ACCELERATORS 2023.

Highlights and Annual Report

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

ACCELERATORS 2023.

Highlights and Annual Report

So much more than just hot air!

The cover picture highlights DESY's technical infrastructure, including heating, ventilation, air conditioning, power supply, water generation and cooling systems. These components are essential for operating accelerators, supporting experimental facilities and developing sustainable research and laboratory buildings on the campus.
Picture: Markus Fäsing & Ralf Sabatini, DESY

PETRA IV – investment in science and innovation

With its planned future project PETRA IV (see p. 34), DESY will lead the use of accelerator-based X-ray light sources into a new era: With a broad portfolio of experimental options and individualised support as well as a rapid access model for science and industry, the new accelerator facility is designed to meet the highest requirements and fulfil the growing demand for non-destructive testing. DESY's flagship project will be the brightest synchrotron light source in the world for decades to come. PETRA IV will be equipped with targeted AI tools, allowing data to be widely used for scientific and industrial purposes and to be channelled directly into industrial value chains.

Picture: Gesa Harms, DESY

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Chairman’s foreword

Dear Colleagues and Friends of DESY,

The world is facing unprecedented challenges. The consequences of climate change are becoming increasingly evident in devastating extreme weather events. Even as the aftershocks of the COVID-19 pandemic continue, we are still exposed to potential new viral and bacterial pathogens whose effects we do not know. Concurrently, the global community is shaken by geopolitical upheavals: Putin’s horrifying war in Ukraine and the brutal terrorist attacks on Israel, just to name a few. Now more than ever, we must advocate for a sustainable and peaceful future so that we do not leave a ruined world for future generations.

What role can a research centre like DESY play in shaping a liveable future in Germany, Europe and the world? How can DESY contribute to limiting climate change and to preventing future pandemics and other health issues? And how do we navigate international collaborations with partners from nations that challenge democratic values, such as China?

Preliminary answers to these questions can be found in our draft of the DESY Strategy 2030 Loop. Under the guiding principle “The Decoding of Matter”, DESY remains deeply rooted in fundamental research. Our commitment as a national centre to the international particle physics organisation CERN remains unchanged, and we continue to expand astroparticle physics. A significant move in this direction is the establishment of the German Center for Astrophysics (DZA) in the Lausitz region – a political decision to which Christian Stegmann, Director in charge of Astroparticle Physics at DESY, has made significant contributions. By 2024, decisions should be made regarding DESY’s position within the DZA.

In recent months, we have vigorously advocated for the timely realisation of DESY’s flagship project, PETRA IV. The conversion of our existing synchrotron radiation source PETRA III into a state-of-the-art fourth-generation X-ray light source is essential to remain competitive worldwide. In particular, the USA and Asia are already heavily investing in similar research infrastructures. All our endeavours regarding PETRA IV have received substantial local political backing from the Hamburg Parliament, which committed to funding 10% of the project’s investment costs. This strong support continues at the national level: During the Federal Budget Committee session on 16 November 2023, a decisive step was taken with the approval of 40 million euros in seed funding for the project – highlighting the pivotal relevance of PETRA IV for future science.

Figure 1

DESY researcher Johannes Hagemann (left) shows German Health Minister Karl Lauterbach (right) the experiments at the PETRA III beamline P06 together with Helmut Dosch (second from left), Hamburg Science Senator Katharina Fegebank (middle) and Gesa Miehe-Nordmeyer from the Federal Chancellery (second from right).

Over the past months, we have seen remarkable support from the high-tech and deep-tech industries. Our industrial dialogue partners recognise that they stand at the brink of a profound transformation: Climate change solutions demand a shift towards sustainable materials and processes, while precision data emerges as the new currency in international competition. Those with the best databases will lead AI-driven developments, be it in custom materials or pharmaceuticals. Fourth-generation synchrotron radiation facilities are globally recognised as vital for generating this invaluable pool of data.

The coming decade will be pivotal for our research centre. For DESY, it is crucial to ensure the swift implementation of PETRA IV and further advance photon science, uphold our leadership in plasma-based particle acceleration developments, expand new methods in astroparticle physics and make a significant national contribution to the High-Luminosity Large Hadron Collider (HL-LHC) at CERN. Concurrently, we must ambitiously drive our vision of creating a dynamic research innovation ecosystem with DESY at the core of the Science City Hamburg Bahrenfeld, incorporating innovative and sustainable digital structures and processes.

Realising this master plan is in itself a monumental challenge. The current financial situation, with volatile energy and gas prices among other effects leading to rising inflation, poses significant difficulties for the DESY management. We face a new reality at DESY: the need to craft a globally competitive research programme with diminishing resources, which is achievable only with stringent prioritisation. The dramatic rise in the construction cost index in recent years has jeopardised several of our planned construction projects. However, we were able to successfully launch the civil engineering work for our DESYUM visitor centre in Hamburg as the first major construction initiative. Construction is progressing swiftly, giving us hope that we will meet all set milestones on time. Up next is the new accelerator centre CAST, which will also house the accelerator control room and the DESY Innovation Factory, a centre for start-ups. Ideally, we would like to implement these projects before the intensive construction phase of PETRA IV.

DESY is held in high international regard in fundamental research. It is imperative to emphasise that our success would be inconceivable without talented researchers and engineers who consistently pioneer the development of new technologies. My special thanks therefore go to them and all the DESY staff, our national and international users as well as our partners for their dedicated work. This is also reflected in the numerous awards they have earned. I would like to highlight two from DESY team members here:

Figure 2

Visualisation of the DESY visitor centre DESYUM, close to the main entrance on the DESY campus in Hamburg

Franz Kärtner, founder of the deep-tech start-up Cycle GmbH and professor at Universität Hamburg, was honoured by the UNIPRENEURS initiative in Berlin for his innovative entrepreneurial spirit. The UNIPRENEURS award is Germany’s most prestigious recognition for outstanding engagement in scientific entrepreneurship.

The Bjørn H. Wiik Prize was awarded to DESY engineer Julien Branlard for implementing the radio frequency control system of the European XFEL X-ray laser. Without the system primarily developed by Branlard, stable operation of the superconducting linear accelerator would have been unattainable. His exceptional engineering achievements have gained international attention, further bolstering DESY’s global reputation in accelerator development.

The crucial message is: We must persistently strive to cultivate an attractive and innovative environment for the world’s brightest minds, or risk falling behind in the international competition – and this is not just about DESY. In challenging times, the ability to provide answers to difficult questions is needed more than ever, and this is precisely where the strength of fundamental science lies. The scientific results in this annual report are good examples of what we can achieve when we work together for a better future!

Yours

Helmut Dosch
Chairman of the DESY Board of Directors

Accelerators at DESY

Introduction

Dear colleagues and friends,

I have now been working at DESY for more than five years as Director of the Accelerator Division. DESY's accelerators are important instruments for science in the service of society, and outstanding specialists with the highest level of expertise work here. DESY has always been a pioneer in accelerator research and development, courageously setting new standards and enabling cutting-edge research. Reflecting on 2023, I am reminded of the many challenges we have already faced and overcome together. The resilience and adaptability of the DESY staff members have been remarkable, ensuring that DESY remains a beacon of scientific excellence. It is this collective spirit and shared dedication that make working at DESY so rewarding.

With the impact of our user facilities and our fundamental research, we at DESY are part of the solution to the major challenges facing society. We should take the lessons learned from the pandemic to accelerate the health research of tomorrow. When Federal Minister of Health Karl Lauterbach visited DESY in June 2023, he praised the interdisciplinary work at DESY as an outstanding example of cutting-edge research in Germany.

In 2023, DESY achieved significant milestones, reinforcing its status as a global leader in accelerator science and research. The progress in the PETRA IV upgrade project and the ongoing developments at our user facilities and at the European XFEL X-ray laser have been particularly inspiring. With the federal Budget Committee's decision to fund a pre-project for the fourth-generation synchrotron radiation source PETRA IV, with co-financing by the City of Hamburg, preparatory measures can now begin, in particular for the construction and prototype of an innovative, energy-saving plasma injector and for the conversion of the business model.

A study carried out by the Fraunhofer Institute for Systems and Innovation Research in 2023 showed that DESY's light source PETRA III has created 2.25 billion euros in added value. The PETRA IV upgrade could add a further 7.35 billion euros in value – possibly even considerably more.

Furthermore, DESY is not only a significant driver of scientific progress, but it also has an economic impact as an employer and through the commissioning of commercial companies.

Delivering high-quality electron beams at high availability is key to the success of our accelerator facilities. When PETRA III went into operation at DESY in 2010, it was the world's most powerful X-ray source at the time. Since then, it has been generating unique scientific findings and furnishing essential data for innovative developments. More than 3500 researchers carry out their experiments here every year, somewhat more than half of them from Germany. Converting the facility into PETRA IV will ensure that it continues to meet the constantly increasing requirements and growing demand for non-destructive nanoscale analyses in the future. Once completed, PETRA IV will be an anchor facility for the Science City Hamburg Bahrenfeld and the world's most powerful X-ray source. This upgrade is essential for Germany and Europe as a centre for science and innovation in order to be internationally competitive in a wide range of technologies.

Important developments pursued on both the accelerator and the free-electron laser (FEL) sources of the European XFEL have yielded record FEL photon energies and intensities. One highlight in 2023 was the demonstration of single-spike lasing with high intensities at the SASE2 undulator by shaping the electron beam through self-fields and detuning of the deflection arc optics. Preparations are under way to upgrade the accelerator to continuous-wave or high-duty-cycle operation, with a conceptual design expected by 2027. DESY is developing an all-superconducting photoinjector for this purpose. In 2023, a breakthrough test demonstrated successful high-gradient operation with a copper cathode, advancing this effort.

After the first phase of the FLASH2020+ upgrade and the replacement of the two oldest accelerator modules with two freshly refurbished modules, the FLASH FEL facility was routinely operated in 2023 with an energy gain of 450 MeV, bringing the electron beam energy to over 1.35 GeV and pushing the photon wavelength down beyond 3.5 nm. A major milestone on the way to a seeded FLASH1 user facility, which is described in this report, was the successful demonstration of external seeding using echo-enabled harmonic generation with parallel self-amplified spontaneous emission operation in the FLASH2 beamline. The impressive results leave us excited about the future performance of the seeded FLASH1 user facility.

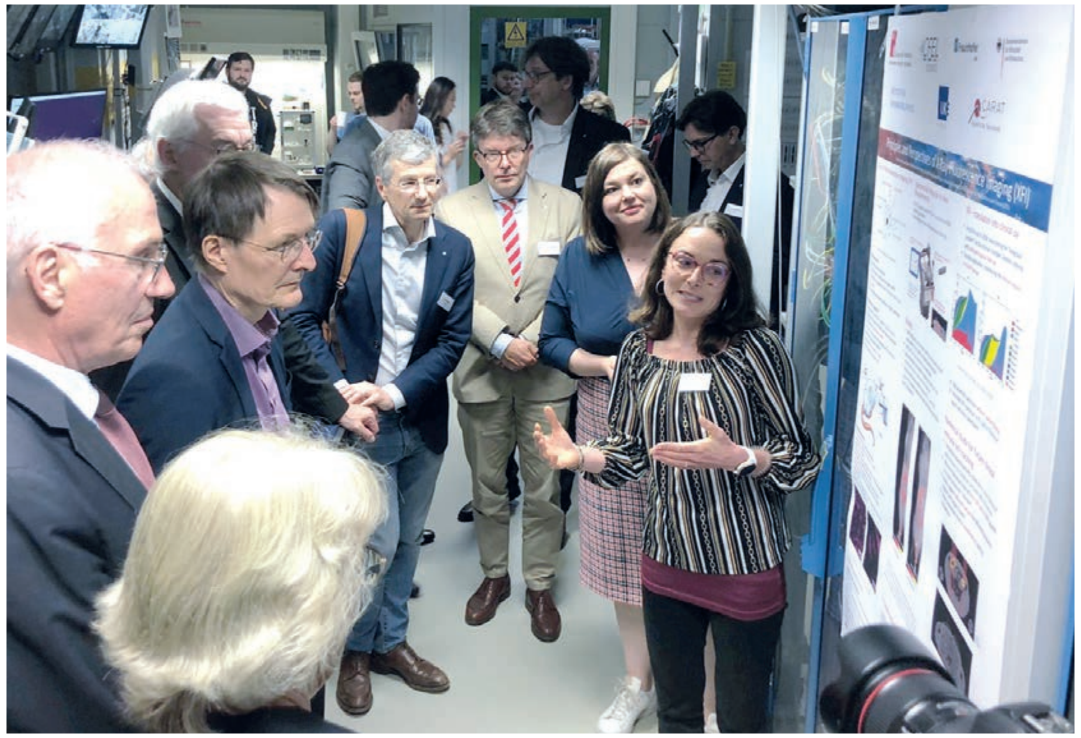


Figure 1
During his visit, Federal Minister of Health Karl Lauterbach commended the interdisciplinary work at DESY as an outstanding example of cutting-edge research in Germany – and of how this research directly benefits people's healthcare.

Accelerator R&D at DESY has always been at the forefront of scientific innovation. Coming from an engineering background myself, it fills me with great pride that the 2023 Bjørn H. Wiik Prize – DESY's most important science award – went to an engineer, Julien Branlard, in recognition of his outstanding contributions to developing the low-level radio frequency systems for the stable, reliable and extremely precise operation of the linear accelerators driving the European XFEL and FLASH. In 2023, we have also deepened our understanding of the physics behind the tuning and optimisation of laser plasma acceleration. This further lays the foundation for applying this technology in the years to come.

