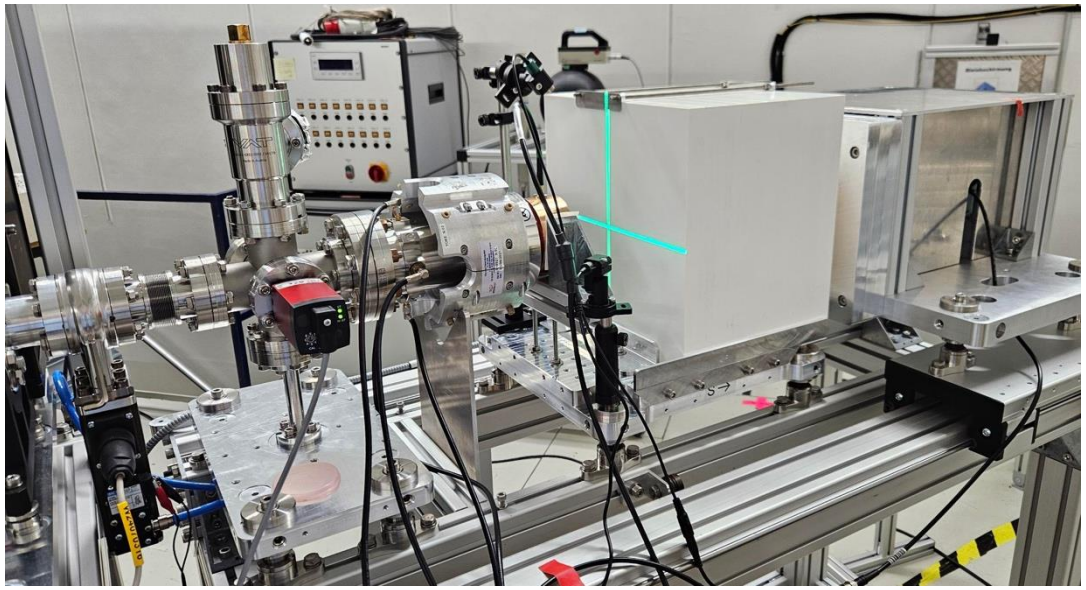
Courtesy: M. J. Nasse





Status of FLUTE
Accelerator Test Facility at KIT

www.ibpt.kit.edu/flute

- Test benc
  - Compa
  - Button
- Versatile
  - …syst
  - …deve
  - …test

FLUTE & KARA test facilities are part of Euro-Labs

- Support for travel & accommodation costs for experiments
- Relatively simple application process
- Open for proposals (for EU and EEC labs)!
- Contact: Robert Ruprecht (KIT, IBPT): robert.ruprecht@kit.edu

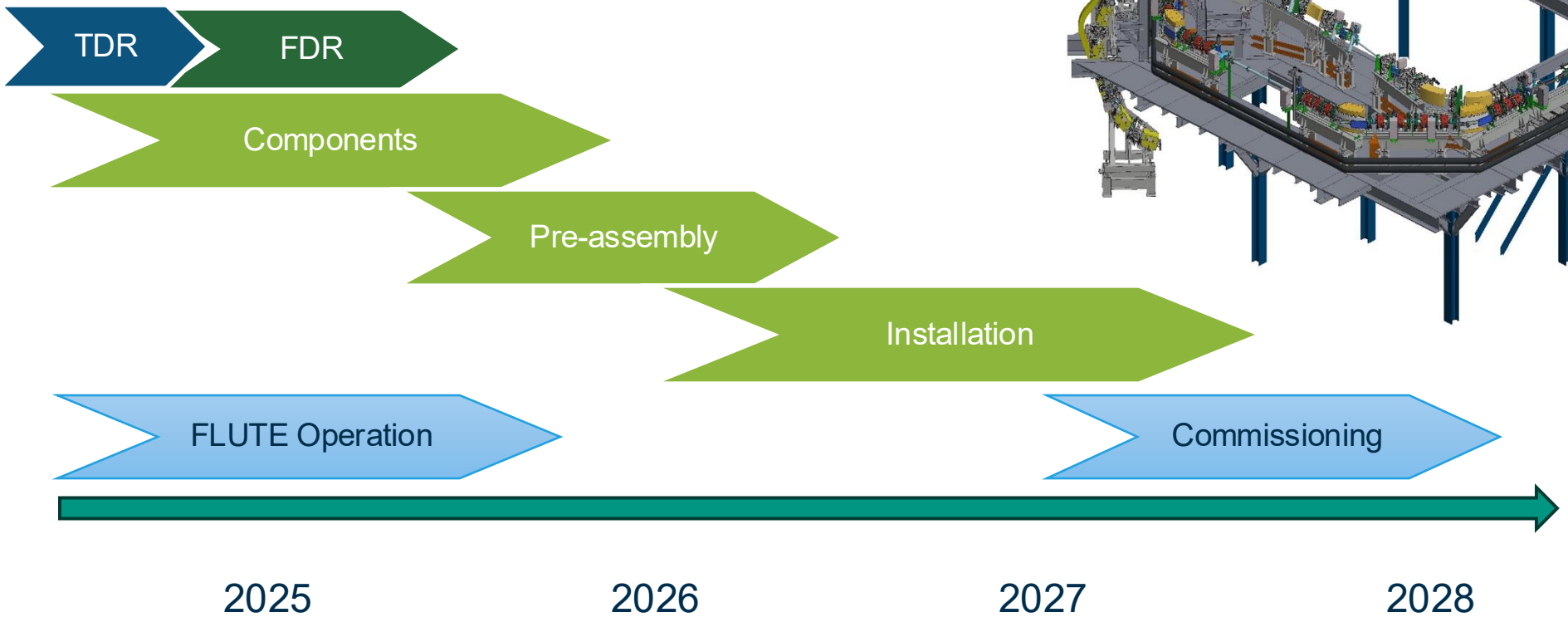
EURO-LABS
EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

