ARES Linac @ SINBAD

A Precision Tool for Accelerator Science, Technology and Application Developments

UK Accelerator Institutes Seminar Series

Florian Burkart for the ARES team

with input from R. Assmann, H. Dinter, A. Eichler, S. Jaster-Merz, J. Kaiser, M. Kellermeier,
W. Kuropka, F. Mayet, B. Stacey, O. Stein, T. Vinatier,

Acknowledgements to R. Brinkmann, W. Leemans and the DESY M Technical Groups and FS-LA

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

SINBAD

MT ARD

DESY.

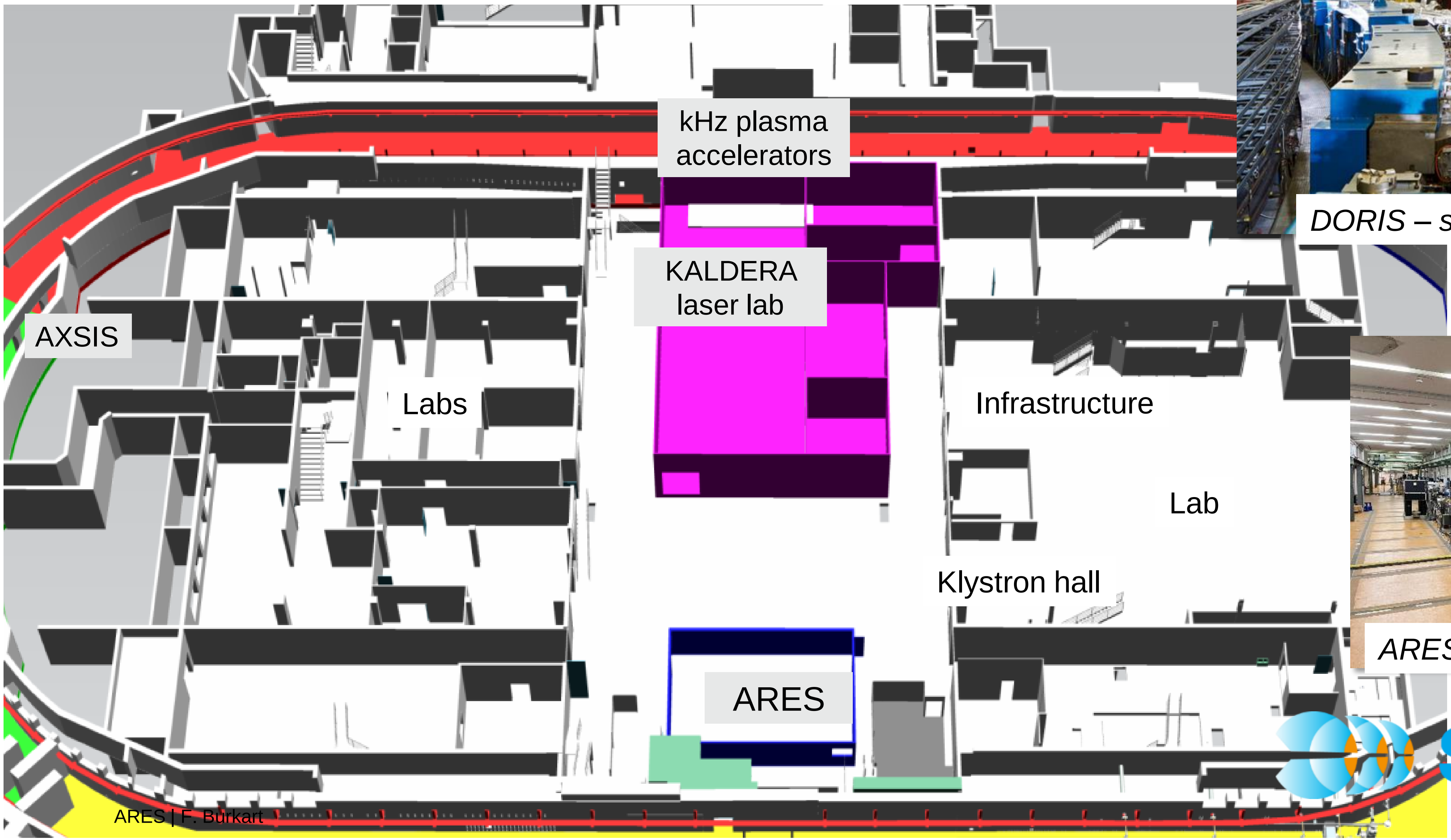
Outline

- What is ARES?
- Infrastructure & Stability
- Scientific program
- Medical applications
- Conclusion and Outlook

ARES Linac @ SINBAD

SINBAD - From a synchrotron radiation source to a modern R&D complex

Short and innovative bunches and accelerators at DESY




DORIS – storage ring, 1974-2012

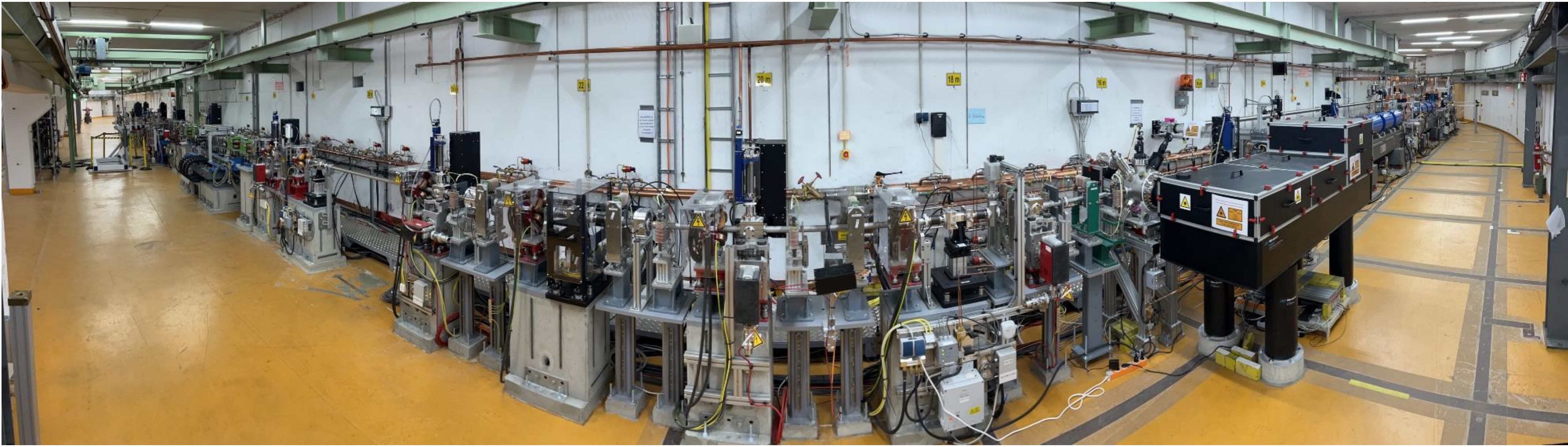

ARES – linac, since 2018

SINBAD

ARES – A part of the SINBAD facility

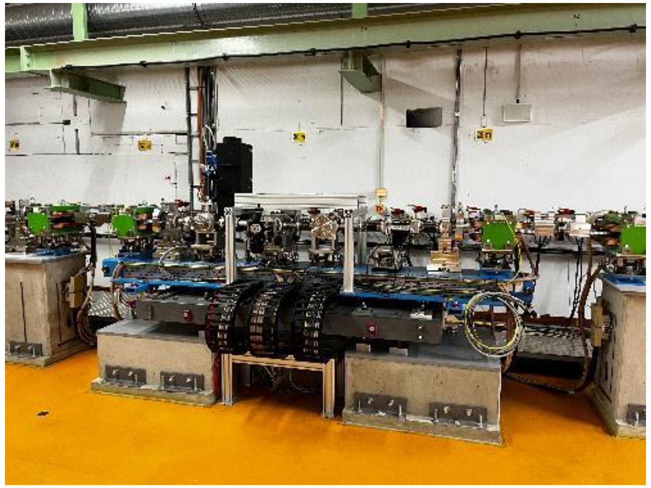
In operation since 2020

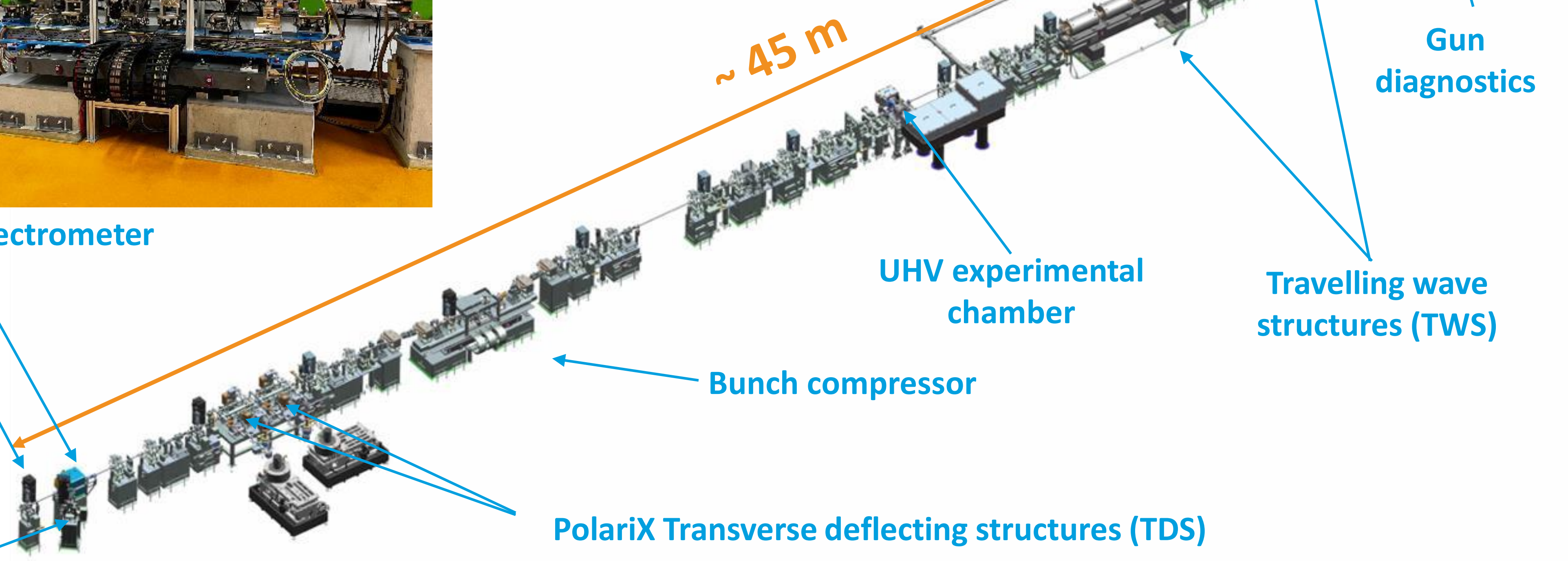
- Normal conducting 160 MeV electron linac for the production of **ultra-short electron bunches and diagnostics development**
- **Novel acceleration techniques / beam manipulation testbed (dielectric laser acceleration)**
- **Accelerator components R&D and medical applications**



ARES in a nutshell

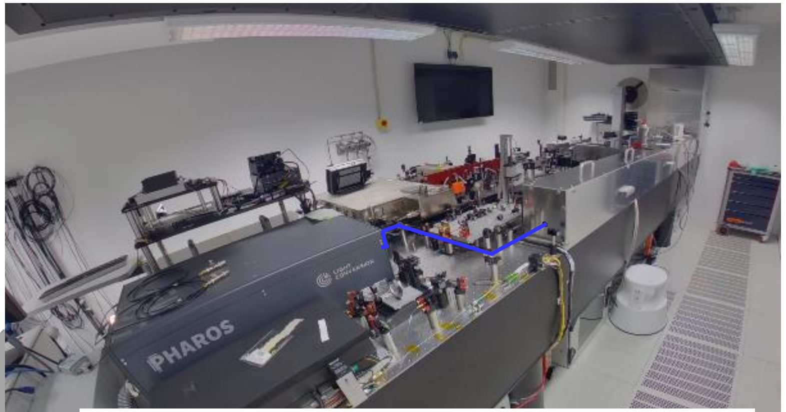
45m of conventional accelerator technology



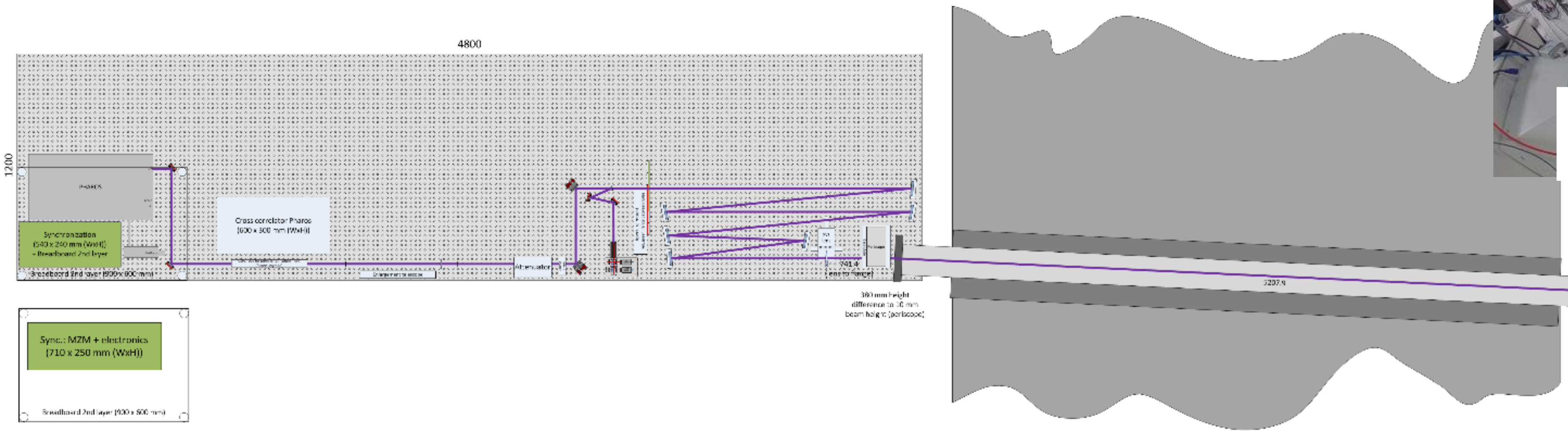


Photocathode Laser System

Light Conversion PHAROS Laser



2micron experimental laser also included in the laserlab

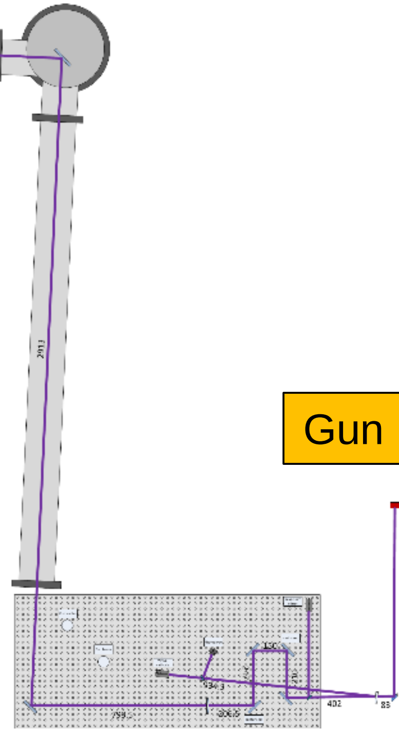


femtosecond pulses with millijoule pulse energies

fourth harmonic output of the laser at 257 nm with a pulse width of 227 fs is being used for photoelectric emission of the cathode in the RF gun.

flat-top beam is then imaged onto the cathode with a spot size of 320 µm.

Full Pharos system has been integrated into the DOOCS control system and, therefore, can be remotely controlled by the operators.



Numerous diagnostics available

Testbed for the DESY diagnostics group

- Intensity monitors
  - Two Faraday cups
  - 2 Cavity based
  - 2 toroid coils
  - 2 Integrating Current Transformers at the end of the beam line

- Cavity based beam position monitors
  - 7 along the beamline
  - One additional high precision device
  - Range of +-5mm, few micron resolution.

- Scintillating screen stations
  - 11 screen stations with 45 deg observation angle, 200um thick GAG scintillators
  - 2 Scheinpflug optics, 20um res.
  - 1 microscope optics, 2um res., 50um thick YAG
  - 1 in air screen station
- Wirescanners and BLMs
  - Micro-wire scanner in experimental chamber
  - At the in-air station

Already close to nominal parameters

waiting for XBand PolariX TDS.

