ACCELERATORS 2024.

Highlights and Annual Report

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

ACCELERATORS 2024.

Highlights and Annual Report

Sustainability meets precision

The PETRA IV girder is a precision-engineered support structure that positions the magnets for DESY's flagship project PETRA IV with extreme accuracy to keep the particle beam perfectly aligned in the accelerator ring. DESY is pioneering an innovative metal casting technique to produce these lightweight, vibration-resistant frames. Designed using algorithmic topology optimisation, the girders require at least 15% less material than similar structures, are fully recyclable and deliver exceptional mechanical stability. Following successful prototyping and testing, DESY is set to begin series production of all 288 high-performance, sustainable girders (see p. 34).
Picture: Riccardo Bartolini, DESY

Next-generation superconducting cavities and cryomodules

DESY is at the forefront of superconducting radio frequency (SRF) accelerator technology, focusing on advancing the European XFEL X-ray free-electron laser. Recipes for SRF cavities developed at DESY achieve unprecedented high fields and enhance the cryogenic performance of accelerator modules, paving the way for next-generation SRF technology (see p. 44).

Picture: Thorsten Büttner, DESY

Contents

The year 2024 at DESY

Dear Colleagues and Friends of DESY,

In a time of significant challenges – financial constraints, geopolitical instabilities and heightened international competition – DESY faces a demanding landscape. Rising personnel costs, volatile energy prices and inflation-driven reductions in purchasing power put us under considerable pressure, and the priority is to lead DESY safely into the future.

At the heart of our strategy stands the ambitious PETRA IV upgrade project. The conversion of PETRA III into a state of-the-art fourth generation X-ray light source is essential not only for DESY's advancement but also for strengthening international research and securing Germany's technological sovereignty. As the world's most advanced and brilliant X-ray source, PETRA IV will enable unprecedented precision in studying materials and biological macromolecules, paving the way for pioneering innovations, such as AI-driven material design.

The DESY infrastructure focus also includes transformative projects. The new DESYUM visitor centre, whose construction is progressing according to plan, will soon be a public landmark and could become the iconic symbol of the Hamburg-Bahrenfeld campus. Through our Centre for Accelerator Science and Technology (CAST) and the DESY Innovation Factory, an integrated technology and start-up centre, we are expanding the "Bahrenfeld ecosystem" by linking research and innovation to drive technological and economic development.

This is my last foreword for an annual report as the chairman of the DESY Board of Directors, and I would like to take this opportunity to make a few personal remarks: It has been an honour to serve in this role. I would like to thank all DESY employees and our national and international partners for their trust over the past 15 years, and especially the Board members for their unique team spirit and constructive cooperation. Together, we have achieved numerous successes, including the remarkable construction of the European XFEL from 2009 to 2017, a masterpiece "made by DESY", the establishment of the Astroparticle Physics Division, the strategic expansion of nanoscience and laser plasma research and the successful operation of PETRA III, FLASH and the European XFEL as Hamburg's flagship photon sources. We are continuing a long tradition: Since the commissioning of its first particle accelerator in 1964, DESY has been one of the pioneers of research with synchrotron radiation worldwide.

Figure 1
Celebrating 60 years of research with synchrotron light at DESY: (from left) Robert Feidenhans'l, Poul Nissen, Edgar Weckert, Saša Bajt, Massimo Altarelli, Jerome Hastings, Jochen Schneider, Tetsuya Ishikawa, Laurent Chapon, Francesco Sette, Harald Reichert, Rolf Heuer and Helmut Dosch

Figure 2
Visualisation of the DESY Centre for Accelerator Science and Technology (CAST), close to the PETRA III experimental hall "Max von Laue" (right)

I reflect with pride on the growth of the two DESY sites in Hamburg and Zeuthen together with our partners. The new interdisciplinary research centres – CFEL, CSSB and CXNS for photon science, the recently opened Science Data Management Centre (SDMC) for astroparticle physics, the ongoing projects mentioned above as well as the planned Wolfgang Pauli Centre for theoretical physics (WPC) and Centre for Molecular Water Science (CMWS) – are visionary initiatives that will contribute to strengthening Germany's research landscape as a whole and the innovation regions of Hamburg and Zeuthen in particular.

A highlight of my time at DESY has been the recruitment of renowned scientists. With the appointment of over 30 W3 professorships, including 15 women, and close collaborations with universities in Hamburg, Schleswig-Holstein, Berlin, Brandenburg and beyond, we have enhanced our scientific network and supported our university partners' excellence. Particularly noteworthy are the new members on the DESY Board of Directors in 2025: Beate Heinemann, Wim Leemans, Britta Redlich, Christian Stegmann and Arik Willner, bringing science, innovation and technology transfer expertise. With this exceptional team, DESY is well equipped to master future challenges.

When I will hand over the helm to Beate Heinemann in spring 2025, I will do so in a turbulent time not only for DESY. Research and social issues can no longer be addressed only on the national level. Sharing expertise and infrastructures and thereby strengthening international cooperations is becoming more important: Innovation is the key for our future. Therefore, the pending political decision for PETRA IV is crucial for DESY and our national and international partners and users, and I hope for swift action in the next period.

I extend my best wishes to all DESY staff, hoping you will continue to lead this remarkable research centre into a bright future. Thank you all and also our partners for constant support and excellent cooperation over the years. I wish DESY continued success and that essential extra bit of luck.

Yours

Helmut Dosch
Chairman of the DESY Board of Directors

Figure 3
The Science Data Management Centre (SDMC) building for the CTAO gamma-ray observatory on the DESY campus in Zeuthen

Accelerators at DESY

Introduction

Dear colleagues and friends,

2024 was a year marked by both scientific milestones and moments of deep reflection for the DESY Accelerator Division. On the scientific front, our teams continued to push the boundaries of accelerator technology and performance. DESY's flagship project PETRA IV – the conversion of the synchrotron radiation source PETRA III into a state-of-the-art fourth-generation X-ray source – took a significant step forward, as the German Federal Ministry of Education and Research included the project in its national prioritisation process for large-scale research infrastructures. Designed to be the most brilliant X-ray source of its kind, geared towards sustainability and operational excellence, PETRA IV will enable revolutionary studies in materials science, nanotechnology and biomedicine. The evaluation phase is now under way, with a funding shortlist expected in summer 2025.

Concurrently, a major upgrade of DESY's FLASH free-electron laser (FEL) facility began as part of the FLASH2020+ project. Since June 2024, one of the FEL beamlines has been undergoing a complete redesign to support externally seeded FEL operation at 1 MHz repetition rate. With new capabilities, the upgrade represents a major leap for ultrafast science.

A standout breakthrough was achieved when researchers at DESY and European XFEL successfully generated attosecond hard X-ray pulses at megahertz repetition rates, a milestone in ultrafast imaging. This advancement opens new possibilities for observing atomic and electronic motion with unprecedented precision and minimal sample damage.

DESY's plasma acceleration efforts continue to gain momentum. The FLASHForward team achieved a key milestone by preserving the emittance of particle beams during plasma acceleration. Innovation flourished through projects like SPLASHH and BEETLE, where precision 3D printing and ultrafast laser plasma accelerator technologies hinted at a compact, connected and patient-centred scientific future.

DESY's accelerators rely on control and synchronisation systems of exceptional precision, enabling scientific breakthroughs and stable, around-the-clock operations. Whether keeping electron beams aligned to the quadrillionth of a second at the European XFEL or detecting seismic waves from a Taylor Swift concert two kilometres away, DESY's technological finesse is remarkable, and our teams continue to push technical boundaries. Advances like the revamped Distributed Object-Oriented Control System (DOOCS) system, the development of beam dynamics simulators such as Cheetah and artificial intelligence-driven accelerator tuning all reflect how DESY continues to innovate at the frontiers of complexity and how DESY's excellence in controls and synchronisation lays the groundwork for future facilities like PETRA IV.

On the management side, we welcomed Thomas Feurer as Chairman of the European XFEL Management Board, succeeding Robert Feidenhans'l, who guided the X-ray laser facility for the past seven years. At DESY, we celebrated the appointment of Britta Redlich as the next Director in charge of Photon Science and honoured Edgar Weckert's long-standing leadership of the Photon Science Division.

Meanwhile, the DESY spirit shone brightest in community and cooperation: Israeli high-school students and Ukrainian scholars found inspiration on our campuses, thousands came to touch science first-hand on Science City Day 2024 in June, which was one of the many highlight events of the year – an event that brought together researchers, staff, families and the public in a celebratory and welcoming setting. The atmosphere was one of curiosity, collaboration and shared purpose, reflecting the vibrant and human side of the science we pursue every day – a spirit that becomes all the more important in the age of artificial intelligence.

DESY's success is fundamentally driven by the expertise, dedication and creativity of its people. Talent management remains a key strategic priority – ensuring that we attract, develop and retain outstanding individuals across all areas of the research centre. Our colleagues' excellence is reflected not only in their daily work, but also in the numerous prizes awarded to them each year. These recognitions highlight the high calibre of scientific and technical contributions made at DESY and underscore the centre's role as a leading research environment for top talent.

Figure 1

Margot and Helmut Dosch, together with Rainer Wanzenberg, Wim Leemans and Stefan Choroba from the Accelerator Division, enjoying a visit to DESY's PETRA III accelerator tunnel and other amusements on Science City Day

Yet, 2024 also brought moments of loss and challenge. In April, we mourned the passing of Siegfried "Siggi" Schreiber – a guiding force behind FLASH, an exceptional accelerator physicist and an inspiring mentor and colleague to many. Siggi's dedication, curiosity and kindness defined him, and his contributions will remain integral to FLASH's and DESY's identity and vision.

We also faced further unexpected challenges, notably a fire in the central electronics room of the DESY II booster synchrotron, the pre-accelerator for PETRA III. While it temporarily disrupted operations, the swift and coordinated response by our teams in cooperation with the Hamburg Fire Department underscored DESY's culture of professionalism, resilience and community.

As we reflect on the year, it is clear that the progress of 2024 is a foundation for the future of DESY and the wider scientific community.

For 16 years, Helmut Dosch served as Chairman of the DESY Board of Directors and played a pivotal role in guiding the research centre through significant periods of growth and challenge. His visionary leadership has solidified DESY's position at the cutting edge of global research. A highlight of his final year was his visit to the PETRA III tunnel during Science City Day (Figure 1), a fitting moment that underscores his enduring connection to DESY's scientific core. Now, as he transitions into his well-deserved retirement and hands over the baton to Beate Heinemann, the mark he has left on the centre will resonate for the years to come, and his influence will remain a part of DESY's continued success.

As we turn the page to the future, we carry with us both the achievements and the spirit of the past year. We do so grounded in the legacy of 60 years of synchrotron research at DESY and with the momentum of attosecond breakthroughs that will redefine the tempo of discovery. With each experiment, each collaboration and each spark of curiosity, we move closer to answers that matter – not just for science, but for society. Together with our partners around the world, we at DESY remain committed to advancing the technologies and ideas that will shape the discoveries of tomorrow.

Wim Leemans
Director of the Accelerator Division

PETRA IV – the ultimate 4D X-ray microscope

PETRA IV is the planned ultralow-emittance upgrade of the existing PETRA III synchrotron radiation source (see p. 34). DESY's flagship project will deliver the brightest synchrotron light in the world. Academic and industrial users will benefit from the enormous increase in coherent X-ray photon flux, the planned cutting-edge beamlines, the novel experimental possibilities and the new business model in preparation for the facility.

Picture: DESY, Science Communication Lab

News and events

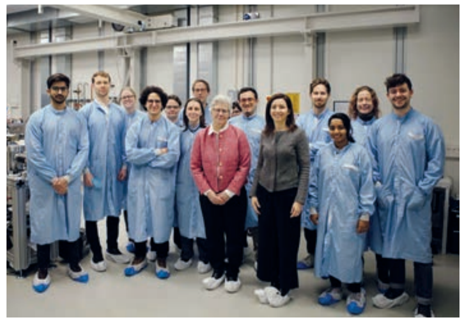
News and events

A busy year 2024

January

Nobel laureate Anne L'Huillier visits DESY

Anne L'Huillier from the University of Lund in Sweden visited DESY in Hamburg and the Center for Free-Electron Laser Science (CFEL). L'Huillier and two colleagues had received the Nobel Prize in Physics in 2023 for their groundbreaking work on experimental methods that generate attosecond pulses of light, enabling the study of electron dynamics in matter. After a tour of the attosecond and laser research laboratories at DESY and CFEL, the Nobel laureate, who is also a senior scientist at the Helmholtz–Lund International Graduate School (HELIOS), gave a lecture in the DESY auditorium.



Anne L'Huillier (centre left) in the attosecond laboratory at PETRA III

Topping-out celebrated for DESYUM visitor centre

The topping-out ceremony was held for the building that will house the DESY visitor centre, called DESYUM. Since its foundation stone was laid in May 2023, six storeys have been constructed near the Notkestraße entrance on the DESY site in Hamburg. With 3250 m² of usable space, DESYUM will accommodate a two-storey exhibition area, meeting rooms, offices, an auditorium, a cafeteria and a green roof with rooftop terrace. DESYUM will open to the public in 2025. Some 150 guests, including Hamburg Science Senator Katharina Fegebank as guest of honour, attended the ceremony.

Thomas Feurer takes office at European XFEL

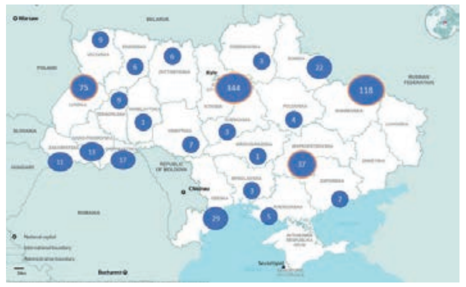
In January, physicist Thomas Feurer from the University of Bern in Switzerland took over as Chairman of the European XFEL Management Board, as Robert Feidenhans'l passed on the baton after seven years in the role. Feidenhans'l, who remained an advisor until his retirement in July, led the development of the European XFEL Strategy 2030+, the implementation of which began under Feurer's leadership with a strategy information event.

Robert Feidenhans'l and Thomas Feurer at the strategy information event

February

EURIZON fellowship programme for Ukraine begins

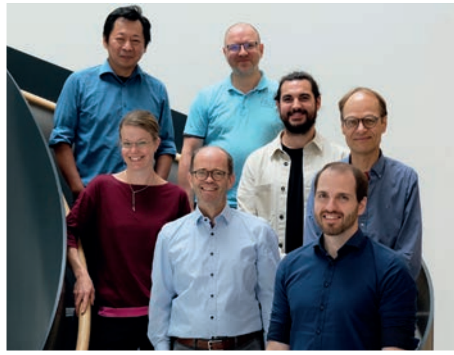
On 1 February, the EU project EURIZON kicked off its fellowship programme for scientists in Ukraine. These fellowships are designed to support scientific research in Ukraine, especially during the ongoing Russian invasion. EURIZON is an EU-funded project that is coordinated by DESY and involves 27 European research institutes. Their main aim is to encourage collaboration among European research centres and to support research efforts in Ukraine. A total of 18 fellowships were allocated in the first round, with more to follow from a large pool of applications.



Locations of the 780 applications for fellowships across Ukraine

SPLASHH: advanced 3D printing for compact accelerators

The project SPLASHH – Shaping Plasma Accelerators in the Hanseatic City of Hamburg, a collaboration between DESY, the Fraunhofer Institute for Additive Production Technologies (IAPT) and the Hamburg University of Technology (TUHH), was successfully concluded with the development of compact laser plasma accelerator components using advanced 3D printing. Key achievements include a precision-etched glass chip and a high-purity copper holder, both tested at DESY's LUX accelerator. The project highlights the potential of additive manufacturing for future high-tech applications and strengthens ties between science and industry in Hamburg.



The SPLASHH project team

Sergii Fomin

Joint DESY–Ukraine project receives DFG grant

Sergii Fomin, leading researcher at the National Scientific Centre "Kharkov Institute of Physics and Technology" (NSC KIPT), was forced to leave Ukraine after the start of the Russian invasion. Employed as researcher at DESY in the Accelerator Diagnostics and Instrumentation group, he received a grant from the German Research Foundation (DFG) to study the feasibility of extracting electron beams in a booster synchrotron using a bent crystal technology, which might be of interest for future test beam facilities.

One hundred years of living physics history

A life marked by scientific milestones, major decisions, ever larger accelerators and a great deal of science diplomacy: Herwig Schopper, former DESY and CERN Director General, turned 100 years old on 28 February and was honoured at a festive symposium at CERN on 1 March. DESY, which he headed as Chairman of the Board of Directors from 1972 to 1980, owes him a lot. Congratulations from DESY on completing a century!

Herwig Schopper was Chairman of the DESY Board of Directors in the 1970s.

March

DESY and Helmut Schmidt University expand collaboration

DESY and Helmut Schmidt University (HSU) in Hamburg will expand their strategic and operative cooperation. DESY Director Helmut Dosch and HSU President Klaus Beckmann signed a corresponding agreement on the occasion of the Day of Research at HSU on 26 March.

Klaus Beckmann (HSU, second from left) with Wim Leemans, Helmut Dosch and Beate Heinemann from DESY at Helmut Schmidt University

April

Helmholtz Meeting on Optics, Photonics and Lasers

Helmholtz Meeting on Optics, Photonics and Lasers place at DESY in Hamburg on 8–10 April. Bringing together scientists, engineers and experts from all Helmholtz centres, the workshop fostered knowledge exchange and collaboration across a broad range of topics – from artificial intelligence in photonics and advanced laser technologies to X-ray optics and attosecond sources. Strategic discussions also focused on future directions in view of the next Helmholtz funding period.

Israeli high-school students visit DESY

A group of 23 Israeli students visited DESY in Hamburg for a week. The students came from the Israeli Schwartz/Reisman Science Education Centers, a unique platform for physics enthusiasts in Rehovot and other cities in Israel and an institution under the umbrella of the renowned Weizmann Institute of Science.

A group of students from the Schwartz/Reisman Science Education Centers visited DESY.

Siggi Schreiber

DESY mourns the loss of Siegfried Schreiber

On 23 April, Siegfried “Siggi” Schreiber, scientific head of the FLASH accelerator at DESY, passed away at the age of 64. Siggi was a key figure in the development of accelerator-based light sources in Europe. Over nearly three decades at DESY, he made pioneering contributions to radio frequency (RF) electron guns and high-gain free-electron lasers (FELs), technologies that lie at the heart of modern accelerator science. His work helped shape the field and contributed significantly to DESY’s global reputation in accelerator research.

In 2006, he assumed leadership of operations coordination for the TESLA Test Facility (TTF) and, shortly afterwards, led the machine coordination of the newly established FLASH FEL user facility. Under his guidance, FLASH grew into a world-leading source of ultrashort extreme-ultraviolet and soft X-ray pulses for cutting-edge scientific experiments. Siggi’s scientific achievements were widely recognised for their quality and originality. His passing is a profound loss to the accelerator physics community.

Future Day for girls and boys

25 April was Future Day for girls and boys throughout Germany. Pupils were invited to the DESY campuses in Hamburg and Zeuthen to gain their first practical insights into the world of work and familiarise themselves with the variety of apprenticeships and study opportunities. This annual day of action for initial career orientation successfully contributes to overcoming the traditional, gender-specific categorisation of professions.

The young guests were given an insight into working life at DESY.

May

BEETLE – compact lasers for medical and industrial applications

The BEETLE project aims to advance laser-based secondary-radiation technology for medical and industrial applications by developing compact, efficient femtosecond lasers. In a collaboration between DESY, TRUMPF Scientific Lasers, Active Fiber Systems, the University Medical Center Hamburg-Eppendorf (UKE) and the affiliated partner Fehrmann, the project focuses on compressing pulse durations of ytterbium lasers to just 10 fs without sacrificing performance. Funded with 7.8 million euros by the German Federal Ministry of Education and Research (BMBF), BEETLE supports the market readiness of laser plasma acceleration, especially in radiological medicine. As part of the Hi-Acts innovation platform, BEETLE exemplifies successful collaboration between research and industry to accelerate technology transfer.

The BEETLE project team at the kick-off meeting

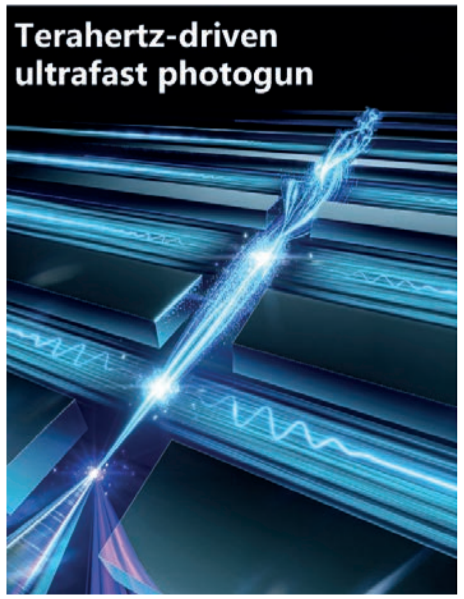
Science on tap: Cutting-edge science in a cosy atmosphere

Can cancer be cured in a fraction of a second? How do you unravel a 5000-year-old letter secret? And how do you trick artificial intelligence with maths? Once again, the “Science on tap” event brought researchers from all disciplines to Hamburg’s bars and pubs. On 2 May, curious visitors were given insights into the world of science in entertaining lectures and then had the chance to chat with the speakers over a drink.

First practical terahertz-powered ultrafast photogun

A team from Shanghai Jiao Tong University, DESY and Universität Hamburg developed the first practical terahertz-driven photogun, a major advancement in ultrafast electron source technology. Their novel, compact device uses terahertz radiation – naturally synchronised with the optical trigger pulse initiating the process under study – for high-gradient electron acceleration, achieving energies around 14 keV and exceptional beam quality.

Key innovations include a multicell waveguide design, a movable cathode for phase control and an integrated rebunching cell that compresses electron bunches to 167 fs. The study also demonstrated high-quality electron diffraction and projection microscopy, showing the strong potential of the photogun for applications in compact, high-performance research instruments. The breakthrough, published in *Nature Photonics*, sets new records in energy, beam quality and acceleration gradient for terahertz-powered devices.



Artistic representation of the principle of the photogun. Electrons are generated, accelerated and manipulated in a millimetre-scale multicell cavity.

June

Science City Day: Welcome to DESY!

On 1 June, DESY and its campus partners opened their doors and showed their future neighbours what they can look forward to. On the occasion of the Science City Day, the research centre invited the public to a big open day on the campus in Hamburg-Bahrenfeld. Over 1000 volunteers gave guided tours, inflated balloons, conducted experiments and encouraged people to do them themselves, and talked about science from morning to night. Visitors were able to enter the huge experimental halls and experience science up close, understandable and hands-on, in more than 100 events, activities and lectures. In total, around 15 000 people attended the event and were given an insight into research and the other activities on campus.

With the planned Science City Hamburg Bahrenfeld, science faculties of Universität Hamburg are moving to the Bahrenfeld district, and university buildings, a conference centre, flats, innovation centres and everything else a growing science district needs are being built on the site of the former racecourse in Bahrenfeld. The DESY campus is right at the heart of it all.

June

FLASH upgrade

Since 10 June, one of the two free-electron laser (FEL) beamlines at FLASH has been undergoing a comprehensive modernisation, scheduled to continue through August 2025. The first beamline (FLASH1) is being completely redesigned to support externally seeded FEL operation at 1 MHz. As part of this effort, 110 m of the beamline are being dismantled and rebuilt. The new configuration will enable polarisation control of FEL pulses with narrow bandwidths, at wavelengths ranging from 40 nm down to 4 nm. This upgrade marks a major advancement and opens up exciting new opportunities for research at FLASH.

Transatlantic Big Science Conference 2024 kicks off in Berlin

Opening ceremony of the Transatlantic Big Science Conference 2024

The second Transatlantic Big Science Conference took place in Berlin on 27–28 June, bringing together key figures from the realms of science and politics from across the USA, Europe and beyond. This landmark event aims to enhance transatlantic cooperation in research and technology, fostering sustainable and reliable partnerships to address global challenges and set the groundwork for common research policies.

Network "Kleine Forscher Hamburg" celebrates fifth birthday

On 18 June, the network "Kleine Forscher Hamburg" – now called "Neugier ahoi!" – celebrated its fifth birthday at DESY. The network primarily offers training courses aimed at educational specialists and teachers in Hamburg's day-care centres and primary schools. The topics range from maths, computer science, natural sciences and technology to education for sustainable development and are always based on children's everyday lives. Since its launch at DESY, the network has processed almost 2000 applications. Nearly 200 day-care centres and primary schools have taken part in a training course for the first time, and many specialists return to the training courses again to continue their education.

Celebrating five years of "Kleine Forscher Hamburg" (from left): Bettina Schmidt ("Kleine Forscher Hamburg"), Margret Lohmann ("Kinder forschen" Foundation), Kay Petersen (Hamburg Authority for Labour, Health, Social Affairs, Family and Integration), Beate Heinemann (DESY) and Inken Stobbe ("Kinder forschen" Foundation)

Parliamentary breakfast in Berlin

At the DESY PETRA IV parliamentary breakfast on 27 June in Berlin, members of the German Bundestag and research leaders discussed the importance of linking science, industry and applied research. DESY's flagship project PETRA IV – the upgrade of its existing synchrotron radiation source PETRA III to the world's most brilliant X-ray source of its kind – was highlighted as a vital tool for advancing innovation, medicine and technological sovereignty, with strong support from politics, academia and industry.

July

Behind the scenes of DESY's general power supply

How does electricity actually get to DESY, and how is it distributed on campus? In early July, DESY's general power supply team opened the doors of Building 16 to interested parties for Switchgear Open Day. The new building houses the modernised switchgear of Mainstation A, which now ensures a more stable power supply. This is particularly important for the operation of the sensitive accelerators. Mainstation B is currently being modernised. The entire project costs 6 million euros and is being financed with funds for non-scientific infrastructures.

Markus Faesing and his team presented the new Mainstation A.

The 2024 summer students at the DESY campus in Hamburg

Summer student programme and Ukraine summer school begin at DESY

In summer 2024, a total of 112 participants from 27 countries performed research on the Hamburg and Zeuthen campuses for seven weeks as part of the DESY summer student programme. This year's novelty: For the first time, a DESY–Ukraine summer school was held simultaneously, with 14 participants coming from Ukraine. Due to the many positive responses from participants of the earlier DESY–Ukraine winter school, the organisers around Olaf Behnke had decided to offer even more places for Ukrainian students this year.

Otto Haxel Dissertation Prize for Kaja Schubert

DESY physicist Kaja Schubert received the Otto Haxel Dissertation Prize 2021 at the summer reception of the Karlsruhe Institute of Technology (KIT) on 15 July for her doctoral thesis entitled "The electronic structure and deexcitation pathways of biomolecular ions", which she had completed in the DESY Photon Science Division and at the University of Göttingen. As the whole awarding procedure was delayed because of the COVID-19 pandemic, the official handover had to be postponed until 2024. Since summer 2021, Kaja Schubert has continued to work at DESY as scientific project manager for the KALDERA laser in the Plasma Acceleration and Lasers group in the Accelerator Division.

Kaja Schubert (centre) at the presentation of the Otto Haxel Dissertation Prize

Strengthening cooperation with BTU Cottbus-Senftenberg

DESY and the Brandenburg University of Technology Cottbus-Senftenberg (BTU) are exploring closer cooperation, particularly in the field of healthcare innovation in the Lusatia region. During a visit to DESY's Zeuthen campus, BTU representatives showed strong interest in PITZ, the only research-focused particle accelerator in Brandenburg. PITZ plays a key role in developing advanced radiotherapy techniques, such as *FLASH* radiation therapy, which could significantly reduce treatment times and side effects for cancer patients. The visit marked a promising step towards intensified collaboration and joint regional innovation projects.

BTU Vice President for Research and Transfer Michael Hübner and BTU President Gesine Grande (both left) visited PITZ at DESY in Zeuthen.

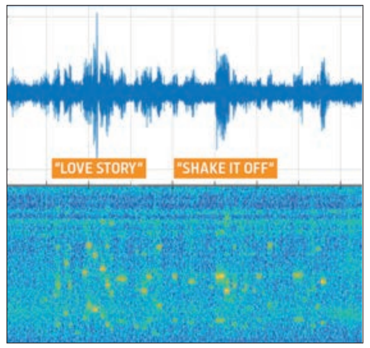
DESY team wins "Hamburgiade" 2024

More than 500 participants from around 80 companies and company sports associations competed against each other in 48 different sport events at the two-week "Hamburgiade", organised by the Hamburg Company Sports Association. DESY, which came ninth last year, won eight gold, eight silver and three bronze medals, bringing the "Hamburgiade Merkur" challenge cup to the campus for the first time.

July

"Swift quakes" in the accelerators

During pop superstar Taylor Swift's concerts at Hamburg's Volksparkstadion on 23 and 24 July, sensitive scientific instruments at DESY were able to detect the resulting ground vibrations, known as "Swift quakes". The seismic and geo-acoustic measurement network WAVE, which uses 19 km of fibre optic cable with 19 000 sensors and extends from Science City Hamburg Bahrenfeld to the European XFEL X-ray laser facility in Schenefeld, recorded the tremors caused by the enthusiastic fans. Researchers even provided a live stream of the seismic data. Located around 2 km from the stadium, WAVE registered the strongest vibrations during the song "Shake It Off". The WAVE network is a collaboration between Universität Hamburg, DESY, Helmut Schmidt University, GFZ Potsdam and European XFEL and measures such vibrations in order to counteract their influence on measurements at the PETRA III and European XFEL light sources and the ALPS II dark matter experiment, which all require extremely precise tuning.



WAVE's 19 000 sensors help scientists to monitor ground movements that could affect their data in the PETRA III and European XFEL facilities.

August

SRI 2024: Top X-ray researchers meet in Hamburg

From 26 to 30 August, DESY and European XFEL hosted the 15th International Conference on Synchrotron Radiation Instrumentation (SRI) at the CCH Congress Centre in Hamburg. The event brought together over 1200 experts from 210 institutions across 34 countries, making it the world's leading forum for advancing instrumentation at large X-ray light sources, such as the European XFEL and DESY's own facilities. First held in Hamburg in 1982, the SRI conference has since taken place every three years at locations around the globe.

60 years of research with synchrotron radiation at DESY

DESY's success story began in 1964, when pioneering physicists launched the first particle beams through what was then the largest particle accelerator in the world – the DESY electron synchrotron, which laid the groundwork for visionary research and an X-ray revolution. On 26 August 2024, DESY marked the 60th anniversary of research with the powerful radiation produced by its accelerators with a festive colloquium attended by 300 guests. The event also honoured the farewell of Edgar Weckert as DESY Director in charge of Photon Science. Weckert joined DESY in 2000, led the PETRA III project from 2004 and joined the Directorate in 2008. He has now returned to scientific research at DESY.

September

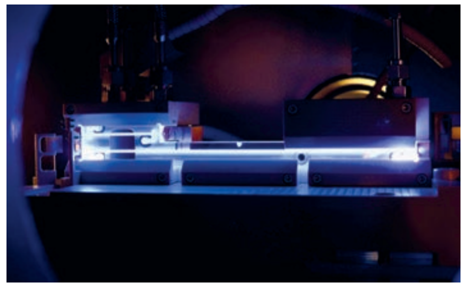
CERN School of Computing held in Hamburg

Participants of the CERN School of Computing

DESY hosted the 2024 CERN School of Computing, a two-week school designed for computer scientists and physicists with an interest in computing. A total of 70 students from 32 countries were trained by computing experts from CERN and elsewhere in lectures and hands-on exercises – and enjoyed Hamburg for two weeks.

FLASHForward achieves critical acceleration quality

For the first time, a research team at DESY's FLASHForward plasma accelerator has successfully preserved the emittance of particle beams during acceleration, a crucial step for improving plasma accelerators. By carefully controlling the electron bunch and plasma properties, the team maintained the beam's transverse quality, which is essential for applications like particle colliders and free-electron lasers. The breakthrough, published in *Nature Communications*, could enable plasma accelerators to serve as compact energy boosters, enhancing X-ray energy while preserving beam quality, and opens up new possibilities for advanced accelerator technologies.



The FLASHForward plasma cell at work

October

Strong signal of solidarity with science in Ukraine

A delegation from DESY led by DESY Director Helmut Dosch travelled to Kyiv to demonstrate its solidarity with the Ukrainian scientific community. The exchange with the students of Taras Shevchenko National University, including participants of the EU-funded EURIZON project, clearly showed the challenges that young Ukrainian scientists are facing in times of war. Dosch emphasised that freedom of science and international cooperation are the cornerstones of every democratic society. Peaceful coexistence on the basis of international law is an indispensable prerequisite.

Helmut Dosch during a meeting with students at Taras Shevchenko National University, Kyiv

DESY joins Lasers4EU network

DESY has joined the Lasers4EU network, adding five laser setups dedicated to ultrafast science to the network's portfolio. These include two lasers in the attosecond range, one laser in the picosecond range for high-energy materials science applications and two femtosecond lasers, one of which can generate several colours simultaneously. Lasers4EU is a European network that provides coordinated access to 27 laser installations across Europe, fosters collaboration and advances laser research. DESY's membership strengthens European laser research and provides opportunities for training and collaboration within the wider scientific community.