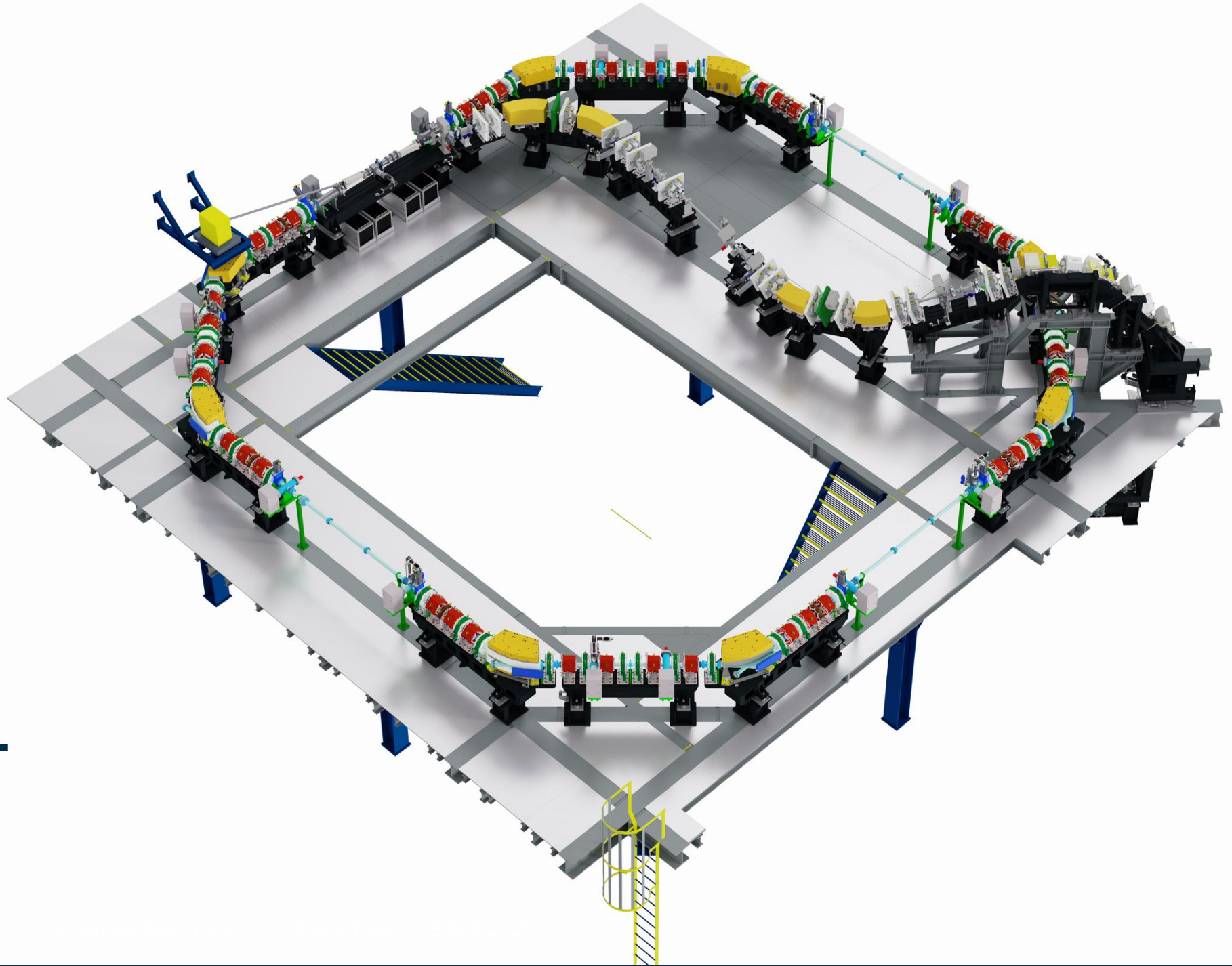
esy: M. J. Nasse

cSTART

5

cSTART Project plan





cSTART

Acknowledgements

The accelerator team (partial list)

- Axel Bernhard, Edmund Blomley, Simon Braner, Erik Bründermann, Felipe Donoso Aguirre, Dima El Khechen, Samira Fatehi, Stefan Funkner, Julian Gethmann, Christian Goffing, Andreas Grau, Bastian Härer, Erhard Huttel, Igor Kriznar (rip), Bennet Krasch, Artem Kuzmin, Anton Malygin, Sebastian Marsching, Yves-Laurent Mathis, Katharina Mayer, Wolfgang Mexner, Akira Mochihashi, Matthias Nabinger, Michael J. Nasse, Joseph Natal, Gudrun Niehues, Marvin Noll, Alexander Papash, Nathan Ray, Micha