Parameter	Design parameters	Actual commissioning parameters
Energy	50 – 160 MeV	50 – 160 MeV
Charge/pulse	0.5 – 200 pC	0.001 – 280 pC
Rep. rate	Single pulse @ 50 Hz (*)	50 Hz
Bunch length	few fs / sub-fs pulse length	20 fs (resolution limited)
Momentum spread	10^{-4}	10^{-4} (resolution limited)
Normalized transverse emittance	< 0.8 π.mm.mrad	≈ 0.07 π.mm.mrad

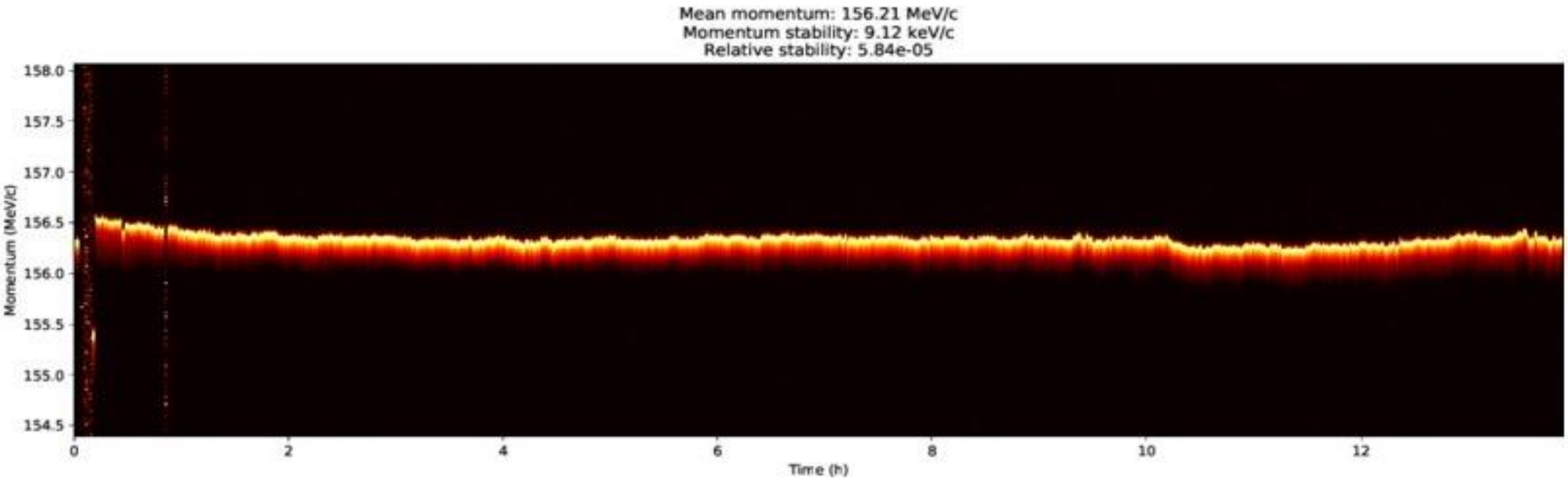
*arrival time jitter of <10 fs rms

Infrastructure and Stability

Unprecedented stability at ARES

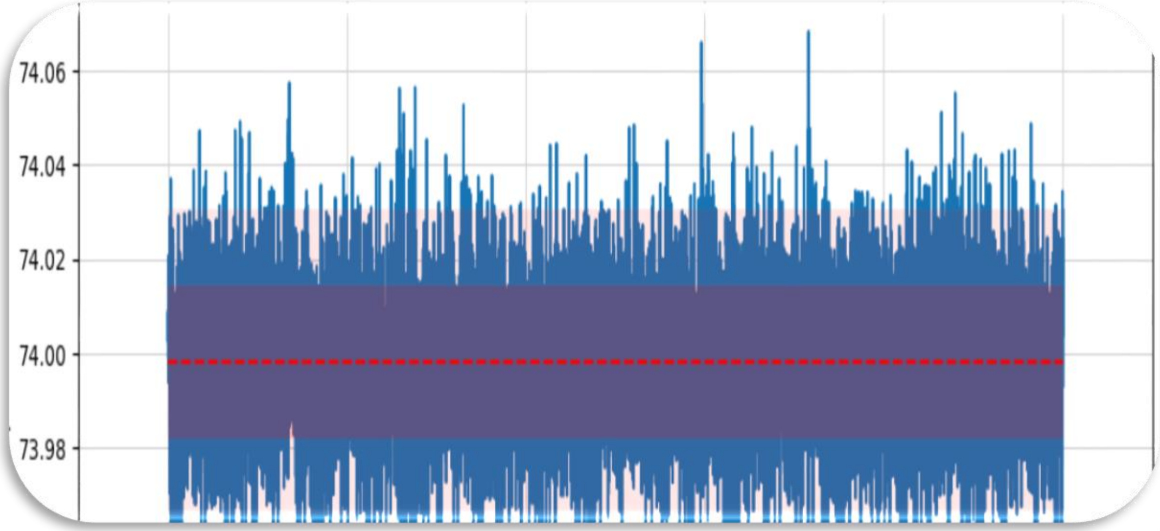
High precision temperature and modulator stabilization has resulted in excellent stability and reproducibility:

- 17 μm rms position jitter (5% of $\sigma_{x/y}$)
- **5.8e-5 rms relative energy stability** over 14 hours (average over 3 days: 2.4e-4) – still room for improvement.



Stable infrastructures (RF power and water cooling)

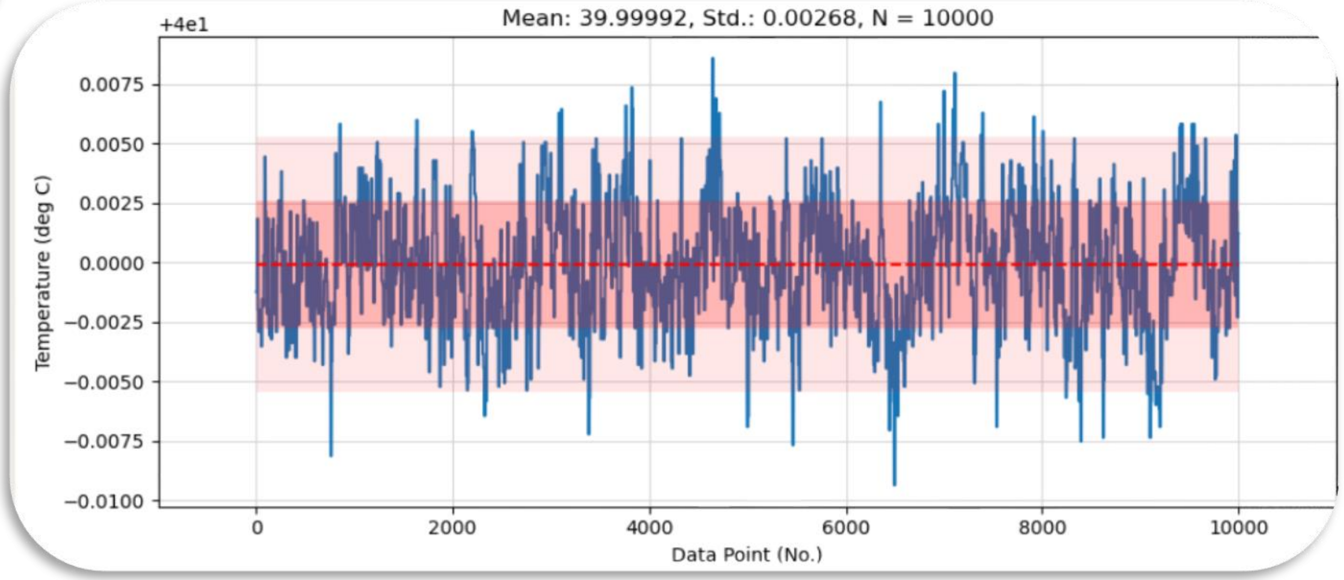
Excellent engineering



Gun Modulator from Scandinova.
Gun RF power calibrated to gradient. Std: 0.016

View inside the klystron hall

measured over 2.7 h



Gun precision water cooling, Std: 0.0027

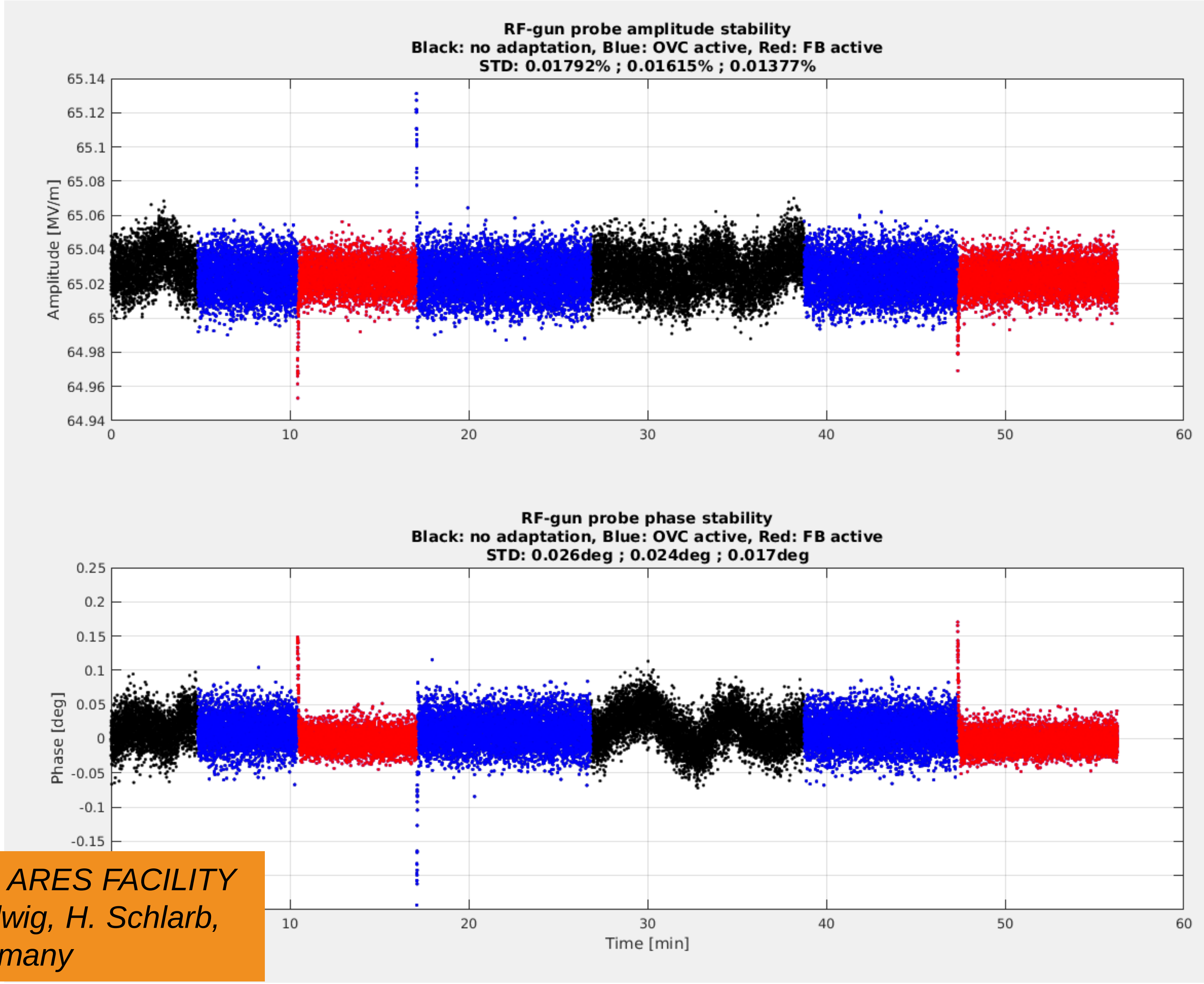
LLRF operation of the gun section

amplitude and phase stability

51 data points per RF pulse averaged

- Black: FF only
  - 0.018% / 0.026 deg (rms)
- Blue: OVC – pulse to pulse correction of drive signal
  - 0.016% / 0.024 deg (rms)
- Red: Feedback operation
  - 0.013% / 0.017 deg (rms)

Remark: Switching transition not taken out of the computed standard deviation

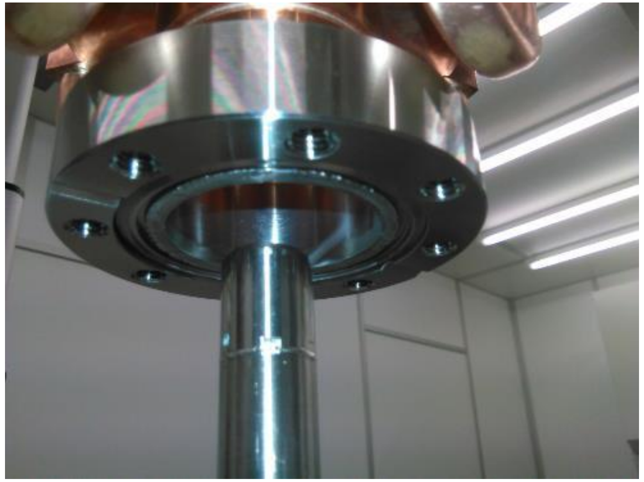


LLRF CONTROL AND SYNCHRONIZATION SYSTEM OF THE ARES FACILITY
S. Pfeiffer, J. Branlard, F. Burkart, M. Hoffmann, T. Lamb, F. Ludwig, H. Schlarb, S. Schulz, B. Szczepanski, M. Titberidze, DESY, Hamburg, Germany

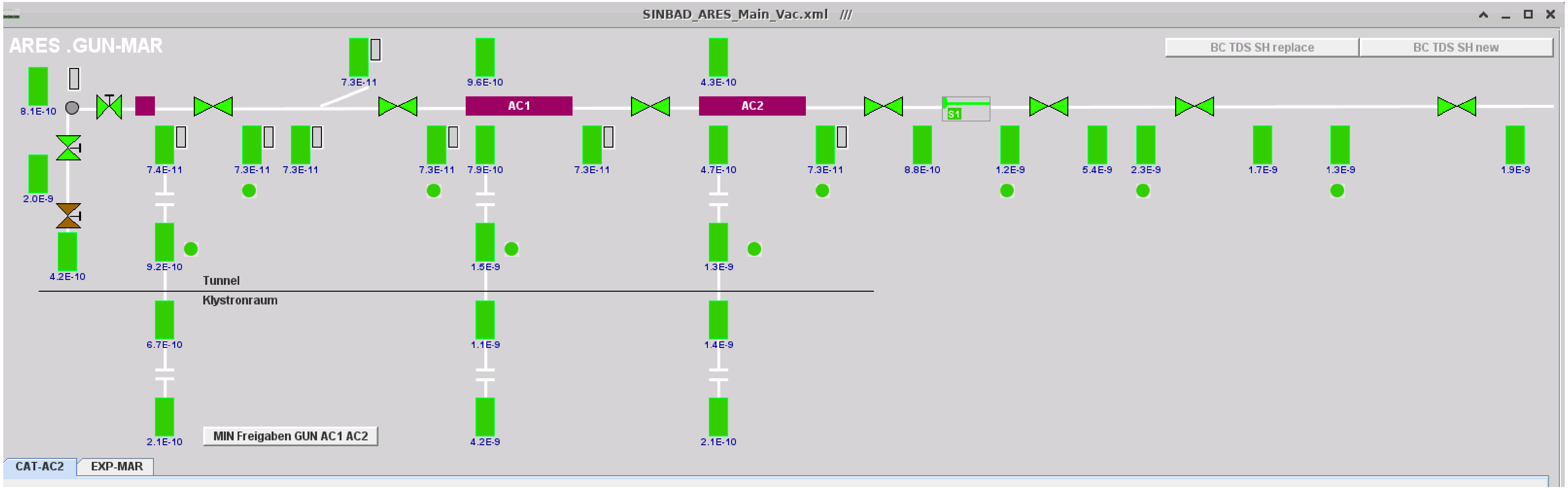
Vacuum requirements

Full accelerator under UHV and particle free

→ 10 pC dark current from the gun.
→ Lost in the gun section or scraped away.