Another highlight of my tenure during the past five years has been witnessing the focus and successful implementation of our comprehensive sustainability strategy. This initiative is not just about reducing our environmental footprint but also about innovating in ways that make our research infrastructure more efficient and resilient. Utilising the waste heat from our accelerators to heat the campus is a testament to our commitment to sustainability and operational excellence, and I am delighted that the Helmholtz Association has approved funds of around 8 million euros for the project implementation in 2023. Furthermore, our technical groups have also explored options to run our facilities in modes that reduce energy consumption, and they have successfully implemented measures that are having a significant impact.

Last but not least, the DESY management and staff would like to thank Robert Feidenhans'l for his exemplary leadership as Chairman of the Management Board at European XFEL until the end of 2023, for his unwavering commitment to excellence and the strong partnership with DESY, in particular with the Accelerator Division. We wish him all the best and every success in his future endeavours. At the same time, we warmly welcome Thomas Feurer, who has taken over as the new Chairman of the Management Board at European XFEL at the beginning of 2024, and we look forward to continuing the great collaboration with our partner institute.

As we look to the future, I am excited about the possibilities that lie ahead. DESY's commitment to innovation, sustainability and scientific leadership is unwavering. I am confident that we will continue to achieve great things, driven by our shared passion for discovery and excellence. Thank you to everyone who has contributed to our successes this year. Your hard work and dedication are what makes DESY a truly exceptional place to work.

Wim Leemans
Director of the Accelerator Division

High-precision operation: low-level radio frequency system

Renowned for their stable, reliable and extremely precise operation, the linear accelerators of the European XFEL and FLASH free-electron laser facilities owe much of their success to the low-level radio frequency (LLRF) control system developed by DESY engineers. The LLRF system can precisely measure and control the field in the superconducting cavities that accelerates the electron beam. Radio frequency control systems are right at the heart of particle accelerators and interact with many other subsystems.

Picture: Julien Branlard, DESY

News and events

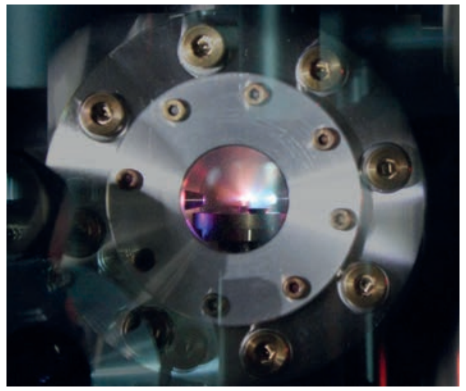
News and events

A busy year 2023

January

Unique live view into plasma acceleration

An international research team led by DESY has achieved a breakthrough by accurately measuring the acceleration process in a plasma without disturbing the process itself. The findings, published in the journal *Physical Review Letters*, open up a new possibility to understand the acceleration process in plasmas more precisely – a result that is key to developing this novel acceleration technology more quickly. The team used Thomson scattering and X-ray detection to track electron acceleration within the plasma, revealing detailed insights into the acceleration process. The findings are expected to aid in the development of compact laser-plasma-driven X-ray sources for medical imaging and other innovative applications. This work, which is part of the BMBF Innovation Pool project PLASMED X, involved collaborations with Universität Hamburg, Queen's University Belfast and Rutherford Appleton Laboratory.



Light from the one-millimetre-long helium plasma in which the electrons were accelerated

DESY school lab celebrates 25th anniversary

The name says it all, and the concept is more relevant today than ever: The DESY school lab "physik.begreifen", in the sense of "touching", "trying out", but also "understanding" physics, aims to raise pupils' interest in the natural sciences and reduce prejudices. More than 110 000 school kids have already conducted research in what was the first school lab in the Helmholtz Association. "physik.begreifen" celebrated its 25th anniversary in a ceremony attended by Hamburg's Senator for Schools Ties Rabe and physics entertainer, book author and former DESY scientist Michael Büker. The guest of honour was DESY's former administrative director Helmut Krech, who founded the school lab.

Celebrating the 25th anniversary of the DESY school lab "physik.begreifen"

DESY becomes a member of the Laserlab-Europe AISBL consortium

In January, DESY became a full member of the Laserlab-Europe AISBL consortium. Francesca Calegari, lead scientist for attosecond science at DESY and professor at Universität Hamburg, will represent DESY in the Laserlab-Europe General Assembly. AISBL is an international not-for-profit association that brings together 46 leading laser research infrastructures in 22 European countries. Jointly, they are committed to coordinating operations and research and development efforts to facilitate the development of advanced lasers and laser-based technologies and to promote the efficient utilisation of advanced laser facilities by users from academia and industry. The majority of the members provide open access to their facilities to scientists from all over the world to perform experiments in a large variety of interdisciplinary research, covering advanced laser science and applications in most domains of research and technology.

Laserlab Europe

Parliamentary State Secretary Mario Brandenburg visits DESY

Mario Brandenburg, Parliamentary State Secretary at the Federal Ministry of Education and Research (BMBF), visited Hamburg in January to discuss DESY's planned future project, the 3D X-ray microscope project PETRA IV. The meeting, which was held at the Start-up Labs Bahrenfeld, focused on DESY's sustainability strategy and the dovetailing of research and industry.

Parliamentary State Secretary Mario Brandenburg (front row, second from left) at DESY

Great interest in joint DESY and European XFEL Users' Meeting in Hamburg

"Finally meeting in person again!" This was one of the catchphrases on the DESY campus at the 2023 Users' Meeting, after the meetings of the last two years had to be held purely virtually due to the COVID-19 pandemic. For almost a week, more than 1100 scientists from over 25 counties who are conducting experiments at the DESY light sources FLASH and PETRA III and at the European XFEL exchanged views on the status and future of research at the light sources in the Hamburg area.

February

DESY–Ukraine Winter School creates opportunities

The DESY–Ukraine Winter School was held from 31 January to 10 March. A total of 22 students from Ukrainian universities worked on DESY research projects on the Hamburg and Zeuthen campuses for six weeks. The projects enabled the students to interact with scientists in research areas that would otherwise have been out of reach given the current geopolitical situation. No distance was too far: Some of the students were picked up from the Polish–Ukrainian border by bus transport organised by DESY.

Students from Ukrainian universities who joined the DESY–Ukraine Winter School in Hamburg and Zeuthen

Environmentally responsible research: workshop on critical materials at DESY

The possibility of using the expression "conservation of resources" in the same sentence as "magnets" was a key topic during a three-day workshop at DESY as part of the Innovation Fostering in Accelerator Science and Technology (I.FAST) project. The event, titled "Critical materials and life cycle management: the example of rare earths – curse or blessing?", gathered over 50 international experts to discuss the sustainable use, recycling potential and supply chain management of permanent magnets. Key contributions highlighted the complexity of recycling due to current design and economic challenges, but also promising advances in certification processes for sustainable practices. DESY aims to incorporate sustainability criteria in future tenders, particularly for projects such as the PETRA IV 3D X-ray microscope, emphasising the importance of recyclability and environmental protection in scientific research.

Jugend forscht 2023

Under the motto "Mach Ideen groß" ("Make ideas great"), 137 pupils presented themselves at this year's "Jugend forscht" regional science competition. DESY hosted the Hamburg-Bahrenfeld regional competition for the 11th time. A total of 14 projects from technology, mathematics, informatics, biology and chemistry were awarded prizes.

March

Anna Grebinyk honoured for research into novel cancer therapy

Anna Grebinyk, a postdoctoral scientist at the PITZ photoinjector test facility at DESY in Zeuthen, was awarded the 2023 Research Prize in the Research-Oriented Achievements category by the Technical University of Applied Sciences in Wildau (TH Wildau). The award recognizes her work on the FullDrug project, which explores new cancer therapy approaches using C_{60} fullerene complexes. Grebinyk's research demonstrated the effectiveness of using these nanoparticles for targeted photodynamic chemotherapy. In addition, she and the PITZ team are developing *FLASH* radiotherapy, a method that delivers radiation in extremely short, intense bursts to reduce side effects and enhance treatment efficiency. This research bridges accelerator physics and biomedical research, aiming to improve cancer treatment outcomes.

Anna Grebinyk (left) received the award for research-oriented achievements at TH Wildau.

May

Mikhail Krasilnikov receives Gersh Budker Prize

DESY scientist Mikhail Krasilnikov was awarded the Gersh Budker Prize of the European Physical Society's Accelerator Group (EPS-AG) for his significant contributions to the accelerator field, notably in developing high-brightness electron beams and a high-power, tuneable THz self-amplified spontaneous emission (SASE) free-electron laser (FEL). Krasilnikov demonstrated lasing at the PITZ facility at DESY in Zeuthen in 2022, marking a world-first achievement. The prize was presented at the International Particle Accelerator Conference IPAC'23 in Venice, Italy. Krasilnikov's work focuses on the physics of high-brightness photoinjectors and their applications, optimising the PITZ injector for the European XFEL and FLASH facilities and developing a THz SASE FEL for pump-probe experiments.

Mikhhail Krasilnikov at the award ceremony during the IPAC'23 conference

Start of the innovation platform HI-ACTS

The Helmholtz Innovation Platform for Accelerator-based Technologies and Solutions (HI-ACTS) aims to make accelerator-based technologies specifically accessible for industrial and medical applications. HI-ACTS is jointly operated by DESY as project coordinator, Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Helmholtz-Zentrum Berlin (HZB), GSI Helmholtzzentrum für Schwerionenforschung and Helmholtz-Zentrum Hereon. Accelerator technologies run by the Helmholtz Association will be made available to industrial users in the form of a cost-effective full-service infrastructure. This will make existing research infrastructures, such as DESY's synchrotron radiation source PETRA III and its planned successor PETRA IV, more attractive for industrial users and applications.

HI-ACTS Helmholtz Innovation Platform for Accelerator-based Technologies and Solutions

KALDERA web application wins iF Design Award

For its outstanding presentation of plasma acceleration, the interactive web application kaldera.desy.de was awarded the iF Design Award 2023. Conceived and designed for DESY by the Science Communication Lab in Kiel together with KALDERA scientists, the info portal allows users to interactively explore the complicated process of laser plasma acceleration. Users can switch back and forth between the levels of the microworld and the real experiment. Honoured in the User Experience category, the application combines scientific accuracy with aesthetic appeal, demonstrating effective science communication. Plasma acceleration, a technology for creating smaller and cheaper particle accelerators, was depicted using sound scientific data. Future developments may include virtual reality experiences to further enhance user interaction.

Representing the KALDERA team in Berlin: Sören Jalas, Kaja Schubert and Manuel Kirchen (from left to right)

Foundation stone laid for DESY visitor centre

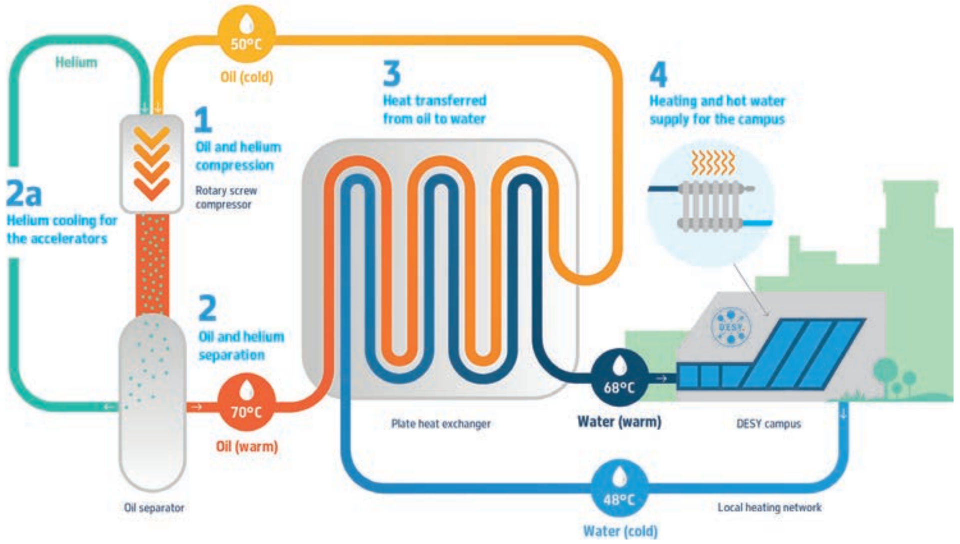
Inserting the time capsule into the DESYUM foundation stone

Hamburg Science Senator Katharina Fegebank, DESY Director Helmut Dosch and other guests of honour laid the foundation stone for the new DESY visitor centre, called DESYUM. Alongside a large atrium, a cafeteria and offices, the six-storey building will host a lively multimedia exhibition that makes DESY's research and innovations accessible to the general public. The DESYUM will be a landmark on the campus, serving as a public meeting point and a forum for everyone. Its opening is planned for 2025.

June

Fast particles heat laboratories and offices

DESY's particle accelerators consume substantial electricity, much of which is converted into waste heat. A new project, funded with around 8 million euros by the Helmholtz Association, aims to use this waste heat to warm buildings on the DESY campus, with implementation beginning in summer 2023. The project includes connecting cooling systems from accelerators and computer centres to a local heating network and using a large heat pump to elevate cooling water temperatures. The system is expected to allow DESY to almost entirely self-heat its campus, saving over 500 000 euros annually. In addition, similar projects are planned for new buildings and for the DESY site in Zeuthen (with heat from the computer centre), further enhancing energy efficiency and sustainability.