DESY spirit during cleanup after fire in electronics room

Everybody felt great relief after a fire broke out on the night of 29 October in the central electronics room of the DESY II booster synchrotron, the pre-accelerator for PETRA III. The fire was quickly extinguished thanks to the determined efforts of DESY's technical emergency service and the Hamburg Fire Department. The close cooperation across all DESY divisions and a strong team spirit enabled the facility to be put back in operation within just three weeks. A dedicated cleaning line was set up to remove soot and fire residues from sensitive electronics, with teams working in shifts. Valuable lessons have been learned from the experience of this incident. The event both demonstrated the effectiveness of DESY's teamwork and provided insights for improving future safety and operational reliability.

A complete cleaning line for removing soot and extinguishing-powder residues from electronic components was set up in the Test Beam hall. Thanks to the concerted effort, damage was minimised, everything cleaned up, and user operation resumed.

November

PETRA IV – moving forward towards funding

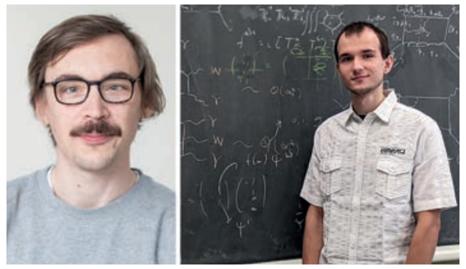
The German Federal Ministry of Education and Research (BMBF) officially confirmed the participation of PETRA IV in the "National Prioritisation Procedure for Large-scale Research Infrastructures". A team from DESY had submitted a corresponding concept, which is currently being evaluated. In addition to the expected gain in scientific knowledge, the concepts will be evaluated on their innovation and transfer potential, the sustainability of construction and operation as well as the costs and risks. The BMBF plans to publish a shortlist of the best projects in summer 2025.

Rendering of the tunnel of the proposed X-ray source PETRA IV

November

DESY Day 2024

DESY Day was held on 13 November to recognise scientific achievements, welcome newly appointed scientists and honour long-standing contributions from DESY staff. The event featured research highlights, the presentation of awards and prizes, the Jentschke Lecture and opportunities for exchange across the DESY community.



Sören Jalas and Florian Lorkowski received the 2024 VFFD PhD Thesis Prize.

The PhD Thesis Prize of the Association of the Friends and Sponsors of DESY (VFFD) was awarded in equal parts to Sören Jalas from the Plasma Acceleration and Lasers group for his thesis "Machine-learning-based optimisation of laser-plasma accelerators" and to Florian Lorkowski for his thesis "Measurement and NNLO QCD analysis of jet production in deep inelastic scattering at ZEUS".

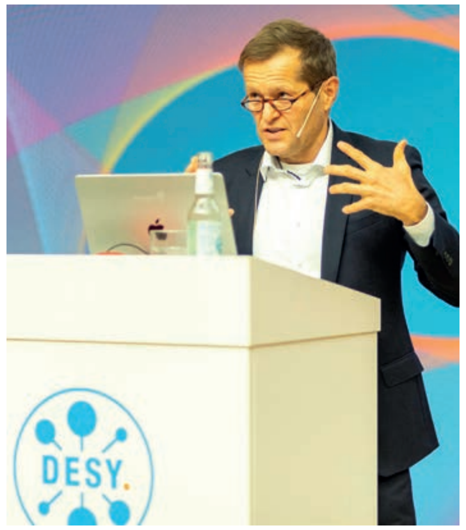
Ludovica Aperio Bella, a particle physicist in the DESY ATLAS group, received the Bjørn H. Wiik Prize, DESY's most prestigious scientific award. The Innovation Award went to Christoph Heyl from the Ultrafast Photonics Research and Innovation group and his team. DESY's Golden Badge of Honour was awarded to Ulrich Gensch, who served as leading scientist and representative of the DESY Directorate in Zeuthen from 1998 to 2012.

As in previous years, four scientists – each representing one of DESY's research divisions – offered a glimpse into their fascinating work, each in just 150 seconds. Representing the Accelerator Division, physicist Marie Kristin Czwalinna from the Beam Controls group highlighted the topic "Synchronisation: A clockwork for the European XFEL as precise as a quadrillionth of a second". She noted that what excites her most about her work is how scientists at DESY are constantly pushing the limits of what is technically feasible.

Marie Kristin Czwalinna represented the Accelerator Division in the scientific highlights session, where she presented the ultraprecise synchronisation of the European XFEL.

Ferenc Krausz, Director at the Max Planck Institute of Quantum Optics and one of the three researchers awarded the 2023 Nobel Prize in Physics for his work in attosecond laser science, delivered an engaging talk for the Jentschke Lecture, in which he shed light on the insights gained from probing subatomic motion and explored innovative applications of the technology. During his visit, he toured DESY's laboratories, sparking intriguing discussions about the future of attosecond science.

Prize winners, highlight speakers, newly appointed scientists and other contributors joined in celebrating DESY Day.



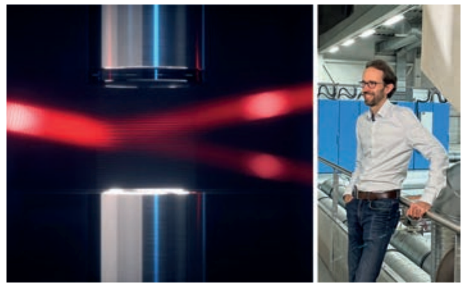
Nobel Laureate Ferenc Krausz gave the 2024 Jentschke Lecture.

December

DESY Innovation Award for Christoph Heyl

The 2024 DESY Innovation Award was awarded to Christoph Heyl and his team from DESY, the Technical University of Darmstadt and Aalen University for their project "Gas-phase sono-photonic light control". The team developed a method to control light in air or gases using intense ultrasound, enabling new applications in laser plasma acceleration, semiconductors, healthcare and manufacturing. The award highlights the strong innovation potential of basic research and recognises high-impact, market-relevant technologies developed at DESY.

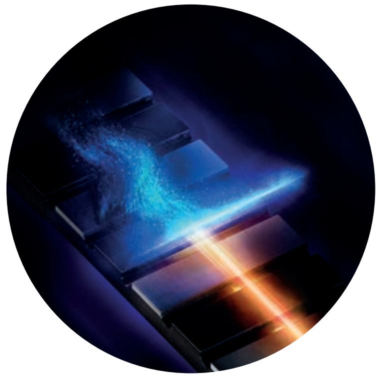
In December, Christoph Heyl, who is a research group leader in the DESY Photon Science Division and at the Helmholtz Institute Jena, was also awarded a prestigious ERC Consolidator Grant for his research project "Gas Phase Sonophotonics (GASONIC)".



The 2024 DESY Innovation Award went to Christoph Heyl.

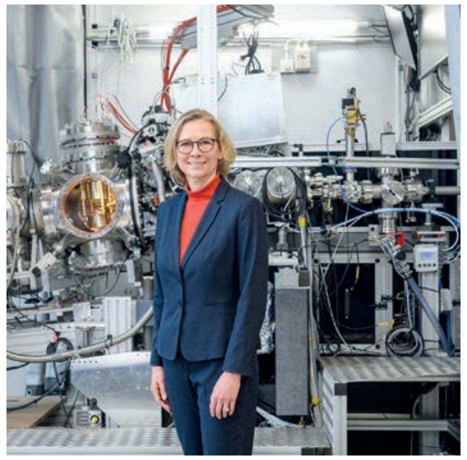
Squeeze it! Attosecond pulses at the European XFEL

Researchers at European XFEL and DESY have made a significant advance in X-ray science by generating attosecond hard X-ray pulses at megahertz repetition rates – marking a new milestone for ultrafast science. Published in *Nature Photonics*, their method enables high-power, ultrashort pulses using a novel self-chirping approach that preserves the electron bunch charge, achieving terawatt-scale peak power. This innovation allows atomic-scale imaging without damaging samples and enables the observation of ultrafast electron dynamics. The results are expected to accelerate research in fields ranging from biology and chemistry to quantum materials and condensed matter physics.



Highly accelerated electrons (blue cloud) are strongly compressed with the help of special beam optics (bright line in the centre). This leads to very bright X-ray pulses (yellow) with pulse durations of only a few hundred attoseconds and powers in the terawatt range.

Britta Redlich to become new Director in charge of Photon Science at DESY



As of 1 January 2025, Britta Redlich will be the new Director in charge of Photon Science at DESY. The chemist and professor of experimental physics was previously the director of the FELIX free-electron laser facility and the High Field Magnet Laboratory of Radboud University in Nijmegen, the Netherlands. She is a senator of the Helmholtz Association for the research field Helmholtz Matter and a member of international consortia, such as LEAPS, LaserLab Europe and FELs of Europe. Britta Redlich succeeds Edgar Weckert, who led the Photon Science Division for 16 years.

Breaking ground for new technology and start-up centre at DESY

A combined total of over 8500 m² of workspace for the new DESY Innovation Factory will be created in three years of construction at two locations: the main site on the DESY campus and a second close by in the Altona Innovation Park. Complex laboratories, offices and open working environments will be built to foster the flow and transfer of knowledge and technology from research to industry and society.

Breaking ground for the DESY Innovation Factory (from left): Helmut Dosch (DESY), Volkmar Dietz (Federal Ministry of Education and Research), Melanie Leonhard (Hamburg Senator for Economics), Eva Gümbel (Hamburg State Councillor for Science), Arik Willner and Hansjörg Wiese (both DESY)

Keeping our facilities at the forefront

The FLASH2020+ upgrade ensures that DESY's FLASH free-electron laser (FEL) facility remains a leader in FEL science. A 14-month shutdown began in June 2024 to implement external seeding. Thanks to DESY's technical groups, engineers and mechanical workshops, the old 110 m long FLASH1 FEL beamline was removed from the tunnel, and the infrastructure is being prepared for the new installation in 2025 (see p. 48).

Picture: Lucas Schaper, DESY

Accelerator operation and construction

PETRA III

Overcoming operational challenges with the DESY spirit

2024 was a year with several challenges for the operation of the synchrotron radiation facility PETRA III at DESY. The extraordinary efforts of all technical groups made the most crucial contribution to minimising the effects of three unforeseen but major faults that occurred at PETRA III in 2024. Two consecutive, almost identical vacuum leaks at the main absorbers in the wiggler sections West and North and a fire in an electronic room of the booster synchrotron DESY II accounted for about 480 h of cancelled user run, corresponding to around 90% of the overall fault time of the storage ring in 2024. This led to a reduction of the availability to only 89.7%.

Manufacturing non-conformities in the wiggler end absorbers

PETRA III's horizontal emittance of 1.3 nm·mrad is achieved by a total of 20 permanent-magnet damping wigglers installed in two long straight sections in the West and North of the storage ring. A single wiggler generates a synchrotron radiation power of about 25 kW at a beam current of 120 mA. Each wiggler is therefore followed by a synchrotron radiation absorber to protect downstream components. At the end of each wiggler section, the accumulated on-axis power of 10 wigglers reaches about 80 kW, which need to be captured by larger end absorbers, one in the straight section West and one in the straight section North. At the time of construction of PETRA III, these components in the wiggler sections were manufactured at BINP in Novosibirsk, Russia, in collaboration with DESY, including one spare for each critical component.

On 7 May 2024, a deterioration of the vacuum was detected in the region of the western end absorber. A small leak at a flange in this multisectional absorber was discovered and initially provisionally glued. Ultimately, however, the absorber had to be replaced by the spare absorber in the last week of May. As a consequence, seven days of user run had to be cancelled, but were partially rescheduled as test run during vacuum conditioning. Figure 1 shows the successfully installed spare absorber in the wiggler section West.

Figure 1
Main absorber in the wiggler section West after installation of the spare absorber

Figure 2
View inside the damaged absorbers of the wiggler sections West (top) and North (bottom)

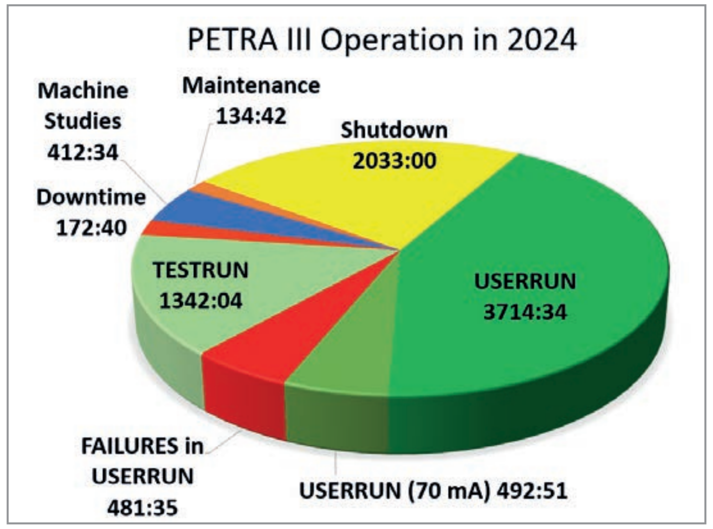


Figure 3
Time distribution of PETRA III machine states in 2024 [hours:minutes]

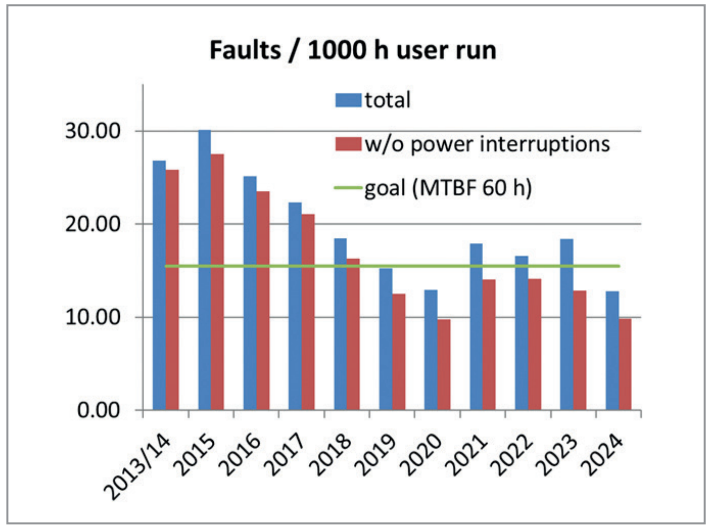


Figure 4
Long-time development of the number of faults during user runs

On 6 June, a similar situation was detected at the end absorber in the wiggler section North. Since a second spare did not exist, the deinstalled western absorber had to be repaired. The vacuum leak at the northern absorber could be glued and, with a reduction of the total electron beam current to 70 mA, user operation could be continued until the service week at the beginning of July 2024, when the repaired western absorber was installed in the wiggler section North. Figure 2 shows a view inside the damaged parts of the two absorbers after opening. Both exhibit melted copper in the upper right corner and a manufacturing non-conformity (inner diameter approximately 1 mm too small), which was mitigated during the repair.

Operation in 2024 and plans for the next run period

Regular user operation resumed on 23 February 2024 after a commissioning and study period of about two weeks. Eventually, 4689 h of beamtime were scheduled for the user run and delivered with an availability of 89.7%. About 90% of the user run downtime of 481 h in total was caused by the aforementioned absorber faults and a fire in an electronic room of the DESY II booster synchrotron on 28 October, which required extensive cleaning of electronic equipment and prevented operation of the PETRA III complex for about 29 days. The time distribution of the different machine states in 2024 is shown in Fig. 3. In addition to the total of 4207 h delivered for the user run, 1342 h of test run time could be provided to the users. 47% of the user time was allocated to the 480-bunch mode and 53% to the 40-bunch mode. The category "Failures" in Fig. 3 corresponds to faults during the user run, while faults during the test run are counted in "Downtime".

The long-time development of the number of faults during user runs of PETRA III normalised to 1000 h of user run time is shown in Fig. 4. The blue bars represent the total number of faults, while the red bars exclude faults caused by power interruptions, most of which are short power glitches (of less than 120 ms) that cause beam loss. The green line indicates the number of faults corresponding to the target average mean time between failures (MTBF) of 60 h, which was met in 2024 with an MTBF of 69 h.

In 2024, the focus of the machine development programme was on supporting the technical design of PETRA IV. Nevertheless, a number of special studies, such as a collaboration with CERN on robotics (see p. 40), were also successfully carried out.

It was observed that many cables in the wiggler sections suffered from radiation damage. An extended replacement campaign was therefore planned for the winter shutdown 2024/25. In addition, an inspection of the wiggler section North was part of the work during the shutdown, not least to clarify the cause of the absorber faults. The operating year 2025 will be a regular year with at least 4680 scheduled hours of user run.

Contact: Rainer Wanzenberg, rainer.wanzenberg@desy.de
Michaela Schaumann, michaela.schaumann@desy.de

FLASH

High availability for user experiments, FEL and accelerator research

The FLASH free-electron laser (FEL) facility at DESY features a common photoinjector and superconducting linear accelerator that serves two undulator beamlines – FLASH1 and FLASH2 – in parallel. A third beamline hosts the beam-driven plasma wakefield acceleration experiment FLASHForward. In 2024, the linear accelerator delivered beam for a total of 3774 h for user experiments, FEL developments, photon beamline and experimental station R&D as well as accelerator-related experiments. The second big shutdown of the FLASH2020+ upgrade project, which will convert FLASH1 into an externally seeded FEL with variable polarisation, began on 10 June 2024.

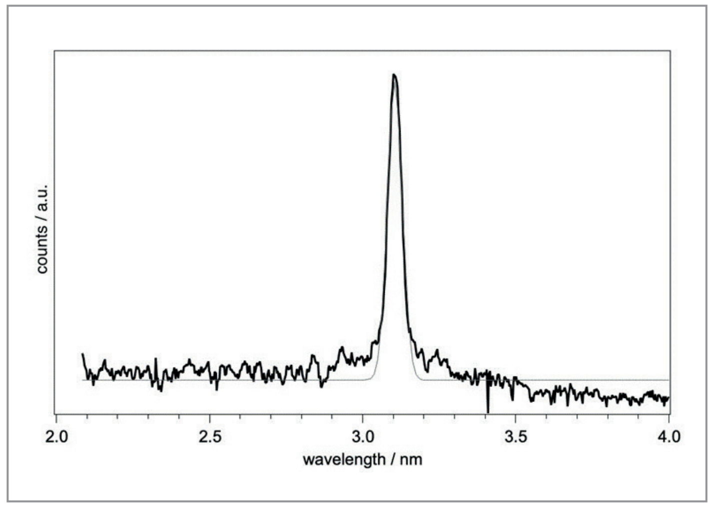


Figure 2
SASE spectrum measured at FLASH2

Operation

In 2024, the FLASH linear accelerator delivered beam for 3774 h. Of these, 1886 h were devoted to user experiments, 1103 h to FEL studies and preparation of user experiments and 785 h to accelerator R&D (Fig. 1). The beamtime for users includes the time required for setup and tuning of the experiments. The FLASH team has worked hard on streamlining the corresponding procedures. As a result, a record low of 6.7% at FLASH1 and 8% at FLASH2 of user beamtime required for initial setup and tuning was achieved in 2024. For comparison, 21% were required for tuning in 2014 and 12% in 2019. In 2024, the availability of the facility was at 98.1% overall. The downtime for users amounted to 2.3% at FLASH1 and 1.8% at FLASH2.

As part of the FLASH2020+ upgrade project, the photocathode lasers were successfully replaced by modern, flexible laser systems called NEPAL (NExt generation PhotocAthode Laser), developed at DESY [1]. The former photocathode laser systems, developed at the Max Born Institute in Berlin, were installed in 2010 and 2012 and operated continuously and very reliably up to 2024. The new lasers went into standard operation in January 2024 and are working very stably.

The highest power consumers at FLASH are the radio frequency (RF) stations and the cryogenic plant. In April 2024, the setting of the RF stations and the low-level radio frequency (LLRF) system were optimised to reduce the power load while preserving the maximum beam energy and possible number of bunches. The power required to operate all FLASH RF stations could be reduced from 825 kW to 620 kW, i.e. by around 25%.

Operation at the maximum electron beam energy of 1.35 GeV could be established, and self-amplified spontaneous emission (SASE) pulses with wavelengths down to 3.2 nm in the fundamental were achieved with a pulse energy of about 6 μJ (Fig. 2). In May 2024, FLASH was operated very reliably and stably at maximum electron beam energy for a full user block of four weeks. The first successful user experiments exploiting the variable polarisation of the APPLE-III-type afterburner undulator were also carried out within this block. This afterburner undulator serves as a prototype for the future FLASH1 undulators. A new access mode was also tested to increase the efficiency of the facility. In the standardised access mode, five different user experiments were performed within two weeks using the same FEL setup and the same end station, with FEL pulses at 3.8 nm and 5.4 nm with a bandwidth below 0.5% and pulse durations of about 50 fs.

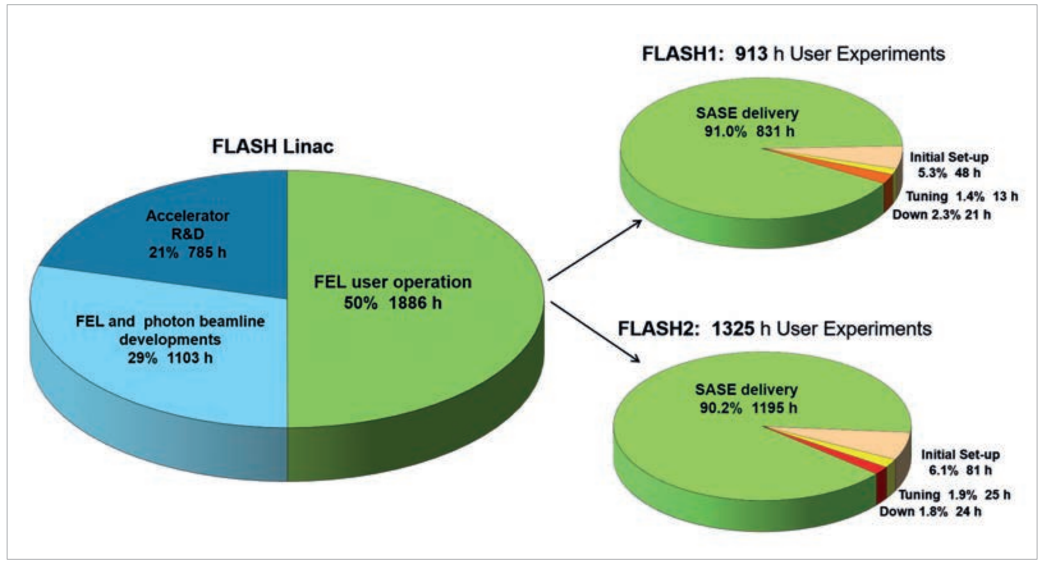


Figure 1
FLASH operation statistics in 2024. A total of 3774 h of accelerator beamtime could be delivered. Of these, 1886 h were devoted to user experiments. The time for setup and tuning of experiments prior to handover is indicated in the apricot-coloured slice.

The experimental campaign FLASH Laser-Assisted Reshaping of Electron bunches (FLARE), performed in collaboration with TU Dortmund University, proved the concept of generating non-uniform heating of electron bunches with a special laser heater setup and enabling control of the FEL pulse length. It was demonstrated that partial overheating can reduce the radiating region and thus generate short FEL pulses. The concept of local bunch compression within the bunch to generate high current spikes was shown and is being further investigated for optimised generation of ultrashort FEL pulses.

The X-Ray Oscillator project, carried out in collaboration with Universität Hamburg, demonstrated a transversely fully closed X-ray cavity. A complete roundtrip along the cavity was performed, and future experiments are planned.

The beam-driven plasma wakefield acceleration experiment FLASHForward demonstrated the acceleration of a 1.2 GeV FLASH beam to an energy of 1.7 GeV within a 500 mm plasma cell, and thus an energy gain of 0.5 GeV. In addition, studies for MHz bunch train acceleration in a plasma wakefield accelerator were started.

Upgrade towards an externally seeded FLASH1 facility

The FLASH2020+ project aims to increase the capabilities of FLASH. The FLASH team is working hard to successfully realise the upgrades in order to complete the second shutdown, which began in June 2024. This upgrade will transform FLASH1 into a modern, externally seeded FEL beamline at high repetition rate. FLASH1 will then generate tuneable, multicolour, near transform-limited, fully coherent FEL pulses.

The upgrade includes the replacement of the fixed-gap, planar undulators of FLASH1 by variable-gap APPLE-III-type undulators with controllable polarisation. However, varying the undulator gap affects the electron beam transport, particularly in the low-energy regime. A new compensation algorithm was therefore developed that can cope with the effects of the undulators in FLASH1 (but also in FLASH2).

The FLASH team is very grateful to the DESY support staff for enabling the reconstruction of the FLASH1 beamline to achieve exceptional machine performance.

Contact:
Juliane Rönsch-Schulenburg, juliane.roensch@desy.de

Reference:

[1] C. Li *et al.*, Proc. IPAC2021, WEPAB379 (2021)

European XFEL accelerator

Record delivery hours, availability and bunch usage

The European XFEL accelerator complex – which is run by DESY – was operated for more than 7500 h in 2024, with 4800 h of X-ray delivery and an impressive availability of 95.6%. This record number of delivery hours, availability and actual usage of electron bunches enabled productive use of the facility in its scientific harvesting phase. Key achievements included replacing cold compressor motors to eliminate frequent downtimes and improving radio frequency (RF) pulse controls, which reduced energy consumption by 10–15%. Advanced operation modes, such as ultrashort pulses and high photon energies up to 30 keV, have expanded experimental capabilities. A major six-month maintenance period in 2025 is currently being intensively prepared and will allow safety tests and significant facility upgrades, ensuring state-of-the-art operation and reliability.

Operation summary

In 2024, the European XFEL accelerator complex – consisting of the injector, the 17.5 GeV superconducting linear accelerator, the electron beam distribution system and the beam transport system through the three undulators to the beam dumps – was operated for more than 7500 h, of which a record 4800 h were spent on X-ray delivery to the experiments (Fig. 1). The availability of the facility during X-ray delivery was 95.6%, averaged over all three undulators, which is the highest percentage ever achieved during European XFEL operation. It is also remarkable that, in 2024, more than 25% of the electron bunches available in principle were actually sent through the undulators and thus generated photon pulses. In total, in 2024, the European XFEL produced as many photon pulses as all other hard X-ray facilities together since the year of their respective inauguration.

The excellent availability reflects the unwavering care and diligence that all staff members invested in every subsystem required to operate the facility. Particularly noteworthy is the complete replacement of all cold compressor motors with a newly developed motor type with active magnetic bearings, which eliminated the cause of frequent complete failures of this part of the cryogenic plant, which had resulted in downtimes of up to 36 h in the past. The achievement also marks the successful end of a long-lasting development campaign performed by DESY and the components manufacturer.

In 2024, operation became more reliable and efficient. The development of advanced controls for the RF pulses that accelerate the electrons enabled more energy-efficient operation of the power converters that convert the grid electricity into the RF pulses. This yielded a remarkable 10–15% electricity saving per operation hour, thus compensating for the increase in yearly operation hours (Fig. 2).

X-ray delivery was performed with electron energies of 10.5–16.3 GeV, delivering photon energies of 400 eV – 24 keV to the experiments. In about two thirds of the delivery weeks, free-electron laser (FEL) modes were provided that go beyond standard self-amplified spontaneous emission (SASE) operation. These included special bunch patterns, hard X-ray self-seeding at the SASE2 undulator, two-colour operation at SASE2 and SASE3 as well as short pulses even below 1 fs at SASE2 and SASE3. The re-installed APPLE-X undulators have been partly commissioned, and the possibility to choose the polarisation of the FEL light is in high demand at the SASE3 experiments. All these new features add complexity to the operation of the facility, and the compatibility of operation modes has to be carefully managed.

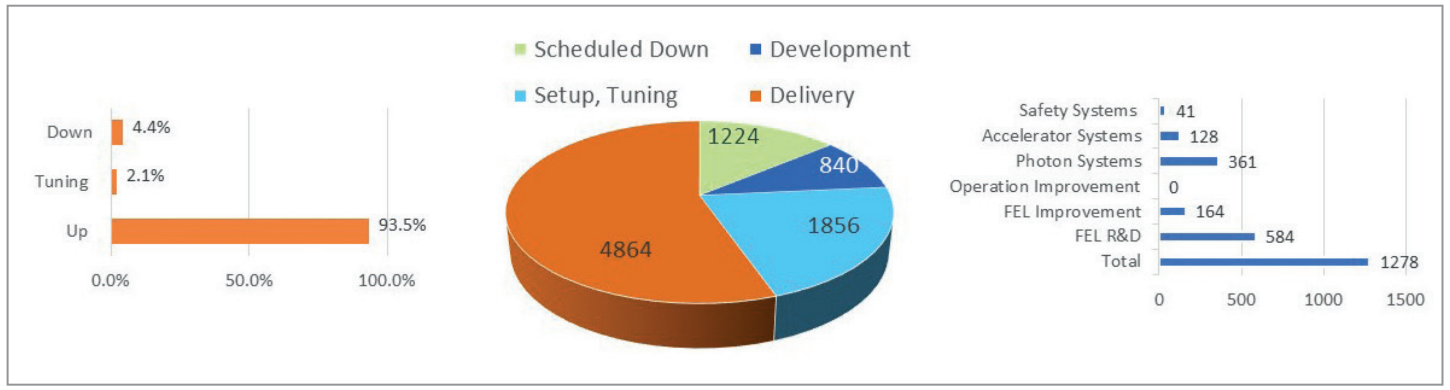


Figure 1
Centre: Distribution of yearly operating hours by category. Left: Average availability during X-ray delivery time in percent. Right: Distribution of development time in hours. Note that the total development hours exceed the scheduled operating hours, reflecting the parallel use of the facility for qualified activities.

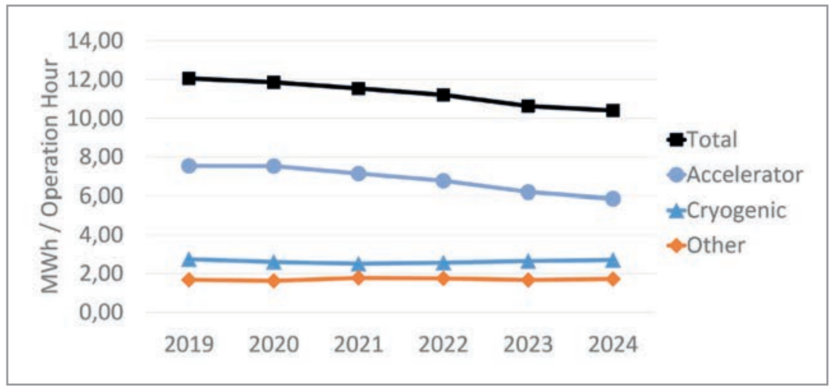


Figure 2
Approximate electricity consumption normalised to operation hours for the accelerator, cryogenic system and all other consumers (including the Schenefeld campus)

Facility development

Facility development beamtimes were devoted to better understanding and diagnosis of the longitudinal phase space, continued development of operation modes beyond standard SASE and research towards advanced radiation schemes.

With the new injector laser system NEPAL, electron bunches can be created in pairs with a distance shorter than the nominal 4.5 MHz. Twin bunches could actually be accelerated within one 1.3 GHz bucket (i.e. with a distance on the order of 100 fs) or in any of the next 1.3 GHz RF buckets (i.e. with a distance of multiples of 770 ps). These modes pose challenges for diagnostics, feedback, high-level controls, safety systems and the setup of proper lasing conditions for each bunch. Initially, exploratory studies were performed, underpinning the feasibility of the operation, but more technical development is needed to include these modes into standard operation.

High photon energies are a unique feature at the European XFEL. User beamtimes with photon energies up to 24 keV were provided, and 30 keV photons were delivered during facility development beamtimes. This operation places highest demands on electron beam formation and undulator alignment, and more experience is gained each time these conditions are set up.

Emphasis was placed on the generation of short (<10 fs) and very short (<1 fs) pulses in both the hard and soft X-ray regime. High electron current spikes can be generated in SASE2 and SASE3, leading to unprecedented intensities at these short pulse lengths. The formation of the current spike is driven by electrical fields that the bunch itself generates during its passage through the accelerator, and it is thus very delicate to control.

Preparations for 2025 maintenance and installation

In 2025, after 8.5 years of continuous operation at 2 K, a mandatory test of the safety valves in the pressure vessels of the accelerator will require a warm-up of all the accelerator modules. The complete procedure of warm-up, tests, reconfiguration and cool-down is scheduled to take about six months. This is the only operation interruption of considerable duration envisioned in the coming years, and the opportunity will therefore be used to perform other upgrades to the facility that would not fit into the regular two- to four-week maintenance periods. Preparation for these activities has been a major focus for many groups in the DESY Accelerator Division.

Contact: Winfried Decking, winfried.decking@desy.de

PITZ

High-brightness electron source developments and applications

In 2024, activities at the PITZ photoinjector test facility at DESY in Zeuthen continued in the three research areas of high-brightness electron beams, high-power THz sources and radiation biology. The focus was on the further development and testing of the next generation of high-brightness electron sources for the European XFEL (Gun 5). Due to the Gun 5 development activities, beamtime at PITZ for other topics was limited (and will still be in 2025). Nevertheless, progress has been made, for example in the utilisation and further development of photocathode laser systems to further improve beam quality, in THz research activities and in research on radiation biology.

Gun 5 production and testing

Gun 5, the new generation of electron sources, was designed to improve operation at the user facilities FLASH and European XFEL. The first gun of this new type, Gun 5.1, had been in operation at PITZ since 2021 and had shown stability issues, which were related to the cathode area, specifically to the radio frequency (RF) contact spring. A breakthrough was achieved in 2024 with the development of a new contact spring design. After promising tests in the laboratory, the new design was implemented into Gun 5.1 and successfully tested for eight weeks before the gun was dismounted from PITZ to prepare the installation of Gun 5.2. As Gun 5.1 showed convincing behaviour with the new contact spring design, the new design is now being implemented and further tested in Gun 5.2 and all new Gun 5-type cavities.