CO2 cleaning of the gun

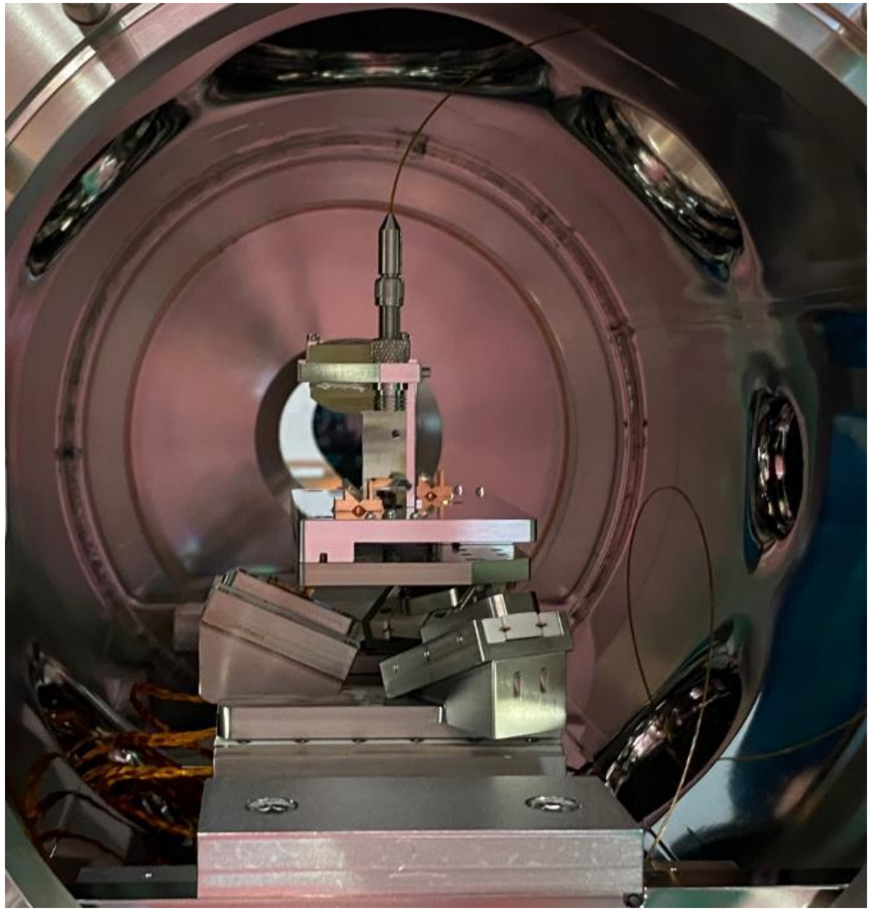


vacuum panel of the gun and linac section

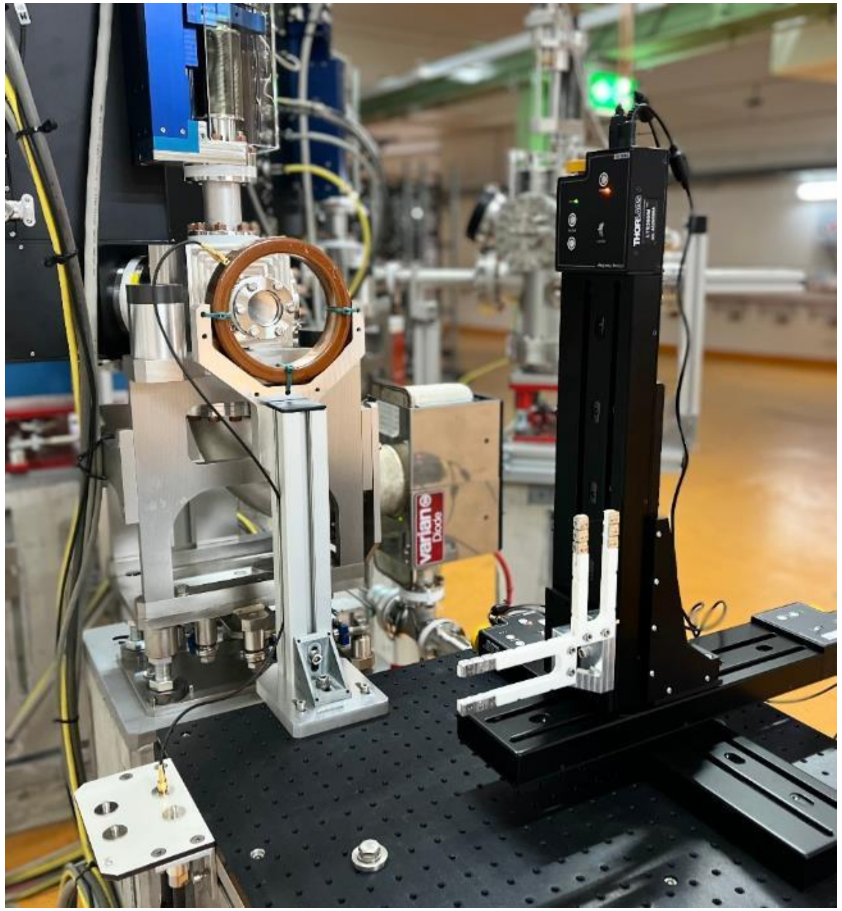
Scientific Program

Three experimental areas available for users

Full flexibility



In UHV, highest precision, best beam control.

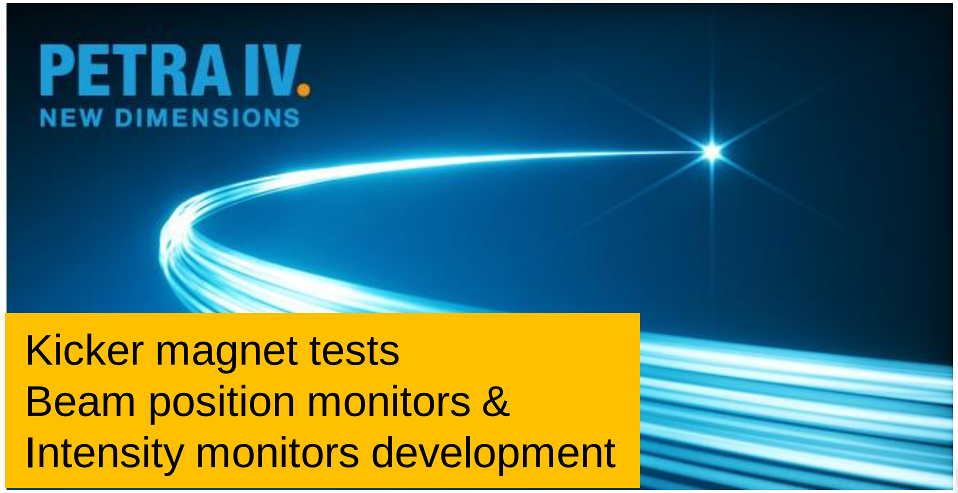


In air, highest flexibility.

In low pressure vacuum,
FH & M detector test stand.

A unique R&D platform

Test components and beam properties with ultra-short, high brightness beams



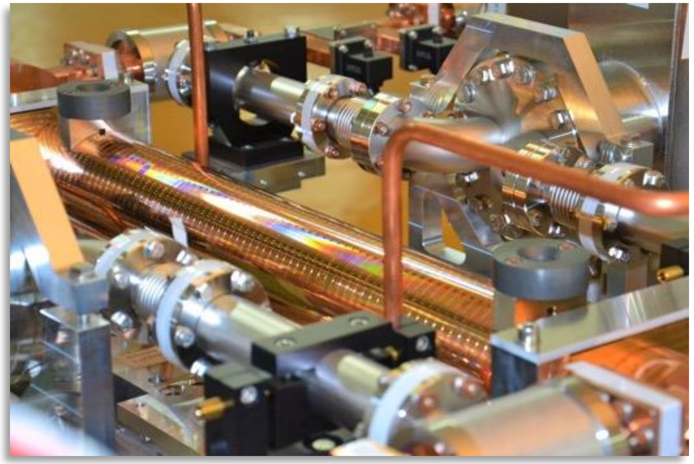
Kicker magnet tests
Beam position monitors &
Intensity monitors development

<u>State of the art beam controls & diagnostics</u>

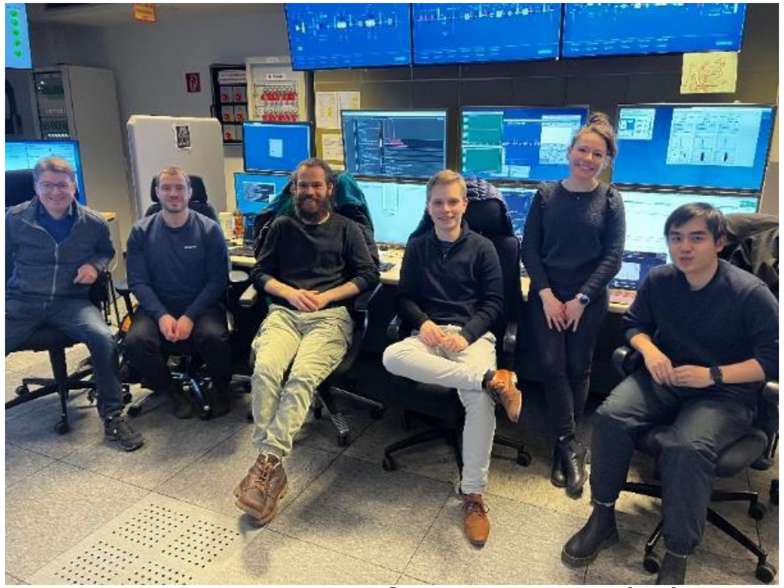
- **Detector development**
- fs synchronization
- **PolariX Transverse deflecting structures**
- Neural network for emittance analysis
- Bunch length measurements
- 5D beam tomography
- EIC pathfinder project with CNRS et al.

<u>Advanced accelerator components R&D</u>

- Vacuum windows
- High stability infrastructures
- Prototyping & 3D printing
- Photocathode Laser development
- …



PolariX - State of the art beam diagnostics



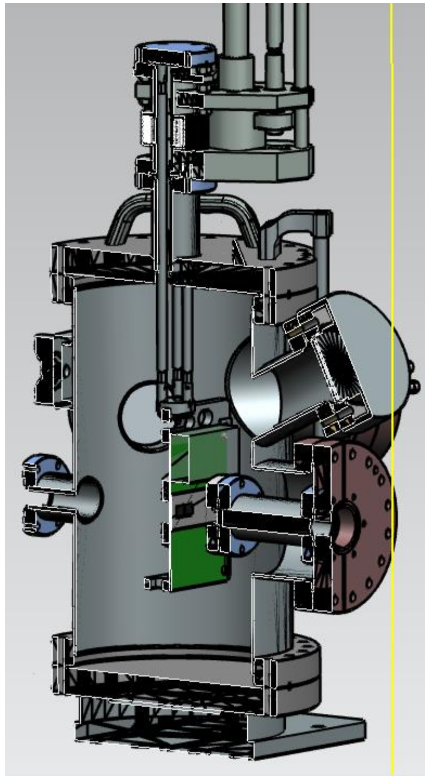
***Autonomous accelerators** workshop with collaboration partners from KIT*

Novel beam instrumentation for low charge electron bunches

Collaboration with DESY-ATLAS

Silicon-based beam profile monitor for beams with low charge (<100 fC).

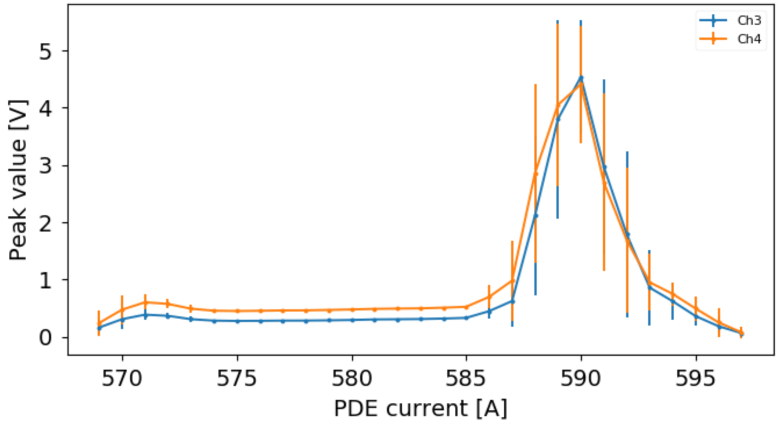
Experimental chamber



CAD of experimental chamber

- Linearity checks
- Beam profile measurements
- Towards in-vacuum applications

Detector PCB



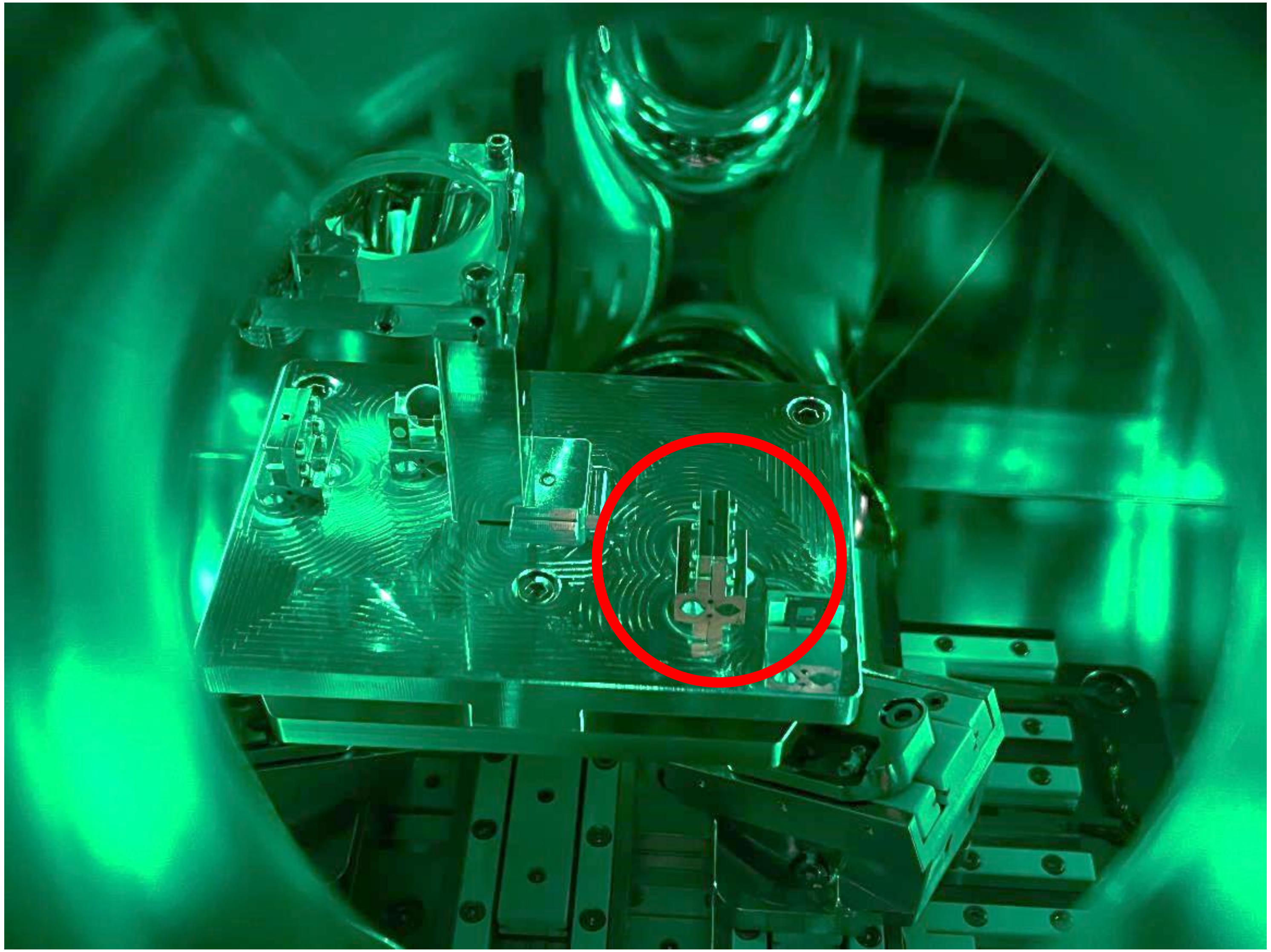
Beam profile measurement at 80 fC

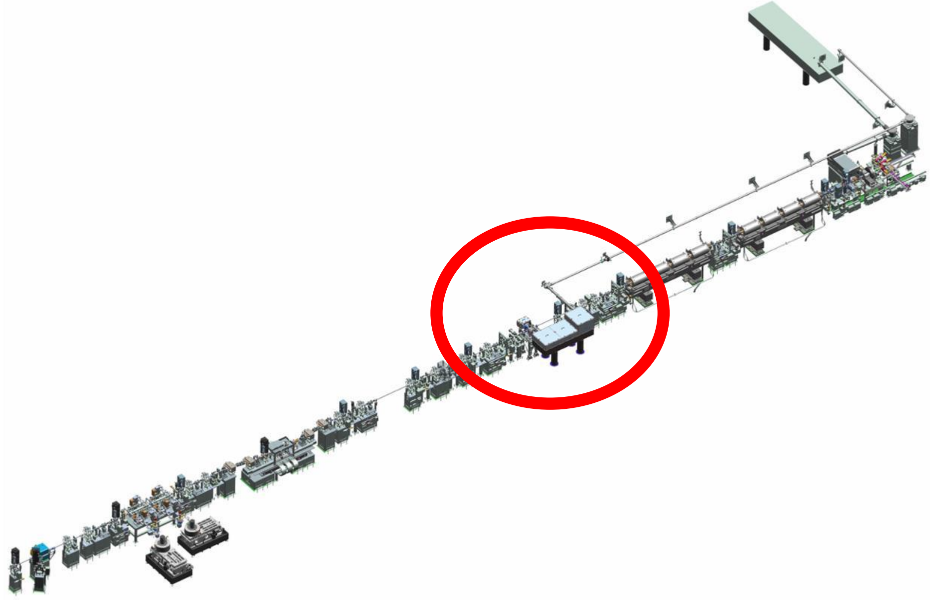
STRIDENAS. Universität Hamburg ATLAS EXPERIMENT