Waste heat recycling system at DESY: The accelerators and their support systems can be used to warm the entire campus. So far, a third of the campus is heated in this way.

Thomas Feurer appointed Chairman of the European XFEL Management Board

The European XFEL Council nominated Thomas Feurer, a renowned laser physicist from the University of Bern, Switzerland, as the new Chairman of the European XFEL Management Board. He will take over from Robert Feidenhans'l on 1 January 2024. Feidenhans'l has led the research facility since its inauguration in 2017, and he will work as an advisor to European XFEL until his retirement in July 2024.

Thomas Feurer

June

Helmholtz AI Conference 2023 hosted by DESY

For the annual Helmholtz AI Conference, around 400 scientists and experts gathered at DESY from 12 to 14 June to share cutting-edge research in artificial intelligence for science. The event brought together AI enthusiasts and AI researchers from the Helmholtz Association and beyond to exchange knowledge and discover the latest advancements and insights in AI, which can enhance and accelerate future discoveries in all areas of science.

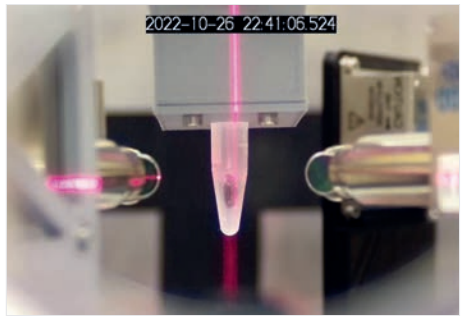
German Health Minister Karl Lauterbach visits DESY

Participants of the Life Science Forum with Hamburg's Science Senator Katharina Fegebank and German Health Minister Karl Lauterbach (centre)

Using the experience from the COVID-19 pandemic to accelerate health research: Karl Lauterbach, the German Federal Minister of Health, visited DESY in Hamburg on 30 June. Lauterbach recognised DESY's unique expertise and the diverse possibilities for application of the centre's accelerator-based light sources, including in health research, and emphasised DESY's prominent role for the future of Germany as a leader in science.

Florian Grüner receives Innovation Award for Synchrotron Radiation

Florian Grüner, professor at Universität Hamburg and at the Center for Free-Electron Laser Science (CFEL), was honoured by Helmholtz-Zentrum Berlin (HZB) for advancements in the field of *in situ and in vivo* tracking using advanced X-ray fluorescence imaging. His pioneering work paves the way for the precise tracking of active ingredients, immune cells, antibodies and drug carriers, enabling real-time assessment of biodistribution in the human body and providing invaluable insights for medical research. The key breakthrough lies in the development of a synchrotron-based method that allows for the detection of the smallest tumours or the tracking of drugs or cells in living organisms. The cutting-edge approach holds significant potential for pharmaceutical research, drug development and the study of biological effects of pollution with nano- or microplastics.



July

Meetings in Berlin and Beijing on research cooperation with China

Germany and China have a strong tradition of science cooperation, but growing geopolitical tensions make it necessary to reassess these partnerships. In May, as part of the WIKOOP-INFRA project at DESY, a conference in Berlin discussed strategic aims for foreign science policy and cooperation with China. This led to joint working groups and visits to Chinese research facilities to address and observe bilateral cooperation challenges and advancements.

On their trip to China, the delegation visited the High Energy Photon Source (HEPS) in Beijing.

Honorary doctorate for Helmut Dosch

DESY Director Helmut Dosch was awarded an honorary doctorate by TU Dortmund University for his contributions to science and science management, particularly in synchrotron radiation methods. The accolade was presented during the Faculty of Physics' anniversary celebration, with the laudation held by Metin Tolan, President of the University of Göttingen.

VHEE Conference 2023 at DESY

The use of very high-energy electron (VHEE, 50–250 MeV) beams for radiotherapy and ultrahigh-dose-rate (≥100 Gy/s) delivery or *FLASH* radiotherapy is an important R&D topic in many laboratories around the world. The Very High-Energy Electron Radiotherapy Conference 2023 was held at DESY from 11 to 13 July to discuss the progress made. In total, 125 participants attended the conference in person or online and followed more than 50 talks on accelerator science, biology, dosimetry and industry.

DESY honoured for outstanding commitment to career orientation

"SCHULEWIRTSCHAFT Hamburg" seal awarded for DESY's commitment to career orientation

DESY was awarded the "SCHULEWIRTSCHAFT Hamburg" seal for its commitment to career orientation at the NachwuchsCampus Experience Day at the Hamburg University of Technology (TUHH). The recognition came for DESY's collaboration with Gymnasium Süderelbe in the TUHH NachwuchsCampus project, which engages students in STEM careers through practical tasks and company visits. The programme included application training, student presentations on DESY topics as well as company tours, culminating in the awarding of the seal.

Summer students are back in town

The DESY summer student programme, which was held from 18 July to 7 September 2023 in Hamburg and Zeuthen, included full-time work in established research groups, a lecture programme on DESY research topics and visits to facilities operated by DESY. Some of the projects also took place on the European XFEL campus in Schenefeld. Each of the projects provided the students with in-depth hands-on experience of real-world scientific investigations, analysis, theory and experiment design and offered networking opportunities.

Summer students at DESY in Hamburg

August

Dieter Trines (1942–2023)

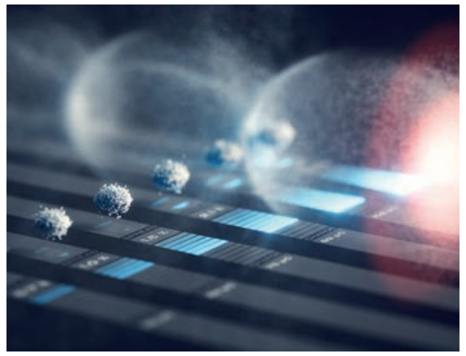
DESY mourns the loss of its former Accelerator Director Dieter Trines. Trines was in charge of the DESY Accelerator Division from 1995 to 2007 and, with his strong commitment to international collaboration, advanced the development of particle accelerators worldwide. His involvement in the design and development of DESY's electron–proton collider HERA and his significant contribution to its successful construction and commissioning, the preparation of the PETRA III synchrotron radiation source project, the paving of the way for the European XFEL X-ray laser project and his major contribution to the recent launch of the ALPS II axion search experiment after his retirement are just a few examples of his many achievements. He passed away on 27 July 2023 at the age of 81.

Dieter Trines in 1993

August

Machine learning customises plasma accelerator beams

Particle accelerators are used in a broad range of fields, such as research, medicine and customs scanning, each of which requires different beam properties. While conventional accelerators are large and easier to adjust, plasma accelerators are much smaller, but their compact size makes it a challenge to control the beam parameters. To address this issue, DESY researchers have been using machine learning to teach a compact particle accelerator to produce customised beams for a number of different applications. The technique expands the conceivable range of applications for laser plasma accelerators – innovative compact next-generation accelerators that are currently under development. The method uses Bayesian optimisation to fine-tune the accelerator settings, overcoming the challenges posed by the accelerator's small size and sensitive parameters. The advancement, which is detailed in *Physical Review Accelerators and Beams*, enhances the practical applications of plasma accelerators by allowing the precise adjustment of beam properties such as energy and charge. It will be applied to the KALDERA accelerator, which is currently under construction.



In a laser plasma accelerator, a high-intensity laser pulse (red) creates a plasma wave (white) in an ionised gas. This wave makes it possible to accelerate electrons to extremely high energies within just a few millimetres. Using machine learning, the scientists at DESY's LUX experiment can now control the properties of the electron bunches, such as charge and energy spread (shown in rows here), with high precision.

September

Franz Kärtner receives UNIPRENEURS Award

DESY researcher Franz Kärtner was honoured by the UNIPRENEURS initiative for his entrepreneurial spirit. Kärtner, who leads the Ultrafast Laser and X-ray Physics group at CFEL, is a professor at Universität Hamburg and founder of the deep-tech start-up Cycle GmbH. He received the award for his developments in the field of ultra-precision synchronisation and for the successful transfer of his research results into a company. Cycle GmbH creates precision time and frequency distribution systems using femtosecond lasers for scientific and industrial applications.

PETRA IV at the annual festival of the Hamburg State Representation in Berlin

Peter Tschentscher (centre), Hamburg's First Mayor, visited the PETRA IV stand.

In September, 2500 guests from politics, business, society and the media came together to network at the annual festival of the Hamburg State Representation in Berlin. Since 2002, the event has provided an important framework for informal dialogue for all those with big plans in the City of Hamburg. For the first time, DESY's future project PETRA IV was represented with its own exhibition stand. Directors and scientists promoted the realisation of the project with high-ranking discussion partners, including Peter Tschentscher, Hamburg's First Mayor, who visited the PETRA IV stand.

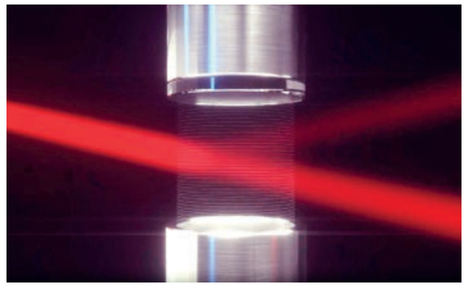
Hamburg says yes to PETRA IV

With PETRA IV, DESY is planning the most powerful synchrotron light source in the world, which will revolutionise both the view into the nanocosmos and X-ray analytics. The goal of PETRA IV is to drastically accelerate the development of new technologies – including for example, new materials or drug development – by using the extremely brilliant light to provide previously unattainable insights for scientific and technological applications. At the same time, PETRA IV will serve as a centrepiece and point of attraction in the emerging Science City Hamburg Bahrenfeld. In its meeting on 27 September, the Hamburg City Parliament set an important milestone for the realisation of PETRA IV by unanimously deciding that the City of Hamburg will secure its financial share of ten percent of the total amount for the project. The total costs amount to 1.54 billion euros, to which DESY will contribute 170 million euros.

October

Lasers deflected using air

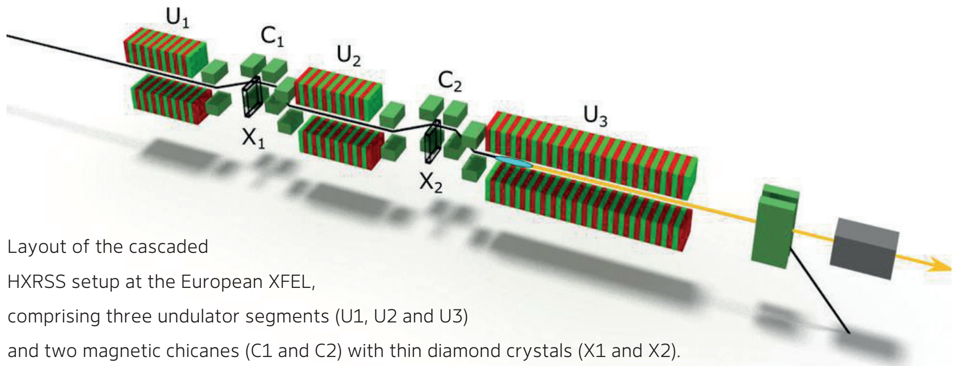
An interdisciplinary team of researchers has developed a novel method to deflect laser beams using only air, leveraging sound waves to create an invisible optical grating. This grating, formed by acoustic density waves, allows precise control of laser light without physical contact, preserving beam quality. The technology was detailed in *Nature Photonics*. The approach could revolutionise high-performance optics by providing a damage-free alternative to traditional optical elements. The technique shows promise for applications in high-power lasers and other optical systems.



A laser beam passes between a loudspeaker–reflector array that creates a grating of air. The laser beam interacts with this grating and is deflected without contact.

Cascaded setup generates bright X-ray pulses

An international team of scientists at DESY and European XFEL has developed a cascaded hard X-ray self-seeding (HXRSS) setup to enhance X-ray laser performance at high repetition rates. This new device significantly boosts the amount of X-ray with sharply defined wavelengths, opening new possibilities for ultrafast X-ray spectroscopy, scattering and imaging. The setup uses three undulator segments and two magnetic chicanes with diamond crystals to generate high-brightness X-ray pulses, overcoming challenges of crystal heating at high repetition rates. This advancement allows for thousands of X-ray pulses per second with high spectral brightness, enabling applications such as Mössbauer spectroscopy and the development of nuclear clocks.



Layout of the cascaded HXRSS setup at the European XFEL, comprising three undulator segments (U1, U2 and U3) and two magnetic chicanes (C1 and C2) with thin diamond crystals (X1 and X2). These create a narrow-bandwidth notch in the spectrum, which is then amplified in the subsequent undulator section, resulting in bright X-ray pulses with sharply defined wavelengths.

Bjørn H. Wiik Prize for Julien Branlard

Renowned for their stable, reliable and extremely precise operation, the linear accelerators that drive the European XFEL and FLASH free-electron lasers owe their success especially to features developed by Julien Branlard and his team. For this reason, the French systems engineer was awarded the 2023 Bjørn H. Wiik Prize – DESY's most important science prize – in recognition of his exceptional engineering skills and dedication and of his contributions to DESY's international reputation. Branlard joined DESY in 2011. He moved from Fermilab in the USA to Hamburg to work on the European XFEL project and took over responsibility as head of the low-level radio frequency work package, where he focuses on developing and managing radio frequency control systems for superconducting accelerator cavities.