In 2024, the FALCO gun commissioning test stand in Hamburg started operation with the conditioning of Gun 5.2, which was then sent to Zeuthen in November for installation, further conditioning and detailed beam tests. The gun will be put into operation at PITZ in January 2025.

The production of Gun 5.3 was complicated by several problems in the numerous brazing steps, but was finally finished in November 2024. The gun has undergone the final preparation steps, e.g. dry-ice cleaning, in order to be set up in Zeuthen in February 2025. Afterwards, it will be conditioned at FALCO. Production of three further guns continues in the DESY workshops in Zeuthen and Hamburg.

THz FEL R&D activities

In 2024, research on a single-pass, high-gain THz free-electron laser (FEL) continued as part of efforts to develop a prototype THz source for pump–probe experiments at the European XFEL. Further experiments were conducted using an LCLS I undulator and high-charge electron beams from the PITZ photoinjector, and significant progress has been made in the detailed characterisation of the generated THz radiation. First spectral measurements were performed using a Fourier transform infrared (FTIR) spectrometer provided by the FLASH THz group, in collaboration with experts from the FLASH Beamlines and Optics group. These measurements revealed a narrow-band spectrum (<2%) centred around a radiation frequency of approximately 3 THz (Fig. 1). Higher harmonics, including the third and fifth, were also observed. Initial imaging of the THz radiation was carried out using a Pyrocam IIIHR THz camera, yielding a waist of about 0.3 mm root mean square (RMS). Simulations of the THz radiation propagation were performed to support these findings. Specific spectral and spatial measurements along the gain curve were also obtained and showed good agreement with simulation results.

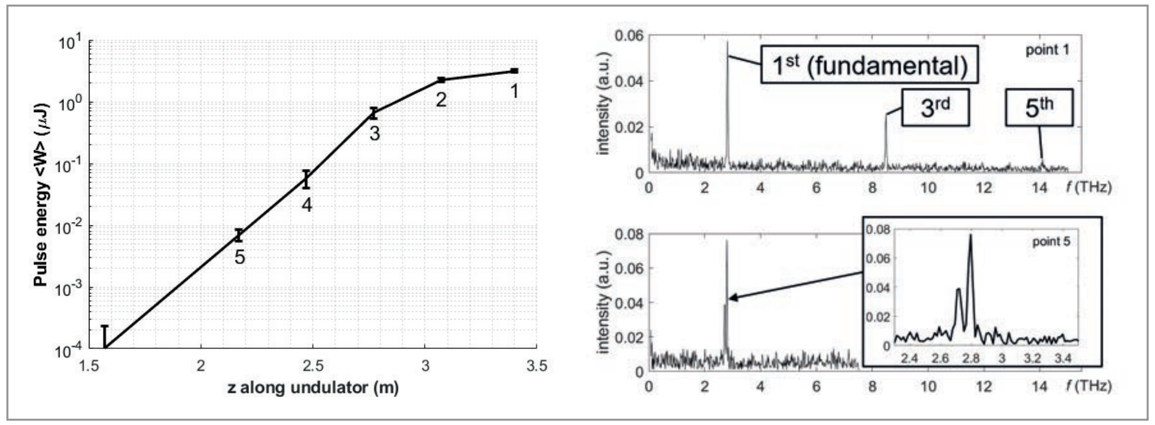


Figure 1
Left: THz FEL gain curve used for spectral measurements. Right: Spectra measured with an FTIR spectrometer for points 1 and 5.

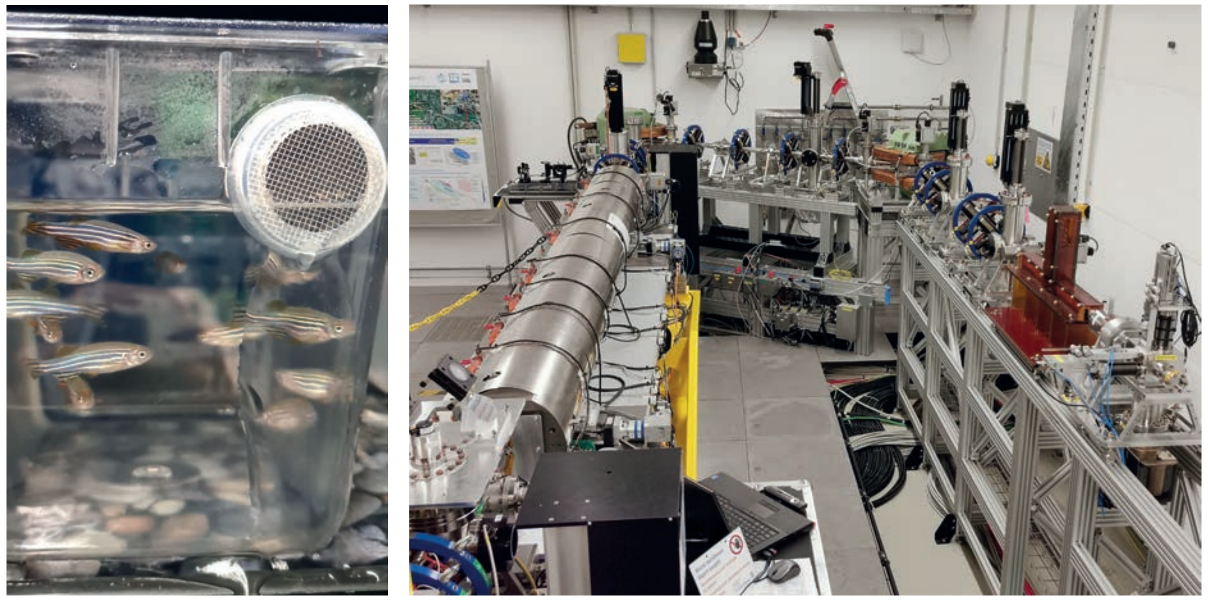


Figure 2
Left: Zebrafish in the fish tank of the laboratory container. Right: Installation of the new FLASH*lab* beamline.

Additional experimental and simulation studies focused on using a 1 nC electron beam, prebunched through a dielectric-lined waveguide, to study new seeding options. Start-to-end simulations, incorporating the PITZ bunch compressor, were also performed. These efforts aim to reduce the required bunch charge for generating high peak power THz radiation while enabling shorter radiation pulses. A proposal how to continue R&D activities at PITZ in the field of THz generation for the next three years was developed and is currently under review by the European XFEL management.

Radiation biology and dosimetry with FLASH*lab*@PITZ

In 2024, the preliminary FLASH*lab* beamline installation was used for different measurements in radiation biology, for both in-house experiments and user experiments of external groups from the German Cancer Research Center (DKFZ), the Federal Institute for Materials Research and Testing (BAM) and the University of Potsdam. The biology laboratory container, which will house the lab's future *in vitro* and *in vivo* experiments, was equipped and put into operation with zebrafish. The Max Delbrück Center for Molecular Medicine (MDC) prepared the genetically varied starting group of 367 fish that was used to initiate fish husbandry at PITZ with support of TH Wildau in August (Fig. 2).

The design of a new beamline dedicated to radiation biology and FLASH radiation therapy (FLASH*lab*@PITZ) was finished, and the beamline is currently being installed, together with the first version of a flexible experimental area that will allow for very different experimental setups. Dosimetry capabilities at PITZ were extended as well, and new collaboration partners have been found to assist the experiments at PITZ over the whole range from dosimetry to *in vivo* experiments and medical applications. To support the activities, proposals for third-party funding are being drawn up – in 2024, a total of about 1.6 million euros was acquired for projects in radiation biology and dosimetry as well as for hardware support, with more proposals under review and in preparation.

Contact: Anne Oppelt, anne.oppelt@desy.de

Microbeam mode at REGAE

New 3 GHz laser enables experiments with micro- and nanocrystals

The new experimental capabilities of DESY's ultrafast electron diffraction facility REGAE have enabled the first successful 3D atomic structure determinations of 2D-layered materials. However, sample preparation for classes of samples has remained challenging, as the current operation mode requires extremely thin but laterally large "pancake-like" samples. To overcome this limitation, a new 3 GHz laser system was implemented, which makes it possible to generate a coherent microbeam at REGAE. This is achieved by spreading the total charge over several thousand bunches instead of only one bunch, thereby tremendously reducing space charge effects. This new operation mode will enable structure determination from nanocrystals as well as microscopy experiments with high spatial resolution on samples that are too thick for conventional lower-energy electron microscopes.

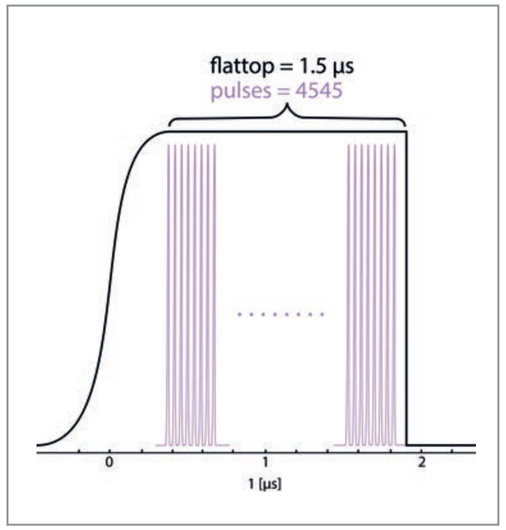


Figure 2

3 GHz pulse train mode: About 4500 bunches are equally distributed over the flat-top RF pulse length of 1.5 µs.

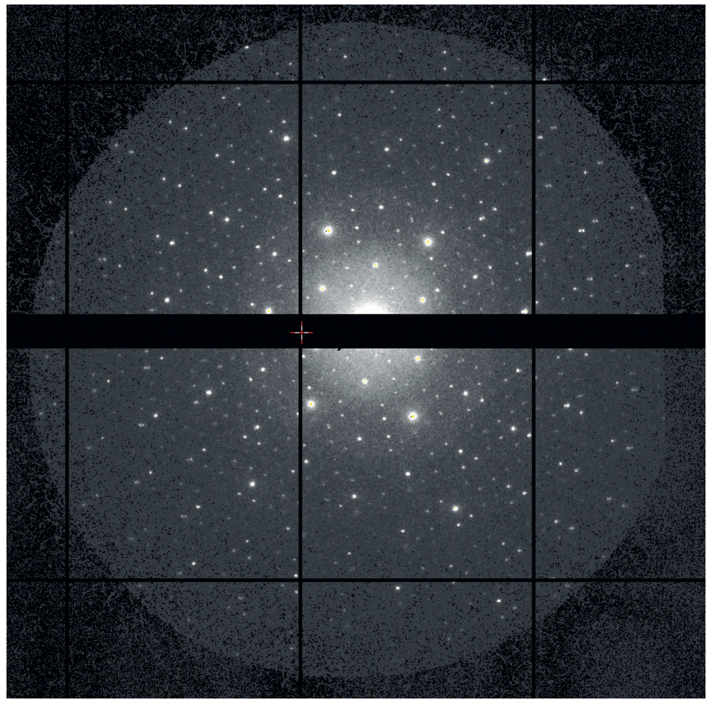


Figure 3

Diffraction pattern from a TaS_2 sample recorded with the new microbeam mode at REGAE, using the 3 GHz laser system developed by the DESY Laser R&D group

New 3 GHz laser system

The 3 GHz laser system was developed by the Laser R&D group at DESY. It is based on the technique of electro-optical frequency comb generation (EO comb) [1]. In addition to enabling very high repetition rates, this approach has the advantage that the radio frequency (RF) field driving the EO comb can be derived directly from the accelerator RF, thus making the laser inherently synchronised to the accelerator. Figure 1 shows the technical realisation in the REGAE laser laboratory. The laser light from a continuous-wave (CW) seed laser at 1030 nm is spectrally broadened by phase modulators, leading to the generation of side bands. An intensity modulator picks segments with linear chirp, which are compressed and further amplified in a fibre-based amplifier. The frequency of the light is quadrupled in a two-stage frequency conversion setup before the light is coupled into the laser-to-cathode beamline by a flip mirror.

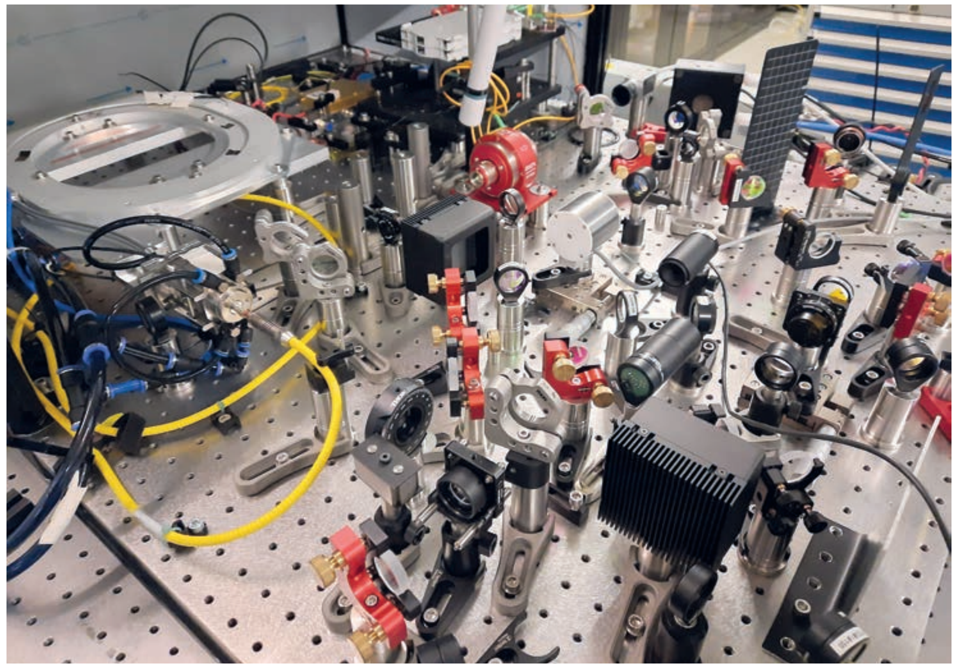


Figure 1

Experimental setup of the new 3 GHz laser system in the REGAE laser laboratory with the fibre amplifier at the top left

Microbeam mode

REGAE is currently operated at a repetition rate of 12.5 Hz. To accelerate the electrons emitted from a photocathode to their final energy of 2–5 MeV, an S-band RF electron source (gun) is typically powered for a period of 2.5 µs. For single-bunch experiments, only one of the 7500 generated RF buckets is filled with a charge of up to 100 fC. In this way, highest temporal resolution can be achieved; however, due to space charge constraints, the transverse beam quality is limited and the beam should not be focused too strongly to avoid further quality degradation.

In the microbeam mode, the RF cavity is rapidly filled and tuned for a flat-top pulse of about 1.5 µs, in which up to 4500 RF buckets are filled with charge (Fig. 2). The pulse train is passed through a collimating aperture, so that the charge per bunch is tremendously reduced, while the integrated charge over the pulse train is again about 100 fC, as required for diffraction experiments. The pulse train now has an extremely good transverse quality and can be focused to small beam size without problems, enabling diffraction experiments with nanocrystals as well as electron microscopy experiments in imaging mode.

The laser was installed in the REGAE laser laboratory and integrated into the accelerator setup so that first photoelectrons could be produced. The energy spread of the pulse train corresponds to the single-bunch energy spread, showing excellent synchronisation with the RF frequency of 3 GHz. However, the ultraviolet conversion of the laser pulse train still needs some improvement in order to be able to generate the specified total charge before beam collimation. First diffraction data were taken without beam collimation.

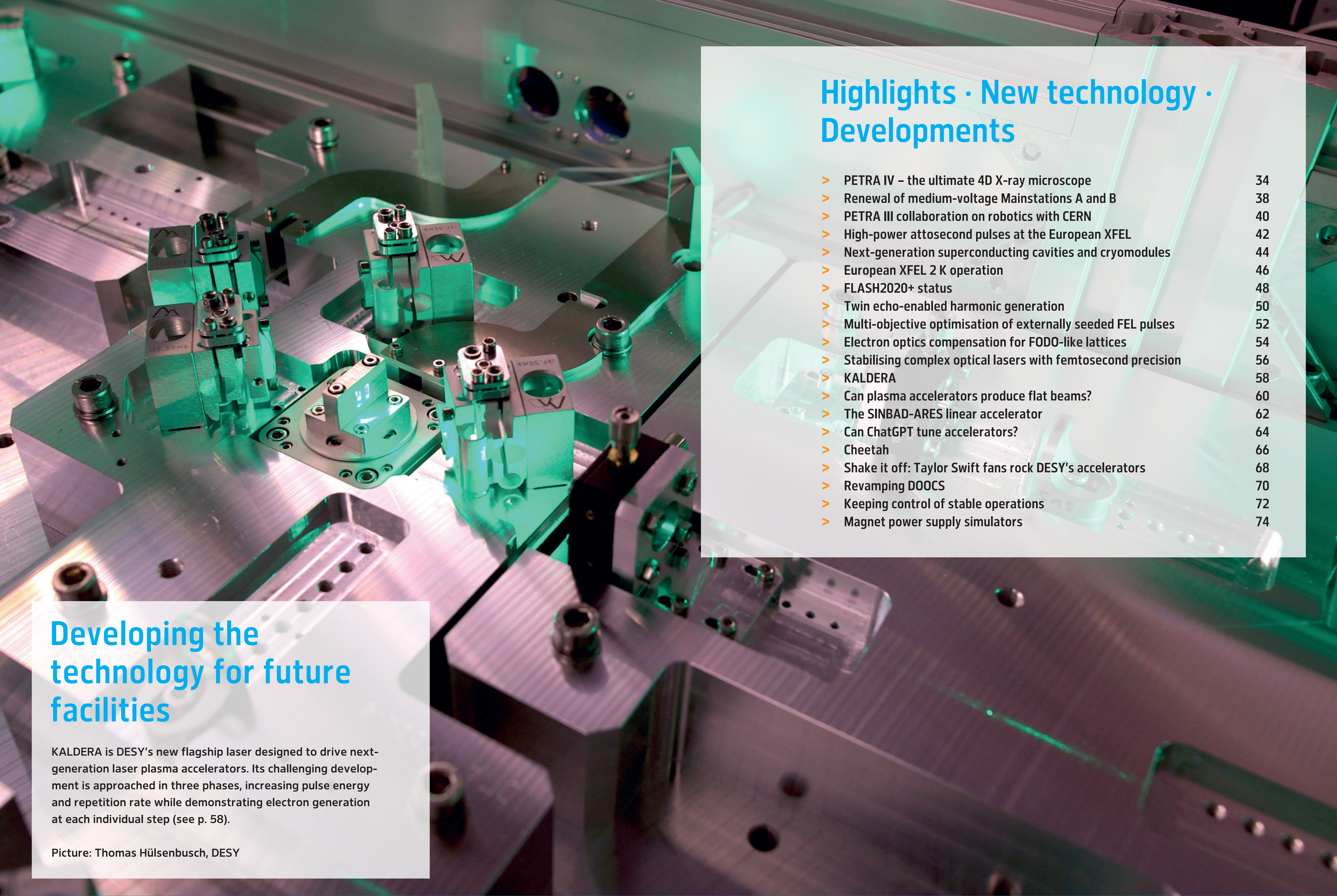
First microbeam diffraction experiments

First diffraction experiments using the new 3 GHz microbeam mode at REGAE were carried out with the existing diffraction setup using a tantalum disulfide (TaS_2) sample with a thickness of 30 nm. An exemplary diffraction pattern from the experiment is shown in Fig. 3. The excellent separation of the diffraction spots highlights the excellent coherence properties and low emittance of the electron beam. With further optimisation of the setup, we expect to further reduce the beam size of 50 µm used for the current experiment down to the envisioned 1–2 µm to enable the measurement of isometric micro- and nanocrystals.

Contact: Alke Meents, alke.meents@desy.de
Klaus Flöttmann, klaus.floettmann@desy.de

Reference:

[1] C. Mahnke *et al.*, EPJ Web Conf. 307, 02030 (2024)



Highlights · New technology · Developments

Developing the technology for future facilities

KALDERA is DESY's new flagship laser designed to drive next-generation laser plasma accelerators. Its challenging development is approached in three phases, increasing pulse energy and repetition rate while demonstrating electron generation at each individual step (see p. 58).

Picture: Thomas Hülsenbusch, DESY

PETRA IV – the ultimate 4D X-ray microscope

Investing in the future of scientific discovery: Major milestones in 2024 bring the next-generation X-ray facility closer to reality

PETRA IV is the planned ultralow-emittance upgrade of the existing PETRA III storage ring. DESY's flagship project will deliver the brightest synchrotron light in the world. This performance is underpinned by the construction of a new 6 GeV storage ring featuring a completely round beam with an emittance of 12 x 12 (pm·rad)², made possible by the lowest-emittance lattice even among the latest fourth-generation light source projects. Academic and industrial users will benefit from the enormous increase in coherent X-ray photon flux, the planned cutting-edge beamlines, the novel experimental possibilities and the new business model in preparation for the facility. It will provide easy on-demand access, extended services and support for non-expert synchrotron radiation users, especially for the processing and analysis of their data. PETRA IV will be a cornerstone of the Science City Hamburg Bahrenfeld.

Key milestones of 2024

The main activities in 2024 were focused on the compilation of the PETRA IV proposal for the prioritisation process for large-scale scientific infrastructures (FIS) of the German Federal Ministry of Education and Research (BMBF). The proposal was submitted in October 2024, and the result of the evaluation is expected by summer 2025. Continued support for the PETRA IV facility design, prototyping and civil engineering planning has been secured with the execution of the PETRA IV Preparation Project. In fact, with the federal budget law passed in February 2024, 40 million euros were earmarked for the preparatory work for PETRA IV. The Authority for Science, Research, Equality and Districts (BWFGB) of the City of Hamburg granted an additional 4.4 million euros, making a total of 44.4 million euros available for the PETRA IV Preparation Project from 2025 to the end of 2027.

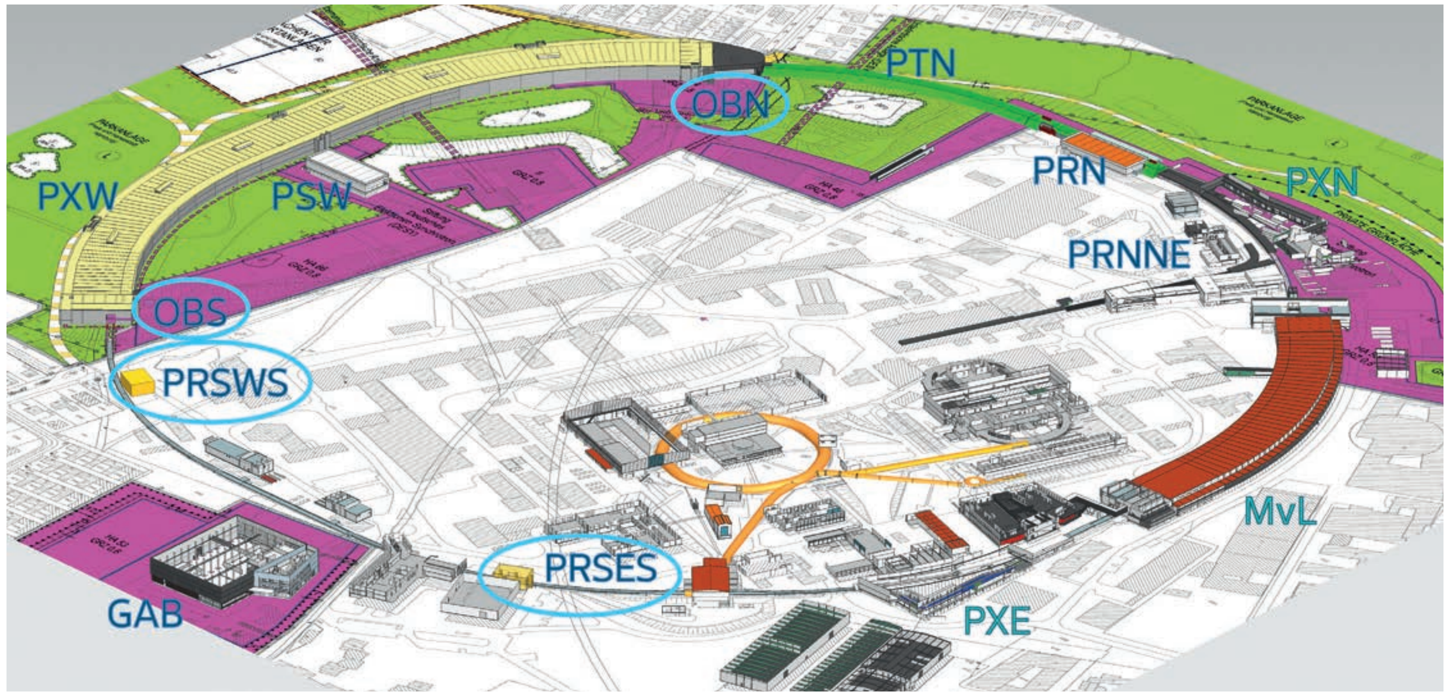


Figure 1

3D CAD model of the PETRA IV complex, including the existing PETRA III experimental halls "Paul Ewald"' (PXN), "Max von Laue" (MvL) and "Ada Yonath" (PXE) as well as new buildings (the abbreviations PRNNE, PRN, PTN, PXW, PSW and GAB show the location of these newly planned buildings on the DESY campus). The buildings circled in blue (OBN, OBS, PRSWS and PRSES) are next in line for the preliminary CAD design.

	σ_x (µm)	σ_x' (µrad)	σ_y (µm)	σ_y' (µrad)	σ_s (ps)	ε_s (10^{-3})
Brightness mode (200 mA, 1920 bunches)	6.1	2.8	2.7	1.2	35	0.96
Full coupling mode (200 mA, 1920 bunches)	5.1	2.3	5.1	2.3	35	0.96
Timing mode (80 mA, 80 bunches)	8.6	3.9	3.8	1.7	68	1.20

Figure 2

Table of electron beam parameters in the standards straights ($\beta_x = \beta_y$ = 2.2 m) in brightness mode (ε_x = 17 pm, ε_y = 3 pm), full coupling mode (ε_x = 12 pm, ε_y = 12 pm) and timing mode (ε_x = 34 pm, ε_y = 7 pm)

Securing the foundation

The design and planning of the civil engineering and the associated technical infrastructure for the operation of PETRA IV have been further refined, and preparations for the tender negotiations for the initial planning of the buildings (up to Service Phase 3, i.e. preparation of the design planning) are under way as the cornerstone of Pillar 1 of the PETRA IV Preparation Project. In this context, the focus is on the planning of the infrastructure for PETRA IV in the western and northern sections of the PETRA complex (Fig. 1). This area includes the new 550 m long PETRA Experimental Hall West (PXW), together with its office, laboratory and media supply buildings, the newly planned building for the radio frequency (RF) system of the electron storage ring in the long straight section North (PRN), and the renewal of the tunnel section (PR) between the PXW hall and the RF building North. In this context, the digitisation of civil construction and technical infrastructure planning will be advanced with the introduction of the Building Information Modelling (BIM) methodology at DESY.

Building the future

Pre-planning for the PETRA IV infrastructure has advanced significantly with the in-house development of 3D CAD models for most of the buildings of the PETRA IV complex, which facilitates optimal use of space for the technical infrastructure, the accelerators and the experimental facilities (beamlines and laboratories). Figure 1 shows an overview of the current layout of the complex. The team has also started to advance elements of the execution planning to be able to further solidify the estimates for the duration of the long shutdown of PETRA III. The results of these estimations have led the team to increase the targeted duration of the shutdown to 2.5 years owing to the massive amount of construction work to be executed during the shutdown (civil construction and installation of technical infrastructure mainly in the new experimental hall PXW).

Refining the storage ring

The design of the storage ring has also progressed significantly with further optimisation of the different operating modes, refinement of the commissioning simulations and analysis of the impact of errors. Further studies showed the feasibility of operation in full coupling mode, which will deliver a round, small-divergence X-ray photon beam with unprecedented brightness. The electron beam parameters at the source point are reported in Fig. 2 for the different operating modes.

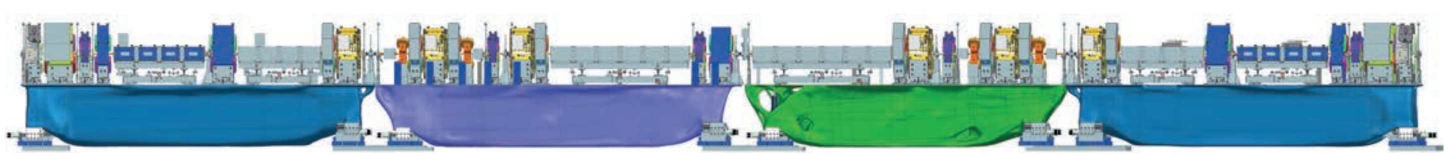


Figure 3

Four-girder configuration in a standard cell

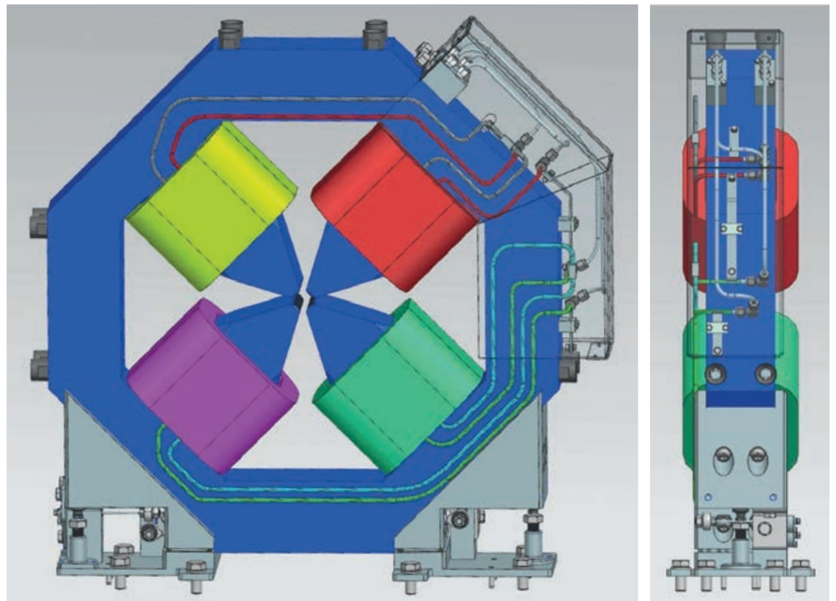


Figure 4
CAD model of the PETRA IV quadrupole magnet (PQE) with power and water connections

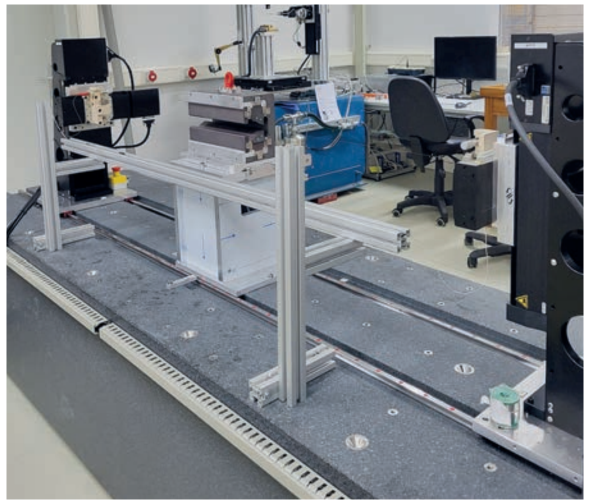


Figure 5
Single module of the combined-function dipole (DLQ) on the ESRF stretched-wire bench

The engineering integration of the lattice has also made significant progress with the design of a four-girder configuration in the regular cells (Fig. 3). The detailed design of the water and power connections is now available, as can be seen in the example of a quadrupole magnet (Fig. 4).

Prototyping for readiness

Pillar 1 of the PETRA IV Preparation Project also supports the completion of the PETRA IV prototyping programme for the PETRA IV accelerators, initiated during the technical design phase. This is to ensure readiness so that the calls for tender for the execution of the main project can begin immediately after the project approval is received. The programme includes the completion of the magnet prototypes with a high-gradient short quadrupole and a combined-function dipole based on permanent magnets (DLQ). Several modules were prototyped to test different material solutions and the capabilities of different vendors. Figure 5 shows a picture of one module of the DLQ combined-function dipole on the European Synchrotron Radiation Facility (ESRF) stretched-wire bench.

Tools for ultimate beam stability

The high-gradient (115 T/m) PQA quadrupole was prototyped by Sigmaphi, while the PSA sextupole was prototyped by Danfysik. The sextupole was used to test different magnetic measurement techniques (vibrating wire and stretched wire) in the newly built climatic cabin in Hall II on the DESY campus. A prototype of a fast corrector with octupole-like geometry (similar to the type used at APS-U) was built and its response to fast current changes is being tested with a high-frequency Hall probe system. The aim of this corrector is to drive the fast orbit feedback (FOFB) with a bandwidth up to 1 kHz. Figure 6 shows pictures of these prototypes.