DesyStrategyFund project: detector development

The UHV chamber

Playground for novel acceleration techniques and diagnostics

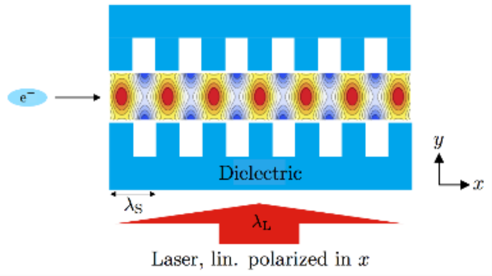


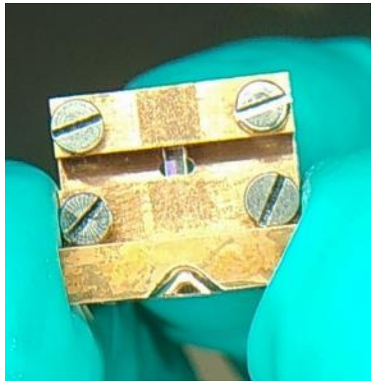


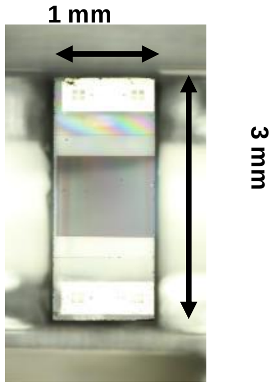
ACHIP @ ARES

Dielectric Laser Acceleration - Status and Perspectives

A 2 µm laser illuminates two SiO_2 gratings with ~2 µm periodicity
→ High gradient (~GV/m) superposition of nearfield diffraction modes

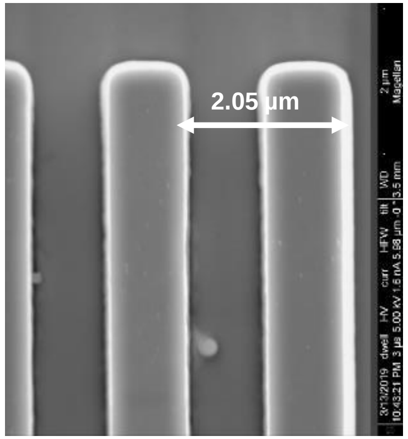






Stage 0 (done): transmission, timing scans, modulation of the bunch.

Stage 1 (in progress): External injection of relativistic (100 to 150 MeV) ultra-short (<2 fs, FWHM) single electron bunches with ~0.4 pC of charge into a 2 µm period grating type DLA with a 1 µm wide aperture
→ Net energy gain with significant charge



F. Mayet, "Acceleration and Phase Space Manipulation of Relativistic Electron Beams in Nano- and Micrometer-Scale Dielectric Structures," Ph.D. thesis, Universität Hamburg, 2019, doi:10.3204/PUBDB-2019-03861

W. Kuropka, "Studies towards Acceleration of Relativistic Electron Beams in Laser-driven Dielectric Microstructures," Ph.D. thesis, Universität Hamburg, 2020, doi:10.3204/ PUBDB-2020-02257

First Energy Modulation from a DLA at ARES

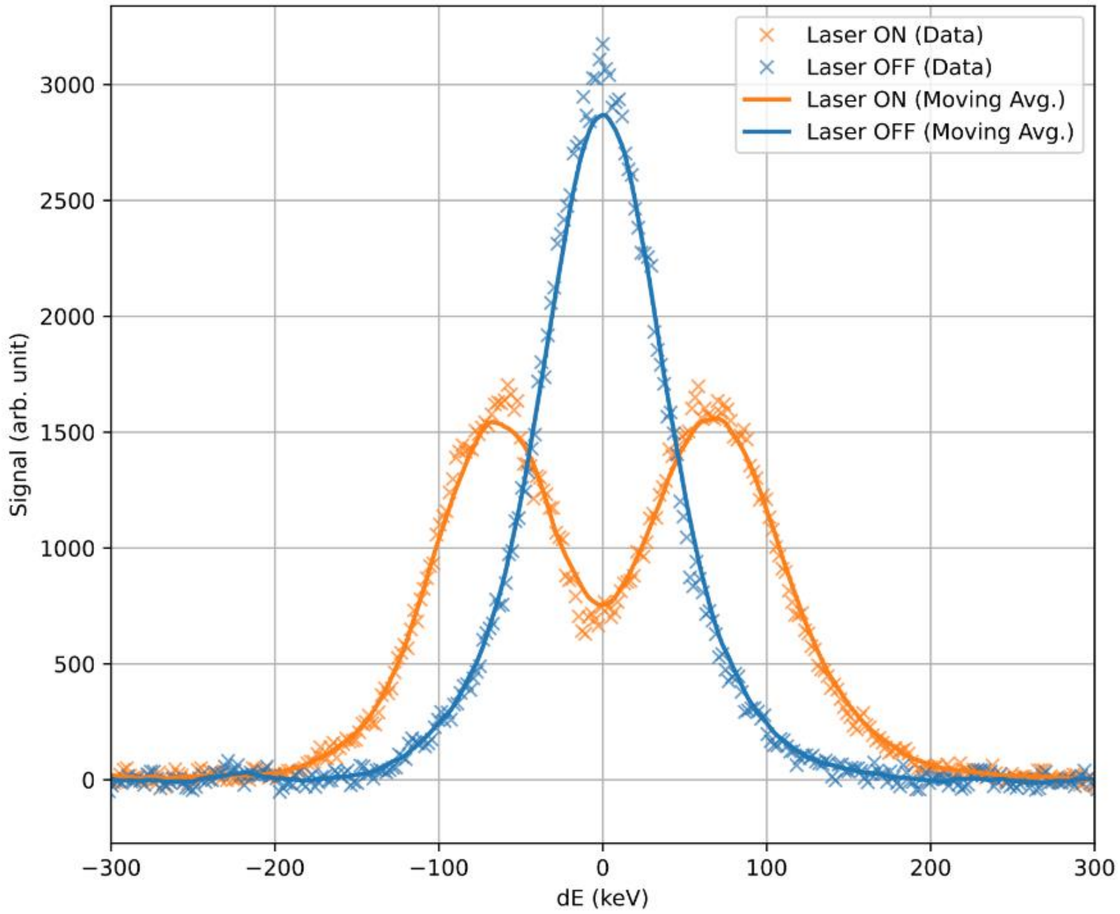
Achieved on March 24th

First results with long bunch
- Record transmission of ~20% (60 fC)
- First modulation of the entire transmitted charge

- For the first time, modulation of the entire transmitted charge
- Record throughput of 60 fC (20%)

Parameter	Value
Central Momentum	154.4 MeV/c
Transmitted Charge	~60 fC
Transmission	~20%
Electron Beam Size	< 10 µm, rms
Electron Bunch Length	~100s of fs (>> λ_{DLA})
DLA Aperture	1µm x 1mm
Laser Spot Size (4σ)	1mm x 50µm
Laser Pulse Energy	~1 mJ (on target)
Laser Pulse Length	2.2 ps, FWHM
Energy Modulation Depth	~75 keV
Peak Acc. Gradient	~107 MV/m

Spectra @ t_0



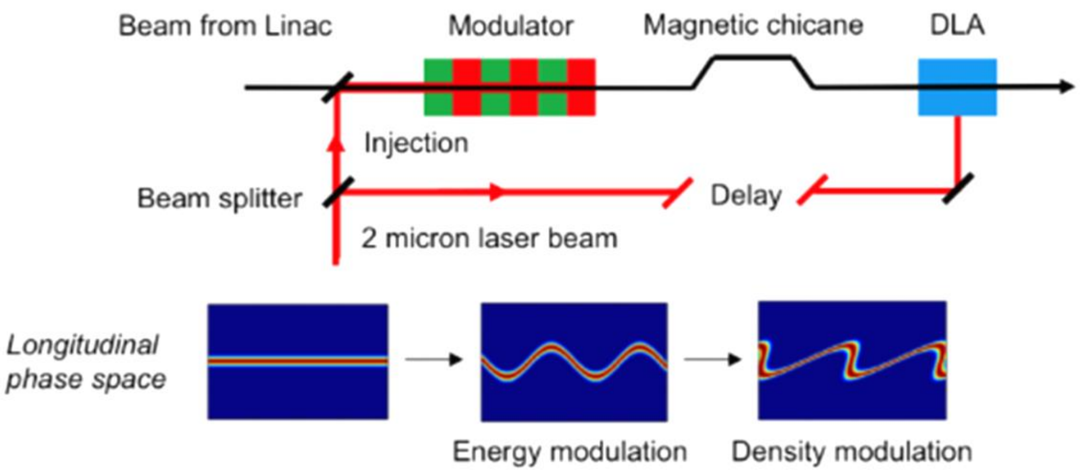
ACHIP @ ARES

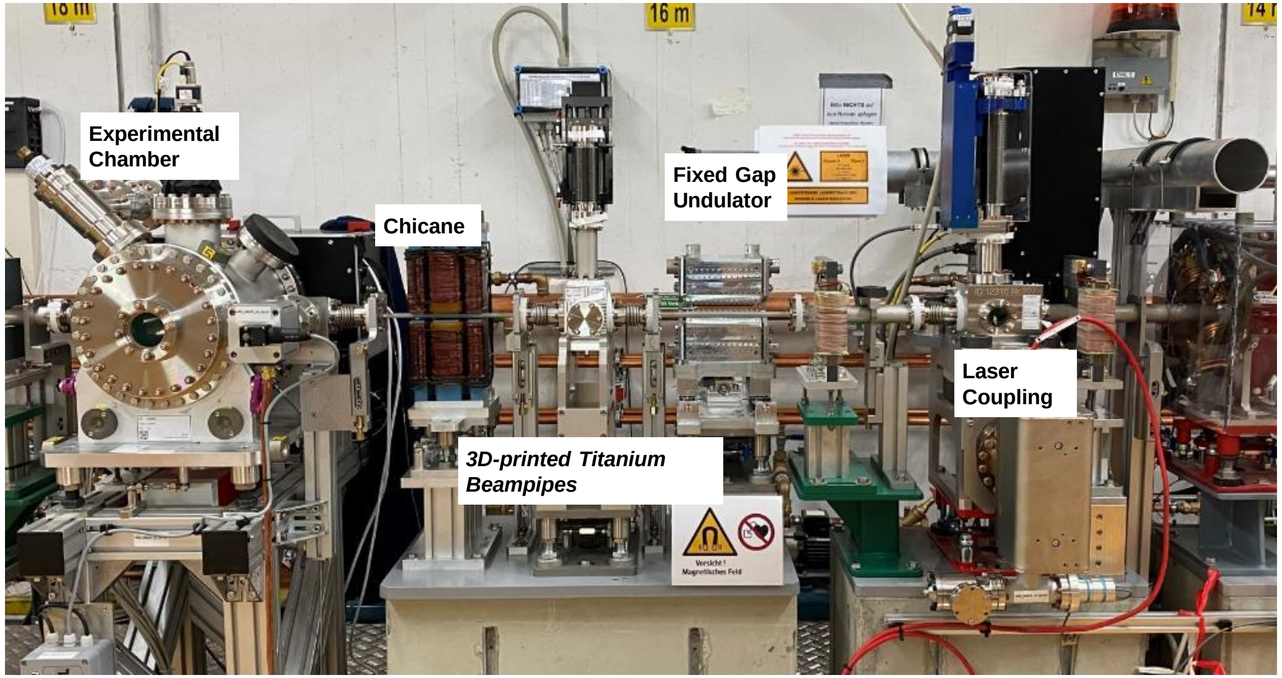
More to come

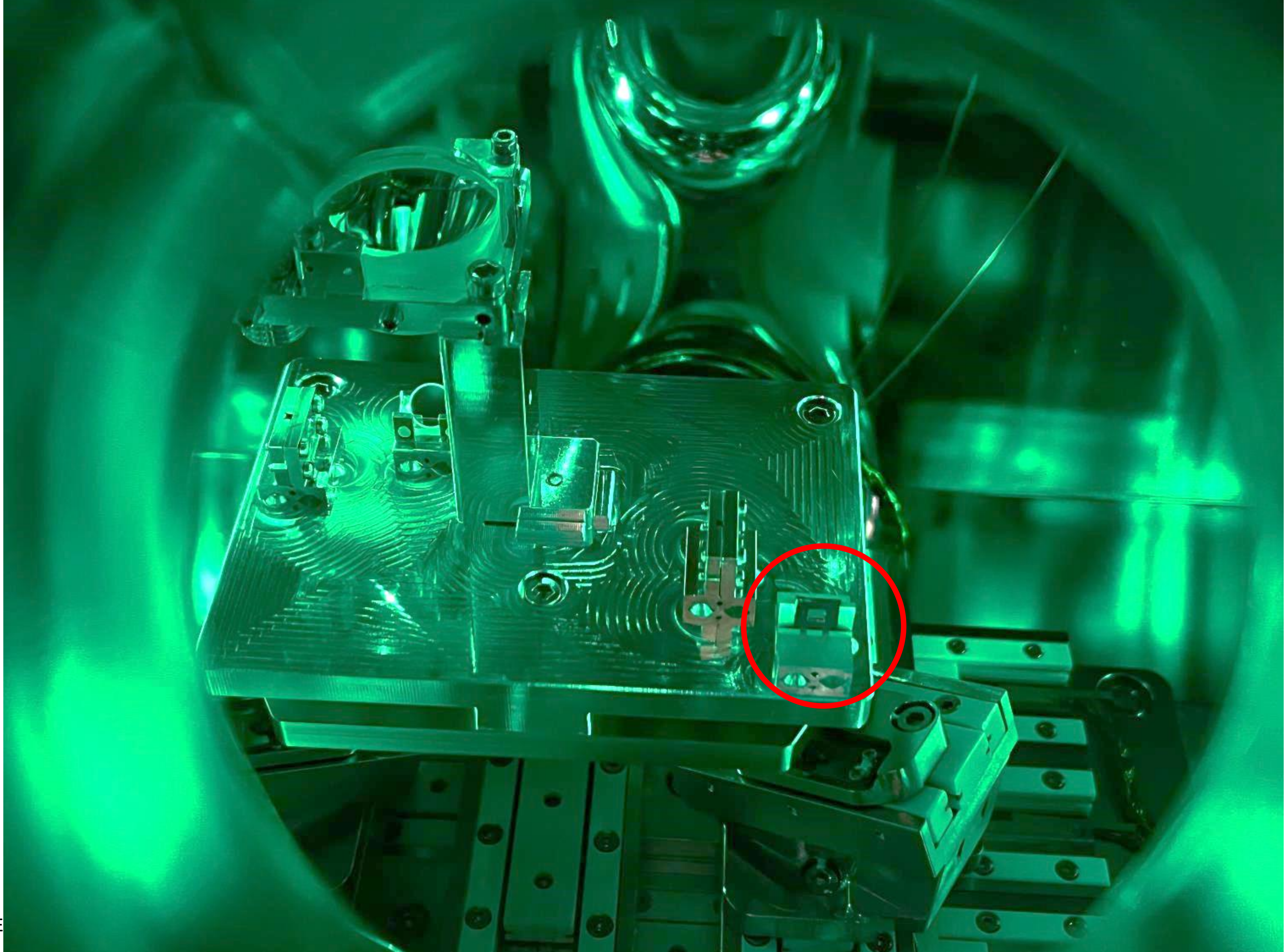
Stage 2 (2023): External injection of relativistic (50 MeV) phase-synchronous optical scale microbunch trains (~70 microbunches per train with ~10 fC of bunched charge each, spaced at the DLA period of 2 µm)
→ Stable net energy gain