Reißig, Benjamin Riedel, Robert Ruprecht, David Saez de Jauregui, Alexander Saw, Jens Schäfer, Thiemo Schmelzer, Patrick Schreiber, Marcel Schuh, Markus Schwarz, Nigel John Smale, David Squires, Johannes L. Steinmann, Pawel Wesolowski, Christina Widmann
  & Matthias Fuchs, Steffen Grohmann, Anke-Susanne Müller

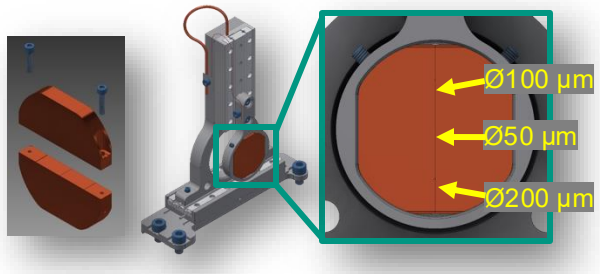
- Selection collaborating KIT institutes: http://atp.kit.edu/members.php

- Selection collaborating EU/EC, Helmholtz & university partners: http://ibpt.kit.edu/project.php

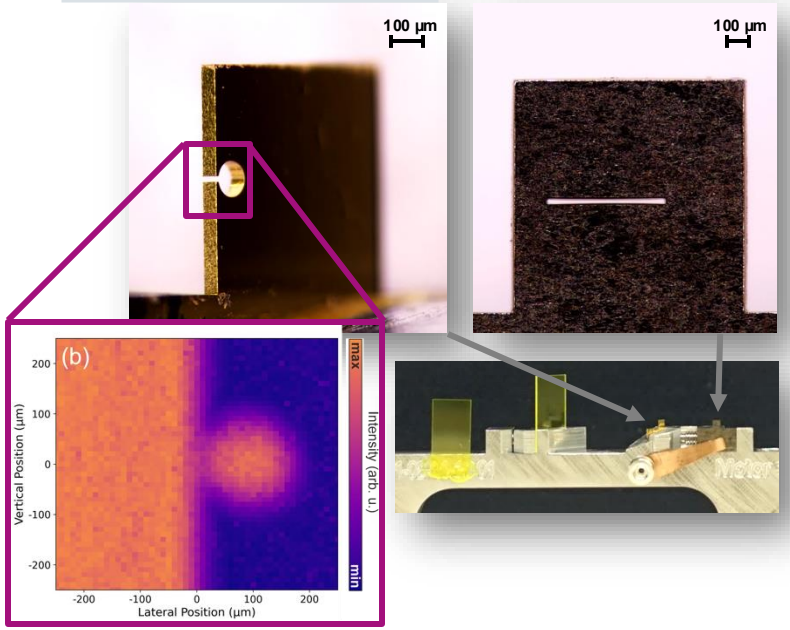
- Selection industry partners: http://ibpt.kit.edu/industrial_activities.php