A higher-harmonic RF system for bunch lengthening will be further developed, including an alternative prototype of the 1.5 GHz cavity and the corresponding solid-state amplifiers. Components for the FOFB system will be finalised to ensure sub-micrometre stability of the electron beam at the source point of the undulators, including the development of the electronics for the beam position monitors and fast corrector magnets. Sophisticated diagnostics to measure the characteristics of the ultralow-emittance electron beam will be developed. A full mock-up of one of the girders in the PETRA IV cell (Fig. 7) has been assembled and used to test the eigenfrequency response as well as the assembly and alignment procedures.

Pushing boundaries with plasma

Pillar 2 of the PETRA IV Preparation Project will advance the development of a full-energy (6 GeV) laser plasma accelerator (LPA) injector for the PETRA IV electron storage ring. The programme is staged in two phases. In Phase 1, a 450 MeV LPA injector will be built to inject electron bunches into the existing DESY II booster synchrotron, which serves as pre-accelerator for PETRA III. The goal is to demonstrate not only sufficient beam quality for efficient injection into DESY II, but also the operation of such an injector with high reliability and availability to prove the maturity of the system as an accelerator for a user facility. Phase 2 should deliver a 6 GeV LPA as proof-of-concept for a full-energy LPA injector. This includes an extension of the existing laser laboratory to accommodate the high-power laser required to accelerate electron bunches to the final kinetic energy of 6 GeV in a single step. The work will extend the concept recently published in the conceptual design report for the 6 GeV injector for PETRA IV.

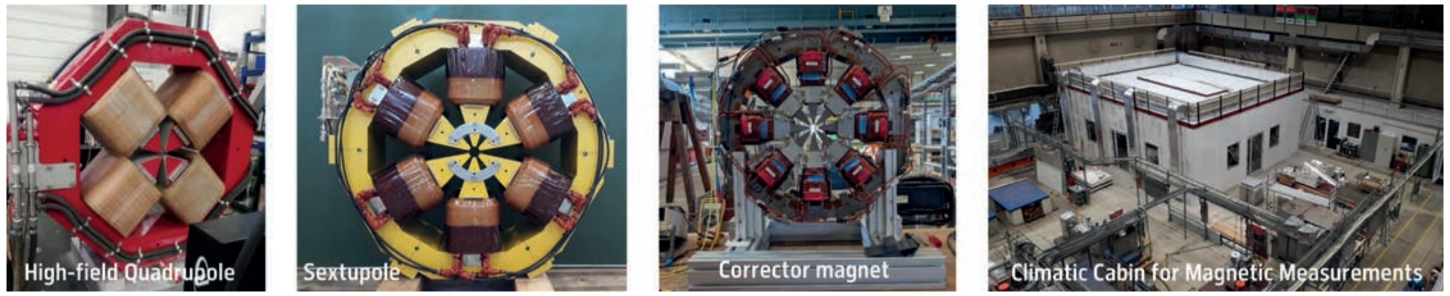


Figure 6
PETRA IV high-field quadrupole (PQA), sextupole (PSA), corrector (PCE) and climatic cabin for magnetic measurements in Hall II

Figure 7
Demonstrator girder assembled in Building 36 on the DESY campus

Making the case for PETRA IV

The PETRA IV preparation phase also supports the prototyping of vibration-free nanostages for the future beamlines and lenses for nanobeam experiments. Other key deliverables of the preparation phase include the development of new insertion devices, such as cryogenic permanent-magnet undulators, and the final design of the damping wiggler. A draft conceptual design report for all PETRA IV beamlines is also in preparation.

In July 2024, the BMBF issued a call for proposals for its prioritisation process for large-scale scientific infrastructures, with a shortlist of potential projects to be announced in summer 2025. Applicants were asked to prepare a 30-page document, complemented by 11 appendices, until October 2024 as input for the evaluation of the planned new facility in three categories: scientific relevance, potential for innovation and transfer as well as assessment of the costs and risks over the full lifecycle of the facility (construction, operation and decommissioning), including aspects such as sustainability.

In August and September, the project team compiled the text, figures and tables for the proposal and conducted a full lifecycle assessment of the PETRA IV project over a 40-year time span with the support of the DESY infrastructure groups. The documents were submitted in October, and confirmation was received in November that all formal requirements set by the BMBF had been met. The proposal is now staged for the evaluation process, which will run from November 2024 to June 2025. A shortlist of prioritised large-scale scientific infrastructures will then be published.

Ready for what's next

With the three main activities in 2024 – the submission of the proposal for the prioritisation process for large-scale scientific infrastructures, the preparation of the beamline conceptual designs and the kick-off of the PETRA IV Preparation Project – the project team has reached several important strategic goals on the way to project approval for the PETRA IV main project. When approval is granted, DESY and the project team will thus be fully prepared to move forward with the implementation of PETRA IV.

Contact: Riccardo Bartolini, riccardo.bartolini@desy.de
Harald Reichert, harald.reichert@desy.de
Ilya Agapov, ilya.agapov@desy.de
Karolin Baev, karolin.baev@desy.de
Stephan Klumpp, stephan.klumpp@desy.de

Renewal of medium-voltage Mainstations A and B

Powering world-class research at DESY

DESY's two medium-voltage mainstations, A and B, are the backbone of its 10 kV power supply. But with Mainstation A dating back to 1960 and Mainstation B to 1975, these aging systems have become unreliable, leading to failures that disrupt accelerator operations. On top of that, sourcing spare parts has become a challenge. The solution is a complete overhaul – Mainstation A got a brand-new building, designed for expansion, with three additional storeys planned to house power supply units and other technical systems for the PETRA IV project, while Mainstation B is being replaced within its existing structure.

Future-proofing with new infrastructure

DESY's technical infrastructure (including power supply, heating, ventilation, air conditioning, water generation and cooling systems) is essential for operating accelerators, supporting experimental facilities and developing sustainable research and laboratory buildings on the campus. To enable scientists to focus on their research questions while ensuring safe and reliable accelerator operation that delivers high-quality electron beams with high availability, the necessary technology must be developed, maintained and operated. This is managed by DESY's technical group for Electric Power, Water, Air Conditioning.


Figure 1

Left: Existing Mainstation A from 1960 with open busbar without arc fault protection and insufficient personnel safety. Right: Mainstation B, manufactured in 1975.

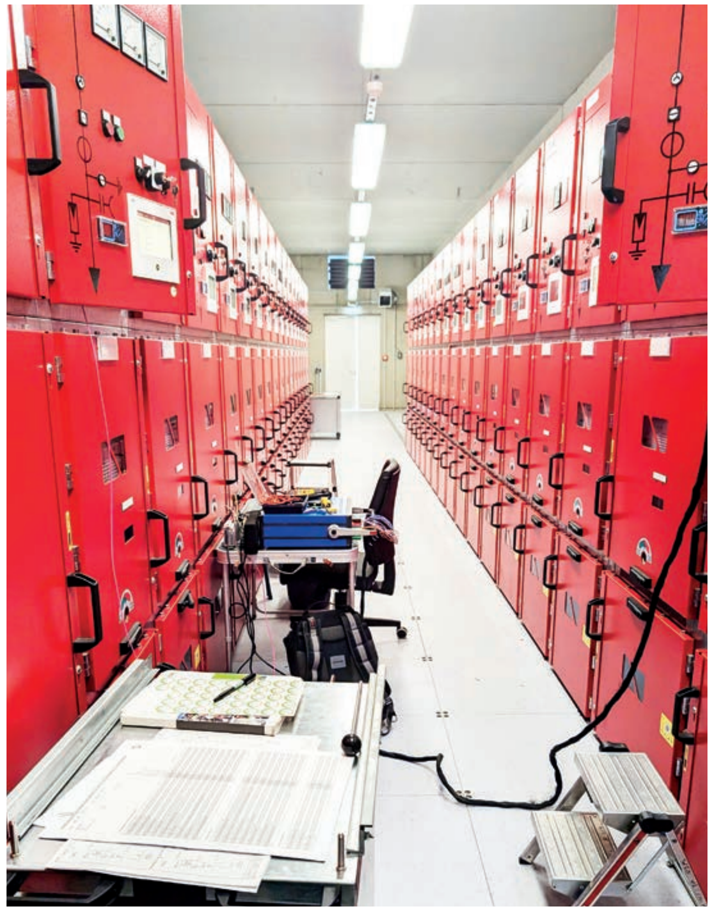


Figure 2

New Mainstation A during commissioning

Figure 3

New Mainstation B on the left; old one on the right

A great deal of electrical energy is required to operate the DESY accelerator facilities in order to generate and accelerate the electrons and convert them into synchrotron radiation. With such energy-intensive operations – including subsystems such as cooling water and ventilation systems, as well as the computer centre and general campus operations – DESY is one of Hamburg's largest electricity consumers.

Out with the old, in with the future

The two medium-voltage mainstations, A and B, are used for the 10 kV main power supply of a large part of the DESY consumer facilities. The 10 kV Mainstation A (Building 16 on the DESY Hamburg campus) is a switchgear from 1960 and Mainstation B (Building 16a) from 1975. Because of their age and the resulting condition and equipment, the switchgears are no longer state of the art.

Both switchgears have failed in recent years due to signs of ageing and have therefore impaired accelerator operation, putting critical research at risk. Furthermore, it is difficult to obtain spare parts for these switchgears. For these reasons, DESY has invested in a future-proof solution, and both systems are being completely renewed: with state-of-the-art switchgear, a new facility for Mainstation A, as it was necessary to construct a new building, and a seamless replacement for Mainstation B in the existing building.

Smart, scalable and remote-ready

The new Mainstation A building was constructed in such a way that it can later be extended by three additional storeys for the planned PETRA IV project. These floors are intended for power supply units and other technical equipment for PETRA IV. The new switchgear for Mainstations A and B can also be operated remotely. This means that switching operations can be carried out from a control station and no longer have to be performed directly at the systems. This reduces the amount of personnel required and allows larger switching operations to be carried out more safely.

With this overhaul, DESY is ensuring a stable, scalable and smarter power infrastructure – ready to support cutting-edge research for years to come.

Contact: Markus Faesing, markus.faesing@desy.de

Collaboration on robotics with CERN

MIRA3 teleoperation and autopilot testing in the PETRA III tunnel

Robotic solutions have a great potential at accelerator-based facilities to support remote maintenance and quality control in harsh environments, long tunnel buildings and for repetitive inspection tasks. At CERN, the Controls Electronics Mechatronics group is responsible for planning remote handling tasks and safely performing operations for remote maintenance. Several robots have been developed at CERN for interventions for remote inspection and maintenance in radioactive areas, including the CERN accelerator complex. During the summer shutdown 2024, the MIRA3 robot from CERN was tested in the accelerator tunnel at DESY's PETRA III synchrotron radiation facility, successfully demonstrating teleoperation and autopilot capabilities.

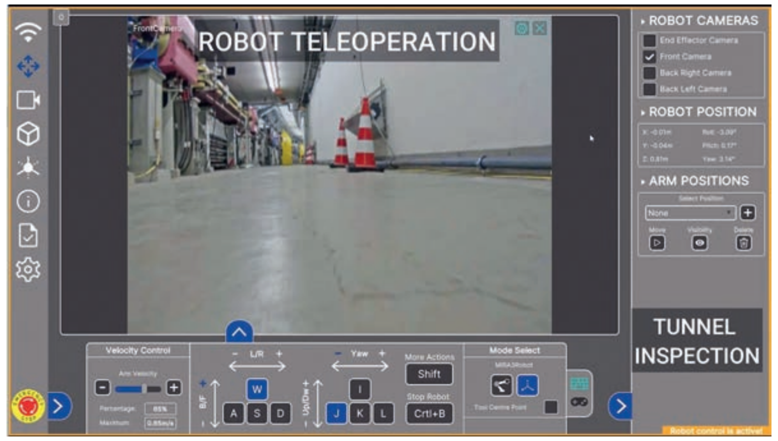


Figure 2

Teleoperation inside the PETRA III tunnel

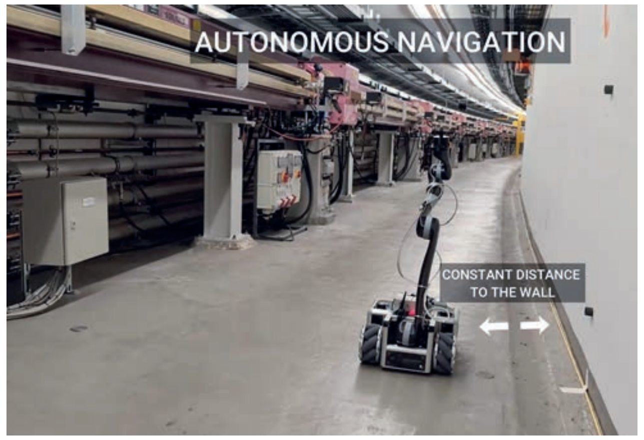


Figure 3

Autopilot test in the arc of PETRA III – holding a constant distance to the tunnel wall

Testing MIRA3 at PETRA III

User operation at PETRA III faced several challenges in 2024 (see p. 22). Nevertheless, in a study in collaboration with CERN, teleoperation and autopiloted operation of the MIRA3 robot were successfully tested in the PETRA III tunnel in July. Equipped with interchangeable sensors – such as optical and thermal cameras or radiation detectors – MIRA3 proved valuable for inspection tasks. In the long run, robots like MIRA3 could also take on maintenance and repair work in the 2.3 km long PETRA III tunnel.

At CERN, the Controls Electronics Mechatronics group is responsible for planning remote handling tasks and safely performing operations for remote maintenance [1, 2]. The group has developed the MIRA3 robot, which is mainly used for inspection tasks in the Super Proton Synchrotron (SPS) accelerator. In July 2024, three colleagues from the CERN group visited DESY to perform the tests in the PETRA III tunnel. The MIRA3 robot was prepared at CERN and shipped to DESY before the visit. Upon arrival, a radiation detector was mounted on the robot to set it up for the inspection of the PETRA III tunnel (Fig. 1).

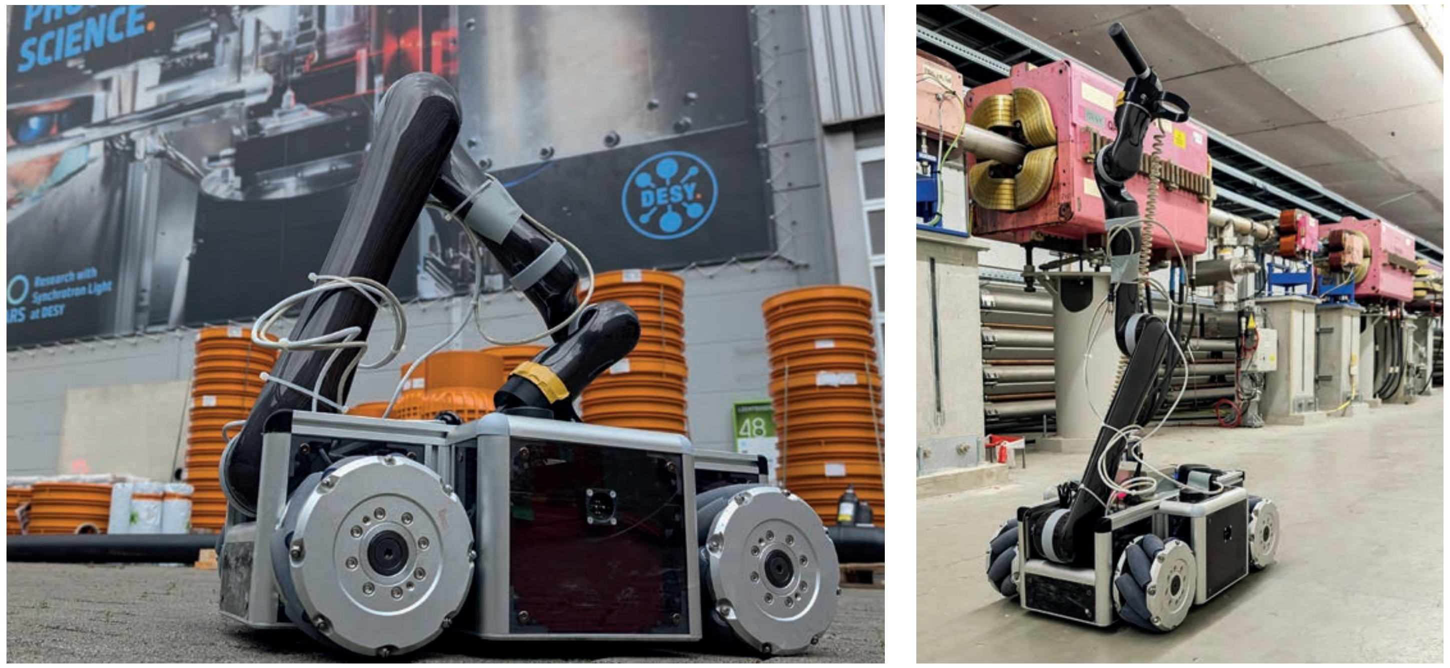


Figure 1

Left: The MIRA3 robot in front of the PETRA III East hall after unboxing. Right: MIRA3 with a mounted radiation detector in the PETRA III tunnel.

The first study day focused on unpacking and functional testing of the robot, while the second day was dedicated to preparations for the teleoperated and autopilot-controlled tests in the PETRA III tunnel. An issue related to the connection to the Wi-Fi network had to be solved first. Finally, three CERN Wi-Fi routers were deployed in the PETRA III tunnel at intervals within their signal range, ensuring a stable remote connection.

Successful demonstration of teleoperation and autopilot

On the third and final study day, the robot was brought into the PETRA III tunnel for the final demonstration. Adjustments to the weighting parameters of the robot arm's joints allowed the arm to remain stable during rapid movements of the robot base. The teleoperation went flawlessly. Thanks to the network of three Wi-Fi routers from CERN, it was possible to cover a large distance (400 m) without losing the connection, and steep ramps were also successfully climbed. The robot arm movements for simulating detailed surveys of accelerator components also worked without any problems. Figure 2 shows a view from the teleoperation cockpit into the PETRA III tunnel.

The autopilot was also extensively tested. It performed very well, correctly adapting its distance to the PETRA III tunnel wall and effectively avoiding objects close to the wall (Fig. 3). After this successful demonstration, the robot and its equipment were placed in the transport box and safely shipped back to CERN.

Looking ahead

All in all, it can be concluded that both the teleoperation and the autopilot test of the MIRA3 robot in the PETRA III tunnel were a resounding success, opening possibilities for deploying robots during beam operation at PETRA III. Future steps include improving the Wi-Fi infrastructure in the PETRA III tunnel or exploring public 5G networks for enhanced connectivity. Additionally, integrating this collaboration between CERN and DESY into the activities of the League of European Accelerator-based Photon Sources (LEAPS) [3] community could drive further advancements in robotic solutions for accelerator facilities.

Contact: Rainer Wanzenberg, rainer.wanzenberg@desy.de
Michaela Schaumann, michaela.schaumann@desy.de
Mario Di Castro, mario.di.castro@cern.ch
David Forkel, david.guenter.forkel@cern.ch

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[3] https://www.leaps-initiative.eu/

High-power attosecond pulses at the European XFEL

Producing terawatt-level hard and soft X-ray attosecond pulses with unrivalled intensity

The European XFEL X-ray laser has achieved groundbreaking advancements in generating high-power attosecond pulses in both the hard and soft X-ray regime, delivering unrivalled intensity and stability at megahertz repetition rates. Attosecond pulses, which are crucial for non-linear spectroscopy and for probing ultrafast electron dynamics, are now available across nearly the entire operational range of the facility. By meticulously shaping electron beam currents and exploiting self-field effects and specialised beam compression techniques, the European XFEL produces highly customisable pulses, including pulse pairs for pump–probe experiments and variably polarised pulses using helical afterburners. Furthermore, innovative characterisation techniques, such as angular streaking and spectral reconstruction methods, enable precise measurements of pulse durations and energy chirps, essential for accurate experimental interpretation. These advancements promise to facilitate revolutionary experimental methods, including atomic-scale imaging, non-linear spectroscopy, real-time visualisation of electron dynamics and quantum imaging.

Generation of customisable attosecond pulses

Attosecond pulses are crucial in applications such as non-linear spectroscopy and ultrafast electron dynamics in atoms and molecules. Free-electron lasers (FELs) are primary candidates for exploring this regime to advance photon science in these areas. At the European XFEL, a special operation mode has been implemented, which allows such attosecond pulses to be delivered over nearly the entire operational range of the facility.

In the soft X-ray range, the production of attosecond pulses dates back to a few years ago. In the hard X-ray range, generation of attosecond pulses is much more recent. The approach used begins by shaping the current of the electron beam into a ramped profile with a pronounced leading spike, which is achieved by fine-tuning the phase and voltage of a high-harmonic accelerating radio frequency structure located before the bunch compressors.

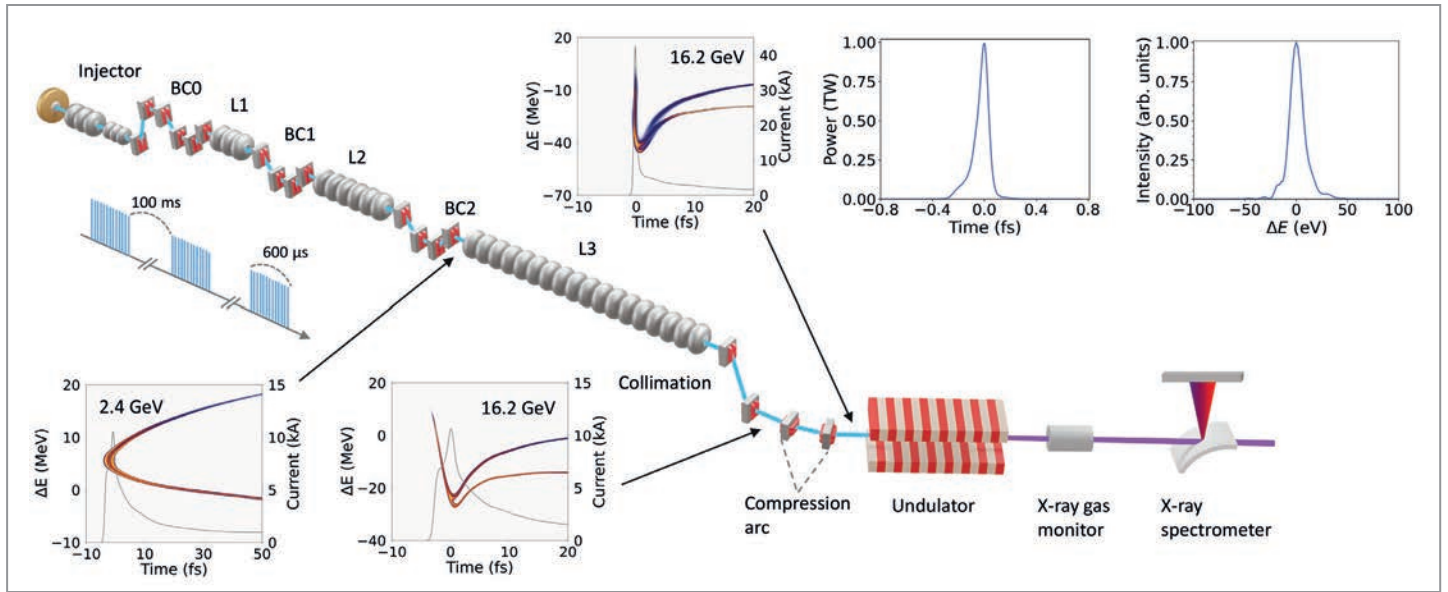

Figure 1

Schematic layout of the self-chirping mode implemented at SASE2. Note the multistage compression that exploits self-field effects along the beamline to further shape the electron current profile [1]. The idea is to first create a current spike that in turn drives self-field effects, which further increase the strong energy chirp, followed by a final compression just in front of the undulator line.

As the beam continues through the accelerator, strong self-field effects locally enhance the chirp of the electron beam. The chirped high-current spike then passes an arc section that serves two purposes. Firstly, it compresses the beam in a special way (by means of a compression mode that uses positive longitudinal dispersion, making it possible to compress beams with negative energy chirp). Secondly, it induces shearing of the electron bunch along its longitudinal axis. Both of these effects shorten the part of the electron bunch that effectively contributes to the light-producing FEL process. Figure 1 exemplarily shows the schematic layout of the experimental setup for the SASE2 undulator [1]. The same principle is also employed at SASE3. The use of these setups makes it possible to generate both hard and soft X-ray high-power attosecond pulses at unrivalled power and repetition rate (Fig. 2).

The produced attosecond pulses are highly customisable. For instance, the additional use of a chicane allows the generation of pairs of attosecond pulses, which can then be used for pump–probe experiments, while the newly installed helical afterburners in SASE3 make it possible to obtain attosecond pulses with variable polarisation.

Characterisation of the attosecond pulses

To successfully perform attosecond experiments, proper characterisation of the photon pulses is just as important as their generation. For soft X-rays, one of the most direct ways is to measure the photon pulse by angular streaking [2]. While this diagnostic technique is not yet available for hard X-rays and is time-intensive to set up for the soft X-ray regime, several alternative reconstruction methods are now under development, which use photon spectra to not only reconstruct the pulse duration but also give first estimates of the energy chirp along these ultrashort pulses [3], an example of which is shown in Fig. 3. In the mid-term, photon diagnostic capabilities will also be expanded by adding both a passive and an active electron streaker.

In summary, high-intensity attosecond pulses with high stability and megahertz repetition rate, as demonstrated at the European XFEL, will open the door to various novel experimental techniques, such as atomic-scale X-ray imaging of protein molecules, non-linear X-ray spectroscopy of functional materials, capturing attosecond electron motions in action and demonstrating X-ray quantum imaging.

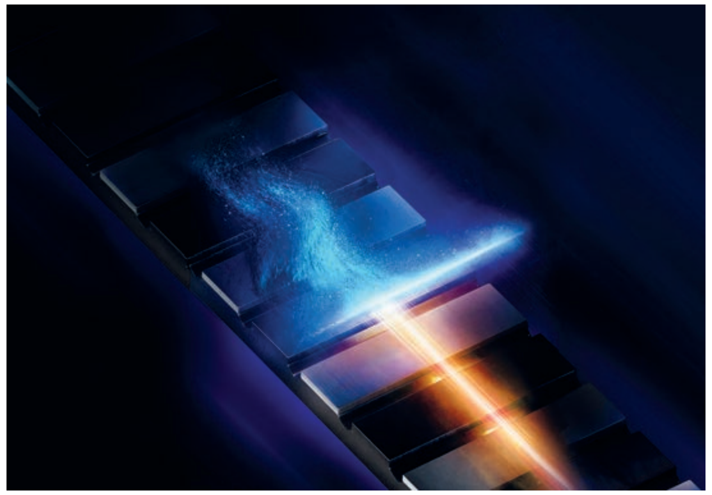

Figure 2

Artistic representation of the self-chirping method: With the help of special beam optics, relativistic electrons (blue cloud) are strongly compressed (bright line in the centre). This leads to a very bright, high-power X-ray pulse on the attosecond timescale.

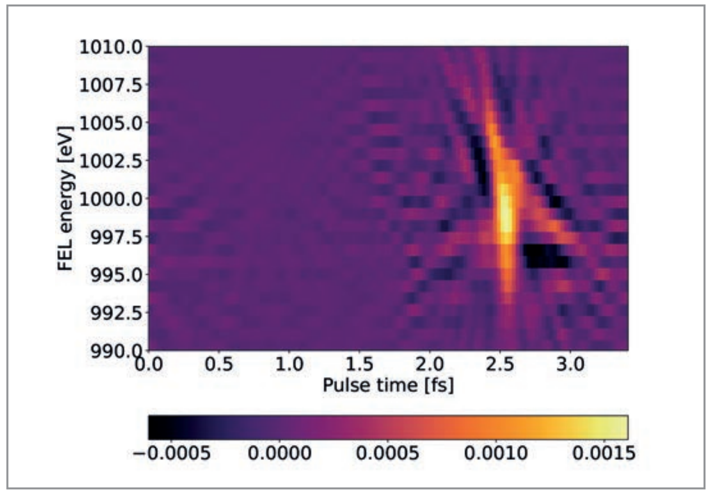

Figure 3

Reconstructed Wigner distribution of an ultrashort radiation pulse generated in SASE2, showing not only the pulse duration but also the chirp of the pulse, which helps to characterise the photon pulse even further for users.

Contact: Marc Guetg, marc.guetg@desy.de
Gianluca Geloni, gianluca.geloni@xfel.eu
Jiawei Yan, jiawei.yan@xfel.eu
Svitozar Serkez, svitozar.serkez@xfel.eu

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Next-generation superconducting cavities and cryomodules

DESY's innovations for a more flexible, high-performance European XFEL

DESY's superconducting radio frequency (SRF) accelerator technology team is leading an ambitious upgrade of the European XFEL X-ray free-electron laser to enable both pulsed and high duty cycle (HDC) or continuous-wave (CW) operation. Central to this effort are advanced heat treatments that significantly boost cavity quality factors, cryogenic studies to support higher thermal loads and the development of optimised cryomodules. In close collaboration with Universität Hamburg, DESY is also exploring next-generation materials beyond bulk niobium, ensuring the long-term performance and flexibility of one of the world's most powerful X-ray lasers.

Preparing for high duty cycle operation

The DESY SRF team is tackling a unique challenge: preparing the European XFEL for both pulsed mode and HDC or CW operation. This ambitious upgrade includes a new SRF-based injector and replacing the first 16 accelerator modules with cutting-edge cavities that achieve extremely high quality factors Q_0 at moderate accelerating gradients ($Q_0 \approx 3 \times 10^{10}$ at 20 MV/m). Additionally, DESY is investigating cryogenic limitations of the so-called long Linac L3 section, which – in the upgrade scenario – will consist of nearly 100 standard XFEL modules.

Heating up for better performance

DESY is leveraging heat treatment techniques – specifically furnace treatments at 250–350 °C, called medium-temperature heat treatment – to enhance cavity performance. Using DESY's unique ultrahigh-vacuum furnace, which is directly connected to an ISO4 cleanroom, cavities undergo mid- and low-temperature treatments without the need for post-processing surface treatments. The result is a major boost in performance. First tests on single-cell cavities show significantly improved quality factor Q_0, surpassing 2×10^{10} at gradients close to 40 MV/m. While not all cavities reach this benchmark of such high gradients and some achieve a high quality factor but are limited around 25 MV/m, many already meet HDC requirements, and further optimisation is under way – particularly for cavities showing high-field Q slope behaviour (i.e. decreasing Q at high accelerating field), which DESY can "heal" using a unique combination of mid- and low-temperature treatment (Fig. 1).

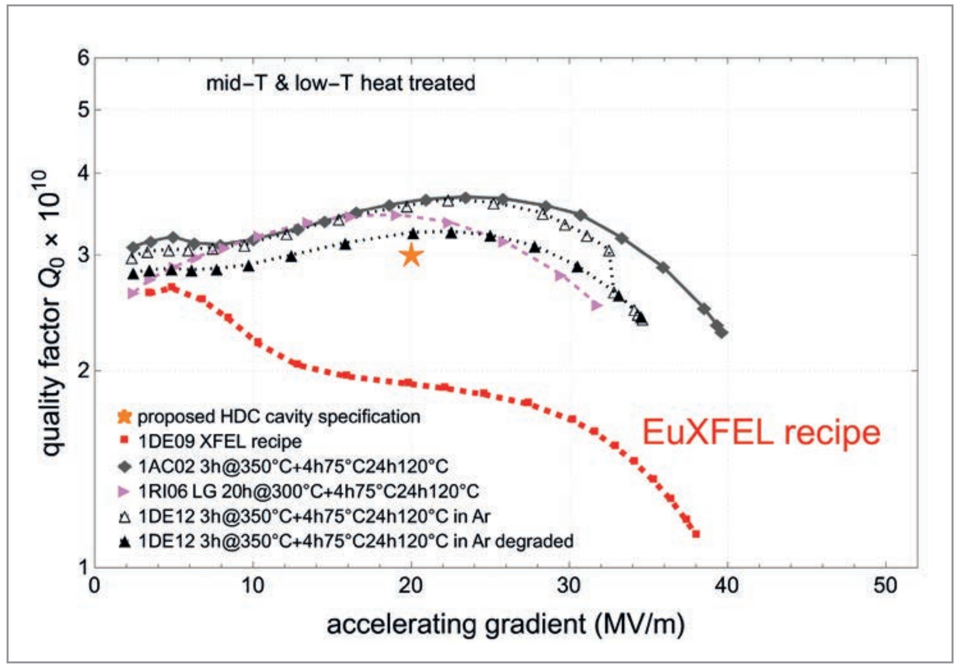

Figure 1
The new DESY recipe using a unique combination of mid- and low-temperature (mid-T / low-T) treatment leads to unprecedented high accelerating gradients at very high quality factors, corresponding to low cryogenic losses.

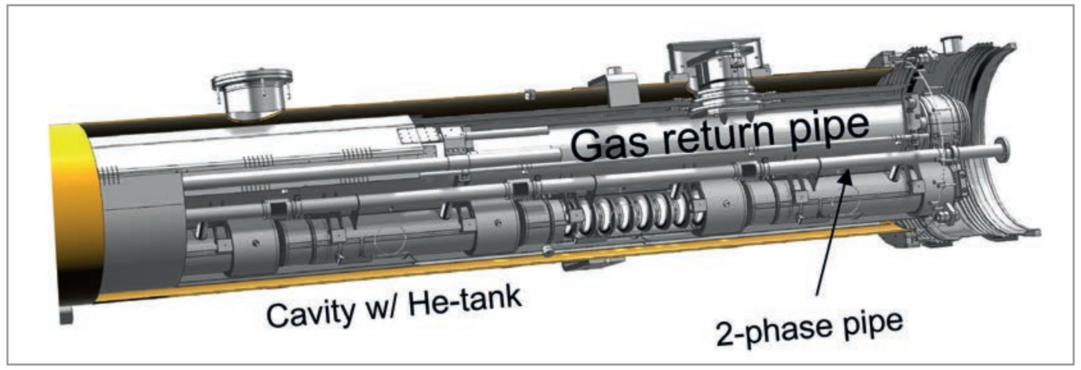

Figure 2
3D image of a European XFEL cryomodule. Recent studies are investigating the heat transport through the two-phase pipe.