Status

- All required equipment installed







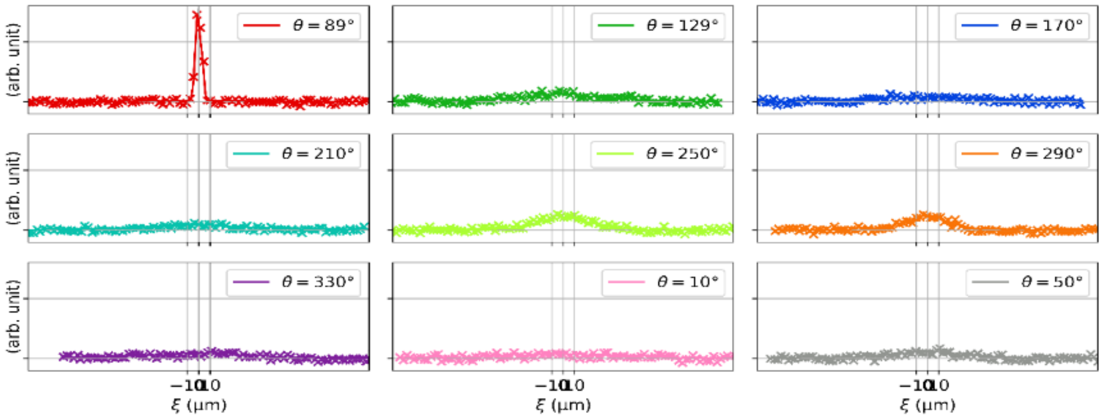
First successful external user experiments

high resolution beam reconstruction and high stability irradiation

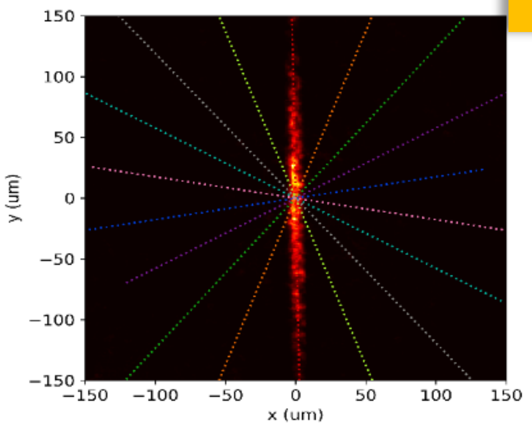
Accelerator Research and Innovation for European Science and Society

In total: 242 h of beam time for externals

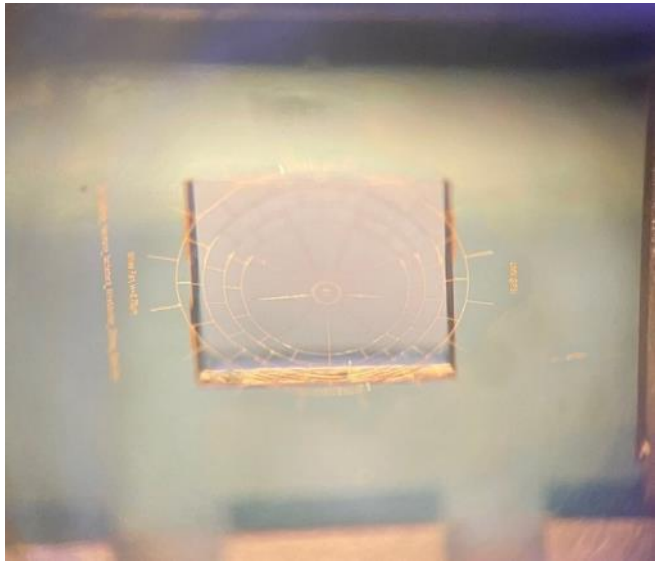
PAUL SCHERRER INSTITUT



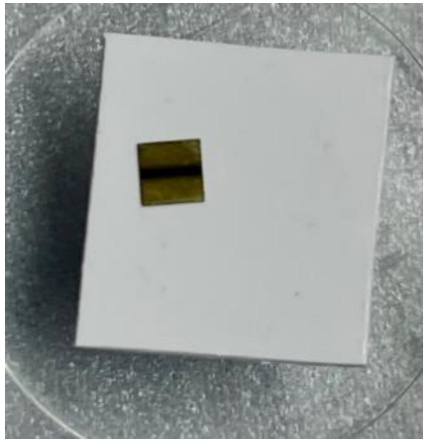
Measured beam losses

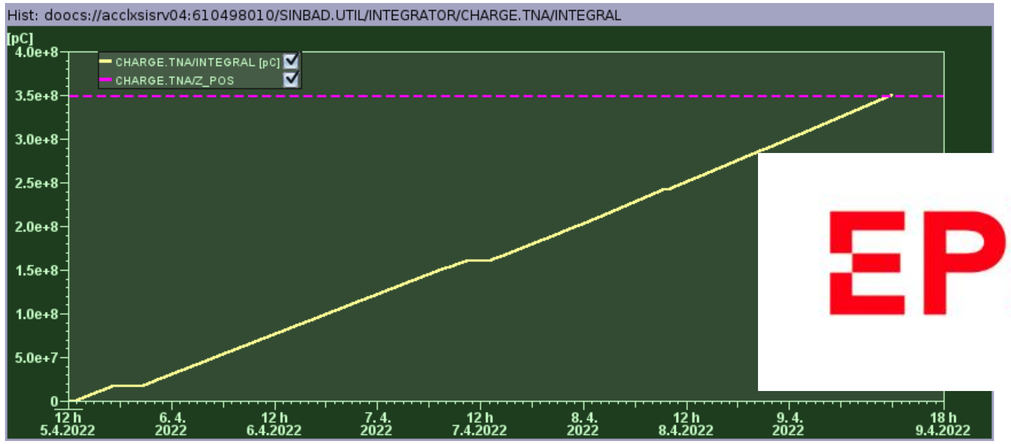


Reconstructed beam



Micro-wirescanner





Around 4 days continuous beamtime to irradiate a diamond sample with 3.5E8 e⁻.

Polarizable X-band TDS enables new diagnostic methods

allow for complete tomographic reconstruction up to 5D (x,x’,y,y’,t).

PolariX TDS installed at the ARES linac.

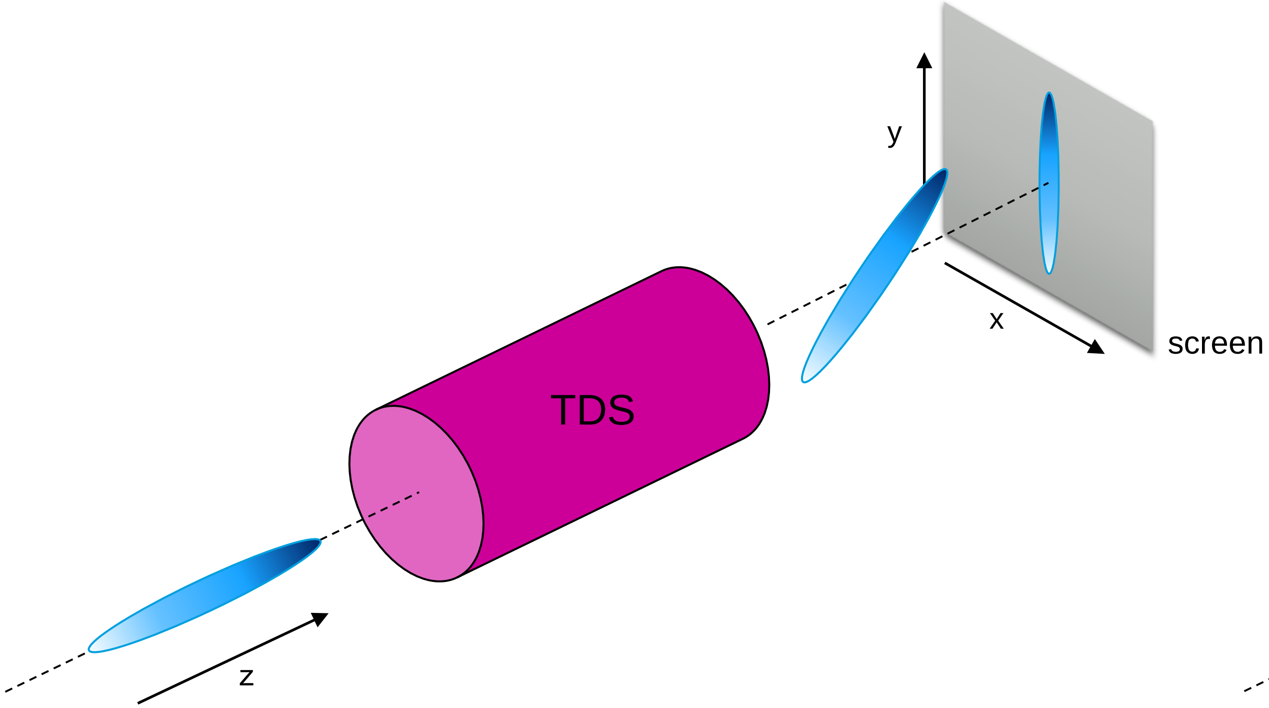
- Designed in **collaboration** between CERN, PSI and DESY [1-3].
- Unique feature: **Variable** streaking angle.

[1] B. Marchetti et al., Sci. Rep., 2021,
[2] P. Craievich et al., Phys. Rev. Accel. Beams, 2020,
[3] A. Grudiev, CLIC-Note-1067, 2016

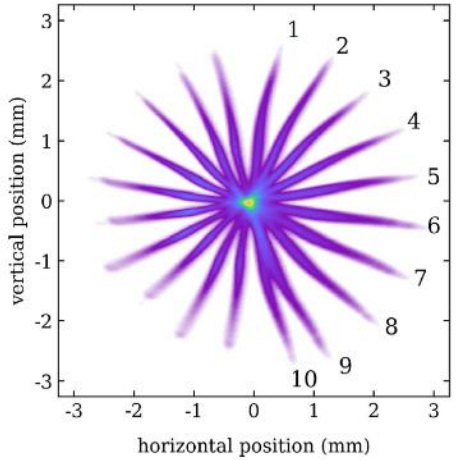
A TDS provides longitudinal information of the bunch

A time-dependent transverse kick is applied to map the longitudinal profile on a transverse plane

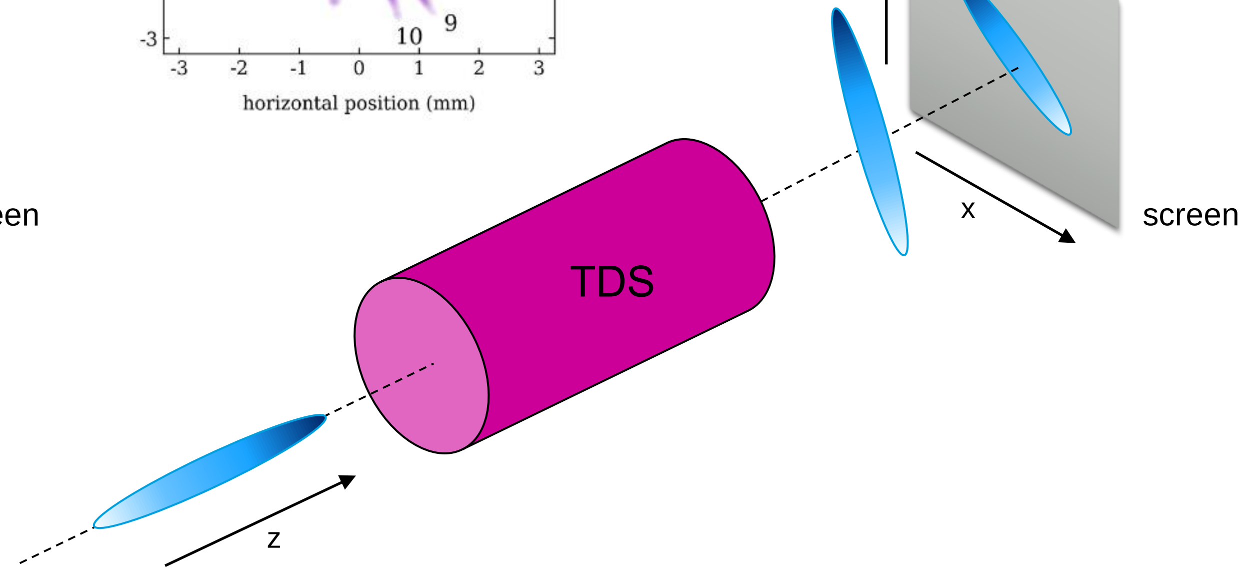
- Standard TDS: streaking in a **fixed** direction (e.g., vertical)



- PolariX TDS: streaking in **any** direction



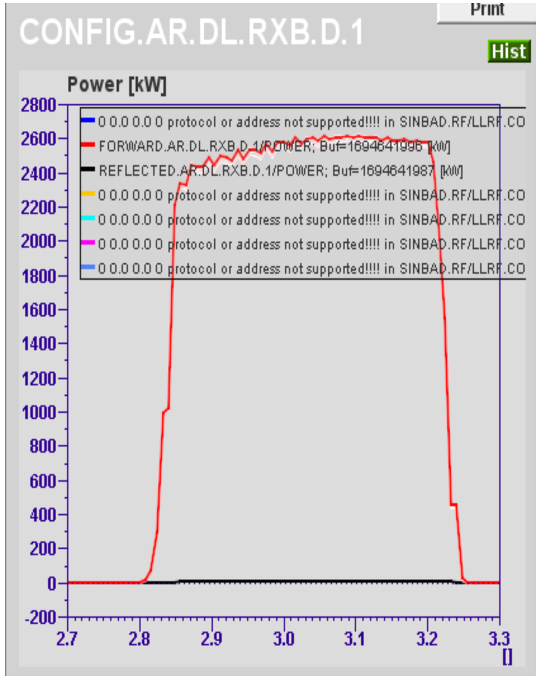
B. Marchetti et al., Sci. Rep., 2021

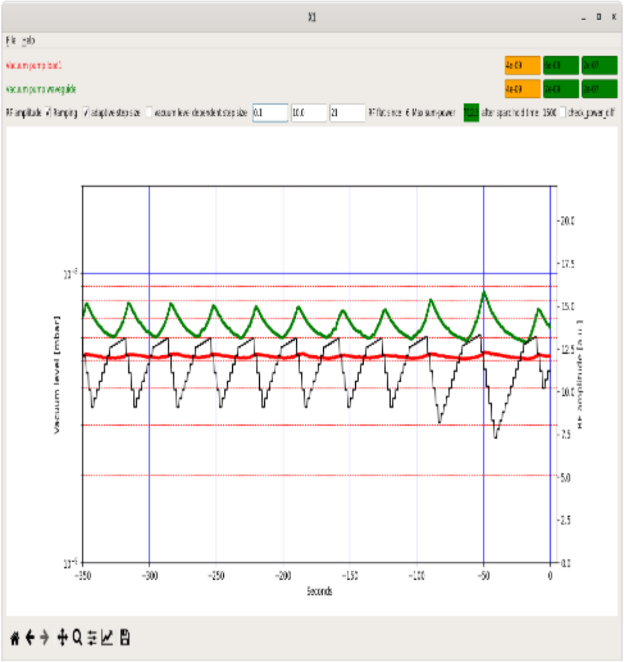


Bunch duration measurements

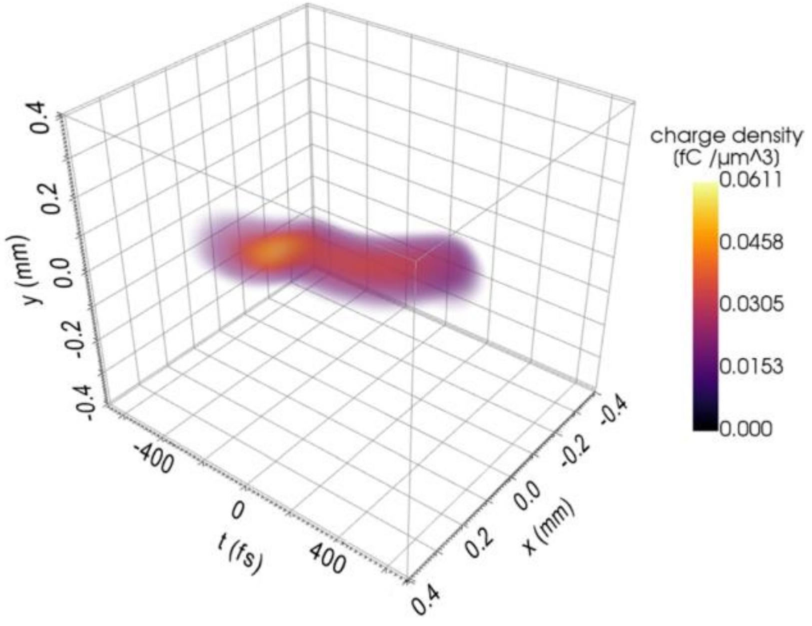
PolariX TDS actual status

- RF-conditioning of klystron (klystron connected to dummy load) started end of April. Now pulse width 400 ns (target 1 µs) and 4.3 MW power (target 6 MW)





- Development of advanced diagnostics methods ongoing (5D tomography). Successful first test at FLASHForward in Nov. 2022.