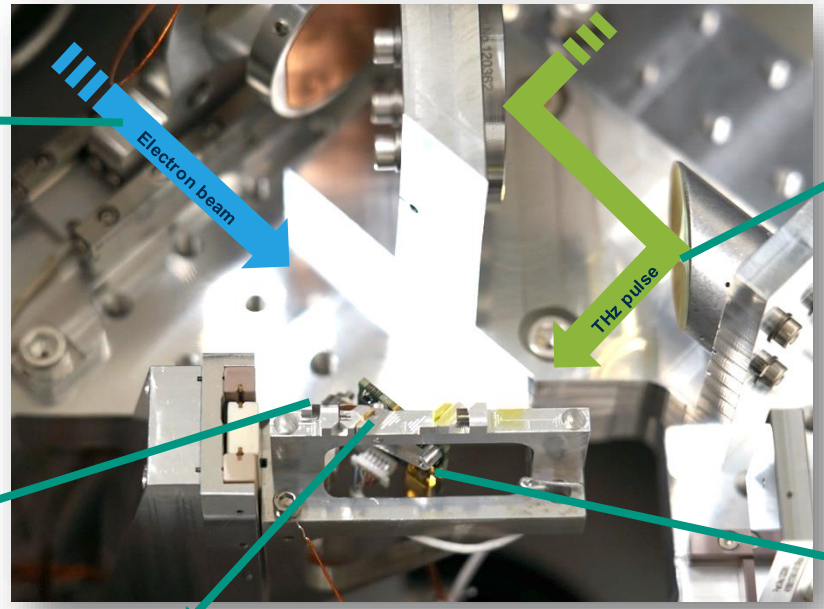
Terahertz Streaking Detection for Longitudinal Bunch Diagnostics at FLUTE