Julien Branlard

November

DESY Day 2023

On 2 November, DESY celebrated exceptional research, significant developments and lifetime achievements on DESY Day 2023. Julien Branlard received the 2023 Bjørn H. Wiik Prize (see previous page), and the event also served to welcome new employees and honour long-term contributions of DESY employees.

Julien Branlard gave the Bjørn H. Wiik Prize science talk.

Particle physicist Paul Söding, who served as DESY Research Director from 1982 to 1991 and Director of the DESY site in Zeuthen from 1992 to 1998, celebrated his 90th birthday in February. Söding has held the Federal Cross of Merit since 2001 and continues to influence DESY through his writings on its history. On DESY Day 2023, he received the DESY Golden Pin of Honour.

Helmut Dosch (right) and Christian Stegmann (left) congratulated Paul Söding (centre) at the presentation of the DESY Golden Pin of Honour.

Robert Feidenhans'l, who chaired the European XFEL Management Board from 2017 until the end of 2023, was awarded the DESY Silver Pin of Honour. He was involved in the European XFEL project from the very beginning, leading the project from the end of the construction phase to the commissioning of the X-ray laser in 2017 and establishing it as a world-class research facility.

Robert Feidenhans'l was awarded the DESY Silver Pin of Honour.

Torben Warnecke and Michael Koepke received the DESY Award for Exceptional Achievements in engineering and technology.

Michael Koepke and Torben Warnecke from the DESY group responsible for heating, ventilation and air conditioning received the 2023 DESY Award for Exceptional Achievements in engineering and technology. They developed a system for using waste heat from accelerator operations to heat the DESY campus, which could potentially be extended to the neighbourhood, reducing CO_2 emissions and operating costs. Their work led to securing 8.2 million euros in funding from the Helmholtz Association for a low-temperature network that utilises waste heat from the European XFEL and PETRA III South radio frequency facilities. This system, which is enhanced by a heat pump, and the existing use of waste heat from the cryogenics plant will meet most of the campus's heating needs, in line with DESY's sustainable energy goals.

Four female scientists from DESY's four research divisions gave an insight into their fascinating work in 150 seconds each. For the Accelerator Division, biochemist Anna Grebinyk, currently a postdoctoral scientist at the PITZ photoinjector test facility in Zeuthen, talked about *FLASH* radiotherapy for cancer treatment, which she and her team have been working on for the last year. Grebinyk emphasised that she is following her deep passion to beat cancer across borders and disciplines.

Anna Grebinyk represented the Accelerator Division in the scientific highlights session, talking about *FLASH* radiotherapy for cancer treatment.

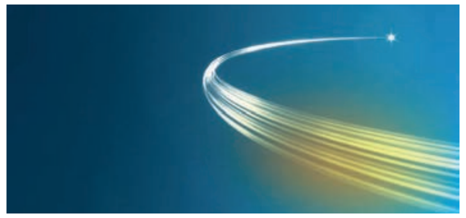
New study: PETRA III created 2.25 billion euros in added value

A study carried out by the Fraunhofer Institute for Systems and Innovation Research (ISI) shows that DESY is not only a significant driver of scientific progress, but that it also has an economic impact as an employer and through the commissioning of commercial companies. Between 2010 and 2022, DESY invested around 815 million euros into building and operating the PETRA III light source. As a result, the facility has produced unique scientific insights, provided essential data for innovative developments and had an economic impact far beyond the Hamburg region. Their added value amounts to more than 2.25 billion euros.

PETRA III and PETRA IV impact study

Groundbreaking decision for PETRA IV

The Budget Committee in charge of the 2024 German federal budget decided to finance an important preparatory project for the fourth-generation synchrotron radiation source PETRA IV at DESY, for which DESY will receive 40 million euros in start-up funding. The funds can be used for preparatory measures for PETRA IV, in particular for the design and prototype of an innovative, energy-saving accelerator technology and the transformation of the business model.



Collaboration for the benefit of research and industry

From new imaging methods to new data formats and analyses, from screening of active agents to biomaterials: The potential that synchrotron radiation holds for applied research is enormous. The Fraunhofer-Gesellschaft, DESY, Helmholtz-Zentrum Hereon and the European Molecular Biology Laboratory (EMBL) have agreed on a strategic partnership to exploit this potential more effectively in the future. The aim is to establish structured collaboration between the four research institutions, with particular emphasis on the use of the analytical infrastructure on the DESY campus in Hamburg, such as the PETRA III X-ray source and the free-electron lasers.

Thank you, Robert!

We would like to thank Robert Feidenhans'l for his exemplary leadership as Chairman of the European XFEL Management Board from 1 January 2017 to 31 December 2023. During his tenure, European XFEL navigated the commissioning phase, emerged as a world leader in X-ray science and developed its Strategy 2030 to address major scientific and societal challenges. Feidenhans'l has been a key person for the collaboration with DESY and in particular with the Accelerator Division, which operates the accelerator that drives the European XFEL. His unwavering commitment to excellence has been particularly valuable to us, and we greatly appreciate our long-standing partnership and joint successes. He will remain with us as a trusted advisor, and we warmly thank him for his dedication and all his valuable contributions.

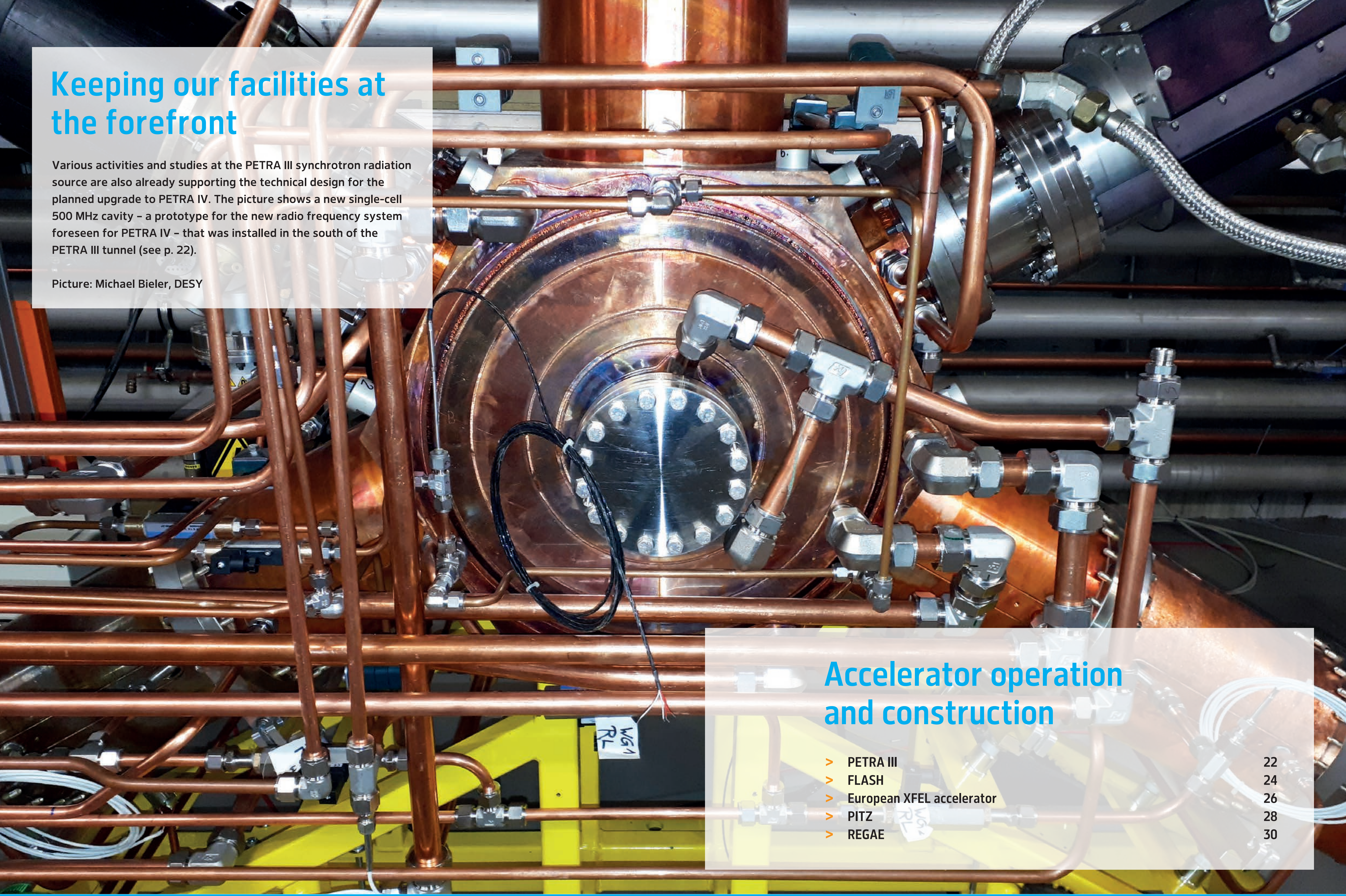
December

New Emmy Noether Group for Rob Shalloo

Accelerator physicist Rob Shalloo will set up an Emmy Noether Group.

Rob Shalloo, a staff scientist in the Plasma Accelerators group at DESY, was selected by the German Research Foundation (DFG) for the Emmy Noether Programme. He has been awarded 1.8 million euros to lead a new research group that will develop advanced plasma source technology for high-energy laser plasma accelerators, which are much smaller and more energy-efficient than traditional accelerators. Shalloo's project, Structured Plasmas for Laser-drIven Control of Electron Beams (SPLICE), aims to create high-quality electron beams for compact X-ray free-electron lasers, with potential applications in various fields. His recognition highlights the expertise and innovation at DESY.

Robert Feidenhans'l



Keeping our facilities at the forefront

Various activities and studies at the PETRA III synchrotron radiation source are also already supporting the technical design for the planned upgrade to PETRA IV. The picture shows a new single-cell 500 MHz cavity – a prototype for the new radio frequency system foreseen for PETRA IV – that was installed in the south of the PETRA III tunnel (see p. 22).

Picture: Michael Bieler, DESY

Accelerator operation and construction

PETRA III

User operation with high availability and a new 500 MHz cavity

The year 2023 was an excellent year for the operation of the synchrotron radiation facility PETRA III at DESY. In total, 4899 h of beamtime were scheduled for the user run, which were delivered with an availability of 98.4%. In addition, the planned upgrade of PETRA III to the fourth-generation X-ray light source PETRA IV received strong support. A new PETRA IV prototype single-cell cavity was installed in the south of the PETRA III tunnel. Vibration and stability tests were performed to gain experience with beam operation during construction work. Moreover, a new undulator was installed for the beamline P25 currently being set up in the "Ada Yonath" hall.

Activities and studies to support the PETRA IV project

During the winter shutdown 2022/23, a single-cell 500 MHz cavity – a prototype for the new radio frequency (RF) system foreseen for PETRA IV – was installed in the south of the PETRA III tunnel (Fig. 1). In the summer shutdown 2023, the installation of the cavity was complemented with a new RF power source, a 120 kW solid-state amplifier. The new cavity was successfully operated, first during beam studies and later also during standard user operation. Furthermore, a new 2 m long undulator (Fig. 2) was installed for the beamline P25, which is under construction in the "Ada Yonath" experimental hall and will be used for medical imaging, powder diffraction and innovation. To support the PETRA IV project, several vibration and stability tests were carried out in order to gain experience with the operation of the beam during construction work (see p. 34).