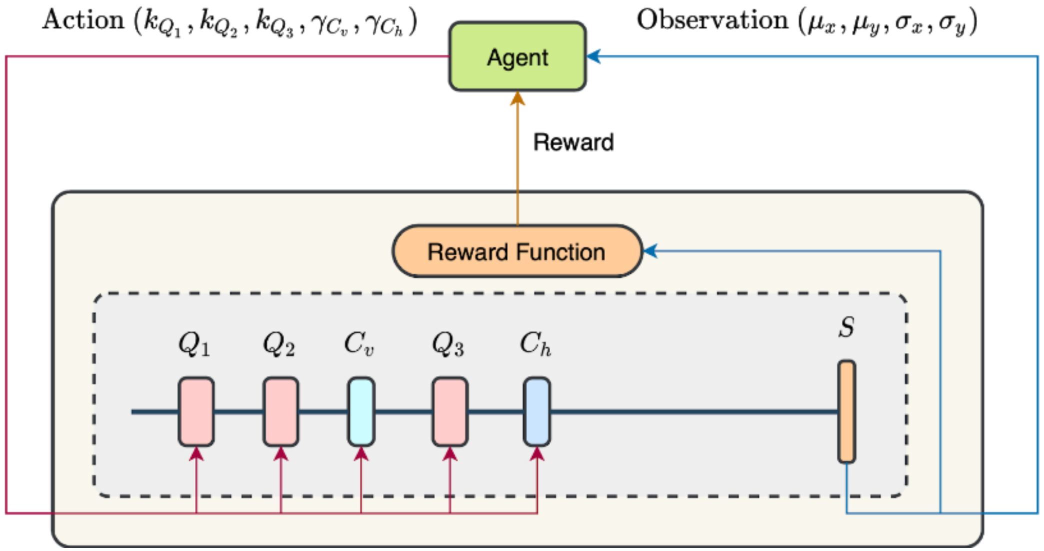
3D charge reconstruction

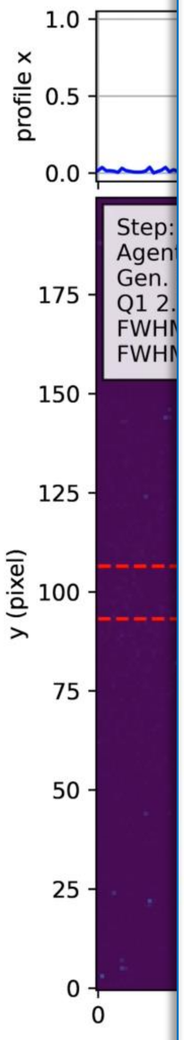
S. Jaster-Merz (IPAC23 proceedings, WEODB2)

Reinforcement Learning at ARES – regular beam times

Automation and Optimisation of Accelerator Operation using Artif

- 2-year project funded by Helmholtz AI, collaboration of DESY and KIT
- **Proof-of-concept**
  Autonomously focus and centre beam in the ARES experimental area in a matter of minutes using quadrupole triplet and corrector magnets





Autonomous Particle Accelerators: Accelerate Smarter With Artificial Intelligence

TOPICS: Artificial Intelligence Deutsches Elektronen-Synchrotron Particle Physics

By DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY NOVEMBER 9, 2020

At DESY´s ARES accelerator, the research team wants to gain experience with autonomous operation. Credit: DESY/F. Burkart

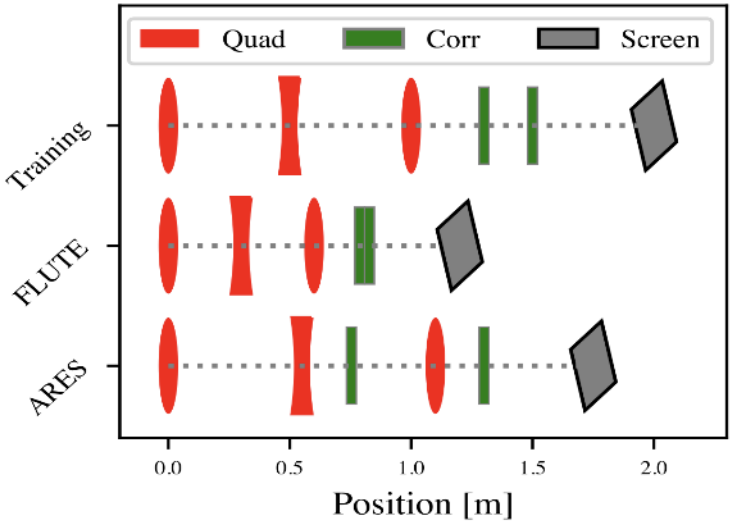
Particle accelerators are universal tools: They help in production processes in industry, in tumor therapy in hospitals and enable unique discoveries and insights in research. Growing demands on the stability and properties of particle beams make a manual operation of these complex devices increasingly challenging – and require the highest possible level of automation to support operators.

Autonomous accelerator studies at ARES

Reinforcement learning and Bayesian PID controller tuning (courtesy J. Kaiser)

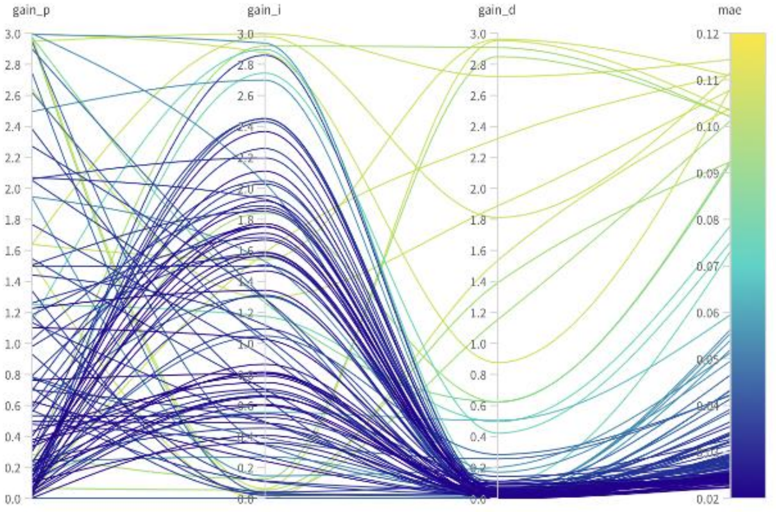
Lattice-agnostic reinforcement learning

- Train reinforcement learning agents to work with any lattice arrangement and geometry as long as number and type of magnets are the same.
- Enable much faster deployment to new optimisation tasks as no retraining is required.
- Demonstrated to work even for transfer between accelerators ARES and FLUTE in paper published at IPAC'23 (THPL029).



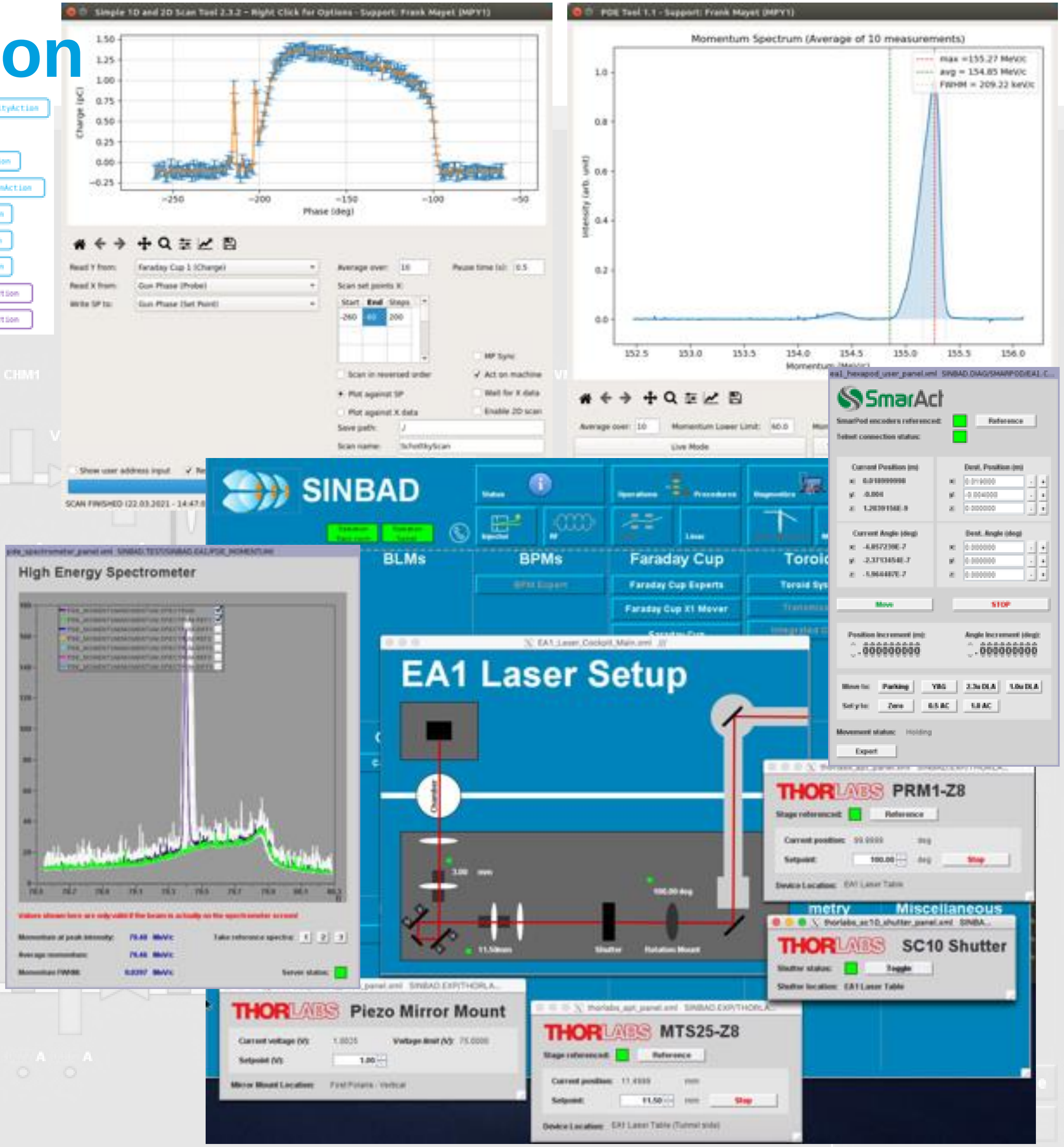
Bayesian PID controller tuning

- Autonomously tune PID controller gains for vertical and horizontal position feedback using Bayesian optimisation.
- Improvement over hand-tuned controller gains of about 20%.
- Alleviates the need for hand tuning in the future.



New tools support ARES operation

- **Python tools**
  - **Scan tool (GUI)**
  - Emittance analysis toolkit (incl. Jupyter notebooks)
  - **Toolkit for scripted (long-term) experiments,** based on *Actions* and *Procedures*
  - High energy spectrometer **spectrum live view and data acquisition tool** (GUI)
- **DOOCS servers**
  - SmarAct Hexapod **device server**
  - Thorlabs APT device server (linear stages, rotation mounts, etc.)
  - Thorlabs laser shutter server
  - PI linear stage server
  - Simple Basler USB3 camera server
  - High energy spectrometer middle layer server
- **Other tools**
  - **Pre-trained neural network for the analysis** of solenoid scan data
  - **ARES Cockpit panel**
  - Several **Matlab scripts for analysis** of e.g. low energy spec. measurements



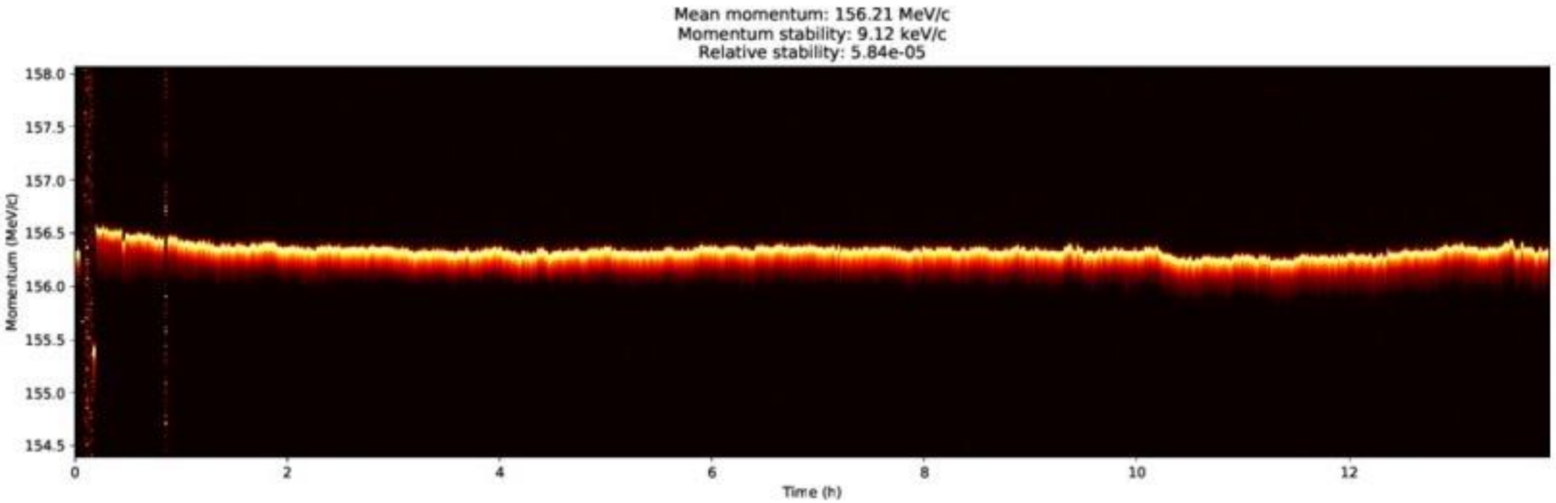
Medical applications @ ARES

New opportunities – new fields

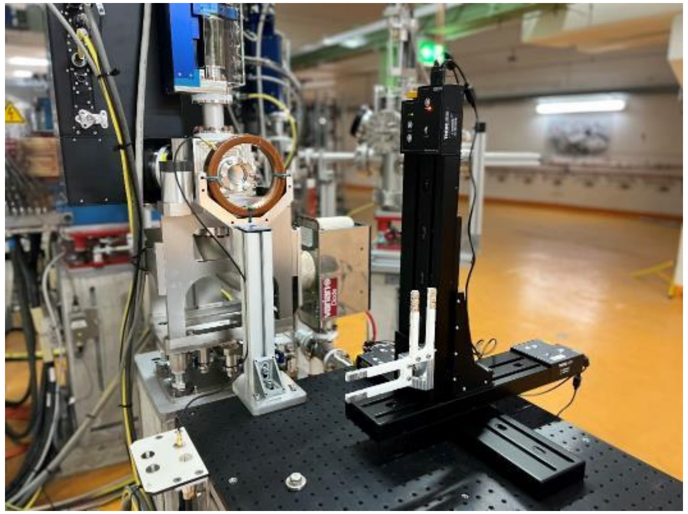
Started to adapt ARES also to the needs of medical research

- Up to 160 MeV high precision electron beams for **research & development**.
  - **Cutting-edge stability** of the electron pulse energy
  - **Excellent beam control**
  - **In-vivo experiments possible**
- Ideally suited for VHEE and medical experiments.

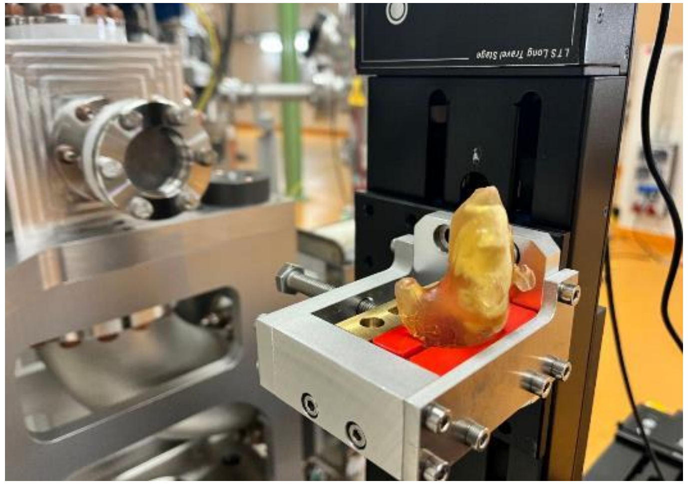
→ Setting up collaborations and infrastructure.