Electron beam control

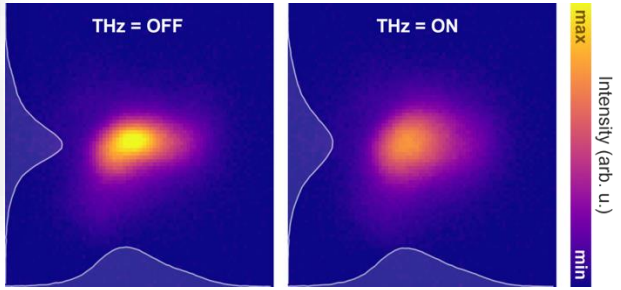


Resonator setup

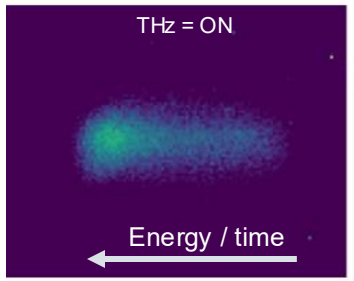




Overlap THz & electrons

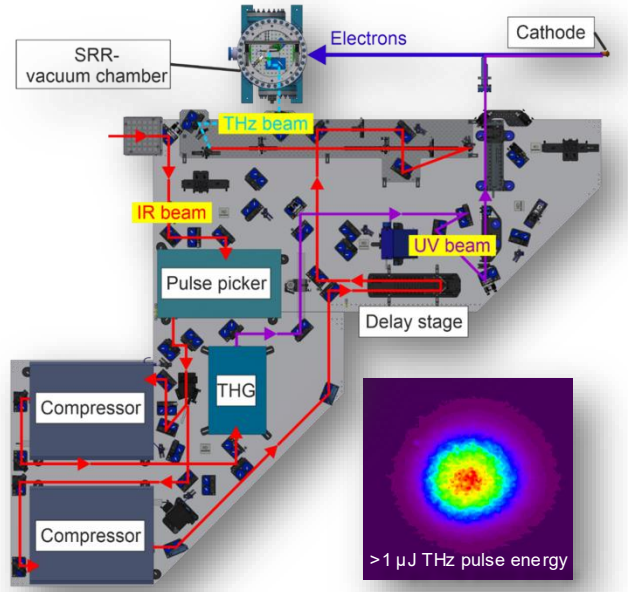


Forward section

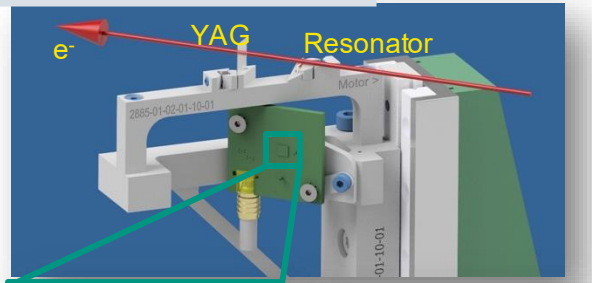


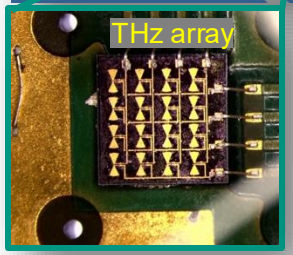
Dispersive section

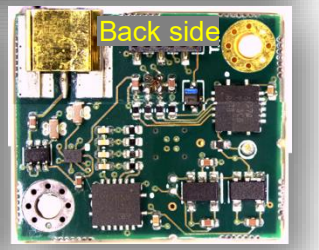
Laser & THz optics



THz diagnostics







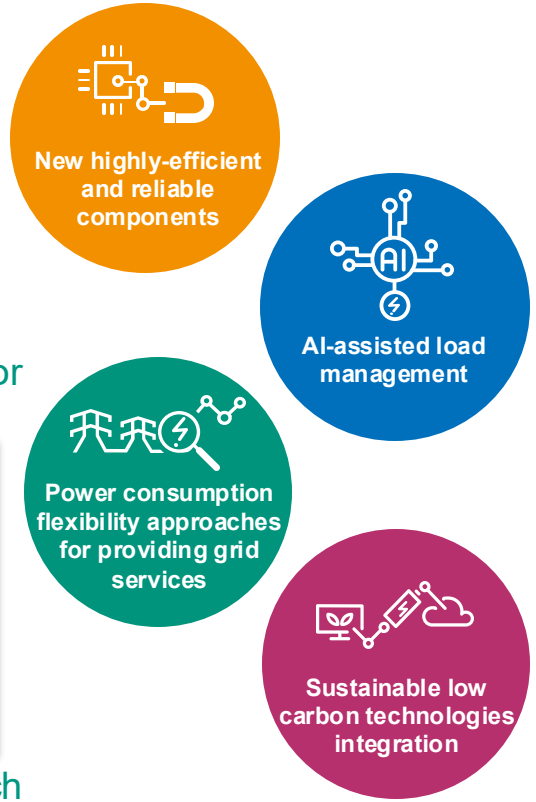
KITTEN - *KIT Test Field for Energy Efficiency and Grid Stability in Large Research Infrastructures*

www.kitten.kit.edu

Datasheet - Link

KARA – Karlsruhe Research Accelerator

Energy Lab – Europe's largest research infrastructure for renewable energy



Real-world laboratory

- **KITTEN - A unique union of two KIT key research infrastructures Energy Lab & KARA**
- **Pioneering the energy future** of large-scale research infrastructures and integration into future power grids
- **Basic research & holistic view** of all aspects
- Highly **complex** system requires researchers from multiple disciplines
- **Transfer** to other large scientific, industrial and medical infrastructures and to European scale (KIT-lead RF2.0) - https://rf20.eu/

Energy-aware systems – Real-time digital twin

Power Hardware in the Loop (PHIL) - Link

Communication Infrastructure

1 MVA power amplifier

Real-time simulator

KARA digital twin

Measurement system

Hardware under test

200 kVA

AI-assisted load management

Power consumption flexibility approaches for providing grid services

Sustainable low carbon technologies integration

10 kHz (100 µs)