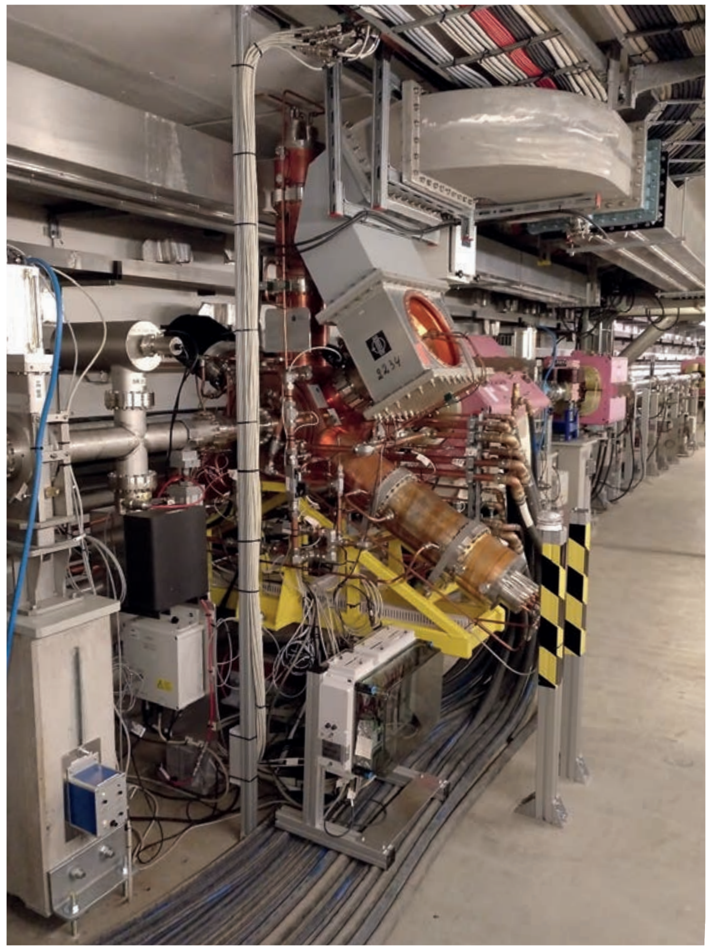


Figure 1

PETRA IV prototype single-cell 500 MHz cavity

Figure 2

New undulator for the beamline P25 installed in the PETRA III tunnel

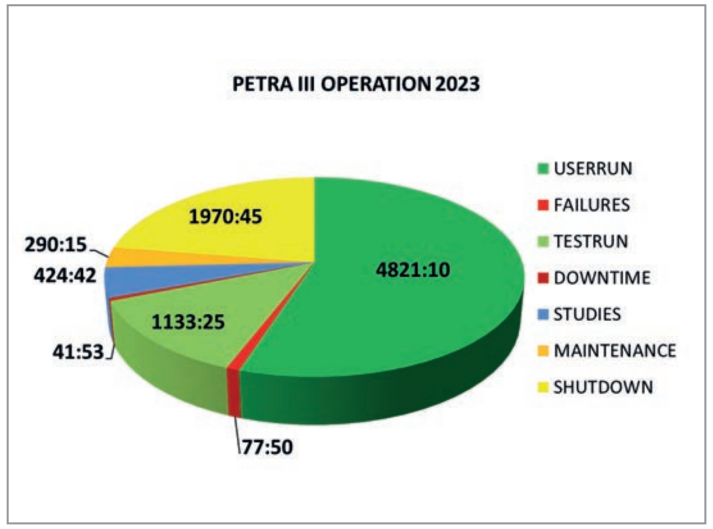


Figure 3

Distribution of the different PETRA III machine states in 2023 (hh:mm)

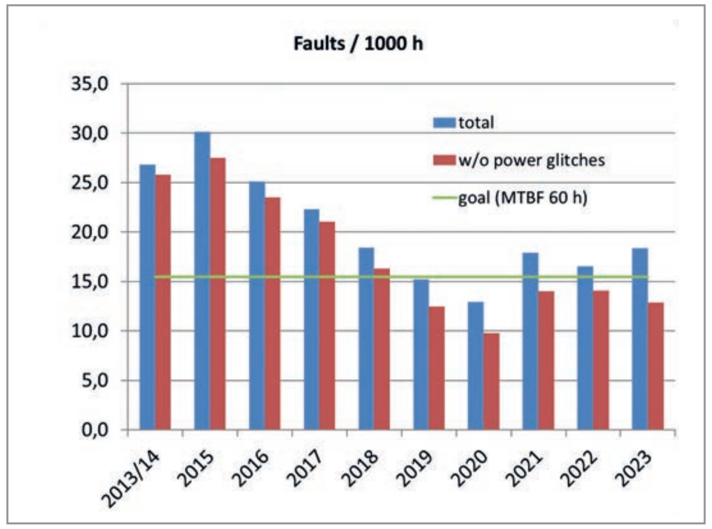


Figure 4

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

User operation

Regular user operation resumed on 22 February 2023 after a short commissioning period of less than two weeks. In 2023, 4899 h of beamtime were scheduled for the user run, which were delivered with a very good availability of 98.4%. Necessary maintenance was done in five dedicated service periods distributed over the year and additionally during the three-week-long summer shutdown. On Wednesdays, user operation was interrupted by weekly regular maintenance or machine development activities as well as test runs for 24 h in total.

The distribution of the different machine states in 2023 is shown in Fig. 3 in hours and minutes (hh:mm). In addition to the 4821 h of beamtime delivered for the user run, 1133 h of test run time could be provided to users. During user runs, the storage ring is operated in two distinct modes characterised by their bunch spacing of either 16 ns (480 bunches) or 192 ns (40 bunches). In 2023, 51% of the user time was allocated to the 480-bunch mode and 49% to the 40-bunch mode. The category "Failures" in Fig. 3 corresponds to faults during the user run, while faults during the test run and study time are summarised in the category "Downtime".

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

While the availability was very good in 2023, the average mean time between failures (MTBF) at the end of 2023 was 53 h, which is below the anticipated target value of at least 60 h. The long-time development of the number of faults during PETRA III user runs 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, which are mainly due to short power glitches (of less than 120 ms) causing beam loss. The green line indicates the number of faults corresponding to the target MTBF of 60 h. In 2023, almost a third of the faults were related to power interruptions. Another source of failures was the ageing of electronic equipment in the signal distribution of the timing system. The root cause analysis of the faults during the user run was assisted by an internal review process monitoring all PETRA III faults, with the aim to improve performance in 2024. The actions and measures initiated by the review panel can only be realised with an essential effort from all technical groups involved.

Plans for the next operation period

The winter shutdown 2023/24 will be dedicated to maintenance work, including the replacement of the power coupler of the single-cell 500 MHz cavity, a survey of the wiggler section in the west of the PETRA III ring and the laying of a fibre optical cable around the full tunnel circumference to extend the intelligent Distributed Acoustic Sensor (iDAS) [1] network on the DESY campus, a developing technique for measuring ground vibrations by means of length variations of such cables. In 2024, further studies are planned to support the technical design for the planned upgrade of PETRA III to PETRA IV.

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Reference:

[1] https://wave-hamburg.eu/

FLASH

Towards a highly flexible FEL user facility

The FLASH free-electron laser (FEL) at DESY consists of a common injector and linear accelerator, two undulator beamlines – FLASH1 and FLASH2 – operated in parallel, and a third beamline that comprises the FLASHForward plasma wakefield acceleration experiment. For 2023, the only complete run year between the two big shutdowns of the FLASH2020+ upgrade project, the decision was made to provide as much beamtime as possible for the facility. The beamtime was used for photon experiments, accelerator R&D and, last but not least, for machine development (FEL studies) dedicated to improving the performance of the facility and preparing the operations team for the upcoming upgrades.

Operation in 2023 after the first FLASH2020+ upgrade

In 2023, as much beamtime as possible was allocated to user operation, FEL and photon beamline development as well as accelerator R&D. In parallel, the second phase of the FLASH2020+ project upgrade was prepared. FLASH was in operation for a total of 8227 h, of which 4996 h (60.7%) were reserved for FEL user experiments.

In the first phase of the FLASH2020+ upgrade, the two oldest and weakest superconducting radio frequency (SRF) accelerator modules were replaced by two freshly refurbished modules from the European XFEL production line. A single RF station supplies power to the two modules through a specially designed, optimised waveguide power distribution system to achieve the highest total beam energy gain. After some initial conditioning of the SRF modules, both of them exceeded the FLASH upgrade goal for the beam energy gain of 200 MeV per module. The RF station was routinely operated in 2023 with an energy gain of 450 MeV. This alone enables an increase of the maximum electron beam energy by 100 MeV. The higher beam energy could be demonstrated and allows operation at shorter wavelengths.

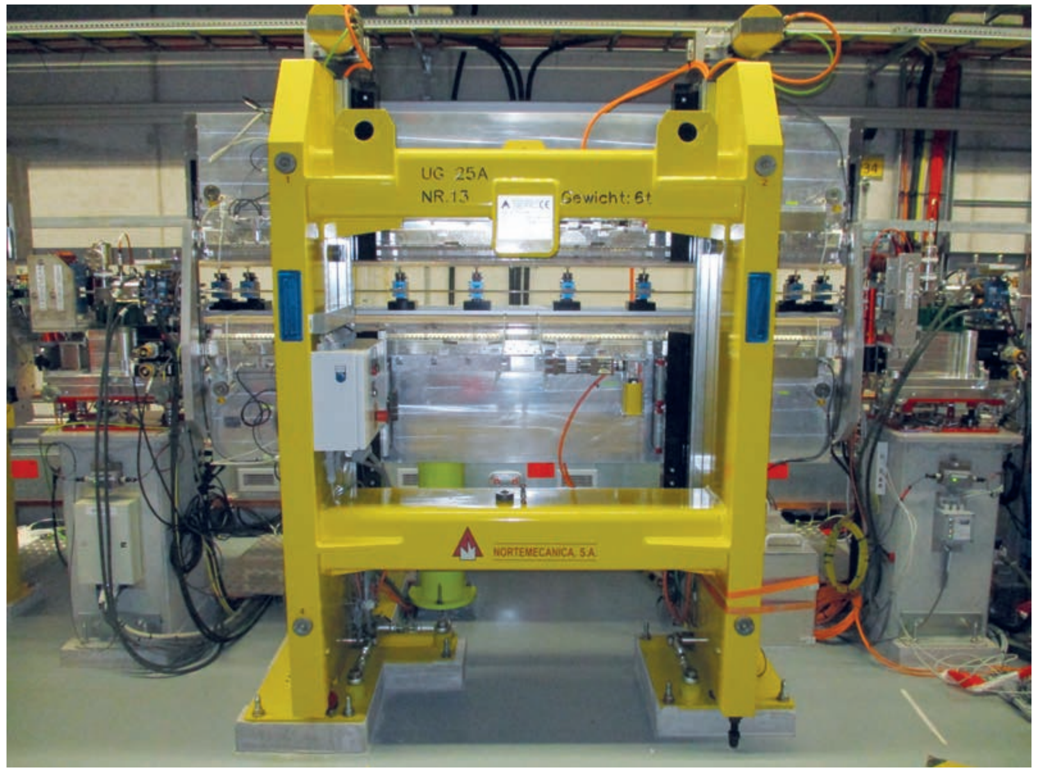


Figure 1
Afterburner undulator after installation in FLASH2

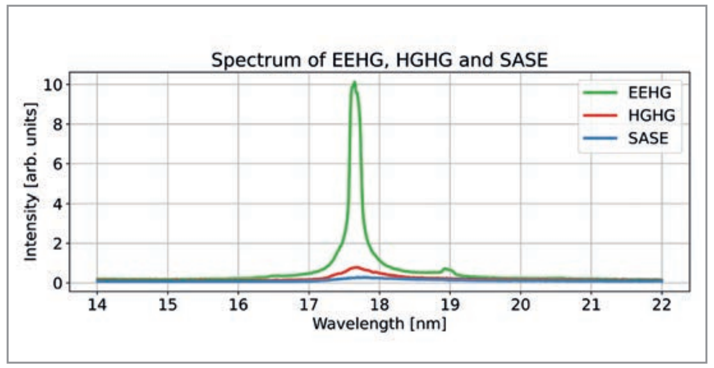
A tuneable so-called afterburner undulator (Fig. 1), optimised for three times shorter wavelengths than the main undulators of the FLASH2 beamline and featuring variable photon polarisation, was installed at the end of the FLASH2 undulator section in September 2023. In a first tuning and measurement campaign, amplification of the third harmonic of the self-amplified spontaneous emission (SASE) FEL was demonstrated. The afterburner thus increases the wavelength range down to the L-edge of iron, cobalt and nickel. Together with the control it provides over the photon polarisation, this is an important feature for certain experiments at FELs and offers new opportunities for science.

User interest in FEL photon pulses with extremely short pulse duration is steadily rising. In the SASE FEL process, the lower limit of the pulse duration that can be generated by standard means is determined by the FEL coherence time. A new, clever concept to beat the coherence time limit has been demonstrated at FLASH2. After generating a pulse close to the coherence time limit, the resonance conditions for the SASE lasing process are detuned by linearly increasing the undulator strength of consecutive undulator segments along the undulator section. Thus, the original FEL pulse is suppressed, while microbunching within the electron bunch is maintained. The last undulator segment is then tuned to resonance with this microbunch structure so that it acts as a radiator for this structure and creates ultrashort FEL pulses below the coherence time limit. In the experiment, a photon pulse with a duration of (1.3 ± 0.4) fs and a pulse energy of 1.5 µJ was measured at a wavelength of 5 nm [1].

FEL experiments often rely on photon energy spectra with reduced bandwidth. This can be achieved by means of monochromator beamlines. However, beamlines with a single-stage monochromator intrinsically lengthen the photon pulse. At FLASH2, a new pulse-length-preserving double-monochromator beamline called FL23 was commissioned, and a first FLASH in-house user experiment was successfully conducted. In parallel, an upgraded beamline-to-beam synchronisation by means of optical lasers was realised and successfully tested at FL23.

The FLASHForward plasma wakefield acceleration experiment set a new record of (59 ± 3)% in wakefield excitation efficiency for drive-beam-generated wakes in plasma. Together with the efficiency of acceleration of the witness beam by the wakefield, this determines the possible overall energy efficiency of the plasma wakefield acceleration.

Figure 2
Spectrum of the 15th harmonic optimised for EEHG compared to the residual high-gain harmonic generation (HGHG) and to SASE



Towards a seeded FLASH1 user facility

The laser heater installed in the shutdown 2021/22 can imprint a sinusoidal energy modulation of controllable amplitude on each of the electron bunches. Due to its short wavelength, the modulation gets strongly overfolded in the adjacent first bunch compression chicane and hence smeared out to generate an almost homogeneous local energy spread of controllable amplitude in the electron beam distribution. This enhanced slice energy spread has the potential to reduce the microbunching gain of the downstream beamline and potentially leads to a smoother bunch and thus to improved and more stable FEL performance. Enhanced beam smoothness is a key ingredient for the future operation of FLASH1 as an externally seeded beamline. Several laser heater studies have been performed to gain experience in operation and improve FEL performance for different operation modes. Moreover, an experimental campaign (FLARE) using the laser heater in an advanced mode to produce ultrashort FEL pulses was started in collaboration with TU Dortmund University in Germany.