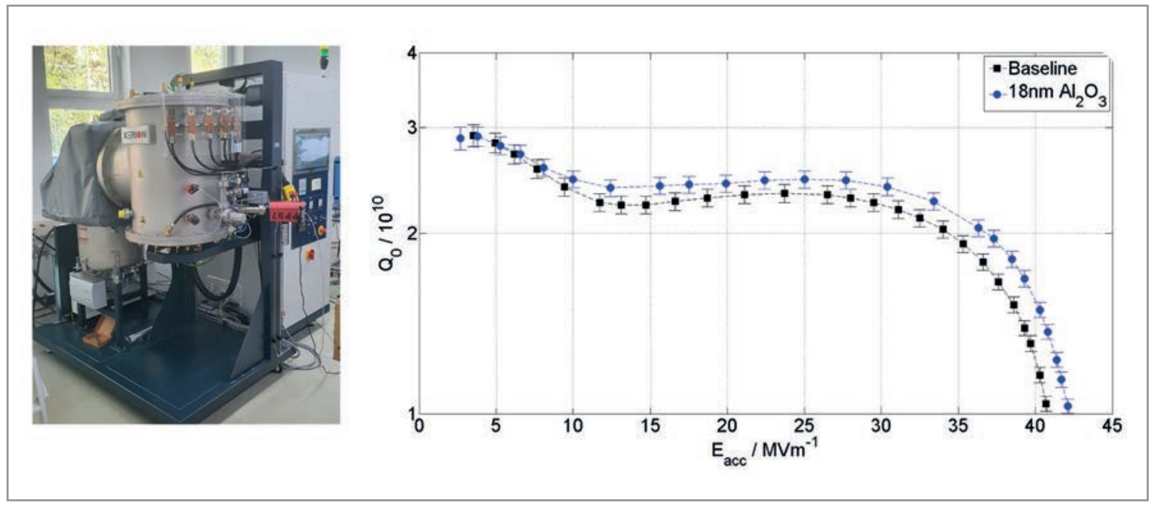

Figure 3
Left: Universität Hamburg operates a dedicated ultra-high-vacuum furnace, which will enable cavity coating by atomic layer deposition in the future. Right: Cavity coating with a thin layer of aluminium oxide (Al_2O_3) does not compromise the performance compared to the conventional baseline cavity, which is an essential milestone for further coating studies.

Cryogenic feasibility for CW operation

The heat load limit of the cryomodules of the European XFEL accelerator is defined by flow criteria to avoid oscillations and instabilities: No stratified wavy flow is allowed in the 2 K two-phase pipe (Fig. 2). Enabling CW operation demands a dynamic heat load of approximately 2.5 kW at 2 K for the Linac L3 section. Through calculations to determine the dynamic heat load limit (and their comparison with the actual operation parameters of the European XFEL) as well as through experimental campaigns using spare cryomodules, DESY has confirmed that this goal is within reach. However, minor design modifications to existing installed components will be necessary to meet the flow criteria and avoid instabilities.

A new generation of cryomodules

The first 16 cryomodules of the European XFEL need to be replaced using a slightly modified design and will be substituted with upgraded versions housing the improved SRF cavities. These cryomodules will also feature enhanced cryogenic design including an additional Joule-Thomson valve, optimised thermal shielding and better RF power coupler cooling. A few spare cryomodules are being modified to test the new design. The modifications include improved instrumentation with added temperature sensors to get a deeper understanding of the higher order mode coupler heating as well as added pressure sensors at the 2 K two-phase pipe. Diagnostics for an *in situ* analysis of vibrations during RF operation are planned as well. A novel "evaporation method" is also explored to determine the single-cavity Q_0 in fully assembled and installed cryomodules.

Innovating for the next generation

Looking ahead, DESY – together with Universität Hamburg – is exploring SRF concepts that go beyond traditional bulk niobium. Thin-layer coating of cavities is a promising new path forward to achieve even higher performance (Fig. 3). Supported by DESY's world-class infrastructure, these collaborative efforts not only drive innovation but also help train the next generation of SRF experts.

Contact: Lea Steder, lea.steder@desy.de
Serena Barbanotti, serena.barbanotti@desy.de
Marc Wenskat, marc.wenskat@desy.de
Hans Weise, hans.weise@desy.de

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European XFEL 2 K operation

Cold compressor upgrade to motors with active magnetic bearings

The European XFEL has been running successfully for more than seven years. The superconducting cavities and magnets – the key components of the accelerator cryomodules – are operated at 2 K in a liquid helium bath. A four-stage cold compressor system is used to generate the 2 K liquid helium by pumping the vapour above the liquid down to 31 mbar. The motors driving the cold compressors were initially equipped with ceramic ball bearings used for radial suspension, which caused systematic motor failures. The cold compressors were therefore upgraded to motors with established active magnetic bearings to reach the specified lifetime of 16 000 h, ensuring continuous user operation without unscheduled interruptions.

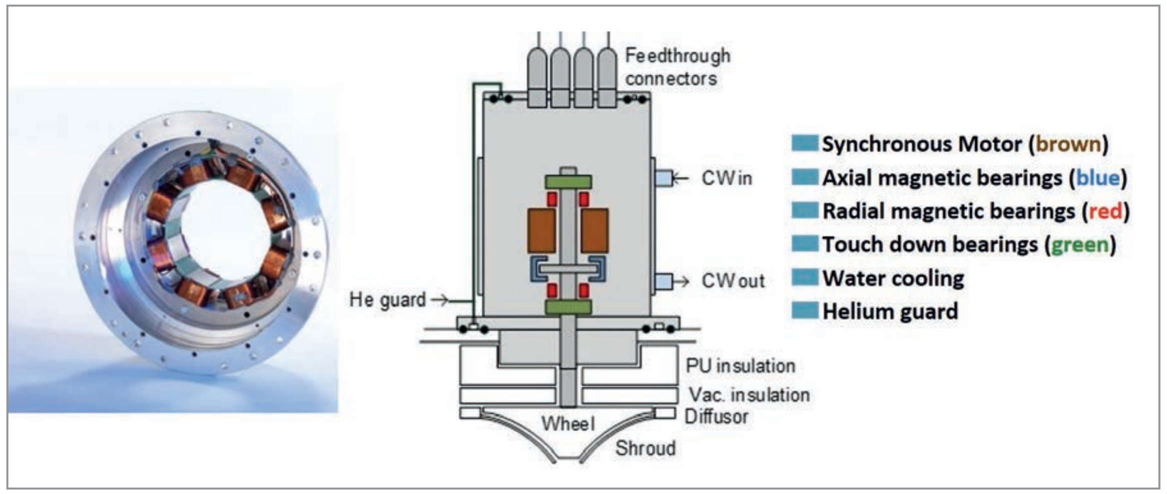

Figure 2
Scheme of the new cold compressor motor with active magnetic bearings (shown on the left)

Initial situation: Motors with ceramic ball bearings

The reliability of the motors used to drive the cold compressors has been a major concern since the start of 2 K operation. The four serial cold compressors are integrated in a cold compressor box, located in the shaft building next to a valve box, where the helium flows of different temperatures are directed towards the European XFEL linear accelerator and the injector [1]. The cold compressor motors were initially equipped with ceramic ball bearings for radial suspension, which caused problems from the very beginning of 2 K operation [2]. Since the first operation at 2 K in 2017, more than 30 motor failures caused by damaged ceramic ball bearings occurred (Fig. 1), resulting in a reduced service lifetime far below the specified 16 000 h and consequently an interruption of several user operation periods. Linde Kryotechnik developed several promising design upgrades in cooperation with DESY, but the improvements in lifetime still failed to fulfil the specification, and user runs still had to be spontaneously interrupted to replace the failed motors. To improve the operating reliability for users, a regular time slot for preventive maintenance of the motors after 4000 h was established. However, unplanned downtimes during user operation could not be avoided by this measure, as bearing failures still occurred within the maintenance time interval. Ceramic ball bearings therefore do not appear to be a suitable technology for cold compressor motors in continuous operation.

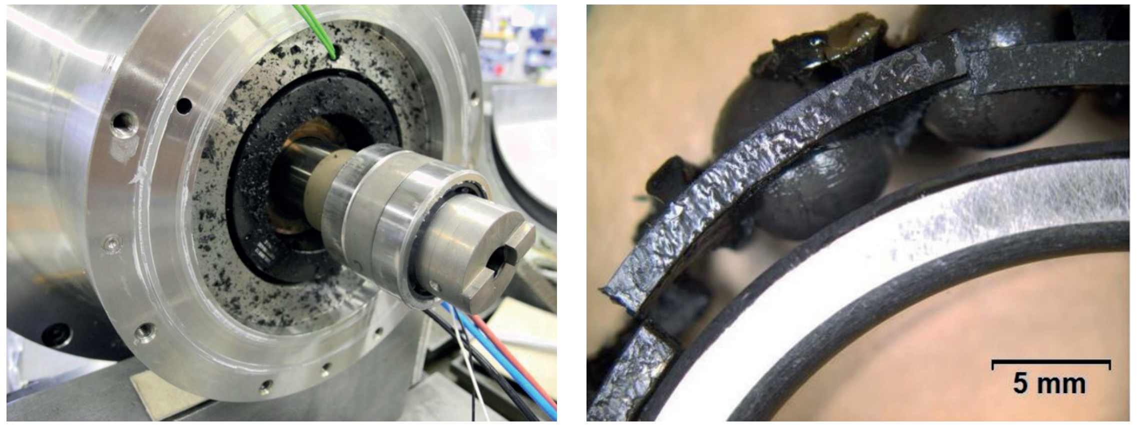

Figure 1
Typical bearing failure of a cold compressor motor with ceramic ball bearings

Conversion to active magnetic bearings

In December 2022, a prototype motor from Linde Kryotechnik in cooperation with Mecos AG using active magnetic bearings (Fig. 2) was installed in the cold compressor box. Whereas the remaining three motors with ceramic ball bearings continued to be regularly exchanged for preventive maintenance, the new motor with active magnetic bearings remained installed and in operation to verify the lifetime of this motor type (AMB-motors).

After successfully operating the prototype motor with active magnetic bearings for more than 12 000 h without any signs of noticeable problems, the decision was made to also convert the three remaining motors with ceramic bearings to motors with active magnetic bearings. Based on the operating experience of the prototype motor, all four cold compressors were finally replaced with optimised motors with active magnetic bearings in June 2024 (Fig. 3).

Operating the new motors with active magnetic bearings has no negative effects on the 2 K pressure stability. Even transient operation modes with sudden radio frequency shutdowns from 15 GeV beam operation still enable a pressure stability of better than 0.3% thanks to an elaborated cold compressor bypass operation in combination with cascaded pressure regulation and automatic heat load compensation, as reported in [2].

Figure 3
New cold compressor motors (metallic pillars in the front) installed in the cold compressor box

Conclusion and outlook

Motors with magnetic bearings seem to be the better alternative to the motors with ceramic bearings. After more than 4000 h of continuous operation (over 12 000 h of prototype motor operation), all four newly installed AMB-motors have run smoothly without any noticeable issues. This reinforces our confidence that the previous cold compressor problems will be resolved with the AMB-motors and that this marks the beginning of a new phase of uninterrupted 2 K operation at the European XFEL.

Contact: Tobias Schnautz, tobias.schnautz@desy.de

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FLASH2020+ status

Commissioning results and preparation for high repetition rate external seeding

The FLASH2020+ project is a comprehensive upgrade programme to boost the performance, flexibility and scientific reach of DESY's FLASH free-electron laser (FEL) facility – positioning it to advance the frontiers of ultrafast science and photon-based research. In 2024, the FLASH2020+ project team made progress on multiple fronts, balancing the commissioning of newly installed components and preparing for a major upgrade of the FLASH1 FEL beamline to provide external seeding as the main feature. Key highlights include extended operation at high beam energy (1.35 GeV), enabling experiments at wavelengths down to 1.45 nm with variable polarisation at the third harmonic. An extensive 14-month shutdown phase began in June, focused on dismantling the old FLASH1 beamline and preparing for the installation of the new seeded beamline, which is set to go into operation in 2025 and see its first users in 2026. These developments mark important steps toward enhanced performance and flexibility for future user experiments.

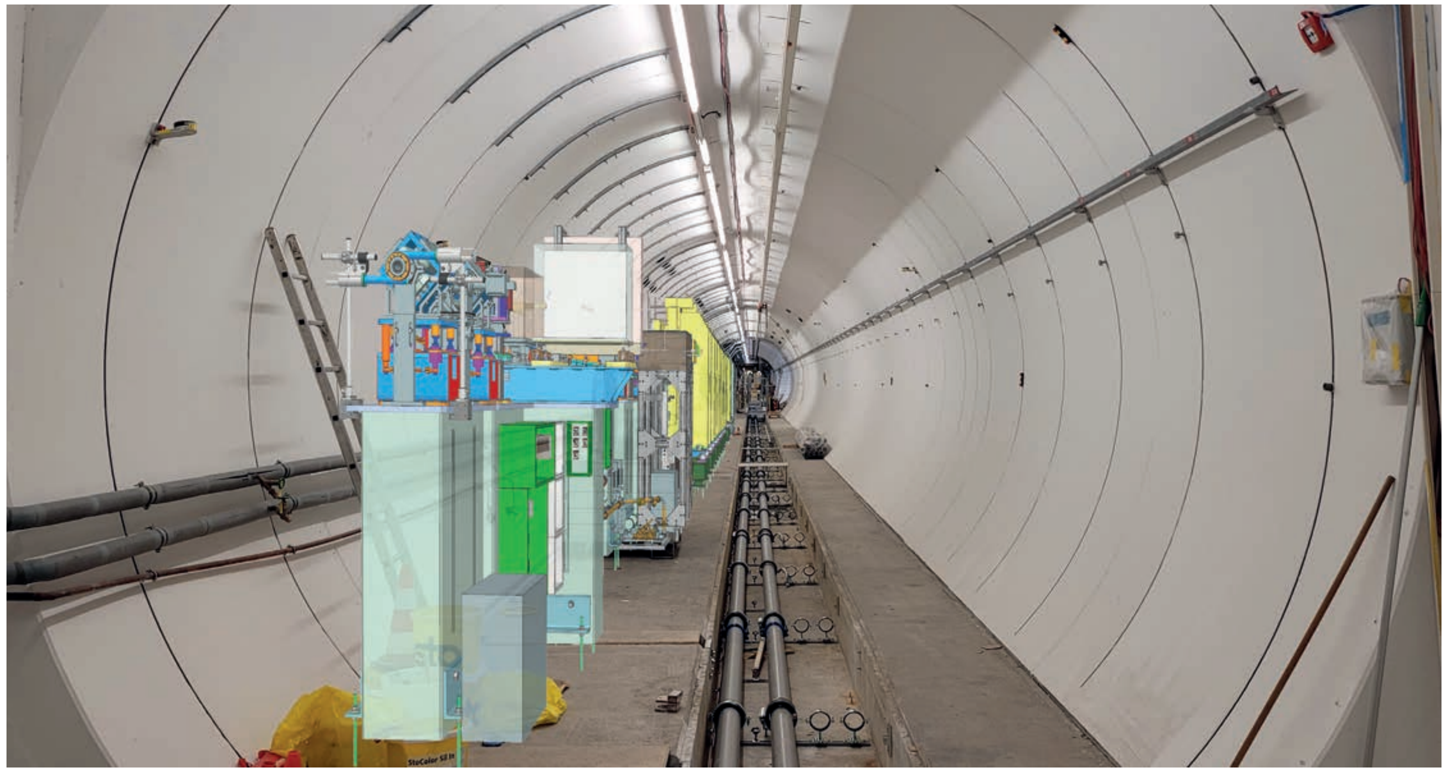


Figure 1

Illustration of the new externally seeded FLASH1 beamline fitted into the emptied and renovated tunnel. Most prominent are the yellow support structures that hold the new force-compensated APPLE-III undulators, which make it possible to generate arbitrarily polarised beams at variable wavelengths.

Early 2024: New injector lasers enhance operational flexibility

For the FLASH2020+ project, the year 2024 was divided into two periods, with the commissioning of newly installed components from the previous shutdown culminating in an expansion of the available parameter range and enabling new user experiments until 10 June, when the machine was taken into the next shutdown for the complete renewal of the FLASH1 FEL beamline.

With the start of the year, FLASH was brought back into operation with two new injector lasers, named NEPAL-F1 and NEPAL-F2. These serve as replacements for the old laser systems, which had exceeded their lifetime, and bring new operation modes and higher flexibility. In view of the increasing demands, especially in short-pulse operation, the new adjustable laser pulse duration feature serves as a new approach to reduce setup time and tailor the resulting pulse properties delivered to users more efficiently.

FLARE project demonstrates advanced pulse shaping

With a similar idea in mind, the ErUM-Pro project FLASH Laser-Assisted Reshaping of Electron bunches (FLARE), carried out in collaboration with TU Dortmund University, used the new laser heater and a self-developed interferometer setup to imprint a substructure onto the electron bunch that includes a linearly increasing energy spread between the two pulses from the interferometer. This can be interpreted as a local chirp on the electron beam, which, upon correct utilisation of the bunch compressors at FLASH, can be turned into a very sharp density spike of adjustable duration. In first proof-of-principle experiments, pulse durations below the resolution limit given by the operation point of the PolariX transverse deflecting structure (an earlier addition within FLASH2020+) at 6.8 fs were observed. It is planned to get these spikes to lase in the FLASH2 undulator beamline and to carry out more precise autocorrelation measurements as soon as FLASH is operational again.

Extended performance and first scientific applications

Apart from the increased electron beam energy of 1.35 GeV, which allows the generation of radiation with wavelengths down to 3.2 nm in the fundamental, further commissioning of the afterburner undulator made it possible to push the lower wavelength limit down to 1.45 nm with full polarisation control, which was immediately used in first experiments investigating magnetic domains. This experimental campaign was part of a four-week programme in which the accelerator was operated at the maximum beam energy of 1.35 GeV for four consecutive weeks, demonstrating the feasibility of future facility operation with a reduced number of working points – and in turn reducing the required setup time and increasing the beamtime available to users.

Preparation for major FLASH1 shutdown

In parallel to commissioning and user operation, the thorough preparation for the imminent shutdown meant a considerable amount of work for everyone involved. Finishing remaining designs, ordering and manufacturing materials and components, testing the latter, organising the logistics for storage and transport, meticulously planning the installation dates and coordinating the groups involved are just a few examples of these activities. From 10 June, the focus was then on decommissioning, starting with the dismantling of the old FLASH1 FEL beamline, during which more than 100 t of material were removed in a radiation-safe manner, before efforts switched to preparing the infrastructure, which continued until the end of the year. The whole team is looking forward to the beginning of the installation phase of the new externally seeded beamline.

Architecture of the new externally seeded beamline

The new beamline starts with a diagnostic section for matching and optics adjustment. This is immediately followed by a modulator section, consisting of three chicanes, where the seed lasers are coupled in and out and the electron beam phase space is modified, and two modulators, in which the seed lasers imprint a sinusoidal energy modulation onto the electron beam. This will enable the seeding mechanisms of high-gain harmonic generation (HGHG) and echo-enabled harmonic generation (EEHG) and will ultimately result in a pre-bunched electron beam, which will then enter the radiator section. Here, a specific radiator arrangement will be installed: three planar radiators, a gap, one APPLE-III-type radiator, a gap and finally five APPLE-III radiators. In the near future, the two gaps are planned to be filled with additional chicanes, enabling the worldwide first realisation of innovative external seeding concepts developed as part of the FLASH2020+ project. Downstream of the radiators, the electron beam will pass through a transverse deflecting structure to allow an in-depth investigation of its phase space before it is bent away from the generated photon beam, passes an additional radiator for wavelengths in the THz range and is finally deposited in the beam dump.

Looking ahead to FLASH1 installation and commissioning

Following the completion of the installation in August 2025, FLASH will enter the commissioning phase, delivering photons to users at FLASH2 while advanced seeding schemes and new experimental capabilities are put into operation at FLASH1. This marks a major step forward for FLASH and paves the way for ultrafast science with unprecedented precision. The team is ready to turn years of preparation into groundbreaking results.

Contact: Lucas Schaper, lucas.schaper@desy.de
Karolin Baev, karolin.baev@desy.de

Twin echo-enabled harmonic generation

Enhanced coherent bunching at short wavelength using novel externally seeded cascaded FEL scheme

A novel externally seeded cascaded free-electron laser (FEL) scheme based on two echo-enabled harmonic generation stages can be used to obtain unprecedented bunching independently of the final FEL wavelength. Its performance has been explored by modelling and numerical simulations, showing unprecedented bunching at very short wavelengths. Higher bunching enables emission of laser-like radiation in the soft X-ray range with large output power in a compact scheme. In contrast to established approaches, in which the initial seed laser wavelength is up-converted to higher harmonics, i.e. shorter wavelengths, the scheme can be operated with either up- or down-conversion to (slightly) longer wavelengths in the final stage.

Introduction

Externally seeded FELs based on harmonic up-conversion schemes represent the most successful approach for generating radiation with laser-like properties at short wavelengths. However, they are limited in the shortest achievable wavelengths, as the harmonic conversion efficiency decreases with increasing harmonic number, even for echo-enabled harmonic generation (EEHG) [1]. Higher bunching is critical to improve the performance of seeded FELs in the soft X-ray range, with large output power and more compact footprint. The performance of the twin echo-enable harmonic generation (TEEHG) scheme was analysed at 4 nm and shorter with numerical simulations, demonstrating multi-GW level, fully coherent pulses with laser-like properties, which paves the way for externally seeded radiation at 1 nm and beyond.

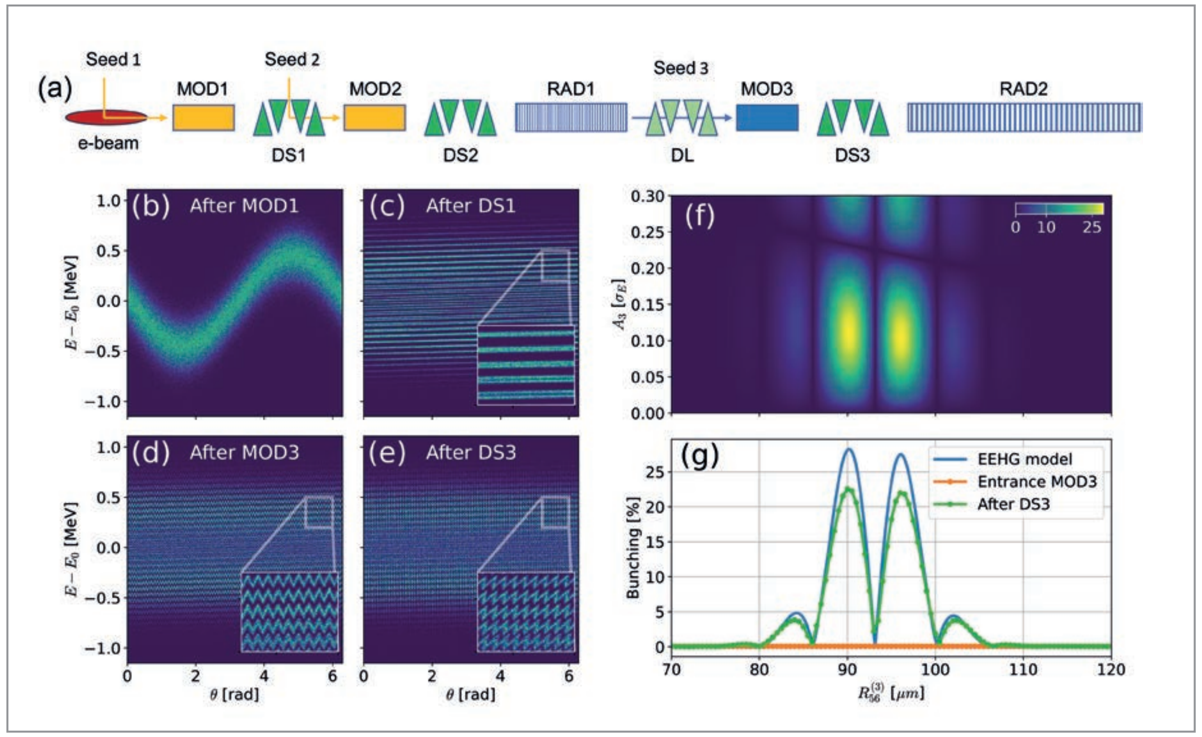
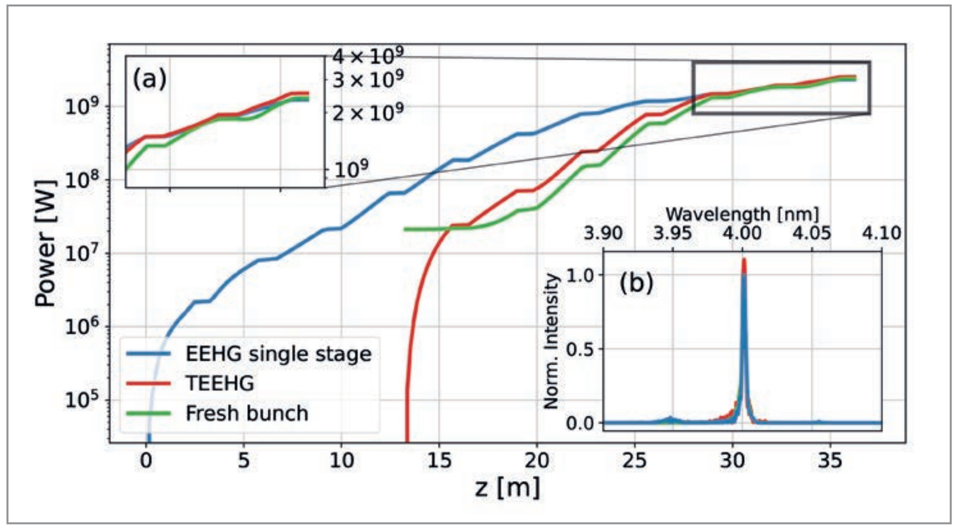


Figure 1

(a) Layout of the cascaded scheme (MOD: modulator section, DS: dispersive section, RAD: radiator). (b–e) Example of the longitudinal phase space for EEHG-2 for one electron beam slice of the size of the seed laser wavelength. Note the modulation at high frequencies in the zoomed inserts, which leads to bunching with proper DS3 tuning. (f) False-colour bunching at 4 nm at the entrance of RAD2 as a function of the modulation amplitude A_3 (generated by Seed 3 in MOD3) and the DS3 strength in down-conversion. (g) Comparison of predicted and simulated bunching vs. DS3 strength for A_3 = 0.108, corresponding to maximum bunching for the left bunching island.

Figure 2

FEL power gain curve for 4 nm. Blue curves correspond to simple EEHG, red to TEEHG (down-conversion) and green to fresh-slice amplification. (a) Zoom towards the beamline end. (b) Radiation spectra vs. wavelength, normalised to EEHG. The gain curves for a fresh bunch and TEEHG have a horizontal offset to represent the space needed for the additional hardware required in cascaded approaches.



Setup description

Figure 1(a) shows the schematic setup for the cascaded scheme, which is composed of two EEHG seeding stages, EEHG-1 and EEHG-2. The first EEHG stage consists of two modulators (MOD1 and MOD2), where two external seed lasers (Seed 1 and Seed 2, respectively) resonantly interact with the electron beam to generate two energy modulations (A_1 and A_2). The first dispersive section (DS1) smears the energy modulation generated in the first modulator section (MOD1) by Seed 1, creating stripes in the longitudinal phase space of the electron beam. The second dispersive section (DS2) is tuned to maximise the bunching at the required intermediate wavelength, emitted by the first radiator (RAD1) to produce the seed for the subsequent stage (Seed 3) towards the tail of the bunch, leaving enough space for the fresh-bunch approach [2]. The second EEHG stage, starting after the fresh-bunch chicane (DL), is used to remodulate the same electron beam with amplitude A_3 in a fresh region where the interaction of Seed 2 in EEHG-1 did not take place. The energy stripes generated by Seed 1 in MOD1 and smeared in DS1 are still present thanks to the long pulse duration of Seed 1.

By proper tuning of the third dispersive section (DS3), an unprecedented amount of bunching is optimised at the final wavelength, emitted by the main radiator (RAD2). While the cascaded approach conventionally relies on the second stage operated in up-conversion (i.e. shorter wavelengths), the proposed scheme can operate both in up- and down-conversion, going towards (slightly) longer wavelengths. This gives best performance in terms of minimum required Seed 3 power (nJ-level) and maximum achievable bunching. An example of the longitudinal phase space for one electron beam slice before and after interaction in EEHG-2 is shown in Fig. 1(b–e). The predicted bunching at 4 nm is 28.7%, an unprecedented level in the soft X-ray range for an externally seeded FEL, as can be seen from Fig. 1(f, g).

Simulated performance

Figure 2 shows a comparison of the simulated FEL performance for simple EEHG, cascaded TEEHG and a simple fresh bunch. While all three considered schemes offer similar performance with approximately 2.5 GW peak power and a pulse energy of more than 50 μJ, TEEHG provides the most economical solution requiring the lowest number of radiators. Spectra for the three cases, normalised to the EEHG maximum, are shown in Fig. 2(b). The radiation pulse length is similar in the three cases. For a more comprehensive overview of the simulations and the technical implementation details, see [3]. By investigating the performance of the TEEHG scheme at 4 nm for FLASH2020+ and at 2 nm for the FEL-2 beamline at FERMI2.0, multi-GW power levels could be demonstrated. The main limitation identified was the finite Seed 3 size, and possible alternative uses were determined, e.g. for amplifying minute signals [3].

Conclusions

The presented novel externally seeded cascaded FEL scheme based on two EEHG stages operated either in harmonic up- or down-conversion could pave the way to fully coherent pulses in the soft X-ray range. Modelling and simulations have demonstrated its ability to create unprecedented bunching independently of the final FEL wavelength, with modest requirements for the intermediate stage (A_3 ~ 0.1, nJ pulse energy).

Contact: Eugenio Ferrari, eugenio.ferrari@desy.de

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Multi-objective optimisation of externally seeded FEL pulses

Identifying the optimum operation parameters for seeded FLASH

In an externally seeded free-electron laser (FEL), sophisticated preparation of the electron beam phase space is key for successful experiments. External seeding comes with increased complexity for setup and operation because of the fine structures implemented in the phase space by the interaction of the electron beam with lasers. The FLASH simulations team systematically explores different computational methods to map the multidimensional FEL optimisation parameter space. Multi-objective optimisation proved to be critical in revealing dominant trade-offs and improving computational efficiency. A case study showed the necessity of structured optimisation frameworks for high-performance seeded FELs.