Record momentum stability of ARES during daily operation.



Experimental station designed for medical research



Mouse phantom for electron CT studies

World Health Organization

- **new cancer cases (2020) worldwide: 19.292.789**
- **deaths (2020) worldwide: 9.958.133**

FLASH RT

Efficiently treat cancer with ultra-high dose rates and within short timescales

With a lot of input from Roger Jones and Hannah Wanstall, University Manchester

- Radiotherapy (a non-invasive radiation treatment which damages and kills tumor cells, CONV-RT) is part of the treatment in **30-50% of the cases**. Unfortunately, radiotherapy also damages the healthy tissue surrounding the tumor.

- Higher doses of radiotherapy are associated with trauma to the healthy tissue surrounding the tumor, whereas **FLASH radiotherapy (FLASH-RT) demonstrates a sparing effect of the healthy tissues without compromising the anti-tumor action.**

- FLASH-RT is a **new technique**, with treatment of tumors at **ultra-high dose rates in ultra-short timescales.**

What is “short timescales” and what is “high dose”???

- Tumor dose (depending on sensitivity and composition): 40 – 70 Gy
- Conv RT dose rates: ~ 0.05 Gy/s

→ irradiation within minutes

- FLASH RT dose rates: ~ 40 Gy/s – 1000 Gy/s (no clear threshold)

→ irradiation time: ~ 100 ms (no clear threshold)

FLASH RT – experiments so far

- First studies in 1960
- Skin reaction reduced in being treated with FLASH-RT compared to CONV-RT
- Reduced tissue toxicity, FLASH-RT also produces the same, maybe even superior tumor response as CONV-RT.
- Mice exposed to brain irradiation at conventional dose rates performed much worse in recognition tests compared to those treated at ultra-high dose rates.
- First patient treated in Lausanne in 2019.

- BUT: many parameters not yet scanned.

pig treated with conv RT and FLASH RT skin reaction – skin reaction.

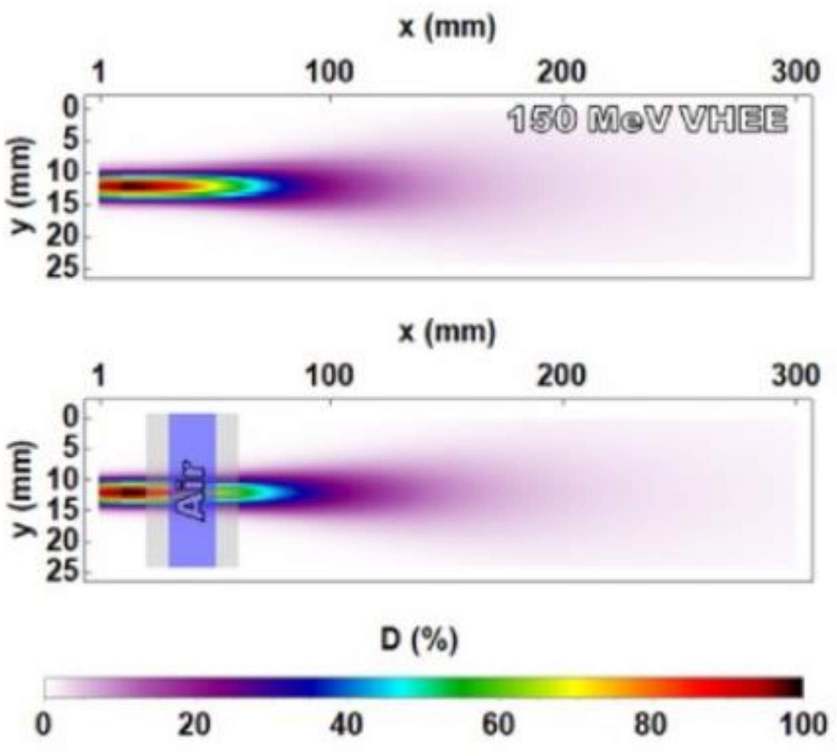
What is Very High Electron Energy (VHEE) treatment?

Ideally suited to treat deep-seated tumors in inhomogeneous regions

- VHEE has potential to treat various cancer types, particularly those located in **inhomogeneous regions** (i.e. lung, prostate)

- Increasing electron energy (100MeV +) **reduces scattering**

- VHEE shows potential for **FLASH radiotherapy –** delivering a **high dose** in a **short time interval** (> 40 Gy/s) vs conventional dose rates (~ 0.05 Gy/s)



Courtesy: H. Wanstall, Uni Manchester

Our main partners

Beamtime on regular basis

+ TU Hamburg for realistic animal phantoms

UKE HAMBURG

Prof. Dr. K. Rothkamm
Scientific Lab Manager
Dep. Institute Director
+ 2 medical scientists, 1 PhD,
1 Master student

- Dosimetry measurements
- Benchmarking of conv. RT with ARES beam
- **Cell-culture experiments at high energies**
- **Studies on medulloblastom cancer treatments.**

NHS The Christie NHS Foundation Trust

MANCHESTER 1824 The University of Manchester

Prof. Dr. Roger Jones
1 PhD

- First **cell-culture experiments** with clinically relevant VHEE energies (100+ MeV)
- Benchmarking of simulations

CANDLE

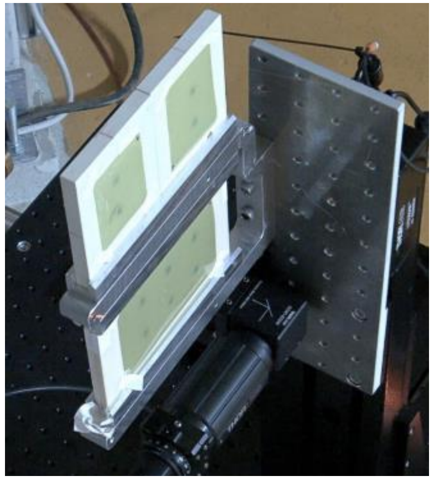
Dr. Gohar Tsakanova
Head of the laboratory
of experimental biology
+ 2 medical scientists

- **Cell culture experiments at 100+ MeV** with variable pulse length.
- **Bio-chemical reaction** experiments
- Collaboration on beam/dosimetry instrumentation.

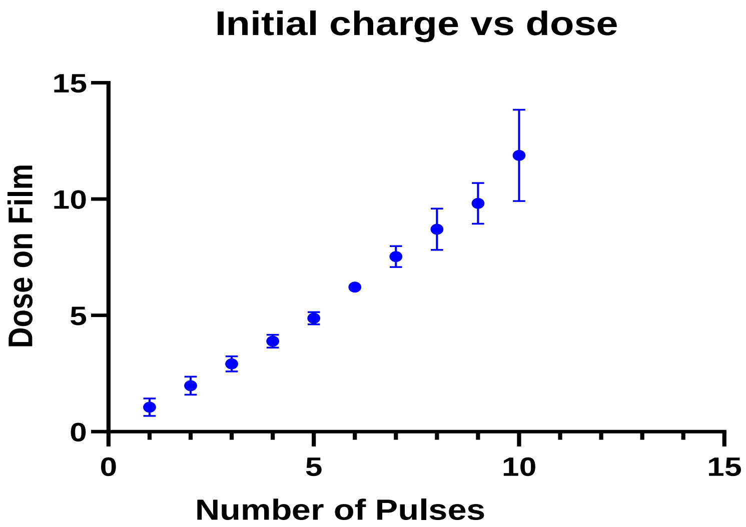
1st prize in the "Best scientific work" in the "Life Sciences" category by the RA National Academy of Sciences, Nov 2022

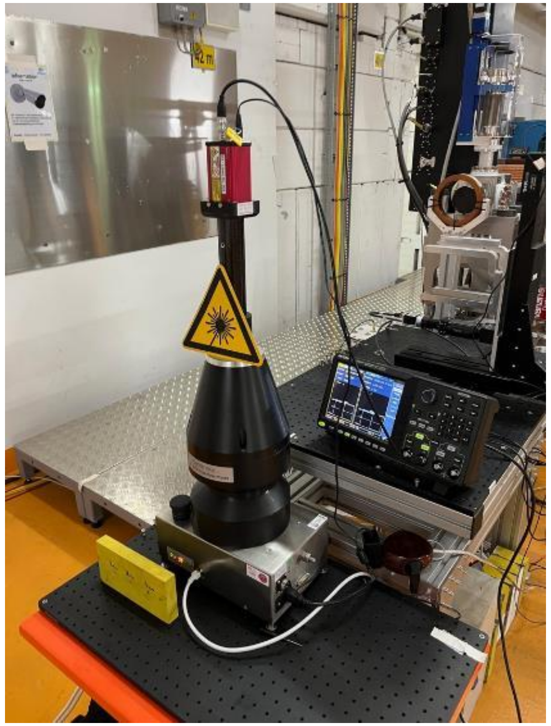
Step 1: Getting the right dose

Synergies with RadioProtection, UKE, Uni Manchester - done



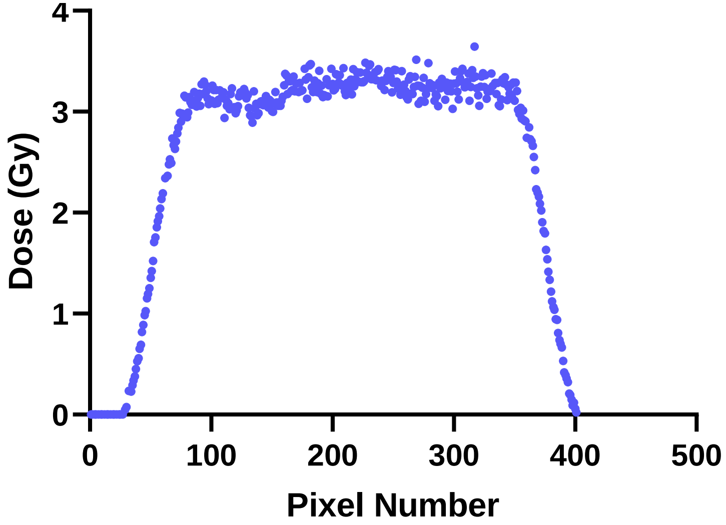
Dose calibration with dosimetry films and water phantoms

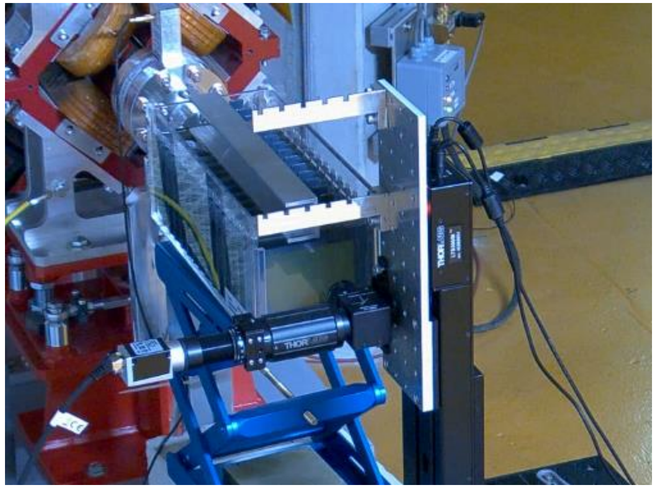




Dose cross-calibration with the DESY RP team, novel online dose measurements

Dose uniformity measurements in an area of 3x1 cm



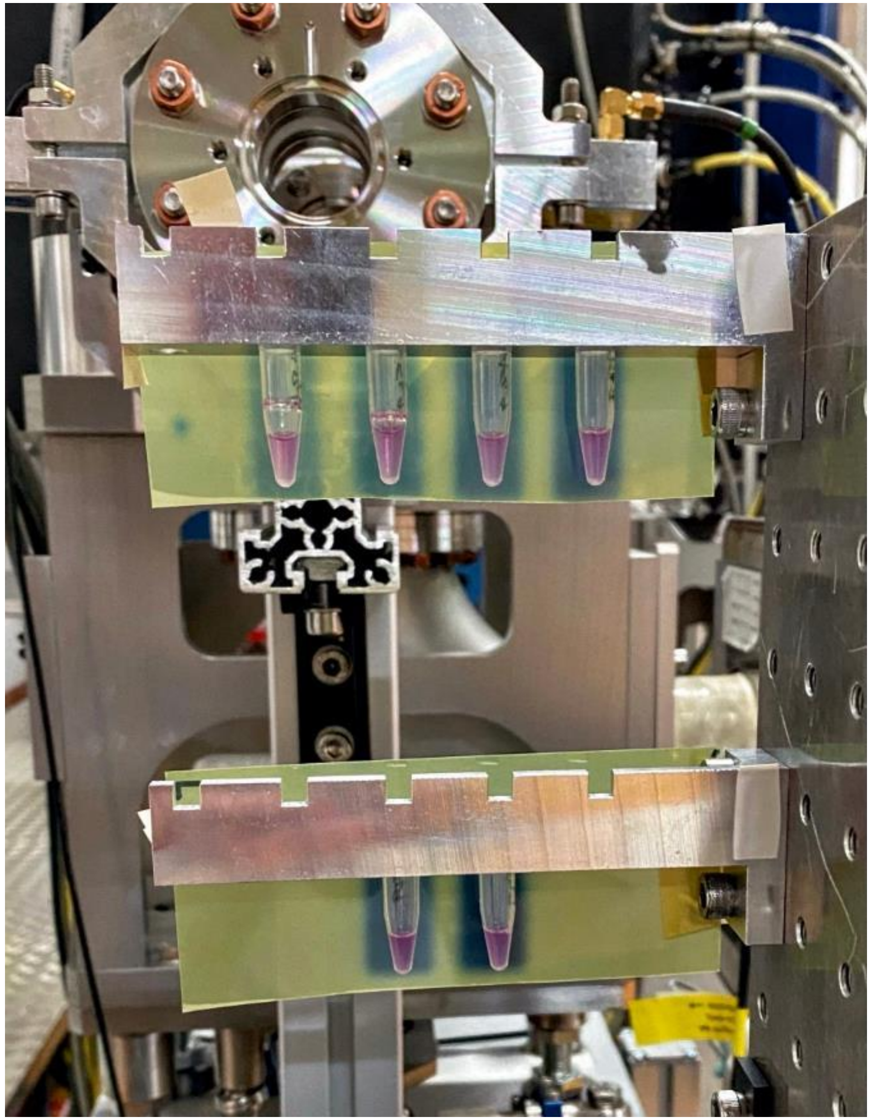


Dose distribution in 30 cm water tank

First VHEE experiments with living cells!

Prof. Roger Jones, Hannah Wanstall

The University of Manchester



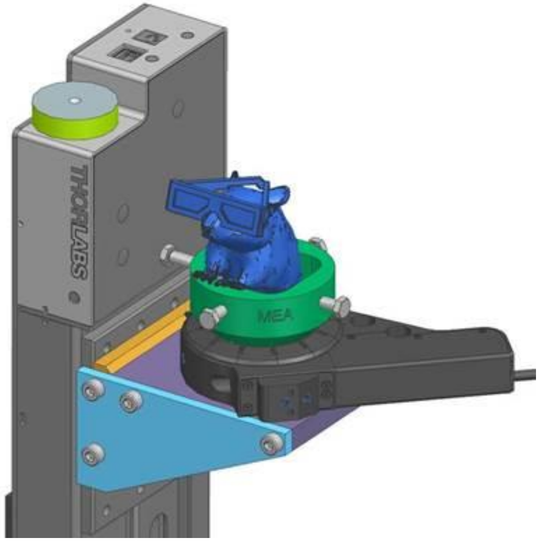
Beam time right now.