A major milestone on the way to a seeded FLASH1 user facility was the successful demonstration of external seeding using echo-enabled harmonic generation (EEHG) with parallel SASE operation in FLASH2 and high reproducibility of the setup. The impressive observed improvement in longitudinal coherence and spectral quality (Fig. 2) leaves us excited about the future performance of the seeded FLASH1 user facility.

Contact:
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Reference:

[1] E. Schneidmiller *et al.*, Photonics 10, 653 (2023)

European XFEL accelerator

High energy, great flexibility, short pulses

In 2023, the European XFEL accelerator complex – which is run by DESY – was in reliable and stable operation, serving the ever-varying operational needs of the European XFEL X-ray laser facility. In addition to regular photon delivery, important developments have been pursued on both the accelerator and the free-electron laser (FEL) sources, yielding record FEL photon energies and intensities. Installations included the addition of an electromagnetic wiggler in front of the SASE1 undulator, a magnetic chicane and vacuum chambers for the X-ray Free-Electron Laser Oscillator (XFELO) demo experiment, a radio frequency (RF) pulse compressor for the transverse deflecting structure after the last bunch compressor and the reinstallation of four APPLE-X undulators together with newly developed upstream synchrotron radiation shielding.

Operation summary

In 2023, the European XFEL accelerator complex was operated for more than 7000 h, of which about 4500 h were spent on X-ray delivery to the experiments (Fig. 1). The availability of the facility was very good (93.9% averaged over all the undulators), but slightly below the self-imposed goal of 95% due to – already well-known – sporadic failures of bearings in the cold compressors of the cryogenic plant. The successful test operation of a new motor type with active magnetic bearings throughout 2023 and the prospect of replacing the remaining three motors with this new type in summer 2024 give reason to hope that the availability can be further improved.

X-ray delivery was performed with electron energies of 11.3–16.3 GeV, yielding photon energies of 400 eV to 24 keV for the experiments. Self-seeding was requested about 50% of the time at the SASE2 undulator, but could not be offered towards the end of the year because of a damaged self-seeding monochromator. The robustness of this setup will be improved in the future.

In 2023, several weeks of operation at a repetition rate of 4.5 MHz were offered and used by a few experiments. Overall, the ratio between potentially available pulses and actually used pulses was below 20% on average over all runs.

Short pulses

Short-pulse operation is a focus in facility development, but was also delivered to users at the SASE3 undulator, where a direct measurement of sub-femtosecond photon pulses was performed with THz streaking. Single-spike lasing with high intensities was demonstrated at SASE2 by shaping the electron beam through self-fields and detuning of the deflection arc optics (Fig. 2). A wiggler and a wakefield structure were installed in front of SASE1 to enable even better control of the electron phase space in the future. A new injector laser, NEPAL-X, was installed and commissioned, offering even more flexibility in terms of individual bunch charges and shapes. Simultaneous lasing was demonstrated with bunches of different charge within a bunch train. The Beam Regions concept, which was established in 2022 and allows for individual control of the acceleration fields, is a prerequisite to benefit from these new capabilities.

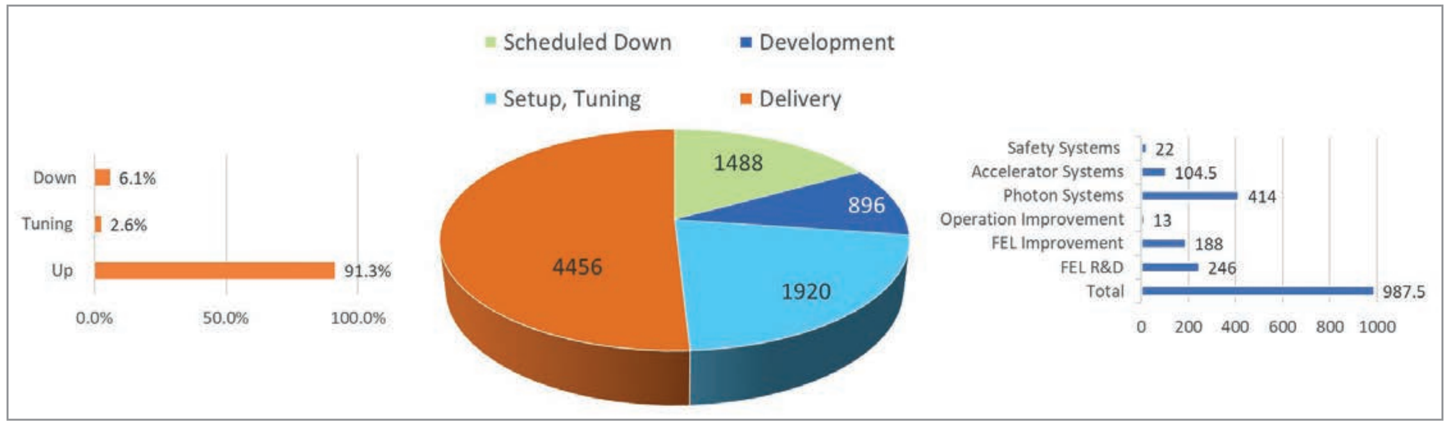

Figure 1

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

Accelerator scientists from DESY and European XFEL during studies to obtain single-spike lasing with high power in SASE2

Facility development

Dedicated facility development focused on better understanding the build-up of slice energy spread in the injector and during bunch compression, which is important to further improve the electron beam quality. Several studies were performed to measure the static and dynamic heat load of the cryomodules, an important input parameter for further detailing the high-duty-cycle upgrade proposal. Another focus was the development of new synchrotron radiation absorbers to be placed in front of the APPLE-X undulators. The effectiveness of the shielding could be demonstrated experimentally, leading to the reinstallation of the four undulators in the winter maintenance period 2023/24.

R&D for future upgrades

The scope of the installations and improvements foreseen for the long maintenance period in the second half of 2025 is fully defined, and preparations are under way. Major activities concern the preparation of the area behind SASE2 for the installation of superconducting undulators, the completion of the tunnel installations for the ASPECT project, which intends to generate attosecond pulses in SASE1 and SASE3, and the insertion of a passive bunch streaker after SASE3 for bunch length diagnostics, similar to the device already installed behind SASE2. A new electron source, Gun 5, will be installed as well. This improvement to the current photoinjector cavity aims to increase the RF pulse length and thus the number of available electron bunches by 30%. The cavity is presently undergoing tests at the PITZ photoinjector test facility at DESY in Zeuthen.

For the long term, preparations are being made to upgrade the accelerator to continuous-wave (CW) or high-duty-cycle operation, with the goal of publishing a conceptual design for the linear accelerator by 2027. A crucial element is the CW injector. Here, DESY is developing an all-superconducting photoinjector that will allow high accelerating gradients and can thus provide small horizontal emittance. A breakthrough test performed in 2023 showed that operation at high gradient with a copper cathode is possible. In the coming years, a full beam test stand will be constructed in one of the bunkers of the Accelerator Module Test Facility (AMTF).

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PITZ

High-brightness electron source developments and applications

In 2023, activities at the PITZ photoinjector test facility at DESY in Zeuthen focused on three main topics: high-brightness source development, THz pulse generation and first radiation biology studies. The electron source (gun) development programme to improve user operation at DESY's FLASH facility and at the European XFEL X-ray laser was carried on. Studies on a tuneable, high-power THz source for pump–probe experiments at the European XFEL were continued, and first seeding experiments using temporally modulated photocathode laser pulses were performed. In addition, experiments on radiation biology and dosimetry were carried out, and a laboratory container to expand these experiments is under construction.

Gun development for FLASH and the European XFEL

The new gun series, Gun 5, was designed to improve user operation at FLASH and the European XFEL. A series of five new Gun 5-type cavities is under production in the DESY workshops in Zeuthen and Hamburg. In 2023, conditioning and beam operation of the Gun 5.1 prototype continued, with special focus on studying the observed mini-breakdowns, which are probably related to a cathode spring problem that manifested in August 2023. The cathode spring was replaced, and the issue was analysed in detail. Different approaches to solving the problem are currently being investigated by groups in Zeuthen and Hamburg.

New photocathode laser system NEPAL-P installed at PITZ

After about 20 years of successful operation of photocathode laser systems built and maintained by the Max Born Institute (MBI) in Berlin-Adlershof, a new photocathode laser system, NEPAL-P, developed by the DESY laser group was installed at PITZ (Fig. 1). It provides a factor of 4.5 more laser pulses per time interval and uses the same technology as the laser systems that are being installed at FLASH and the European XFEL.

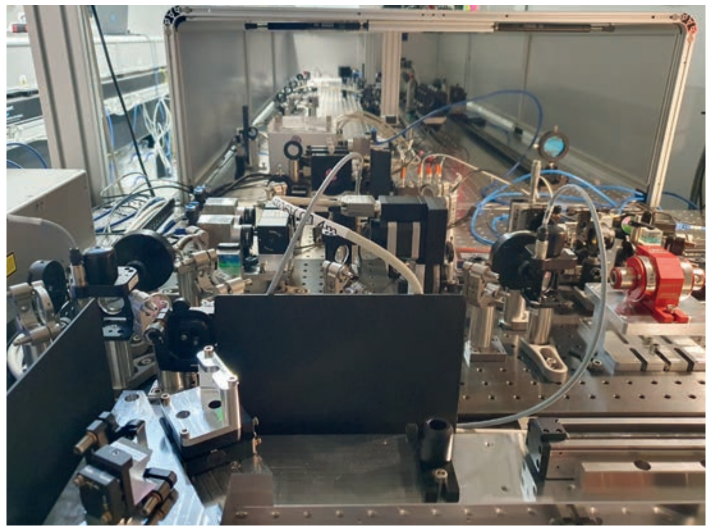

Figure 1

A section of the NEPAL-P photocathode laser system on the laser table

Thanks to the installation of a new fibre-based photocathode laser front-end with in-line spectral shaping, the longitudinal electron bunch properties can be manipulated. The new photocathode laser system can also be optionally coupled with a transverse spatial light modulator to apply arbitrary transverse masking of the laser pulse, effectively becoming a programmable, "virtual" beam shaping aperture. This opens up many fascinating possibilities, from simple homogenisation of the laser spot on the cathode to elliptical truncated Gaussian distributions and more.

THz FEL studies

In 2022, a single-pass THz free-electron laser (FEL) was put into operation at PITZ as a proof-of-principle experiment of a tuneable, high-power THz source for pump–probe experiments at the European XFEL. THz pulses were generated at a radiation wavelength of 100 µm within a 3.5 m long, strongly focusing planar LCLS I undulator. In addition to the self-amplified spontaneous emission (SASE) FEL, first seeding experiments using temporally modulated photocathode laser pulses were performed, clearly demonstrating the seeding effect (Fig. 2). In 2023, further tuning of the THz SASE FEL using 17 MeV electron beams generated by synchronised pulses of a Gaussian photocathode laser led to an increase in the energy of the measured THz pulses to 65 µJ. To allow for proper characterisation and optimisation of the produced THz light, the implementation of dedicated THz diagnostics was prepared.

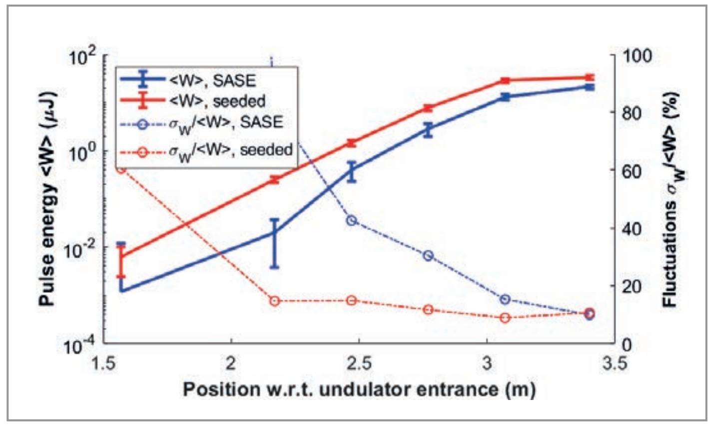

Figure 2

Average power measurements of the SASE THz FEL vs. the seeded case

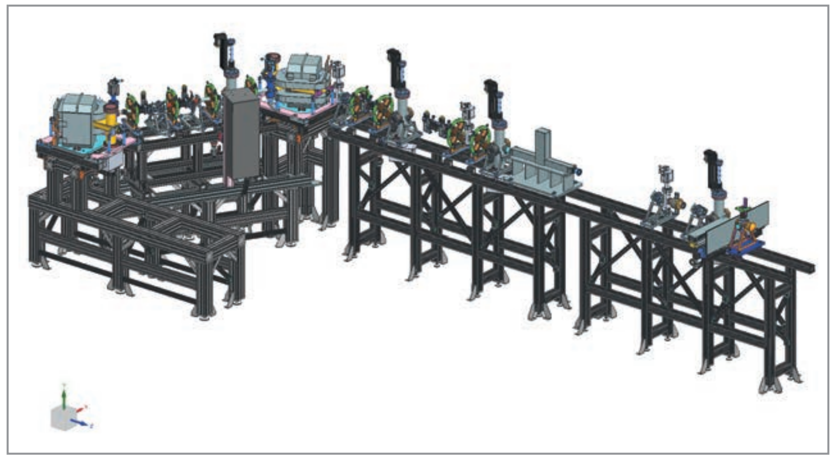

Figure 3

Current design of the dedicated *FLASH*lab beamline at PITZ

Figure 4

Newly installed laboratory container

In May 2023, Mikhail Krasilnikov, the leader of the THz activity at PITZ, received the Gersh Budker Prize of the European Physical Society's Accelerator Group (EPS-AG) for his achievements in the development of high-brightness electron beams and the successful first lasing of a high-power, tuneable THz SASE FEL at PITZ.