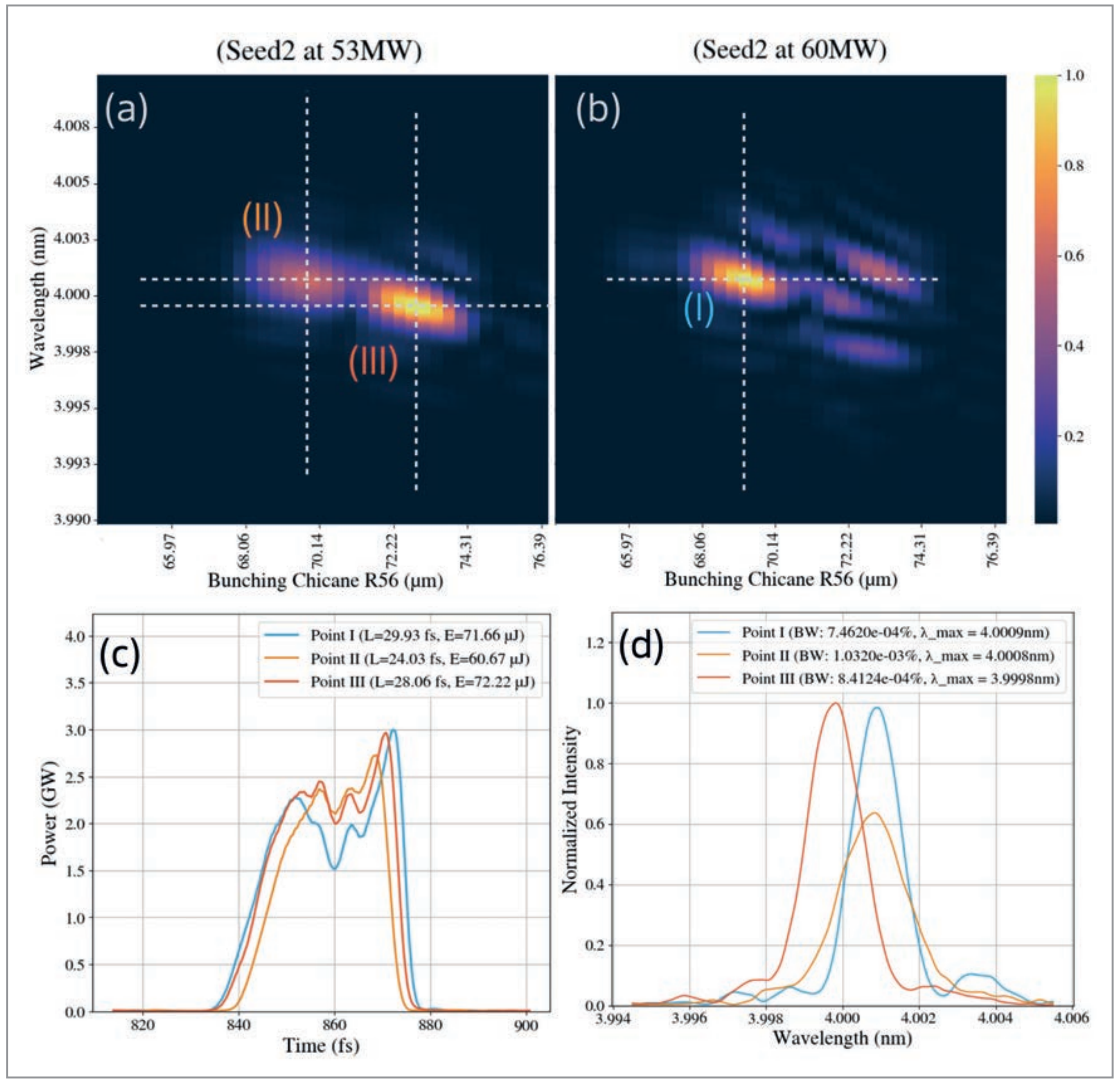

Figure 1

(a, b) Simulation result after the eighth radiator (exponential gain regime) of the new seeded FLASH1 beamline after the FLASH2020+ upgrade. Each inset shows the spectra for a bunching chicane dispersion scan in a tapered radiator setup for two of the top ten non-dominated solutions with a Seed 2 laser energy of 53 MW and 60 MW, respectively. On the *x*-axis, the strength of the bunching chicane is given in R56 (µm), while the *y*-axis shows the wavelength (nm) of the generated photons, with the amount given in the colour code displayed on the right and represented by the FEL power. (c) Power along the bunch with calculated pulse energy (*E*) and pulse length (*L*) for the final optimised points (III) compared to points from earlier optimisation iterations (I–II). (d) Spectra with central wavelength (λ_max) and radiation bandwidth (BW) for the respective evaluated solutions I–III.

Seeding at FLASH and deterministic grid-based search datasets

Echo-enabled harmonic generation (EEHG) is an external seeding scheme that enables the generation of high-brightness, high-coherence and short-wavelength radiation. Using a two-stage energy modulation and dispersive chicanes (one for shearing and one for bunching), EEHG can introduce finest substructures to the electron bunch, allowing the generation of higher harmonics of the original seed laser wavelength and thus shorter wavelength compared to high-gain harmonic generation (HGHG). In reality, however, non-ideal beam characteristics, such as an initial energy-to-time correlation (chirp) of the electron beam, are required to compress the initially long beam, or a non-linear energy variation along the beam imprinted by wakefields or coherent synchrotron radiation. On top of this, the fine bunching structure of an EEHG-generated electron beam is exceptionally delicate to transport and can suffer from space change effects during propagation. Combined, these effects lead to spectral shifts, increased bandwidth and reduced bunching efficiency. Extensive synthetic datasets for evaluating seeded FEL stability in the presence of higher-order effects have already been generated [1]. These datasets enable offline optimisation and facilitate understanding of how to overcome these challenges.

Case study: Optimisation of FEL pulse properties

In recent years, multi-objective optimisation has shown promising results in particle accelerators and photonics [2, 3]. The optimisation strategy focuses on manipulating the bunching chicane dispersion R56 and the Seed 2 laser power to mitigate the effects of beam chirp and other non-linearities. The primary objectives were to reduce the bandwidth and maintain the pulse length within theoretical expectations – avoiding solutions that indicate instability (overly short pulses) or excessive self-amplified spontaneous emission (SASE) background (overly long pulses). To achieve this, a structured grid scan of 50 points was conducted, systematically varying the dispersion of the second chicane and the Seed 2 power to construct a bunching map and identify trends in the FEL output characteristics.

From the 2D scan dataset, the top ten non-dominated solutions were identified, representing Pareto-optimal candidates that provide the best trade-offs between intensity, spectral purity and pulse duration. The optimised starting parameters were further validated in full FEL simulations, capturing their performance after the exponential gain in an optimally tapered radiator section. Point II, shown in Fig. 1, was selected as the best working point at this stage. Finally, to ensure stability and maximise intensity, a final R56 scan for the tapered beamline was performed on the top three Pareto-optimal candidates, resulting in the identification of a more stable and intense solution (Point III). The tapering profile remained constant across simulations in the last step to isolate seeding and bunching conditions rather than changes in FEL amplification dynamics.

This physics-driven optimisation approach offers several distinct advantages: 1) Its deterministic nature ensures a thorough and interpretable exploration of the parameter space, unlike black-box optimisers that can obscure essential physical insights. 2) Given the relatively small and well-defined search space, the computational cost remains manageable, allowing for high confidence in the results without the need for surrogate models or extensive re-evaluations. 3) The method provides a well-characterised, efficient benchmark that can be the foundation for future surrogate models. Identifying Pareto-optimal solutions allows informed decision-making based on the preferred FEL properties, balancing spectral purity, bandwidth and intensity. In addition to improving FEL simulation performance, this approach provides an experimentally feasible tuning method for future EEHG operations at FLASH and other FEL facilities.

Outlook: Extension to machine learning

Once FLASH is back online, integrating machine learning-based techniques would streamline real-time FEL tuning and reduce reliance on time-consuming full simulations. In the future, methods such as genetic algorithms and evolutionary strategies will also be explored to determine which approach provides a competitive advantage at different stages of the optimisation process during machine setup. By leveraging the insights gained from deterministic grid-based search, future optimisation frameworks can combine physics-driven understanding with data-driven efficiency, paving the way for more adaptive and automated FEL control systems.

Contact: Pardis Niknejadi, pardis.niknejadi@desy.de
Lucas Schaper, lucas.schaper@desy.de

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Electron optics compensation for FODO-like lattices

Stabilisation of undulator beamlines against undulator focusing

Both synchrotron light sources and free-electron lasers (FELs) usually employ magnetic devices, called undulators, as radiators in which the electron bunches emit the electromagnetic radiation that these facilities deliver to all kinds of experimental setups in a broad range of scientific disciplines. In addition, undulators affect the electron beam optics in the sense that they focus the beam – potentially in both transverse directions (horizontal *x*) and (vertical *y*). The undulator focusing strength in each transverse direction depends on the strength of the undulator and on several internal undulator parameters determined by the design of the undulator, and is inversely proportional to the square of the beam energy inside the undulator. Thus, undulators potentially perturb the beam transport through the beamline depending on their strengths and the beam energy. In particular, beams with low energies are extremely sensitive to the undulator focusing. In cooperation with the Shanghai Advanced Research Institute and the Shanghai Synchrotron Radiation Facility in China, members of the FLASH group at DESY have developed a semi-analytic algorithm to compensate these perturbations to the beam transport.

Compensating undulator focusing at the FLASH1/2 beamlines

FLASH, DESY's extreme-ultraviolet (XUV) and soft X-ray FEL user facility, employs a superconducting linear accelerator capable of reaching a particle energy of up to 1.35 GeV to drive two undulator beamlines (FLASH1 and FLASH2). The electron beam energy and the undulator strength can be adjusted to tune the wavelength of the FEL fundamental harmonic from 52 nm down to 3.4 nm for FLASH1 and from 90 nm down to 3.2 nm for FLASH2, respectively. The beam energy range of FLASH, together with the used undulator strengths, causes strongly perturbing undulator focusing in certain parameter regimes. At FLASH, the undulators are installed in the empty spaces of so-called FODO cells. A FODO cell can be explained (referring to one – say the horizontal – transverse direction) by a sequence of a focusing element F, followed by an empty space O (like "0"), followed by a defocusing element D and finally a second empty space O. A FODO cell in the horizontal direction acts as a DOFO cell in the vertical, so that both transverse directions are similarly focused – except for a longitudinal shift of a half-cell. FODO cells are a standard building block of beamline design and have proven to be extremely robust. Now, we have modified the plain FODO by inserting undulators U in the plain FODO and yielding what we call a FUDU cell.

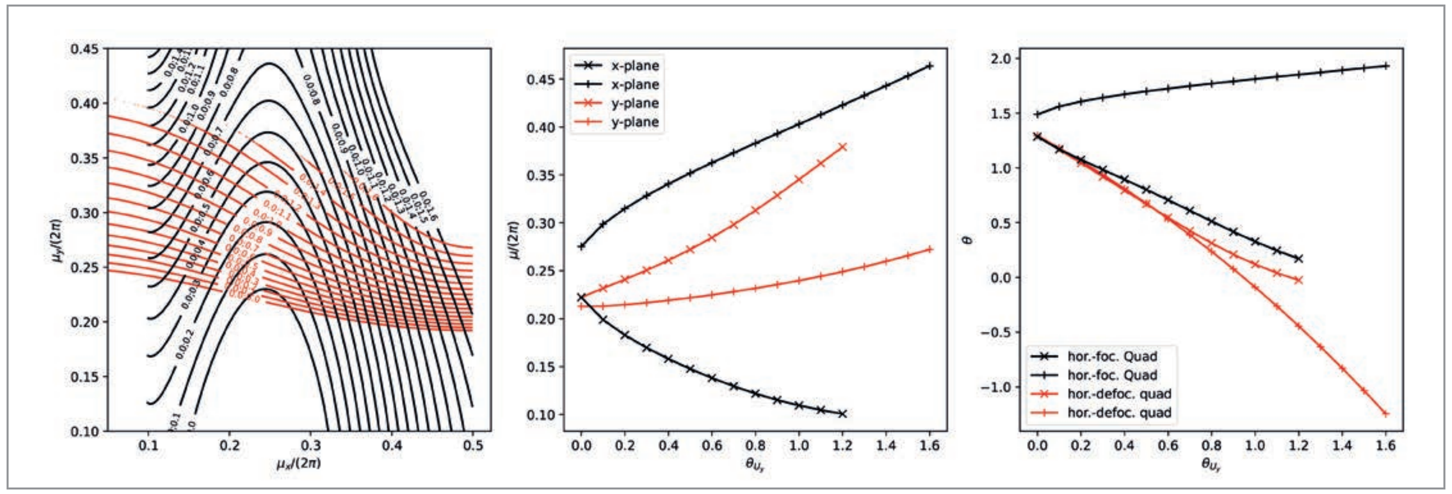

Figure 1

Example of the compensation for a vertically focusing undulator for unperturbed phase advances of $\mu_x = \mu_y = 80°$. Left: Contours of solutions for *x* and *y* where conditions are fulfilled. Centre: Values of intersections of *x* and *y* where conditions are fulfilled for both planes simultaneously in dependence of the undulator strength. Right: Corresponding normalised focusing strengths of F- and D-quadrupole vs. normalised undulator strength.

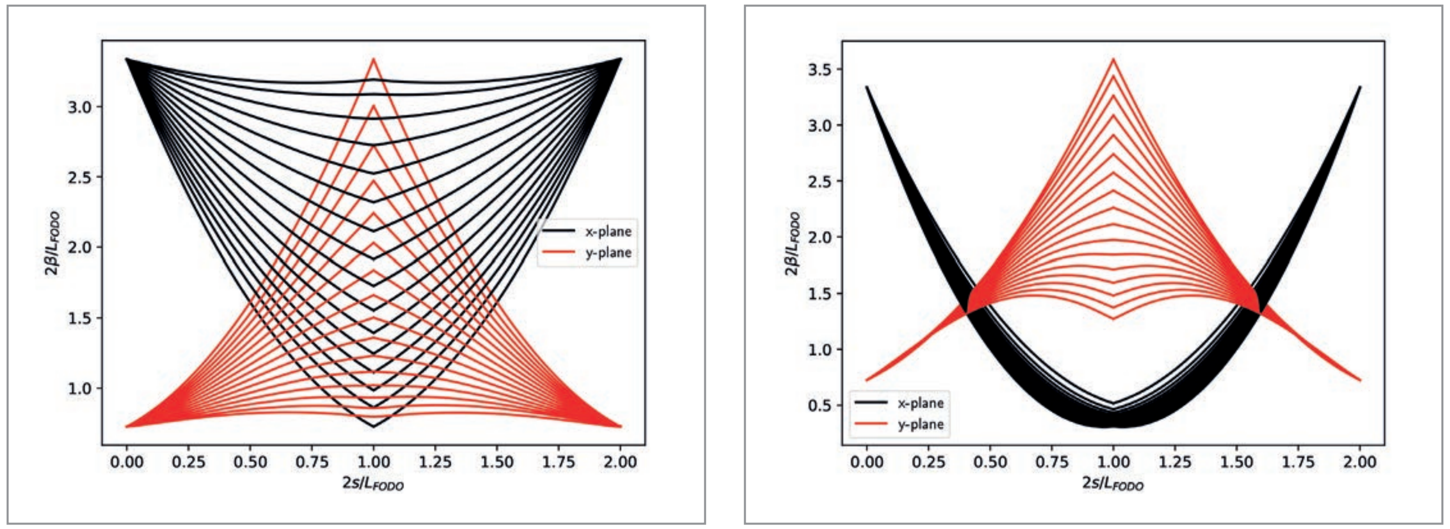

Figure 2

Variation of beta functions along *s* for various undulator focusing strengths for an initial phase advance of 80°. *s* = 0 refers to centre of the F-quadrupole. Left: Solution for the first branch. Right: Solution for the second branch.

We have recently developed a correction scheme that, within a finite range of reasonable undulator parameters and beam energies, preserves the match of the transverse bunch shape into and out of the FUDU sequence [1] and thereby minimises the detrimental beating of the beam sizes inside and downstream of the undulator section. In what follows, we normalise all involved length scales (including the effective focal lengths of F, D and U) by the half-cell length $L_{FODO}/2$ to obtain a scalable parametrisation of the result. The only way to compensate the perturbation due to the varying undulator focusing strength is to vary the strengths of the two quadrupoles (F and D). We have derived analytical formulae for the normalised quadrupole strengths ϑ_F and ϑ_D in dependence of the normalised undulator focusing strengths ϑ_{Ux} (here $\vartheta_{Ux} = 0$) and ϑ_{Uy} (here the independent variable), the phase advances μ_x, μ_y, which are dimensionless measures of the total cell focusing, the constant length scales of the insertion and the chosen fixed incoming matched beam shapes characterised by the so-called beta functions β_x, β_y. This is shown in Fig. 1 (right). In order to obtain the phase advances that ensure the initial incoming beta functions stay matched, shown in Fig. 1 (centre), we need to locate the intersections of the analytically given contours in μ_x / μ_y space of fixed β_x and β_y for given ϑ_{Uy}. These contours are shown in Fig. 1 (left).

The beam shape can only be kept constant at the cell boundaries, while inside the cell it differs from the unperturbed case ($\vartheta_{Uy} = 0$) when varying ϑ_{Uy}. Figure 2 shows the beta functions for various ϑ_{Uy} values along the longitudinal position within the beamline *s*. The solutions for increasing vertical focusing of the undulator show a decreasing average β_y, while for the first branch the average β_x gets larger, for the second branch the average β_x gets smaller in addition. It is obvious from Fig. 2 that the incoming and outgoing beta functions are maintained by the correcting FUDU quadrupoles while the strength of the undulator is changed.

Furthermore, one can derive equations in a similar approach for FU_1DU_2 sequences, i.e. with two different undulators. This includes the case where one undulator is actually missing, two-colour setups where the undulators have alternating strength and/or schemes with undulator focusing in different planes from undulator to undulator. We plan to implement this kind of optic compensation for the FLASH FEL beamlines, but we need to verify that this approach is also robust in operation. The main advantage of our approach over earlier compensation schemes is that the original beam size match into the undulator is preserved for a large range of undulator settings.

Contact: Johann Zemella, johann.zemella@desy.de
Mathias Vogt, vogtm@mail.desy.de

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Stabilising complex optical lasers with femtosecond precision

Towards sub-5-femtosecond stable accelerator facilities

Scientific experiments conducted at the beamlines of accelerator facilities investigate increasingly faster processes. The dynamics of ultrafast processes are explored by means of pump–probe measurements with X-ray and visible to near-infrared photons. An improvement of the pulse arrival time of the laser systems used leads to improved dynamical resolution of these processes and better control of their excitation. Monitoring and correcting the arrival time of these complex laser systems down to the femtosecond level is key to achieving the goal of sub-5-fs stability throughout the facility. At FLASH and the European XFEL, this is enabled by highly stable synchronisation in time of the whole facility, realised with an optical synchronisation system developed and maintained by the DESY Beam Controls group.

Why do FELs require an optical synchronisation system?

Free-electron lasers (FELs), such as DESY's FLASH and the European XFEL, are large-scale accelerator facilities with strict synchronisation requirements. The most critical components throughout these facilities are therefore synchronised in time by means of an optical synchronisation system. The latter comprises a highly stable optical pulse train delivered to each measuring station via actively stabilised optical fibres. These synchronisation signals are used to measure the arrival time of the electron bunches or to resynchronise the radio frequency (RF) wave for electron acceleration with femtosecond precision. Further time-critical clients are the oscillators of the facility's various optical laser systems, for example the photoinjector lasers, the seed laser or the pump–probe lasers. The current synchronisation systems were implemented at FLASH in 2009 and at the European XFEL in 2018 and have since been continuously improved. They are currently able to achieve synchronisation of two laser oscillators 3.4 km apart with a precision of better than 2 fs.

The optical lasers for pump–probe experiments or for the photoinjector are highly complex systems in themselves, starting with a single oscillator and comprising several amplification stages. They often integrate non-linear conversion stages of the oscillator wavelength to reach different colours, depending on the requirements of the final experiments. All these stages and the laser beam transport from the laser laboratory to the experiment or the electron source (gun) add drifts and jitter to the arrival time of the laser pulses. Drifts are defined as variations of the arrival time on timescales larger than a second, whereas jitter encompasses faster variations of the arrival time.

Figure 1

One mirror of a multipass cell. The laser beam bounces back and forth between two mirrors located at both ends of the multipass cell. In the middle, the beam is focused tightly. The cell is filled with a noble gas, e.g. argon. Due to the long beam propagation path of several tens of metres, mechanical instabilities may add substantial drift and jitter.

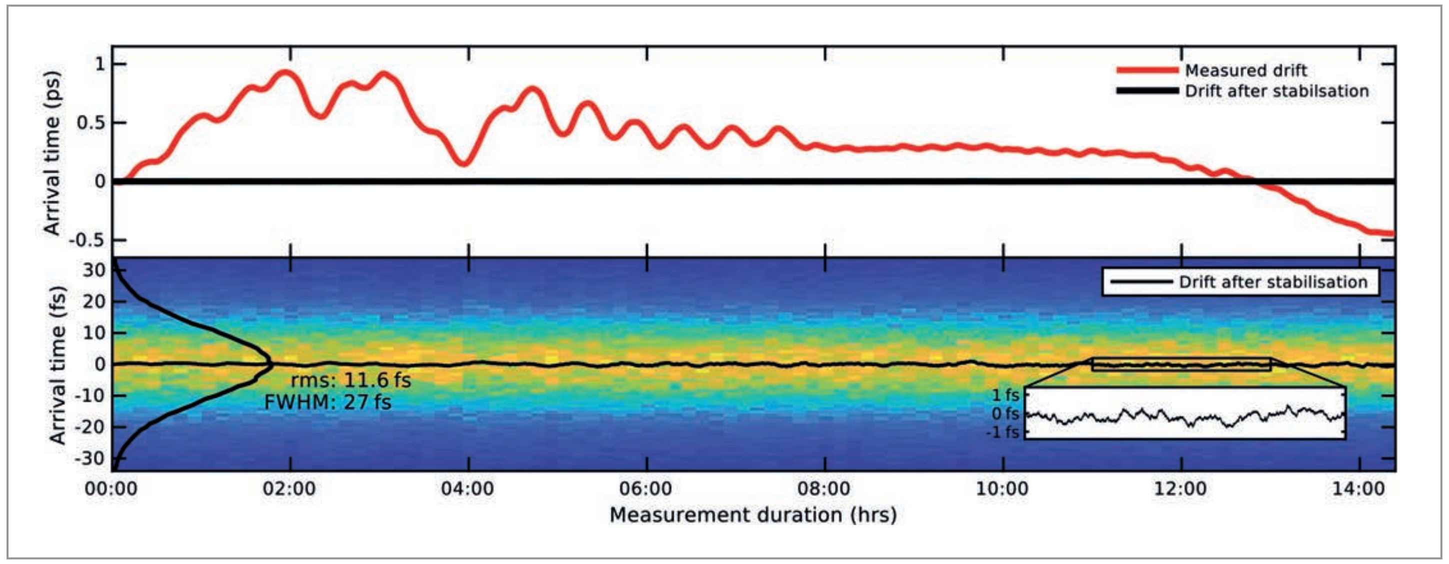

Figure 2

Example of measurement results of the laser pulse arrival time monitor. Upper panel: Drift measured (red) and after compensation (black). Lower panel: The colour bar represents the arrival time of each burst during the measurement, with yellow indicating that the majority of pulses arrived at this time. The black line is the same drift representation as above, zoomed in to better visualise sub-femtosecond stability.

Upgrade of the synchronisation system

Presently, the drifts against X-ray photons measured at the point of the experiment at FLASH and the European XFEL can be as high as picoseconds over a day, i.e. a thousand times worse than at the output of the synchronised laser oscillator, and the jitter can amount to up to 50 fs. Consequently, the next upgrade in synchronisation quality is to improve the arrival time stability of the amplified and converted optical photons at the experiment target to the same range as the X-ray photon arrival time, i.e. well below 5 fs. For this, a novel synchronisation component, called a laser pulse arrival time monitor (LAM), is currently being developed in close collaboration with the Lasers group at European XFEL. It will feature large wavelength coverage and automatically adapt to changes of the laser pulse parameters required by the scientific experiments.

In addition, at FLASH, the European XFEL and other facilities around the world, there is a need for higher optical pulse energy while keeping the pulse duration between 15 fs and 100 fs. This has led to the development of new schemes, such as multipass cell compression, where high-energy, picosecond-long pulses are compressed down to the desired duration, without change of wavelength and with high efficiency, i.e. high output energy.

As part of the FLASH2020+ project, the FLASH laser systems were upgraded with a multipass cell (Fig. 1) added after the high-energy amplifiers. At the European XFEL, a similar multipass cell was installed at the SQS instrument. We investigated the arrival time stability after both of them using a prototype of our novel laser pulse arrival time monitor.

Time drifts and jitter after new laser subsystems

Surprisingly, measurements with our LAM prototype revealed a similar drift and jitter after the new multipass-cell-based compression stages as before them. The jitter amounted to less than 15 fs, while the drifts varied between hundreds of femtoseconds over a few hours up to more than a picosecond over a day. As with established methods of laser delivery, we identified that drifts are mainly induced by environmental factors, such as temperature, relative humidity and air pressure changes. Remarkably, by establishing a slow feedback loop, we were able to suppress these drifts to less than a femtosecond (Fig. 2) [1].

The deployment of LAMs throughout the facilities will be a great improvement for scientists doing long-term data acquisition: The time overlap of the X-ray photons and the optical laser photons will be constant over time, and the experiment will hence be easier to set up. Time variations beyond the feedback bandwidth will be measured and made available to the experiment for pulse-by-pulse data sorting, *de facto* improving the resolution of the process under investigation.

Contact:
Anne-Laure Calendron, anne-laure.calendron@desy.de
Sebastian Schulz, sebastian.schulz@desy.de

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KALDERA

Completion of the first laser development phase

KALDERA is DESY's new flagship laser designed to drive next-generation laser plasma accelerators. Its challenging development is approached in three phases, increasing pulse energy and repetition rate while demonstrating electron generation at each individual step. The first phase was completed in 2024, with the system now delivering pulse energies up to 750 mJ at 30 fs with 100 Hz repetition rate. KALDERA is thus ready to drive a laser plasma accelerator and for the deployment of first active performance stabilisation.

Tackling a key challenge in plasma acceleration with KALDERA

Plasma accelerators create remarkably high field gradients of more than 100 GV/m and therefore enable the acceleration of particles on very short distances. The compactness makes laser plasma acceleration a promising technology not only for accelerators in fundamental research but also for medical and industrial applications.

Today's laser plasma accelerators operate at comparably low repetition rates on the 1 Hz level, which prevents the deployment of active stabilisation and feedback techniques that have long been common to the accelerators powering DESY's user facilities. To close this technology gap, DESY is currently building KALDERA to deliver 100 TW peak power laser pulses at up to 1 kHz repetition rate and kilowatt-level average power. These laser pulses will drive a new generation of plasma accelerators that take full advantage of the significantly higher repetition rates and thus regulation bandwidth to stabilise the plasma accelerator performance.

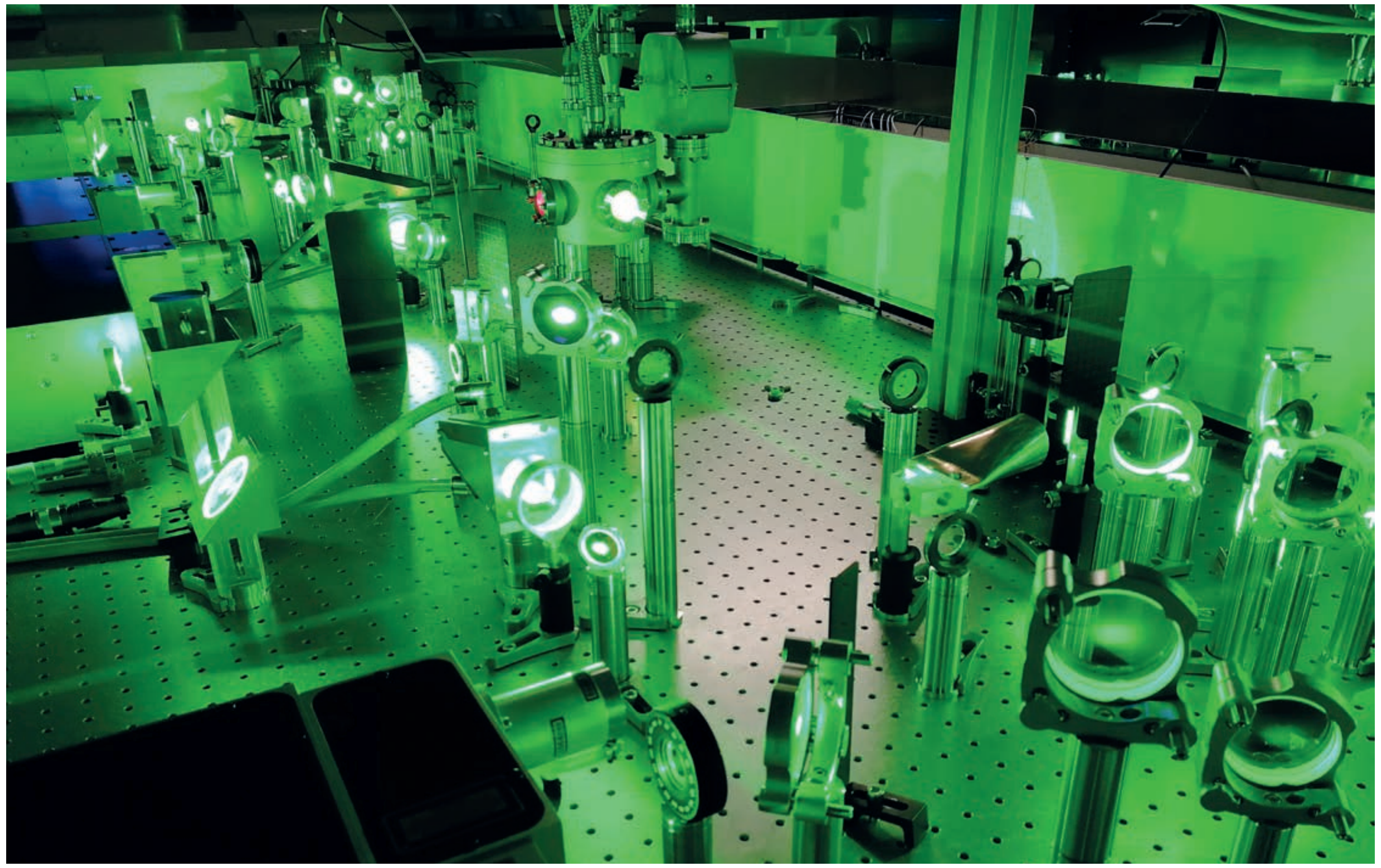

Figure 1

Experimental setup of the last amplifier stage of the KALDERA laser system

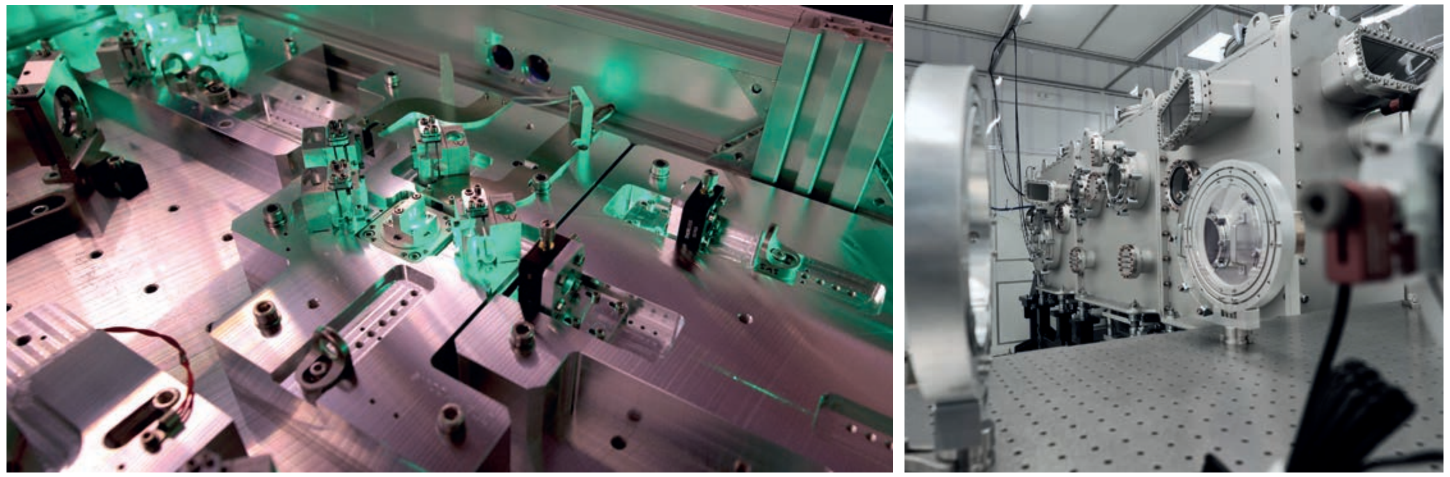

Figure 2

Left: KALDERA frontend. Right: KALDERA compressor vacuum chamber, hosting multilayer dielectric gratings in an out-of-plane architecture [2].

The KALDERA laser system

KALDERA is based on titanium–sapphire technology and a chirped pulse amplification architecture, which poses several technological challenges, including (i) pump laser design, (ii) amplifier design, (iii) pulse compressors, but also (iv) control system and machine protection, all of which must work at kilowatt average power levels. KALDERA is being developed in three phases, increasing pulse energy and repetition rate while demonstrating electron generation at each individual step.

The first development phase, with KALDERA delivering 750 mJ and 30 fs laser pulses at 100 Hz repetition rate, was successfully completed at the end of 2024. In close cooperation with an industry partner [1], a new generation of diode-pumped, ultrastable pump lasers was procured and deployed in the system. The seed and frontend sections in the laser were further optimised with respect to operational stability. Together with partners on campus, a special crystal-bonding technique was used to significantly improve the cryogenic cooling of the laser crystals in the amplifiers. Moreover, a new compressor, based on multilayer dielectric gratings and an out-of-plane architecture [2], was built and is currently being commissioned. Concepts for fast diagnostics and fast data acquisition at up to kilohertz repetition rate were developed and are also being commissioned to support the first generation of plasma electron beams.

Next step: Generate plasma-accelerated electrons with KALDERA

Later in 2025, KALDERA will drive the MAGMA laser plasma accelerator (LPA) to generate electron beams on the 100 MeV level. The whole setup is designed from the ground up to process data at the full 100 Hz repetition rate. Experimental data will be used to decode the mechanisms of even the smallest variations in electron beam parameters and then take advantage of KALDERA's high repetition rate to stabilise the LPA performance. Simultaneously, work to increase the performance and repetition rate of the KALDERA laser system will continue. Phase 2, which will bring the pulse energy of KALDERA up to 3 J on target, has already started.

Contact: Guido Palmer, guido.palmer@desy.de
Andreas Maier, andreas.maier@desy.de

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Can plasma accelerators produce flat beams?

A resonance can turn a flat beam round and increase its emittance, but solutions exist

Particle colliders operate with transversely flat beams, meaning beams travelling in the *z*-direction with a larger emittance and size in the horizontal (*x*) than in the vertical (*y*) direction. This beam configuration naturally arises in storage rings – PETRA III, for example, has a horizontal emittance 100 times larger than the vertical one, PETRA IV will have a factor of 5. Such flat beams maximise collider luminosity while minimising beamstrahlung, an effect that can degrade beam quality. In contrast, plasma accelerators typically produce round beams due to their inherent symmetry. But can they accelerate flat beams? Does a flat beam remain flat when accelerated in a plasma accelerator? These questions are the focus of a recently published study led by DESY researchers [1].