~2 km

> 160 sensors

2x 871 kWh Batteries

543 kWp solar park

1 MW thermal well

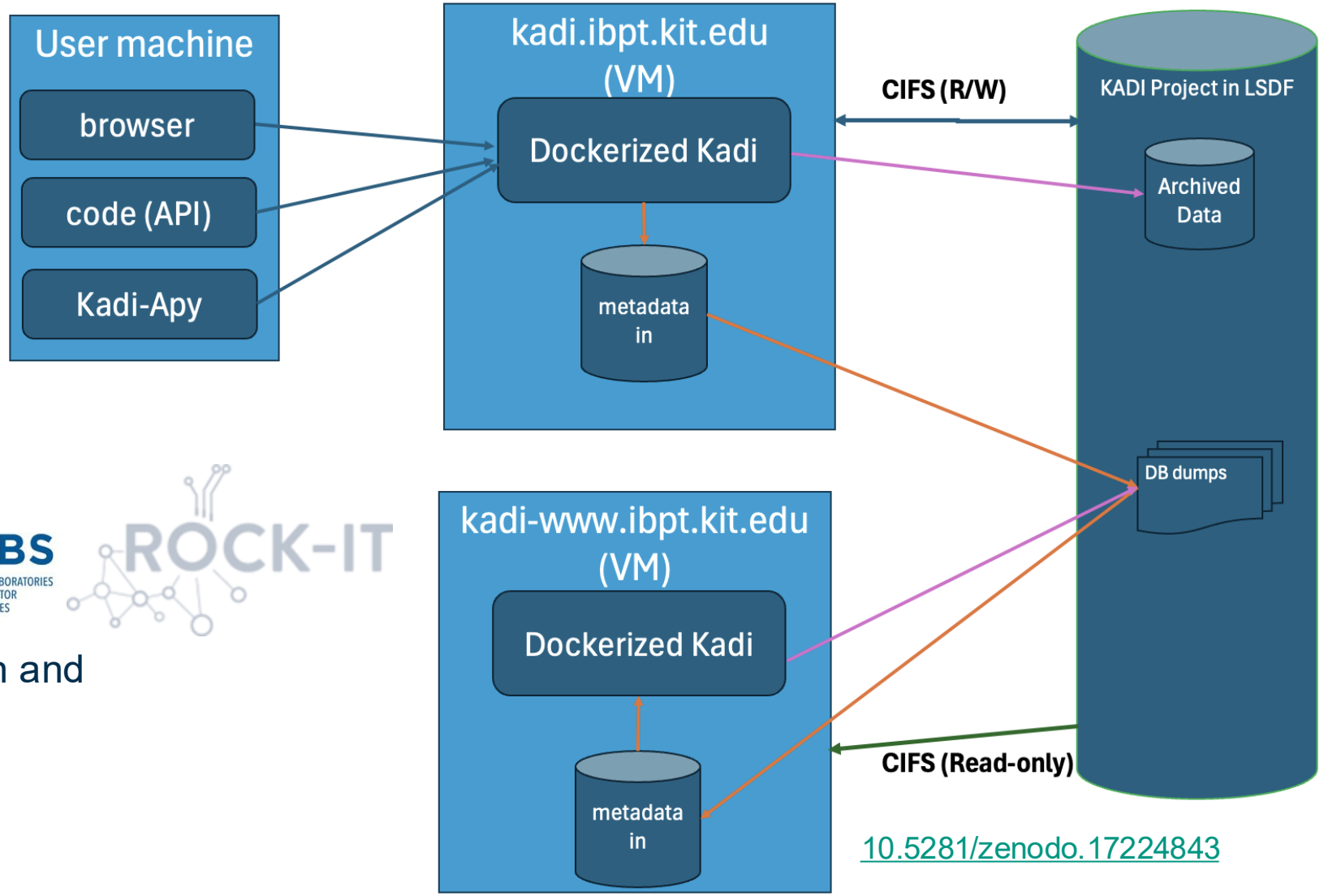
Detailed diagnostics saved already 30% (from 2022 to 2023) of infrastructure energy consumption – **expected more savings with digital twins + more stable power grid + better accelerator beam parameters + faster start-up, commissioning, etc.**

Data management at IBPT

- metadata database (RDM system) is essential
- Enables combination of datasets, reuse of past experiments, and better planning
- Goal: Self-hosted, scalable, FAIR-compliant research data infrastructure for physics data
- Synergies between

✅ Requirement definition, evaluation and performance tests succeeded.

System productive



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