*FLASH*lab@PITZ: experiments for radiation biology and dosimetry

Together with the Technical University of Applied Sciences in Wildau (TH Wildau), PITZ is developing an R&D platform for ultrahigh-dose-rate (UHDR) cancer radiation therapy (RT) called *FLASH*lab@PITZ. The unique parameter space of the PITZ facility allows beams to be delivered with dose rates between 0.05 Gy/s and 10^{14} Gy/s. This provides a unique opportunity to systematically investigate the *FLASH* effect, which has been shown to be less damaging to normal tissue than the application of conventional RT dose rates.

First irradiation experiments with a preliminary beamline have been successfully carried out since November 2022. The first *in vitro* studies were performed with an 18 MeV PITZ electron beam at doses up to 150 Gy and dose rates of 0.05 Gy/s for conventional irradiation and 10^5–10^6 Gy/s for UHDR irradiation. Dose-dependent reactive oxygen species (ROS) were measured for doses ≤60 Gy when irradiating water samples with the electron beam. UHDR radiation at 10^6 Gy/s caused less ROS generation than conventional treatment at 0.05 Gy/s. DNA strand breaks were measured in irradiated DNA plasmids for doses ≤50 Gy in similar amounts at both dose rates. Sarcoma organoids – *in vitro* models of cancer tissue – provided by Charité Berlin were irradiated with a UHDR dose rate of about 140 000 Gy/s and a conventional dose rate of about 0.043 Gy/s. Cancerous and healthy lung cells prepared at TH Wildau were also treated with similar dose rates. Both investigated cell lines were found to be sensitive to the electron irradiation at doses ≤10 Gy. The analysis of the obtained data demonstrated the *in vitro* radiobiological effects, i.e. decreased cell proliferation and intensified DNA damage at increasing doses for both UHDR (10^5 Gy/s) and conventional (0.05 Gy/s) dose rates. The results highlight the potential to further explore even higher UHDR for cancer RT on models with increasing level of organisation.

To continue and extend these experiments, a dedicated beamline is being designed and built at PITZ, together with a dedicated experimental area that will allow for very different experimental setups (Fig. 3). In addition, a new laboratory container is being prepared. The container (Fig. 4) was installed close to PITZ throughout 2023 and is currently being equipped to create the basis for future *in vitro* and *in vivo* experiments at *FLASH*lab@PITZ. To this end, new cooperations have been established in the whole experimental range, from dosimetry through *in vivo* experiments to medical applications.

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2D materials at REGAE

First electron diffraction experiments with quantum materials

In 2023, the technical improvements and upgrades of DESY's REGAE facility for ultrafast electron diffraction (UED) were continued. A new concept for the laser beam transport from the laser system to the photocathode was designed and implemented. The REGAE team further developed new sample preparation techniques, which now allow the preparation of large sample flakes from 2D materials with thicknesses of less than 50 nm. In combination with the newly installed sample chamber and a new crystallography goniometer, this enabled the team to collect first high-quality diffraction data from 20 nm thick tantalum disulfide crystals.

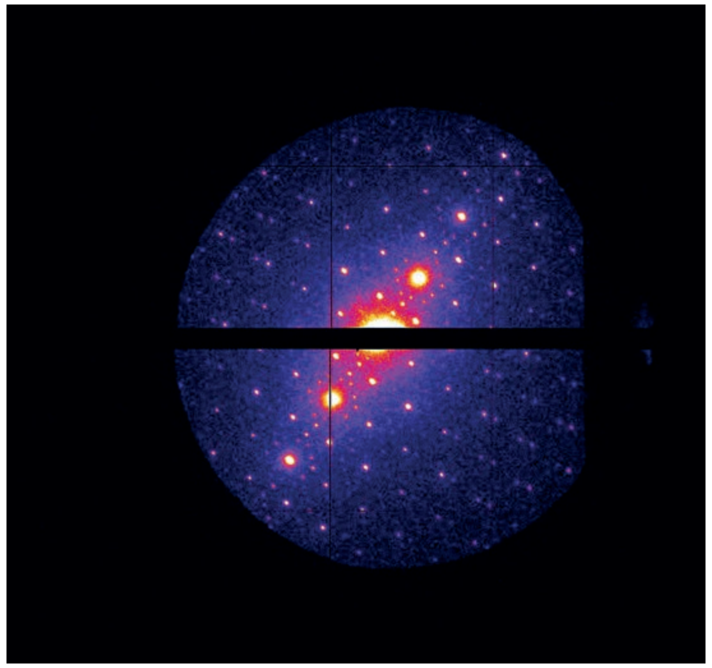

Figure 2
Diffraction image with super lattice reflections from a charge density wave recorded at REGAE from a 20 nm thick crystal of the 2D material tantalum disulfide (TaS_2) obtained by sample preparation with a microtome

New laser beam transport for improved electron beam stability

After the first successful 3D structure determinations at REGAE, efforts were made to improve the pointing stability of the electron beam. For this, a new optical scheme for the laser beam transport from the laser system to the photocathode was designed and installed at the facility. To achieve the outstandingly small emittance of the REGAE electron beam, a very small spot size of the laser beam on the photocathode is needed. Such a small spot would require a large aperture of the illumination optics, but this is limited by the maximum acceptable diameter of the coupling mirror. An improved optical layout of the laser beam transport now allows the team to better control the spot size on the cathode with significantly improved stability. In addition, optical components of the beam transport system were mechanically decoupled from the floor and the sealing of the laser room, leading to a significant reduction of mechanical vibrations and thereby further improving the electron beam stability.

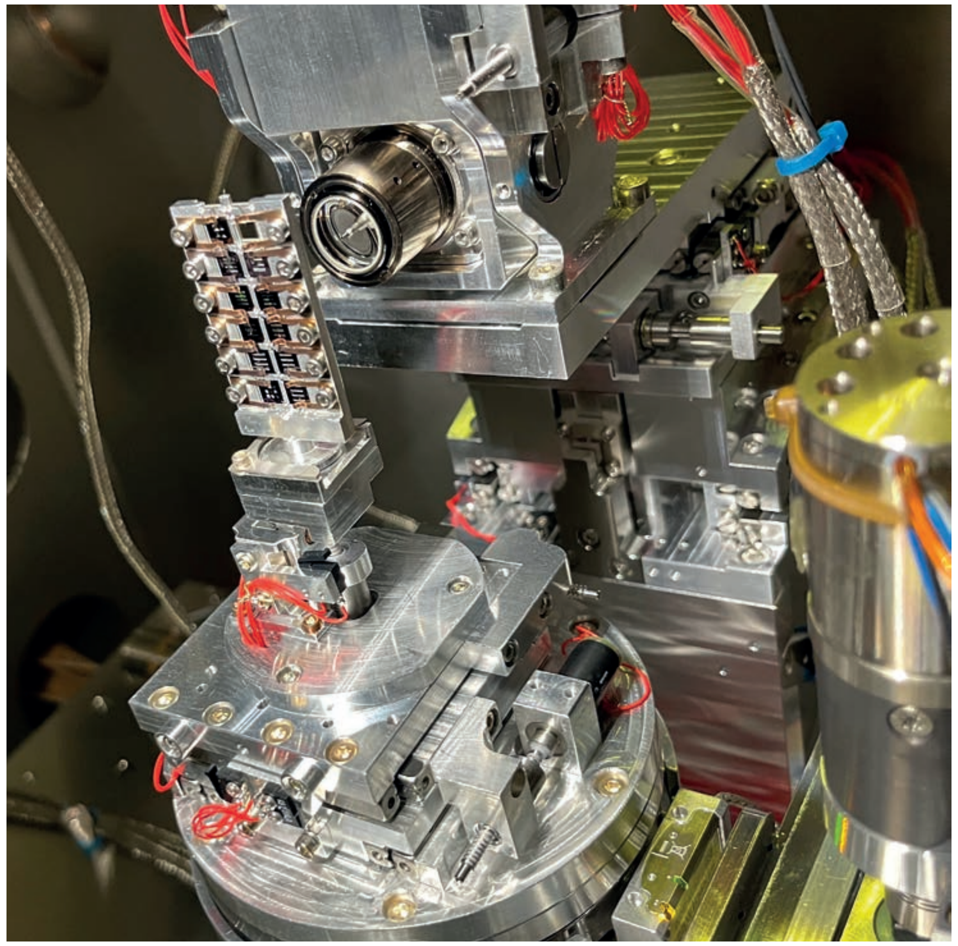

Figure 1
View inside REGAE's experimental ultrahigh-vacuum chamber equipped with an inline sample viewing microscope (top). A sample holder carrying 12 different samples (centre left) is mounted on an e-Roadrunner goniometer (bottom left).

New techniques for sample preparation

For accelerator-based electron diffraction experiments, sample preparation in particular poses a major challenge, as extremely thin samples with a thickness of only a few tens to a few hundreds of nanometres are required. Various approaches were pursued for this purpose, two of which proved to be particularly successful: For 2D layer structures in particular, the samples can be cut or cleaved very well with a microtome, and defect-free samples with a size of several hundred micrometres and a thickness of less than 50 nm were obtained from some relevant materials using this method. To measure the samples, they were mounted on silicon nitride sample holders specially developed and manufactured for REGAE. The method of "confined crystallisation", i.e. crystallisation between two extremely thin membranes, proved to be well suited for the production of thin organic crystals, and suitable samples of various compounds could also be produced.

Electron diffraction experiments from 2D materials

Parallel to these developments in sample preparation, the diffraction experiments already carried out in 2022 were successfully continued and extended to other sample classes. As part of these efforts, crystals of 2D quantum materials were examined for their atomic structure for the first time at REGAE in collaboration with a group from the University of Kiel. Analysis of the diffraction images revealed an increase in electron beam pointing stability by a factor of 6, leading to significantly better quality of the diffraction data.

In collaboration with the University of Salerno in Italy, structural investigations were also performed on lithium battery materials. These samples were prepared using molecular beam epitaxy, another promising method to extend the sample portfolio for UED experiments to inorganic 3D materials.

While the previous experiments were aimed at determining the structure of the ground state, corresponding time-resolved measurements are planned to be conducted in the near future to determine optically excited states. For such laser pump–probe experiments, a new beamline for the excitation laser was designed and the experimental chamber was extended accordingly. These new experimental developments will make it possible to fully exploit the extremely high temporal resolution of REGAE in the femtosecond range and for example to understand extremely fast phase transformations at the atomic level, such as those that are highly relevant for the development of new low-power transistors.

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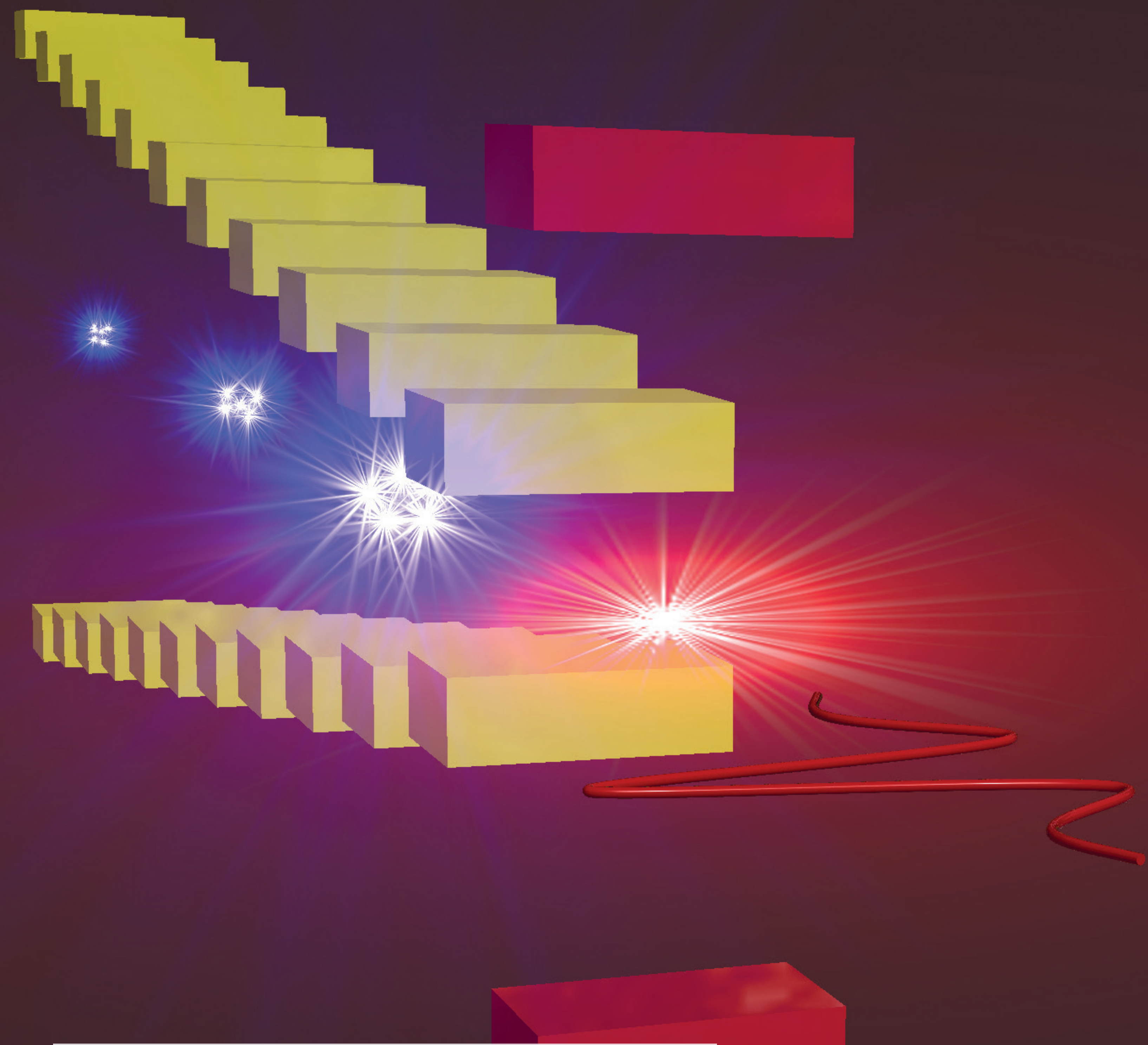


Developing the technology for future facilities

The pulse duration in short-pulse techniques for self-amplified spontaneous emission (SASE) free-electron lasers (FELs) is limited by the so-called FEL coherence time. A recently proposed concept makes it possible to overcome the coherence time barrier and obtain much shorter pulses (see p. 58).