Challenge: Symmetry breaking in plasma acceleration

In a plasma accelerator, a short and intense driver – either a laser pulse or a particle beam – propagates through a plasma, expelling electrons from its path. This process creates an ion-filled bubble following the driver with strong electromagnetic fields suitable to accelerate an electron beam (Fig. 1). In the ideal case, the bubble consists of a perfectly uniform ion density, creating a focusing force that is both linear and axisymmetric. These remarkable properties allow plasma accelerators to preserve the quality and flatness of the accelerated beam.

However, various effects can break this picture and couple the horizontal and vertical motions of the accelerated electrons. An important effect is ion motion, where the space charge of the driver or the accelerated beam is strong enough to displace plasma ions. The resulting ion density is no longer uniform in the bubble and the transverse forces become coupled (the force in *x* depends on *y* and vice-versa), affecting the beam's evolution (Fig. 1). In this scenario, electrons trapped in resonance – when their betatron period is identical in the vertical and horizontal planes – exhibit a precession in the transverse plane

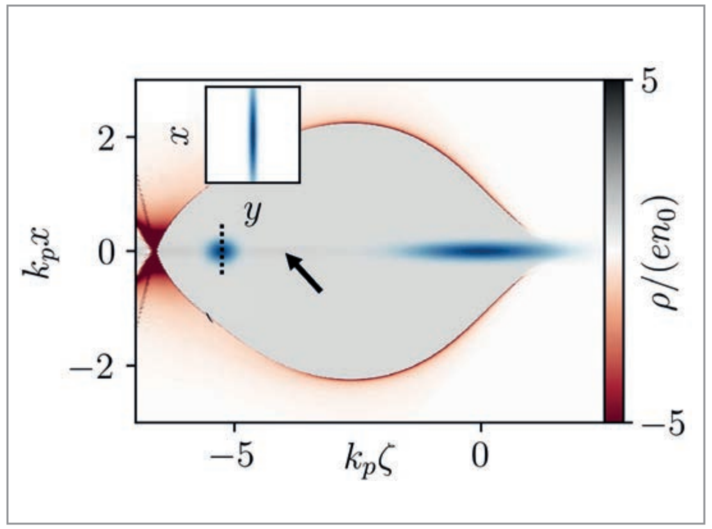

Figure 1

Beam-driven plasma acceleration: The driver beam (right) and accelerated beam (left) are shown in blue. $\zeta = z - ct$ is the co-moving coordinate. As beams propagate to the right near the speed of light, the space charge force of the driver expels plasma electrons from its path, leaving a bubble filled with *almost* uniform ion density. The plasma electrons concentrate in a thin sheath (red), marking the boundaries of the bubble. The inset shows the transverse cut of the accelerated beam at the location of the dotted line. It is 10 times larger in *x* than in *y* (100 times larger emittance). The space charge of the driver causes ion motion: It leaves a trail of slightly higher ion density along the propagation axis, highlighted by the arrow. This slight inhomogeneity creates the non-linear focusing force responsible for the resonance.

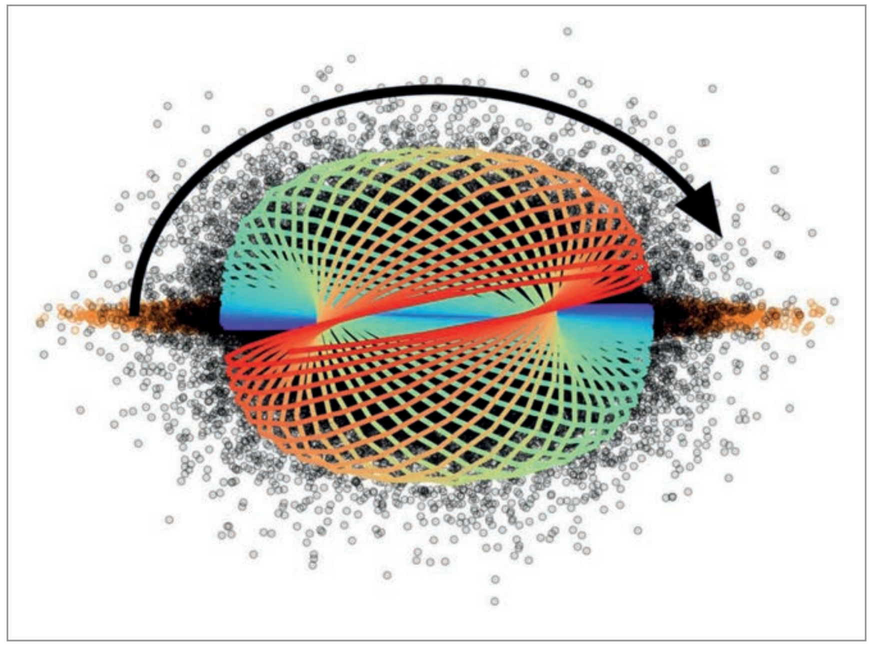

Figure 2

Transverse (*xy*) trajectory of an accelerated electron. The colour indicates the propagation distance (blue → start, red → end). Initially, the electron follows an elliptical trajectory with a major axis near the horizontal direction. Due to non-linearities in the focusing field, this orbit exhibits a precession, causing an initially flat beam (orange) to become round (black) over propagation in the plasma accelerator.

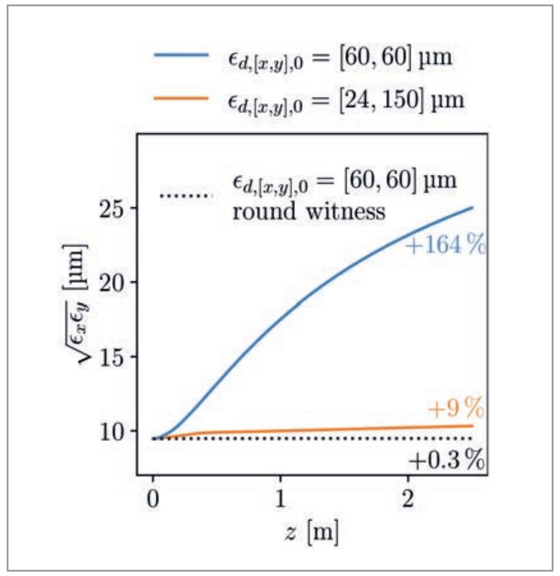

Figure 3

Evolution of beam emittance in the presence of ion motion. Without mitigation (blue curve), the emittance increases by 164% within a plasma accelerator stage. By tailoring the driver geometry (orange curve), the emittance growth can be limited to 9%. This figure shows the geometric average of the transverse emittances in the horizontal and transverse directions, ϵ_x and ϵ_y, as the luminosity is proportional to $1/\sqrt{\epsilon_x \epsilon_y}$.

(Fig. 2). This well-known effect in radio frequency (RF)-based accelerators [2] causes an initially flat beam to become round, leading to significant emittance growth and reduced collider luminosity. This is shown in the blue line of Fig. 3, where the evolution of the emittance is plotted during acceleration over a 2.5 m long plasma accelerator. The resonance results in a dramatic emittance growth of 164%, i.e. a 2.6-fold reduction in luminosity.

A solution: Tailoring the driver beam

Fortunately, mitigation strategies exist. When ion motion is induced by the driver, the accelerated beam's flatness can be preserved by carefully adjusting the driver beam configuration. In particular, a flat driver causes a non-symmetric ion motion that breaks the deleterious resonance: For a horizontally flat accelerated beam (emittance larger in the *x* direction), a vertically flat driver beam (emittance larger in the *y* direction) strongly lessens the emittance exchange. This is demonstrated in the orange line of Fig. 3: After optimisation of the driver's flatness, the emittance increase remains within 9% over 16 GeV of acceleration, compared to a 164% growth in the standard configuration.

This newly identified challenge, first explored by DESY researchers in collaboration with the Lawrence Berkeley National Laboratory in the USA, is now an active area of study in the community. It is of particular relevance for plasma-based collider designs using flat beams, such as the proposed Hybrid Asymmetric Linear Higgs Factory (HALHF) [3], where significant ion motion is expected due to the combination of high beam energies and low emittance. In fact, some ion motion is even beneficial to plasma accelerators as it helps mitigate the hosing instability that can degrade beam quality [4]. Finally, other effects, such as beam-induced ionisation or plasma non-uniformities, can also trigger this resonance, and efforts are under way to develop even more robust mitigation strategies across various plasma acceleration scenarios. More details can be found in [1].

Contact: Maxence Thévenet, maxence.thevenet@desy.de

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The SINBAD-ARES linear accelerator

A precision tool for accelerator science, technology and medical application developments

In 2024, operation time of the Accelerator Research Experiment at SINBAD (ARES) linear accelerator was reduced due to the tight budget situation. This had a major impact on the team and the scientific programme at ARES, but it was still possible to produce and diagnose electron bunches of 3 fs length. Routines to measure a 5D tomography for the first time were developed at ARES and successfully tested at FLASH. Beamtime was also used to train and optimise reinforcement learning agents in order to achieve autonomous accelerator operation. Accelerator R&D for internal and external users was continued with reduced availability. The EIC Pathfinder project THz Wave Accelerating Cavity (TWAC) successfully measured bunch length with dielectric tubes. Medical experiments with living cells irradiated with a 155 MeV electron beam, studies for an electron-based computed tomography (CT) and beamtimes to study online dosimetry were performed with internal partners and collaboration partners, the University Medical Center Hamburg-Eppendorf (UKE) and the University of Wollongong, Australia.

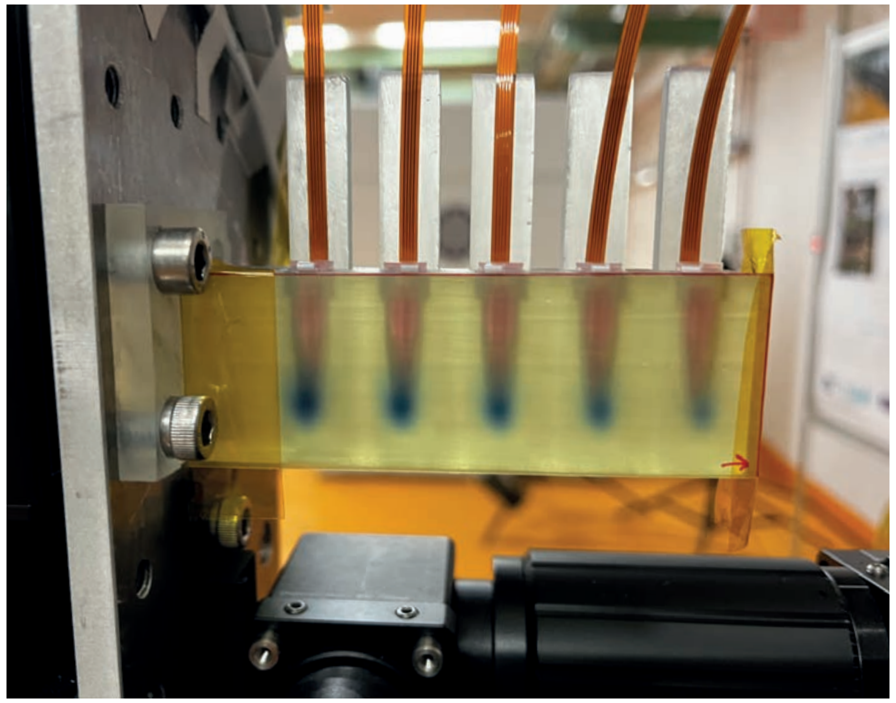
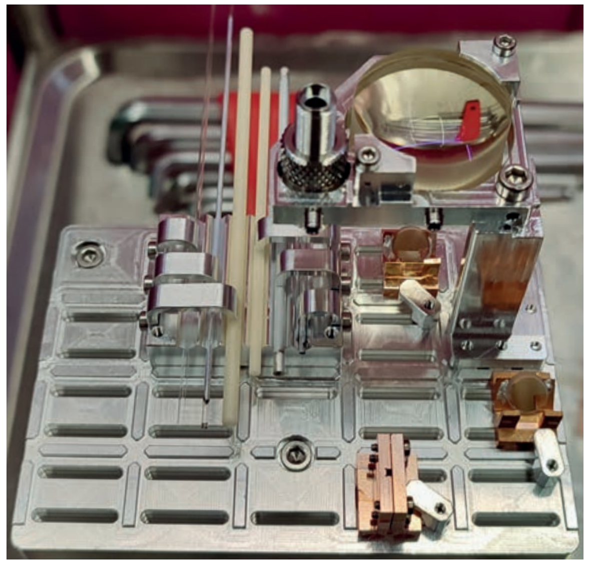


Figure 2
Tumour cell irradiation setup in the in-air experimental area of ARES. The cells are placed in Eppendorf tubes. The online dosimetry sensors are located behind the cells (vertical copper wires). The dose deposition is also visible at the dark spots on a dosimetry film in front of the tubes.

The R&D linear accelerator ARES

As one of the Helmholtz Accelerator Research and Development (ARD) test facilities, ARES is used on a regular basis for various internal and external accelerator research and development projects. Internally, the development of beam position monitors, screen stations and bunch compression monitors within the DESY Accelerator Division continued. ARES was also used for laser developments by the Laser Science and Technology group and for the development of novel dose rate monitor systems by the Radiation Protection group. For the first time, ultrashort electron bunches with a length of 3 fs (RMS) were measured with the polarisable transverse deflecting structure (PolariX TDS). The Beam Controls group regularly used ARES to perform studies for the Helmholtz Autonomous Accelerator project, including shared beamtimes with the collaboration partners from the Karlsruhe Institute of Technology. After successful tests at ARES, these systems will be rolled out to some of the DESY user facilities, e.g. machine learning applications for the "R-Weg" beam transfer line at the DESY II synchrotron or novel beam loss monitoring systems for DESY II.



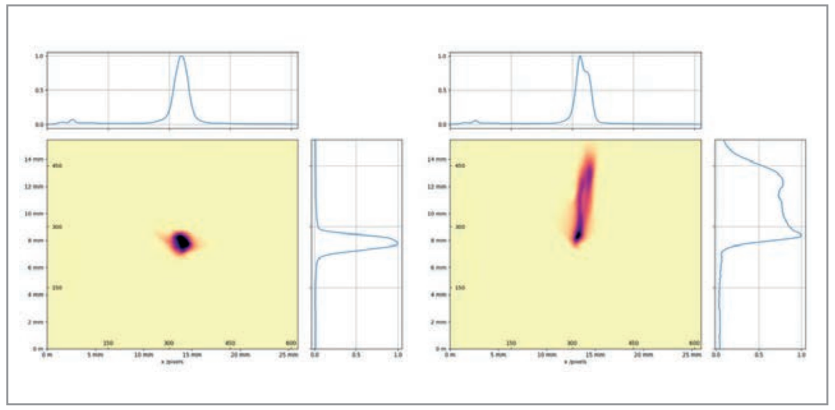


Figure 1
Left: Experimental setup of the TWAC experiment in the ultrahigh-vacuum chamber of ARES. The different dielectric tubes are visible on the left. Right: Unstreaked and streaked beam on the downstream screen. This method is used to measure the bunch length.

TWAC

The EIC Pathfinder project TWAC aims to build a prototype that paves the way towards a compact low-energy and high-peak-current electron accelerator, which is highly sought after for applications in research as well as medical and industrial environments. The project relies on a synergy between several European research institutes and companies. Within the framework of the project, DESY has the task of developing compact electron bunch duration diagnostics with a resolution in the femtosecond range and of benchmarking them at ARES. This objective is a challenge on its own, as it requires a combination of single-digit femtosecond resolution, compactness and minimal complexity of the technical environment so that the diagnostics fit into an overall metre-scale layout. This development work was performed within the ARES team in 2024 with the implementation of dielectric tubes into the ultrahigh-vacuum chamber (by the Vacuum Systems group) and the first successful measurement campaigns to show passive streaking of the electron beam and the resulting bunch length measurements (Fig. 1).

Medical applications

The work on medical applications was successfully continued by the oncologists from UKE with beamtimes to irradiate living tumour cells as well as small animal and human skull phantoms. In addition, an online dosimetry system was developed with UKE and the University of Wollongong, Australia, and tested at ARES for the first time with high-energy electrons. These detectors were successfully benchmarked with dosimetry films (Fig. 2). This effort was third-party-funded by the Helmholtz Innovation Platform for Accelerator-based Technologies and Solutions (Hi-Acts). The work on electron CT with detector experts from the DESY Particle Physics Division, described in the *DESY Accelerators 2023* annual report, continued with further testing and optimisation of the data taking.

Contact: Florian Burkart, florian.burkart@desy.de

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Can ChatGPT tune accelerators?

Tuning of particle accelerators with large language models successfully demonstrated at ARES

Have you ever wondered: "Can ChatGPT do that?" So have we at DESY. Tuning particle accelerators is a constant challenge in daily operations and a significant hurdle to meeting ever more demanding research requirements. While artificial intelligence (AI)-driven optimisation has gained traction, deploying these methods in practice still requires extensive engineering expertise. But what if AI could handle tuning through simple instructions? Recent advances in natural language processing, as seen in ChatGPT, hint at such a future. Studies at DESY's Accelerator Research Experiment at SINBAD (ARES) facility have already shown that existing models can tune accelerators using nothing but a natural language prompt.

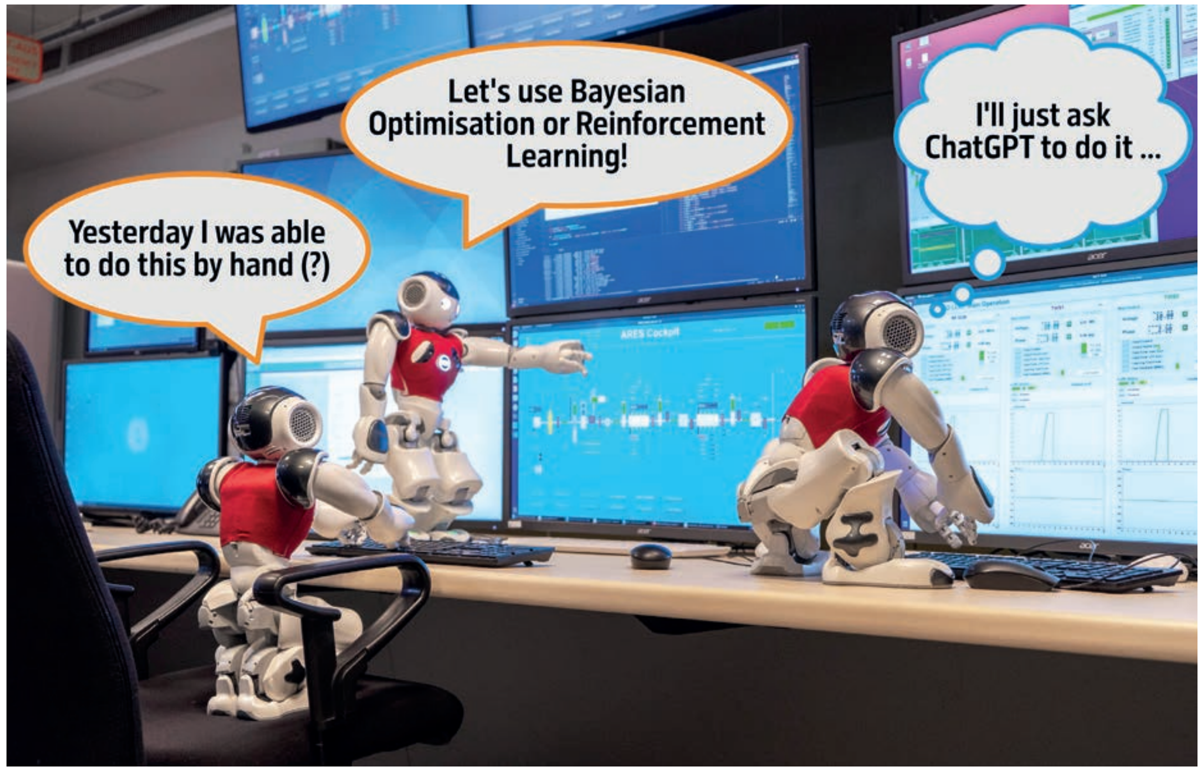

Figure 2

Robots at the ARES control station discuss how to tune the accelerator in this artist's illustration.

Autonomous particle accelerator tuning

The tuning of particle accelerators is a major part of their operations and has significant impact on the availability of these facilities and the quality of their scientific output. Autonomous tuning, with the purpose of reducing tuning times, improving tuning results and making the latter more consistently reproducible, is one of the accelerator community's most difficult challenges to date.

Various methods have been proposed and successfully demonstrated over the years – ranging from classical numerical optimisers to more advanced learning-based methods. Some of the most state-of-the-art methods involve advanced AI techniques and are capable of learning how to tune a particle accelerator on their own by interacting with simplified simulations of it.

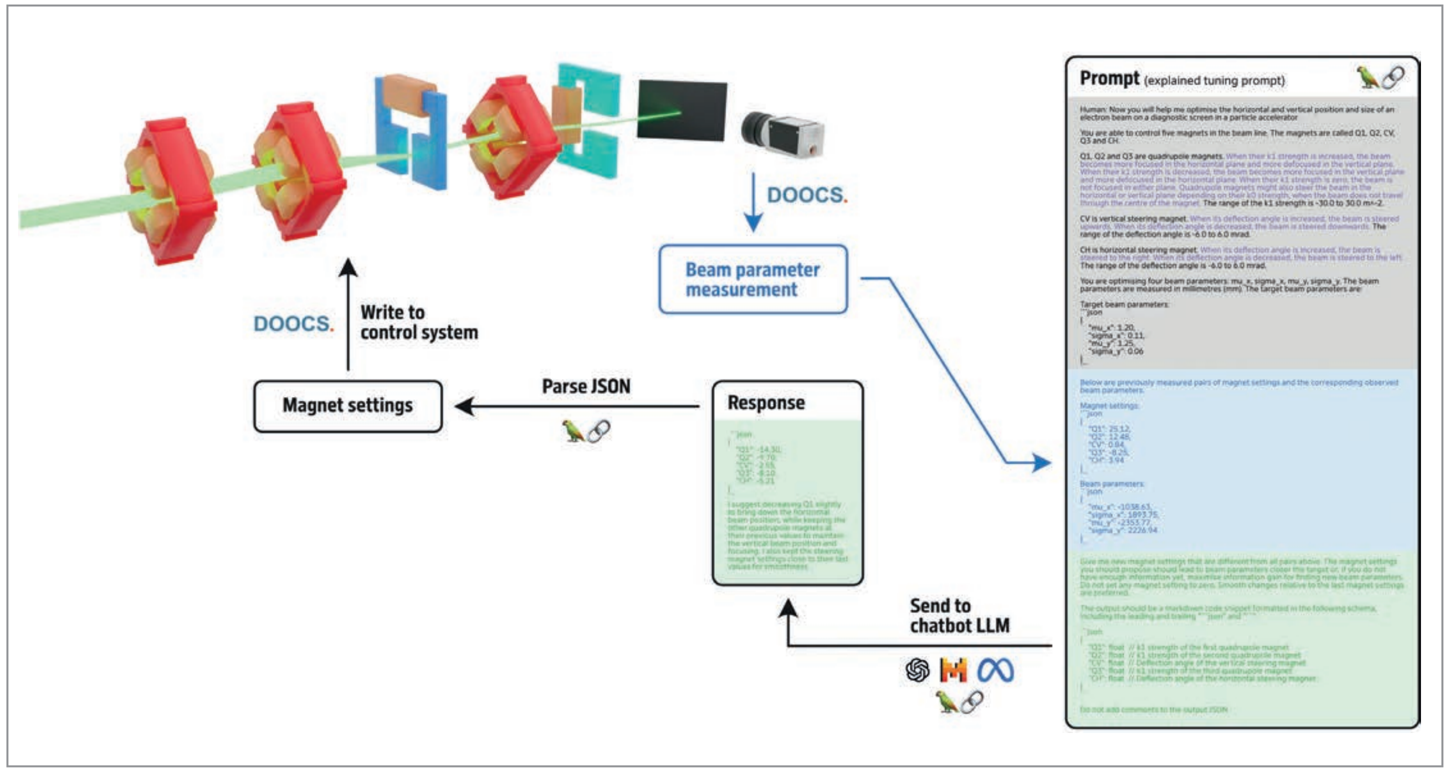

Figure 1

Flowchart illustrating how prompts to large language models (LLMs) are generated and used to tune the Experimental Area subsection of the ARES particle accelerator

ChatGPT and other large language models

However, all of these methods have in common that they require significant expertise in optimisation and machine learning. Instead, turn-key solutions are desired. Recent advances in large language models (LLMs) have led to these exhibiting behaviours that more closely resemble general intelligence than any method before them, raising the question whether systems like ChatGPT can be asked to perform accelerator tuning based on nothing but a natural language prompt by someone who is an expert in accelerators but not necessarily in AI systems.

Natural language-based accelerator operations with the help of AI

In collaboration with Universität Hamburg, researchers of the Intelligent Process Control (IPC) team at DESY have found that this is indeed possible [1, 2]. More so, it was found that, if the model and prompt are chosen wisely, LLMs can tune an accelerator even when they are unaware that this is what they are doing and are instead told they are optimising a black-box function. Despite the performance being inferior compared to machine learning-based approaches like reinforcement learning, the discovery of the ability to perform these tasks has an impact reaching far beyond the tuning of particle accelerators. It represents yet another emergent capability of these state-of-the-art AI systems.

With prompt design being a crucial factor in the overall performance of LLMs, multiple different prompts were evaluated, phrasing the task either as an accelerator tuning task with detailed information on the accelerator hardware, or as a black-box optimisation task where the LLM is not even aware that it is tuning an accelerator, with multiple prompts in between being tested as well. It was found that a minimal task formulation without the accelerator context works best. In addition to demonstrating the ability of LLMs to tune particle accelerators, the present work thus also demonstrates their ability to solve black-box optimisation tasks in general.

Sustainability

LLMs are known for their high computational demands, which inevitably entail significant energy consumption and environmental impact. The environmental impact of using an LLM for accelerator tuning was therefore further analysed. It was found that using an LLM for accelerator tuning would cost up to 5 US dollars per tuning run and require about the same amount of electric energy as running a fridge for 11 h. If LLMs were used exclusively to tune the accelerator, this would amount to 0.003% of the total energy consumption of large facilities such as the European XFEL.

Contact: Jan Kaiser, jan.kaiser@desy.de
Annika Eichler, annika.eichler@desy.de

References:

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Cheetah

High-speed differentiable beam dynamics simulations for machine learning applications

Beam dynamics simulators are essential tools in the particle accelerator community, capable of high-fidelity modelling of numerous physics effects. However, machine learning applications demand vastly faster computations to generate the large datasets required for artificial intelligence (AI) solutions, as well as efficient gradient computation for training. To meet this need, researchers at DESY have developed Cheetah, a novel differentiable simulator designed for data-intensive machine learning methods, such as reinforcement learning in accelerator tuning. Beyond that, Cheetah now enables a wide range of applications, from system identification to autonomous optimisation.

Bridging the gap between beam dynamics simulations and machine learning

Over the years, the particle accelerator community has developed a large number of highly capable beam dynamics simulators. Their purpose has historically been to enable a precise understanding of all the physics happening in these complex machines. Fidelity and support of various physics effects were of utmost importance, while time available for computation was plentiful.

On the other hand, the emerging field of machine learning demands immense amounts of data. To generate these in a feasible time, fast beam dynamics models are needed. More so, gradients are first-class citizens in machine learning and at the heart of common training procedures used today, but existing simulators are unable to provide the gradients of beam dynamics simulations.

Table 3.3: Step computation times of simulation codes in milliseconds [162]

Code	Comment	Laptop	HPC node
ASTRA	space charge	264 000.00	3 605 000.00
	no space charge	109 000.00	183 000.00
Parallel ASTRA	space charge	39 000.00	17 300.00
	no space charge	16 900.00	12 600.00
Ocelot	space charge	22 100.00	21 700.00
	no space charge	182.00	119.00
Bmad-X		40.50	74.30
Xsuite	CPU, no space charge	0.81	2.82
	GPU, no space charge	-	0.57
Cheetah	`ParticleBeam`	1.60	2.95
	`ParticleBeam` + optimisation	0.79	0.72
	`ParticleBeam` + GPU	-	4.63
	`ParticleBeam` + optimisation + GPU	-	0.09
	`ParameterBeam`	0.76	1.29
	`ParameterBeam` + optimisation	0.02	0.04

Figure 1
Step computation times of Cheetah and other existing simulators in milliseconds [1]

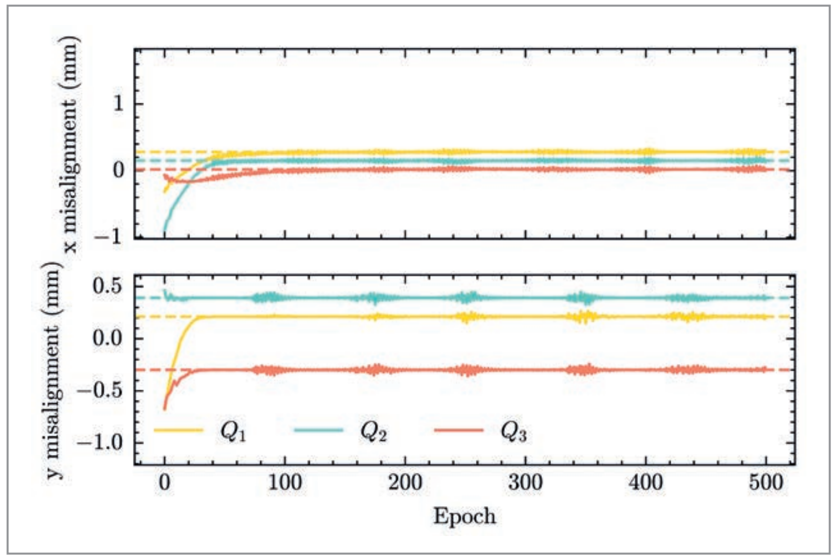

Figure 2
Identification of quadrupole misalignments at ARES using Cheetah over gradient optimisation iterations compared to known ground truth values in simulation (dashed lines)

Figure 3
The Cheetah logo

To solve these issues and combine these two fields, researchers at DESY have developed Cheetah [1, 2], a beam dynamics simulator built on top of the PyTorch machine learning library, providing both speed and automatic differentiation for gradient computation (Fig. 1). Cheetah has since been made available as open source and is increasingly adopted and developed by the community [3], with contributors from eight different institutions now helping with the development. The publication was even selected as one of the top ten articles in the journal *Physical Review Accelerators and Beams* in 2024 [6].

High-speed simulations enable autonomous tuning

Reinforcement learning solutions are notorious for requiring large amounts of data for training, growing into millions of samples even in simple cases. In [4], Cheetah enabled the use of reinforcement learning for tuning DESY's ARES accelerator (see p. 62 and p. 64). In this case, training on the real accelerator would have required three years of non-stop beam time, using a fast conventional beam dynamics simulator would have taken 11 days of computing, and Cheetah managed to reduce training times to just one hour.

Understanding particle accelerators with the help of gradients

The uses of gradients in accelerator operations are vast, ranging from accelerator tuning to virtual diagnostics. In [1], for example, it is shown that gradients from Cheetah can be used to accurately determine the misalignments of quadrupole magnets at the ARES accelerator by means of gradient-based optimisation (Fig. 2). Scaling from this simple use case is possible, with Cheetah now used in day-to-day phase space reconstruction [5].

Contact: Jan Kaiser, jan.kaiser@desy.de
Annika Eichler, annika.eichler@desy.de

References:

[1] J. Kaiser *et al.*, Phys. Rev. Accel. Beams 27, 054601 (2024)
[2] O. Stein *et al.*, Proc. IPAC2022, WEPOMS036 (2022)
[3] Cheetah source code repository, https://github.com/desy-ml/Cheetah
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[5] R. Roussel *et al.*, Phys. Rev. Accel. Beams 27, 094601 (2024)
[6] Phys. Rev. Accel. Beams 2024 highlights hand-picked by the editors, https://promo.aps.org/prab-2024-collection

Shake it off: Taylor Swift fans rock DESY's accelerators

Swift quakes and stadium tremors – monitoring vibrations from local events

Hamburg's Volkspark Stadium is only a few kilometres from the DESY site. In addition to football games, there are frequent concerts with tens of thousands of visitors, making it one of Hamburg's most prominent attractions and a magnet for city tourists. In July 2024, Taylor Swift gave two concerts in Hamburg, attended by more than 50 000 fans on both evenings. Many people do not know that concerts can be a strong source of seismic waves that propagate over large distances in the ground. This article reports on observations with two unique instruments at DESY: a laser-based optical synchronisation system that stabilises the accelerators with femtosecond precision and a distributed acoustic sensing network that makes it possible to monitor seismic waves over large areas. The event also piloted a very successful outreach campaign.

Stadium makes DESY campus vibrate

Seismic vibrations caused by Taylor Swift's concerts and by football matches have become known in the media as "Swift quakes" [2]. On 23 and 24 July 2024, Swift gave two concerts in Hamburg's Volkspark Stadium. The seismic waves from the concerts were detected with the European XFEL laser-based synchronisation (LbSync) system and with a distributed acoustic sensing (DAS) network [1], consisting of optical fibres installed in the PETRA III and European XFEL tunnels and around the campus. Even though both measurement principles are qualitatively completely different, the observed strength and perturbance spectra were in good agreement.