→ Towards „real" VHEE experiments with bigger animal phantoms

eCT experiments - diagnostic and treatment with one machine

DESY internal collaboration with M-FH-ITT

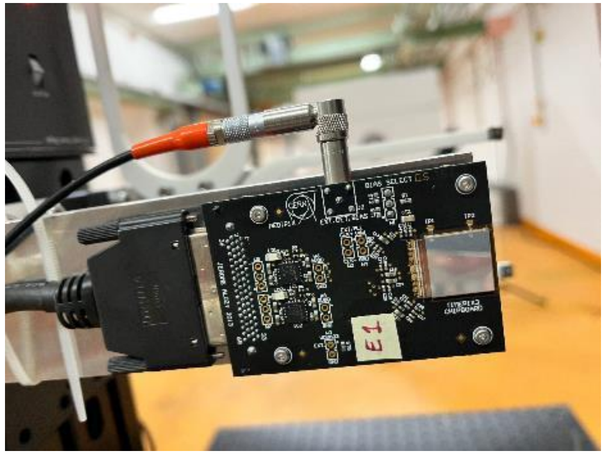
Alfred – our mouse phantom



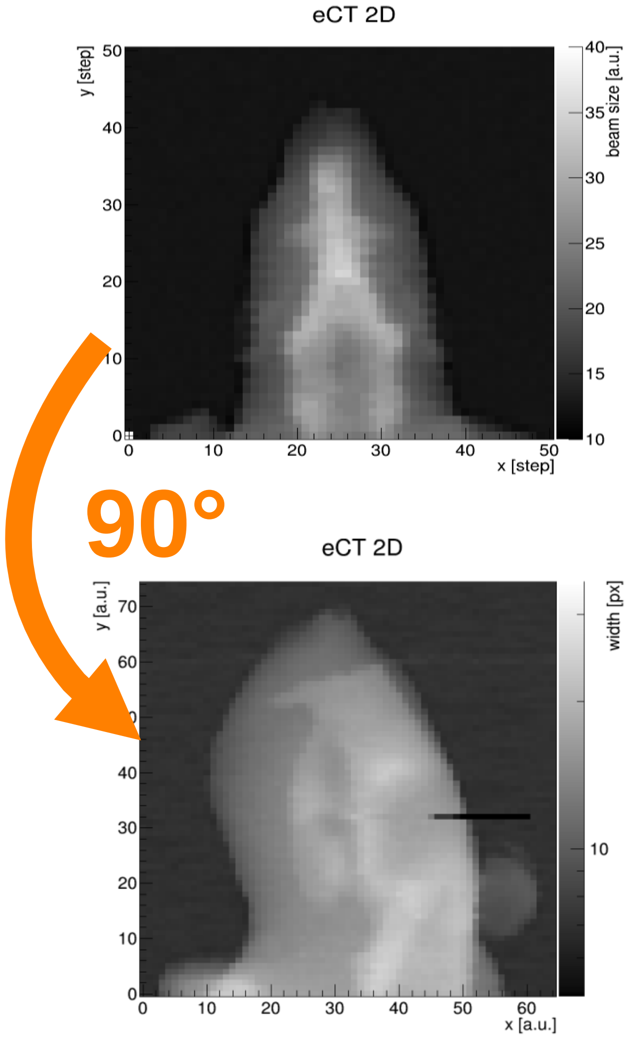
Simon Spannagel, Paul Schütze (FH)

First proof-of-principle successful
But much more homework to do:

- Real tomography
- Optimize charge / dose
- Optimize resolution
- Scan procedure
- …



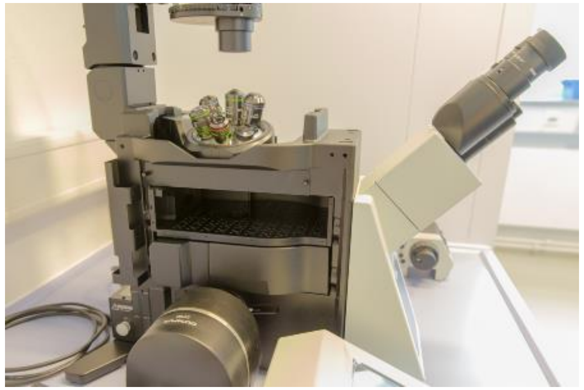
TimePIX3 detector



S2 Bio lab next to ARES

Used for medical experiments at ARES. 5 min walking distance

Work place in the Bio-Laboratory.



inverse fluorescence microscope.

BSL2 safety workbench equipped with a mini centrifuge, vortexer, vacuum pump,…

Provides all the necessary equipment to cultivate, store, manipulate and analyse biological agents

Michael Köpke

E-Mail: Michael Köpke

Phone: +49 (0)40 8998 (9)2406

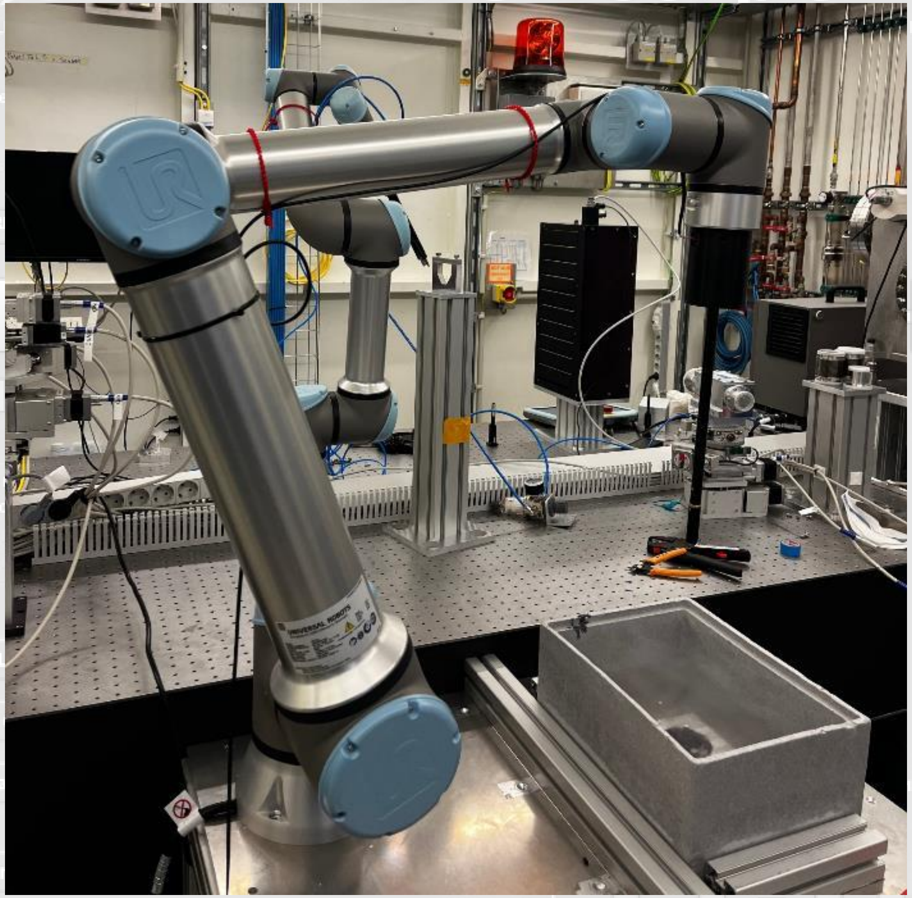
Location: 25f / 257

Project leader biological safety, approval of biosafety declarations

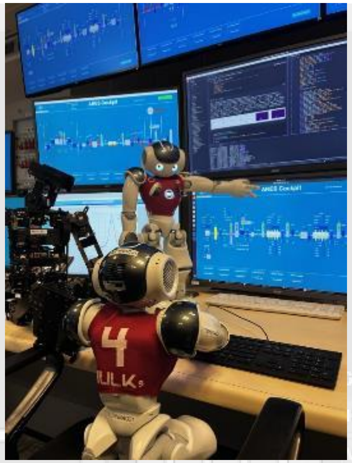
More info:
https://photon-science.desy.de/facilities/on_site_infrastructure/laboratories_technical_infrastructure_shift_service/biology_laboratory_bsl_2/equipment/%20index_eng.html

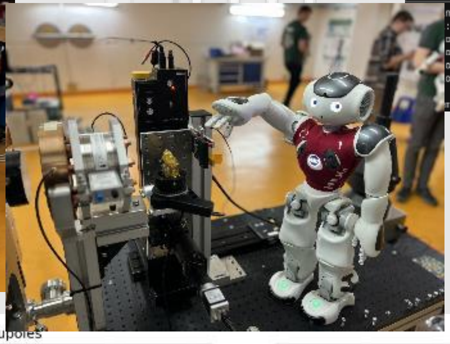
Automation, machine learning, robotics

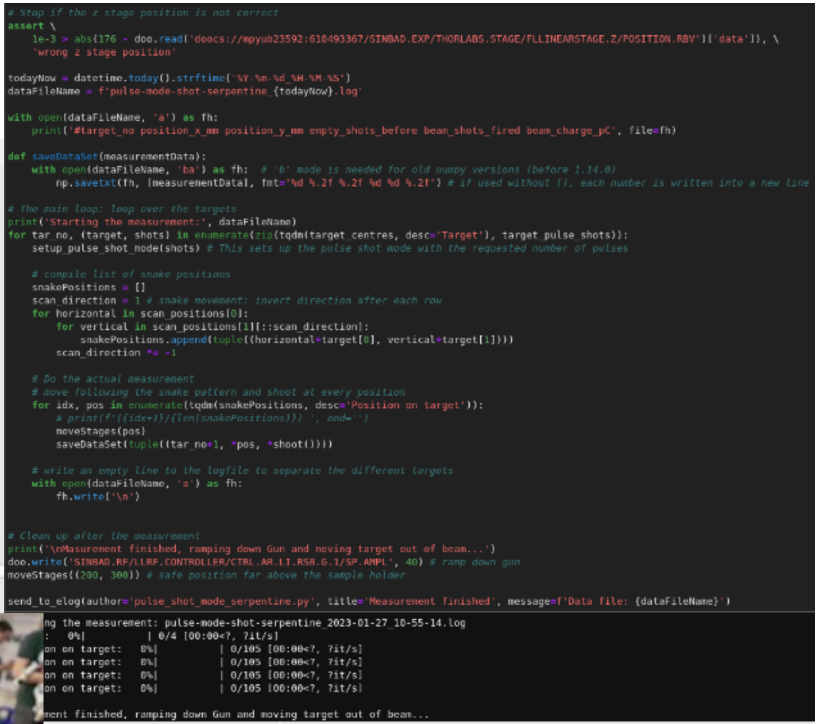
Ease the user operation & gain efficiency



Robot arm currently located at PETRA III, Installation at ARES foreseen mid 2023.







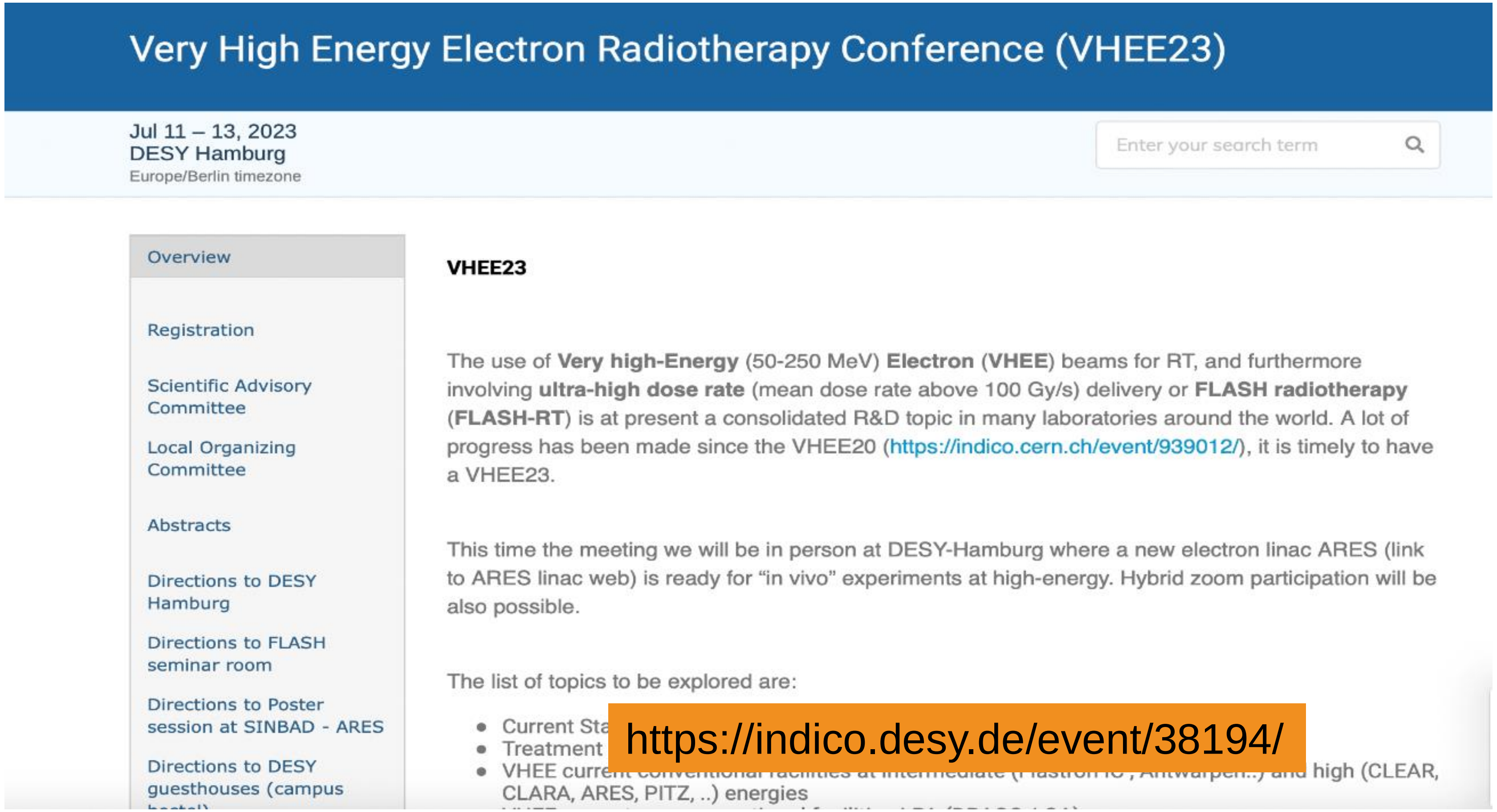
Movementscripts for irradiation patterns

Machine learning to improve orbit feedback

VHEE workshop at DESY

Bringing the experts together!

- SAC chaired by Angeles Faus-Golfe (LAL, former DESY MAC member)
- Bringing the experts together (CLEAR, CLARA, ARES, diagnostics, industry)


Very High Energy Electron Radiotherapy Conference (VHEE23)

Jul 11 – 13, 2023
DESY Hamburg
Europe/Berlin timezone

Enter your search term

Overview

Registration

Scientific Advisory Committee

Local Organizing Committee

Abstracts

Directions to DESY Hamburg

Directions to FLASH seminar room

Directions to Poster session at SINBAD - ARES

Directions to DESY guesthouses (campus

VHEE23

The use of **Very high-Energy** (50-250 MeV) **Electron** (**VHEE**) beams for RT, and furthermore involving **ultra-high dose rate** (mean dose rate above 100 Gy/s) delivery or **FLASH radiotherapy** (**FLASH-RT**) is at present a consolidated R&D topic in many laboratories around the world. A lot of progress has been made since the VHEE20 (https://indico.cern.ch/event/939012/), it is timely to have a VHEE23.

This time the meeting we will be in person at DESY-Hamburg where a new electron linac ARES (link to ARES linac web) is ready for "in vivo" experiments at high-energy. Hybrid zoom participation will be also possible.

The list of topics to be explored are:

- Current Sta
- Treatment
- VHEE curr ... high (CLEAR, CLARA, ARES, PITZ, ..) energies

https://indico.desy.de/event/38194/

if you are interested in beam time…

- for the moment:

Florian Burkart

florian.burkart@desy.de

+49-40-8998-3039

- review process for beam time requests in preparation.

Summary and Outlook

- **A new tool** is available on the DESY campus - ARES.
- **ARES is open for internal and external users - users extremely happy.**
- **High stability infrastructures result in high quality, high stability electron bunches.**

  → This offers unique possibilities and exploitation in multiple areas
  - Ultra-short electron bunches and their diagnostics
  - **Accelerator R&D** for internal and external partners
  - Acceleration and beam manipulation with dielectric structures (ACHIP)
  - Started to adapt ARES to the needs of **medical research - Infrastructure is available**
- **First VHEE experiments** with living cells were done!

  → more experiments with water and animal phantoms in preparation

  → Towards FLASH RT

Acknowledgements

- The ARES team
- R. Brinkmann and W. Leemans
- Our collaboration partners
  - PSI – Rasmus Ischebeck, Pavle Juranic
  - Uni Manchester – Roger Jones, Hannah Wanstall
  - UKE – Kai Rothkamm, Elisabetta Gargioni, Joel Senador
  - KIT – Chenran Chu, Andrea Santamaria
- DESY technical groups for their excellent work.

Thank you!

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Florian Burkart
MPY1
florian.burkart@desy.de
+49-40-8998-3039