Seismic measurements with distributed acoustic sensing

In the DAS network, strain is measured along an optical fibre with high precision by injecting nanosecond laser pulses of kilohertz repetition rate from an interrogator into the fibre. The Rayleigh-backscattered light from the optical cable is analysed by phase-coherent interferometry to determine the amount of fibre stretching. At the same time, the delay of the back-scattered light provides precise localisation of where the fibre stretching has occurred. In this way, an existing fibre optic network can be transformed into a large-scale sensor system with ten thousand strain metres spanning tens of kilometres without additional infrastructure. Figure 1 shows a screenshot of a live stream of the event, with a waterfall plot on the left displaying the Taylor Swift quakes (diagonal strips) during the concert. The colours indicate the amount of fibre stretching. The plot next to the waterfall diagram shows the PETRA III ring, with the widths of the colour bubbles representing the strength of the fibre stretching and the colours indicating the frequencies.

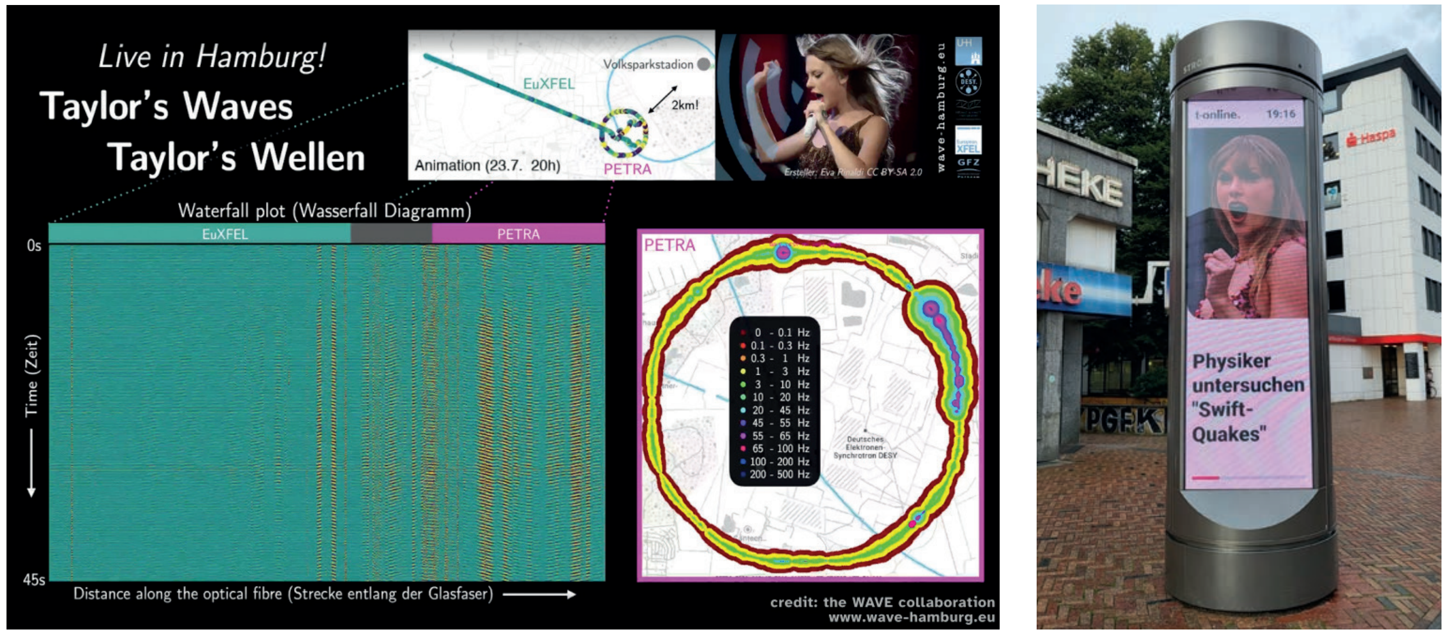
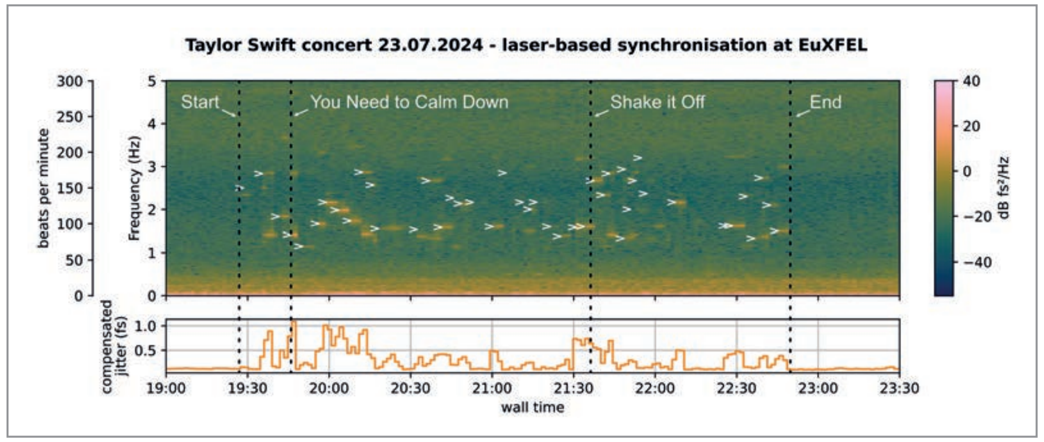


Figure 1
Left: Screenshot of the Twitch live stream during the Taylor Swift concert. Right: Announcement in Hamburg-Altona's pedestrian zone.

Figure 2
Impact of Taylor Swift's concert on the laser-based synchronisation system at the European XFEL [3]



Laser-based synchronisation system at the European XFEL

The second instrument used was the LbSync system of the European XFEL, which ensures precise timing between the various accelerator components. The synchronisation system comprises many elements, including mode-locked lasers, optical distribution, non-linear cross-correlation detectors for laser pulse arrival, radio frequency locking devices and more. For the seismic measurements, the so-called link stabilisation unit was used, a feedback that measures and compensates for small changes in the laser pulse propagation round-trip delay. These changes are mainly caused by temperature, humidity and vibration, but also by ground motions, which can all influence the synchronisation accuracy in the accelerator. Figure 2 shows the feedback correction applied to keep the longest optical link of the system in sync during the Taylor Swift concert.

Impact of seismic waves on accelerators

The DAS and LbSync spectrograms are remarkably similar. Perturbation frequencies are centred at about 2 Hz, corresponding to 120 beats per minute (Fig. 2, white marks). The measured frequencies are consistent with the beats per minute of the Taylor Swift songs, with the second harmonics at twice the frequencies often also visible. Interestingly, the signals could not be seen during the opening act and the ballad songs. In conclusion, the seismic waves were induced by the audience shaking and dancing, not by the loudspeakers' acoustic sound.

Quantitatively, the impact on the European XFEL accelerator was analysed during the song "You Need to Calm Down". The LbSync system compensated for more than 1 fs (in 1 fs, light travels 300 nm), consistent with the DAS observation of a mean strain of about 0.2 nm/m in the longest European XFEL tunnel segment. The optical link feedback can easily cope with this relatively slow, few-hertz perturbation, and a reduction of the residual error by more than two orders of magnitude to less than 0.01 fs was achieved. It should be noted that on these days, there was bright sunshine in the North Atlantic without storms; otherwise, strong ocean wave-induced microseism in a somewhat lower frequency range (0.1 Hz to 0.4 Hz) would have had a substantially bigger impact.

Future work will focus on which disturbances caused by human activities reach the accelerators, where they are detected, and whether they could interfere with accelerator operation. This is particularly important for the planned upgrade of PETRA III to a diffraction-limited synchrotron light source and for improving the temporal resolution of the European XFEL.

Outreach initiative

The opportunity was used as part of an outreach initiative to bring science and society together. A Twitch live stream was set up, and anyone interested could watch the DAS data visualisation in real time while scientists answered questions live in the chat. This prominent and successful outreach activity attracted significant attention, including a billboard in Hamburg-Altona. (Fig. 1, right).

Contact: Erik Genthe, erik.genthe@desy.de
Arne Grünhagen, arne.gruenhagen@desy.de
Holger Schlarb, holger.schlarb@desy.de

The presented work was performed with the WAVE collaboration.

Reference:
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[3] A. Grünhagen *et al.*, arXiv:2502.02453 (2025)

Revamping DOOCS

New foundation for 30-year-old control system

Since its inception in 1992, DOOCS, the Distributed Object-Oriented Control System that drives the European XFEL, FLASH and many other facilities at DESY, has continually evolved into a powerful software framework. To address future challenges, such as meeting the rising complexity of future facilities like PETRA IV, a major modernisation is under way – DOOCS is being enhanced with a new transport protocol and expanded capabilities. These upgrades pave the way for a more flexible and future-ready control system architecture.

Introduction

DOOCS started around 1992 as a humble piece of software for controlling vacuum pumps at DESY's TESLA Test Facility (TTF) and later at the HERA electron–proton storage ring. With the advent of free-electron lasers (FELs) at DESY, DOOCS became the main control system first for FLASH, then for the European XFEL, but also for many smaller accelerators, experiments and lab systems, some of them at partner institutes. It is also set to become the baseline software solution for the accelerator of DESY's flagship project PETRA IV.

The hierarchical DOOCS namespace contains 215 different facilities with a total of almost 30 million properties (Fig. 1). On campus, DOOCS is being operated on more than 1300 nodes that host about 500 different kinds of accelerator controls applications. Users have built almost 22 000 panels for operating accelerators and subsystems with the graphical user interface builder jddd (Fig. 2). Several hundred instances of jddd run on the DESY campus alone, and on many days, more than 4000 individual panels get opened (Fig. 3). For more complex tasks, applications using DOOCS are written in languages as diverse as C++, Java, Python, MATLAB and Lua. The C++ code base alone exceeds 1.5 million lines of code.

Challenges

Future accelerators, such as PETRA IV, are going to raise the complexity of the controls landscape, the amount of data to be handled, the diversity of usage scenarios and the requirements on reliability and software quality. At the same time, the maintenance and development of DOOCS have to be handed over to a new generation of software engineers. This can only succeed if the source code is well-written, tested and documented according to best practices.

New transport protocol

From the beginning, DOOCS was built on top of Sun Microsystem's remote procedure call (RPC) protocol and the external data representation (XDR) format, both of which originate from the 1980s. These venerable technologies, while proving to be extremely reliable, imposed several limits on the development of DOOCS:

- Hard-to-maintain code
- Only synchronous requests (the caller has to wait for an answer before another request can be placed)
- Insufficient capabilities to transport complex and dynamic data types

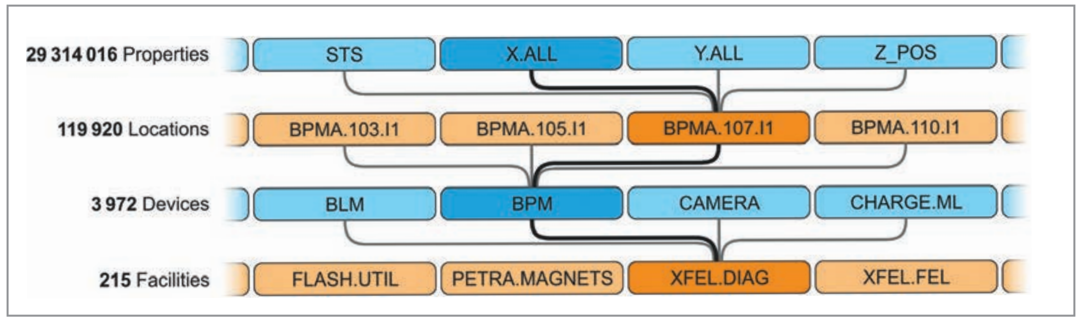


Figure 1

The hierarchical DOOCS namespace contains almost 30 million properties.

Figure 2

jddd panels for operating various accelerators and subsystems

In 2024, the first results came out of a multi-year effort to replace the RPC protocol by ZeroMQ, a state-of-the-art networking framework, echoing similar developments at CERN and in the Tango control system. A custom serialiser replaces the legacy XDR format. This resulted in:

- Simpler and easy-to-extend code
- Native support for the publish–subscribe communication model
- Support for user-defined structured data

Maybe more importantly, these changes are the basis on which we will be able to extend the capabilities of DOOCS in the future. We now have the chance to add features that would have been very hard to implement before (such as asynchronous calls or enhanced wildcard operations). For the time being, the new DOOCS-over-ZeroMQ protocol is still optional. It is already enabled for most servers on the simulation environments for FLASH and the European XFEL so that recent clients automatically use ZeroMQ to talk to these servers. Both clients and servers keep supporting RPC for now to allow for a smooth and transparent migration.

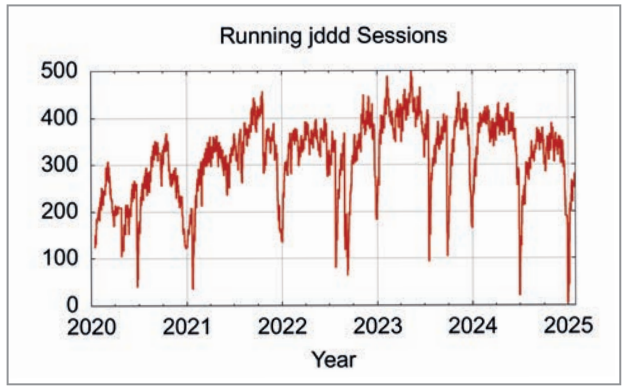


Figure 3

Average number of open jddd sessions on the DESY campus

Outlook

DOOCS-over-ZeroMQ will be enabled gradually on selected production systems starting in 2025. Eventually, DOOCS server applications will stop supporting the Sun RPC protocol, and finally, clients will be able to drop the support as well. Each of the latter two steps will allow us to remove huge chunks of hard-to-maintain legacy code. Similar modernisation efforts are under way for the archiving and configuration subsystems. In addition, many essential and central parts of the codebase are being continuously improved to make DOOCS ready for the challenges of tomorrow.

Contact: Lars Fröhlich, lars.froehlich@desy.de
Raimund Kammering, raimund.kammering@desy.de
Olaf Hensler, olaf.hensler@desy.de
Tim Wilksen, tim.wilksen@desy.de

Keeping control of stable operations

Automatic controls running 24/7 to keep accelerators stable

Beam-based feedback systems are essential for maintaining stable operations at free-electron laser (FEL) facilities, such as DESY's FLASH and the European XFEL. Evolving from early MATLAB scripts to robust server-based solutions in the Distributed Object-Oriented Control System (DOOCS) that drives the European XFEL, these loops now support increasingly complex operations. A centralised feedback manager simplifies the control of dozens of loops, and the future integration of artificial intelligence (AI) tools aims to further automate and optimise accelerator performance.

Introduction

At DESY's pioneering FEL facility called the TESLA Test Facility (TTF), which later became known as FLASH, many operational concepts and controls needed to be developed and commissioned to successfully set up self-amplified spontaneous emission (SASE) operations. Even in the first years of operations of the TTF, it became apparent that several key machine parameters had to be constantly monitored and adjusted in order to achieve and maintain optimal performance of the accelerator. Beam-based feedbacks play an essential role in this context to establish and preserve smooth and stable SASE operations.

Although large facilities such as FLASH or the European XFEL are designed in such a way that influences from the environment are minimised, there are still many sources of interference that affect the various systems of these machines. One could try to isolate the accelerators even further from environmental influences, but this is associated with exponentially increasing efforts and costs. With the sophisticated diagnostic systems installed, the state of the machine can be determined with very high precision. Having these high-fidelity data available online, they can be continuously monitored and counteracted with appropriate actuators to keep the system in the desired state – this is the basic principle of a (here beam-based) feedback loop.

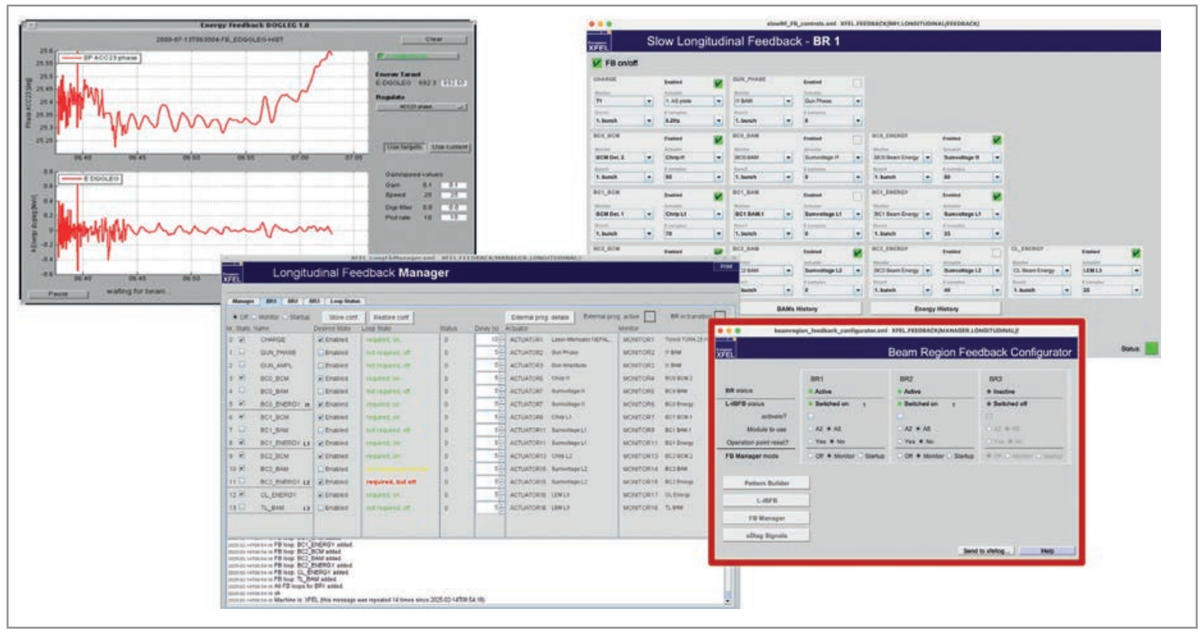
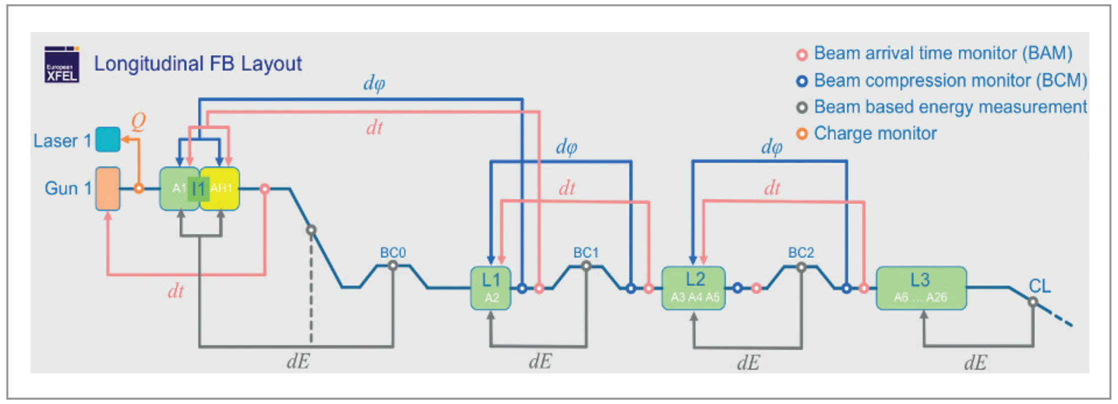


Figure 1
Top left: User interface for one of the first beam-based feedbacks used at the TESLA Test Facility. Top right: Panel for feedback loop operation. Bottom: Feedback manager configuration and the final feedback manager operation panel (red frame).

Figure 2
Schematic overview of all longitudinal feedback loops as implemented at FLASH and the European XFEL



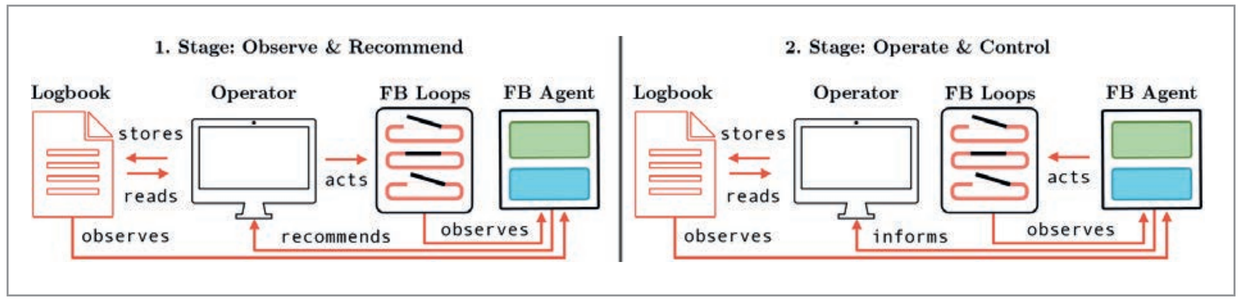


Figure 3
Possible extension of the feedback manager as an AI agent, which learns the desired states instead of using predefined configurations

Development and evolution

Starting with simple MATLAB-based scripts (Fig. 1) during the early days of the TTF, these beam-based feedbacks have evolved significantly and have become an essential part for daily operations, ensuring stable machine conditions for user experiments. For reliability and maintenance reasons, these MATLAB tools have since been ported to server-based solutions using the DOOCS system that drives the European XFEL. This in turn enables continuous and reliable monitoring and supervision of all the essential feedback loops.

Keeping control of the controls

Many of the basic features and challenges encountered at the TTF and later at FLASH were well understood and are now kept stable using various feedback loops. However, as the operation portfolio of these machines broadens, the need for more and more feedback loops arises. Although the chosen architecture makes it easy to add further loops, the operation and interaction between the various loops increases the complexity of the overall system. The number of available feedback loops required to keep the European XFEL running smoothly, for example, amounts to several dozen. Figure 2 shows a sketch of the longitudinal feedback loops as implemented for the FLASH and European XFEL accelerators.

Feedback manager

While the operation of the feedback loops is generally straightforward, the various operation modes of the machines require slightly different combinations and sequences for the operation of these loops. With more operation modes (e.g additional measuring stations), the control of this feedback loops itself also becomes more complex. As a remedy, the idea came up to set up a software application that maintains and operates all these feedbacks from a central perspective. At the European XFEL, such a feedback manager is now used to supervise all longitudinal feedback loops. In its current implementation, the feedback manager takes care of 14 feedback loops per user beamline, adding up to 3 x 14 loops. The manager application makes it possible to set up, monitor and control all loops. This frees the operators from monitoring the status of the 42 possible loops and allows them to focus on other important operational tasks.

Outlook

While the current implementation of the feedback manager nicely integrates into the overall software landscape and eases operation extremely, first investigations using state-of-the-art AI-based methods, such as large language models and agentic AI, are on their way into the control room (Fig. 3 and [1]). This will be the next big step to further automate and simplify operations of the complex FEL machinery at DESY.

Contact: Raimund Kammering, raimund.kammering@desy.de

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Magnet power supply simulators

For developing accelerator control system software

Magnet control systems are vital to the operation of accelerators, and the quality of the control software is critical to the reliability of the systems. Testing modifications to the software components is challenging due to limited access to real hardware. To address this issue, software simulators for power supplies have been developed that mimic real devices and allow comprehensive testing without physical hardware. The simulators enable large-scale tests, creating a virtual environment that is identical to the real system, and support a continuous integration process.

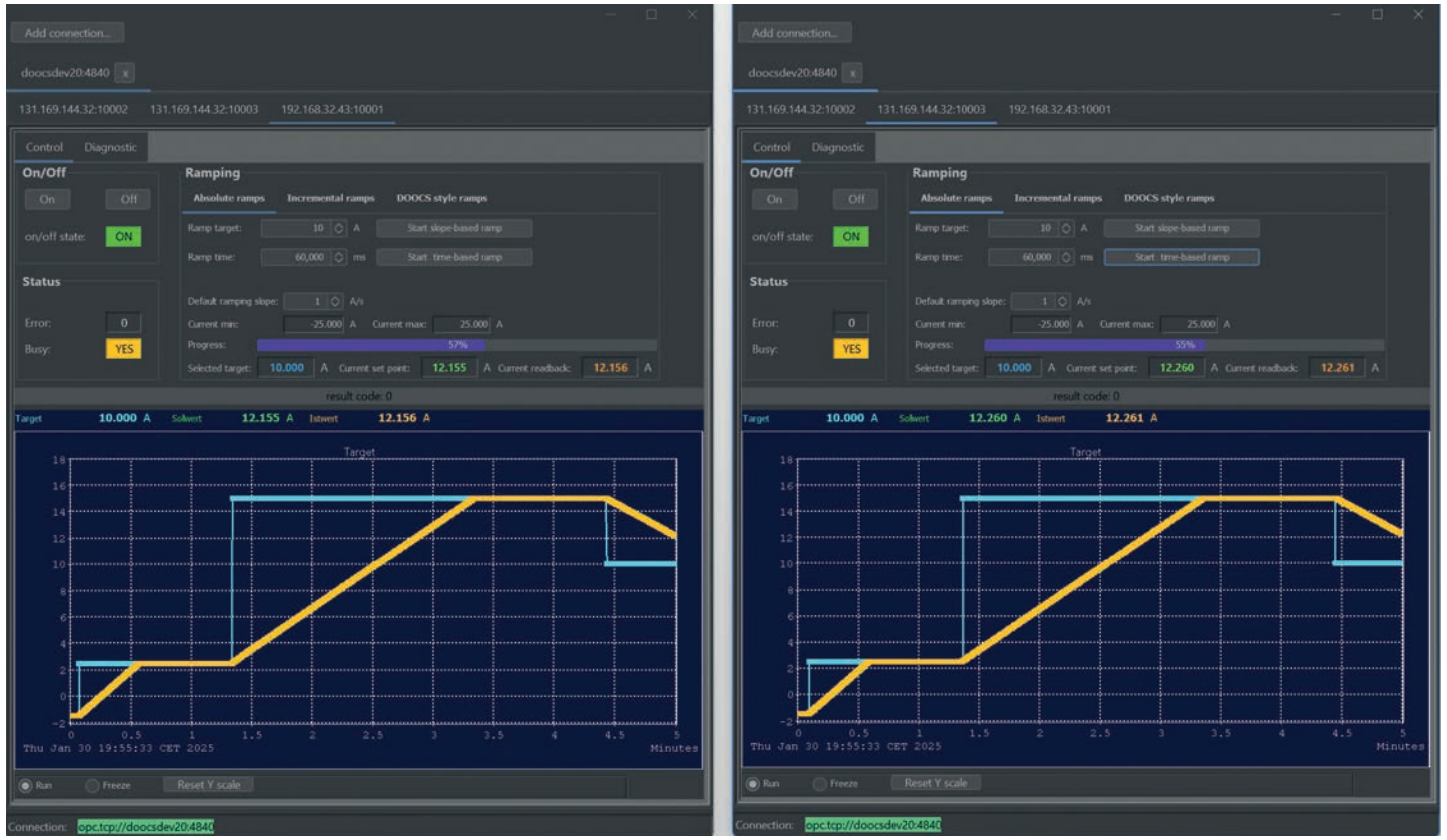

Figure 1

Testing the current ramping procedure. Left: Real CAENels power supply. Right: Simulated device.

Motivation for creating simulators of magnet power supplies

Magnet control systems are crucial for the operation of all accelerators, and the quality of the magnet control software is a key factor in the overall system's reliability. The control software typically consists of several layers, including client layers, middle-layer servers, central servers and device servers. The software is distributed across multiple hosts and runs in numerous instances (e.g. 20 hosts and 25 magnet device servers at PETRA III). Any modification introduced to any of the control software layers must therefore be carefully tested.

Most tests usually require access to the magnet power supplies, and only a few can be performed on small, dedicated test stands, such as the PETRA Magnet Test Stand, which offer a limited number of real power supplies connected to the magnets. Tests using the real accelerator's magnet power supplies can only be conducted during scheduled maintenance days, which complicates and slows down software development.

As a partial solution to the problem of software testing using real hardware, the DESY Control System group has developed software simulators for the power supplies that mimic those used in the accelerators. The stand-alone applications, which run independently on Linux hosts, simulate the real power supplies.

Features and limitations of the power supply simulation

The simulators offer relevant features from the software perspective: the same logical communication interface properties, the same command and data formats, the same status and error codes as well as the same function logic of real device operations.

Simulators connected to the device servers make the entire magnet control system work in most cases as it would with real power supplies, but interaction with other accelerator subsystems (such as machine orbit, interlocks, etc.) is not provided. It is important to emphasise that the simulation is limited to the functionality that is important for control system operations – any electrical properties of the power supplies (such as current trips, output current oscillations, etc.) are not simulated.

Numerous types of magnet power supplies are used at DESY. Most of them communicate with the control system over the Controller Area Network (CAN) / CANopen bus; however, some also use the Transmission Control Protocol / Internet Protocol (TCP/IP) with various ASCII protocols. Currently, most of them can be simulated. In addition, there are already simulators for future devices for PETRA IV, which will feature Open Platform Communications / United Architecture (OPC/UA) connectivity (as recommended for Industry 4.0).

Benefits of using simulators for software testing

Such a solution makes it possible to perform tests of the software before deploying it to the productive system. The device servers can be tested for the implementation of new commands and incoming data processing as well as the handling of error signals generated by power supplies (Fig. 1). We can test how the client applications communicate with the servers, and the graphical user interfaces can be easily evaluated for their functionality. The middle-layer servers can also test communication with device servers and any newly implemented functionality.

The simulation of the hardware layer enables tests to be carried out on a large scale. Because the simulation makes testing independent of hardware development and integration, highly scalable test scenarios can be performed, simulating nearly 700 devices for PETRA III running on a single dedicated host. The simulation of the hardware layer has enabled us to *de facto* create a virtual PETRA III magnet control system with an identical architecture and identical software components to the real PETRA III magnet control system.

At DESY, we can now benefit from testing the entire "build and deploy process chain" of our servers in a virtual environment. To conduct such a test, the Continuous Integration and Continuous Delivery (CI/CD) tool Jenkins is used. It automatically checks out the source code, compiles and pushes it, with predefined configurations for PETRA III, to the virtual PETRA III environment. The subsequent use cases are processed for successful validation. The development team is then notified if any of the tests fail.

An important feature of the simulation system is that it does not require any modification of the device server code. The compiled code, successfully tested with simulators, can be deployed to the target system. Of course, final tests on the real target are always performed, but they are now much simpler and less time-consuming, so they can be done *ad hoc*, even during unscheduled machine operation breaks. Only in very rare cases, where interaction with other accelerator subsystems is needed, are more comprehensive tests in the real accelerator environment still necessary.

The DESY Control System group is also going to use the simulators of power supplies with an OPC/UA interface to test the properties of the power supply network topology for PETRA IV. The simulators and the device servers will be distributed around the ring in a similar way to that planned for the real PETRA IV, so that we will be able to check the efficiency of the network communication and prove the correctness of the magnet control system architecture.

Contact: Piotr Karol Bartkiewicz, piotr.bartkiewicz@desy.de
Marcus Walla, marcus.walla@desy.de

Revamping DESY's power backbone

From particle accelerators to climate control, DESY's technical infrastructure keeps the facilities running. Reliable power ensures smooth operations and high-quality electron beams. To future-proof DESY's main power supply, Mainstations A and B got a complete overhaul (see p. 38).

Picture: Markus Faesing, DESY

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Status of the L-band gun development at PITZ.
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N. Aftab.
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S. Jalas.
Machine Learning Based Optimization of Laser-Plasma Accelerators.
Universität Hamburg, Hamburg, 2024.

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Development of Multi-Alkali Antimonide Photocathodes for High-Brightness RF Photoinjectors.
Universität Hamburg, Hamburg, 2024.

E. S. H. Musa.
Optics measurement and correctionfor future electron circular colliders.
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J. Lamaack.
New Beam Position Monitor System for PETRA IV.
Universität Hamburg, Hamburg, 2024.

Ready for remote maintenance

CERN's MIRA3 robot, equipped with a radiation detector, was tested for autopilot and teleoperation in the PETRA III tunnel, proving its potential for future accelerator remote maintenance (see p. 40).

Picture: Rainer Wanzenberg, DESY

Particle accelerators get an assist from AI copilots

Tuning particle accelerators is a constant challenge in daily operations and a significant hurdle to meeting ever more demanding research requirements. Recent advances in natural language processing, as seen in ChatGPT, hint at a future where artificial intelligence (AI) handles the tuning, which was successfully demonstrated at the ARES facility (see p. 64).

Picture: Jan Kaiser, DESY

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Riccardo Bartolini, DESY
Maike Bierbaum, DESY
Florian Burkart, DESY
Thorsten Büttner, DESY
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Axel Heimken
Miriam Huckschlag, DESY
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Publishing and contact
Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

Hamburg location:
Notkestr. 85, 22607 Hamburg, Germany
Tel.: +49 40 8998-0, Fax: +49 40 8998-3282
desyinfo@desy.de

Zeuthen location:
Platanenallee 6, 15738 Zeuthen, Germany
Tel.: +49 33762 7-70, Fax: +49 33762 7-7413
desyinfo.zeuthen@desy.de

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