Picture: Matthias Dreimann, Uni Münster

Highlights · New technology · Developments

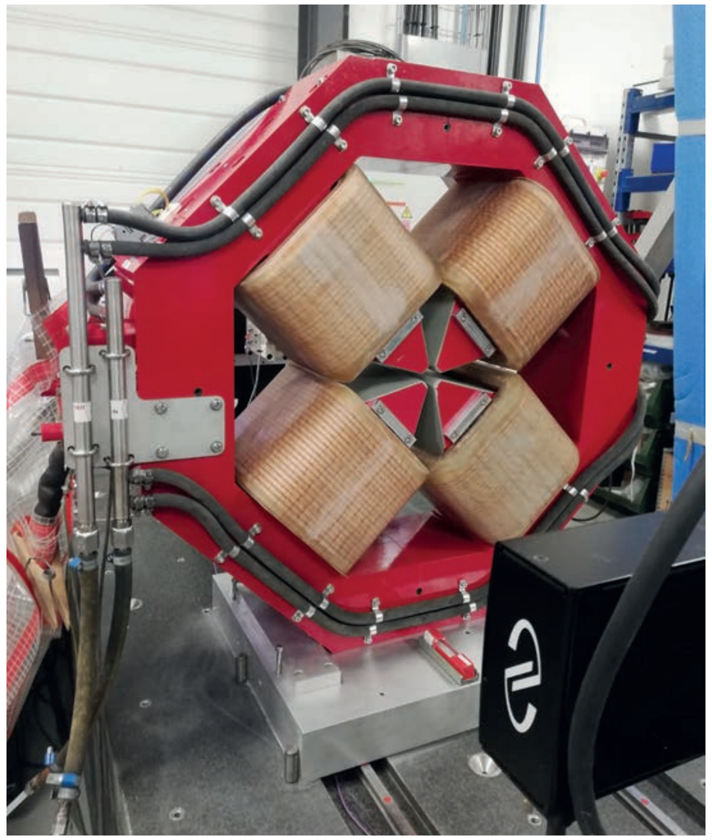
PETRA IV – the ultimate 3D X-ray microscope

Plans for the new light source PETRA IV are taking shape

PETRA IV is the planned ultralow-emittance upgrade of the existing PETRA III storage ring. DESY's flagship project will be the brightest synchrotron light source in the world for decades to come. Academic and industrial users will benefit from the enormous increase in coherent X-ray flux, the planned cutting-edge beamlines, the novel experimental possibilities as well as 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 in the processing and analysis of their data. PETRA IV will be a cornerstone of the Science City Hamburg Bahrenfeld and a central component of DESY's vision of a data- and information-driven solution ecosystem for academia and industry.

Funding for the PETRA IV preparation phase project

In 2023, the PETRA IV project team made progress on the planning of civil construction, the accelerator complex and the photon beamlines. In particular, the team completed the comprehensive project proposal, which comprises the scientific case, technical description, business model, data management plan, project budget and future operation costs for the facility. The largest part of the project proposal is the technical description of PETRA IV itself. Thanks to its level of detail, this part also serves as a technical design report (TDR). For the accelerators, a new design aspect has been introduced. It now includes a second injector branch for the storage ring, based on a laser plasma accelerator (LPA). This LPA will be located in the area of the former DORIS complex. Here, KALDERA, a high-power laser system for the next generation of laser plasma accelerators, is currently being set up and commissioned. From there, a new transfer line will be built that will make it possible to switch between the conventional radio frequency (RF) cavity booster synchrotron DESY IV and the new LPA injector.



In December 2023, the PETRA IV project received confirmation from the federal and local governments of funding for a preparation phase project, including the development of the PETRA IV Plasma Injector (PIP^{IV}), in order to start the implementation of the so-called transformation phase and proceed with the necessary planning. The prototype programme will thus be strengthened, concluding the production of all remaining items, and civil engineering contracts for the planning of the PETRA experimental hall West (PXW) including the supply areas can be issued.

Figure 1

Prototype of the 115 T/m high-field quadrupole magnet for PETRA IV on a test stand at SIGMAPHI

Figure 2

Left: Prototype of the novel girder design cast in metal just before Christmas 2023. Right: Final treated and painted prototype girder by COSWIG GUSS

First prototypes tested on campus

The prototype programme for the most challenging components of the PETRA IV storage ring is well advanced. The prototype of the 115 T/m quadrupole was built by SIGMAPHI (Fig. 1) and is now being tested. The prototype of the sextupole magnets is under construction at DANFYSIK. The hot-swap scheme for magnet power supplies was successfully tested during PETRA III operation without disturbing operation. While this initial scheme is based on a 1:1 pairing of the power supplies, present developments aim at implementing a 1:*n* paring scheme, in which a switching matrix allows one power supply to be available for hot-swap for *n* power supplies. In this way, the total number of power supplies could be substantially reduced, leading to a significant reduction of the requirements for the corresponding infrastructure. The prototype single-cell high-order-mode- (HOM)-damped 500 MHz cavity was delivered and installed in the PETRA III storage ring and is now being conditioned for operation together with a prototype solid-state amplifier. First results are promising.

The prototype of the 1.5 GHz harmonic cavity, built by ALBA in 2022, was installed and successfully tested with beam at BESSY II in Berlin, showing the expected bunch lengthening effect with an active RF drive. A prototype of the fast injection kickers was also built at DESY. Powered with high-voltage pulsers from FID, it was installed and tested at MAX IV in Lund, Sweden. The results on beam-induced heating and the analysis of beam perturbation were very positive, showing that the nominal kick strength is achieved without significant tails or reflection of the high-voltage pulses (in excess of 10 kV with 4 ns total width). The latest successful milestone of the prototype programme in 2023 was the first cast of a specially designed girder for the storage ring (Fig. 2) in a foundry in Dresden. The prototype is expected to be delivered and tested at DESY in 2024. With the production of the magnet prototypes and some further dummy magnets, the PETRA IV team expects to start assembling the full alpha girder (Fig. 3) by mid-2024 to test the assembly, alignment and mechanical performance of the system.

Exploring alternative operating modes

The PETRA IV storage ring is designed to deliver 6 GeV electron beams in two main operating modes: the brightness mode, consisting of multibunch trains with 200 mA in 1920 bunches separated by 4 ns, and the timing mode, consisting of 80 mA in 80 bunches separated by 96 ns. The nominal emittance of 20 pm·rad can be guaranteed only for the brightness mode, while the high charge per bunch in timing mode generates an emittance of about 35 pm·rad.

Alternative operating modes are being discussed to cater to the requests of the user community. The brightness mode with full coupling promises to deliver round beams with a shared emittance of 12 pm·rad in the horizontal and vertical plane. The flexibility of the timing system and injector makes it possible to create very different fill patterns. Increasing the number of bunches in the brightness mode has a beneficial impact on the beam lifetime, and up to 3480 bunches spaced by 2 ns are being considered. Mixed modes with multibunch trains and single isolated high-charge bunches (i.e. camshaft bunches) are also

Figure 3
Visualisation of the view into the PETRA IV tunnel with assembled girders

Figure 4
PETRA IV exhibition at the summer festival of the Hamburg State Representation in Berlin

possible. Of particular interest is an enhanced timing mode with 80 mA in 40 bunches separated by 192 ns. Initial studies show that such a high charge is prone to collective instability, and detailed investigations are ongoing to understand under what operating conditions this timing mode can be delivered. With the refinement of the vacuum chamber design and a clear understanding of the RF impedance budget, it will be possible to define in 2024 which additional operating mode can be provided to the PETRA IV users.

Progress with the PETRA IV injector

In 2023, the lattice of the DESY IV booster synchrotron, initially based on a six-fold symmetric low-emittance FODO cell, underwent a thorough review as a consequence of difficulties encountered during the planning of the installation and assembly in the DESY tunnel. A new eight-fold symmetry lattice was designed, and the corresponding engineering integration was started. Unlike with the previous lattice, the new DESY IV booster does not need to be installed on the ceiling of the DESY tunnel and fits between the present DESY II synchrotron and the old support structure used to hold DESY I and later DESY III. The eight-fold symmetry also allows a better geometric matching to the extraction of test beams, should these be required.

Given the progress of LPAs in recent years and the additional funding obtained to support these activities, the programme for a full-energy plasma injector was strengthened: While the LPA was initially planned to only support top-up injection, new plans envisage that sufficient charge will be provided for the initial filling of PETRA IV as well, thus creating a fully-fledged laser plasma injector that could completely replace DESY IV. Demonstration of high-quality, stable 6 GeV beams with the availability and reproducibility established for standard booster injectors would be a major breakthrough not only for PETRA IV, but for particle accelerator science and technology as a whole. Milestones of this programme will be the ongoing experiment on the LUX dechirper, the KALDERA upgrade to support continuous injection at DESY II (at 450 MeV) and finally the full 6 GeV demonstrator.

Estimated project budget passed all reviews

An essential part of the work on the PETRA IV project proposal was the compilation of the project costs and the required future operation budget. The latter will be evaluated separately by the Helmholtz Association as part of its upcoming Programme-oriented Funding (PoF V) process, which is due to start in 2024. The total costs of the project are estimated at 1.5 billion euros (in 2022 prices), including in-kind contributions from DESY and the Helmholtz Association. All cost estimates were subject to a thorough internal and external cost review focusing on civil construction and infrastructure, the accelerator complex and the experimental facilities of PETRA IV. Both cost reviews were successfully passed, and the committees recommended the implementation of PETRA IV as soon as possible.

The technical design and the cost estimates were also presented to all pertaining advisory committees at DESY, the Machine Advisory Committee (MAC), the Photon Science Committee (PSC) and in particular the Scientific Council and the Foundation Council. In an extraordinary meeting at the end of March 2023, the Foundation Council approved the submission of the project proposal to the appropriate funding agencies. In September 2023, the Hamburg City Parliament unanimously decided that the City of Hamburg will provide its share of 10% of the requested funds and continue to advocate for the remaining share of 90% from federal funds.

PETRA IV in politics and society

The PETRA IV campaign was launched at a senate reception at the Hamburg City Hall in September 2022. Its goal is to raise awareness of the importance of PETRA IV for science, politics and industry in Germany and for the national economy. One of the major events at which DESY presented the PETRA IV project in 2023 was the summer festival at the Hamburg State Representation ("Landesvertretung Hamburg") in Berlin, which attracted great interest and at which many stakeholders at federal and state level visited the PETRA IV exhibition (Fig. 4).

Parallel to the preparation of the project proposal, an impact study (*ex post* for PETRA III and *ex ante* for PETRA IV) was carried out by the Fraunhofer Institute for Systems and Innovation Research (ISI) in Karlsruhe and published in October 2023 [1]. The study found that DESY's light source PETRA III has created 2.25 billion euros in added value and that the PETRA IV upgrade could add a further 7.35 billion euros in value, possibly even considerably more. It also showed that DESY, with its research radiation sources, is not only an important driver of scientific progress, but also has an economic impact in the region, in Germany and in Europe as an employer and through the commissioning of commercial companies.

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Reference:

[1] H. Kroll *et al.*, "Impact-Studie Synchrotronstrahlungsquelle PETRA III im Kontext des Forschungs- und Innovationsökosystems DESY", Fraunhofer (2023), DOI: 10.24406/publica-1929

Let's shake it

Impact of construction work on PETRA III beam stability

In the coming years, the DESY campus will undergo a major upgrade of its support and building infrastructure, also, but not only, in the context of the PETRA IV project. Construction work will unavoidably be performed in parallel to PETRA III operation, entailing disturbances to the electron and photon beams. It is therefore of fundamental importance to assess the impact of the anticipated construction work in order to be able to coordinate the beamtime and schedule experiments accordingly so that user needs and expectations can still be satisfied. In 2023, a series of vibration tests were conducted in which ground motion was deliberately induced at several locations across the DESY site.

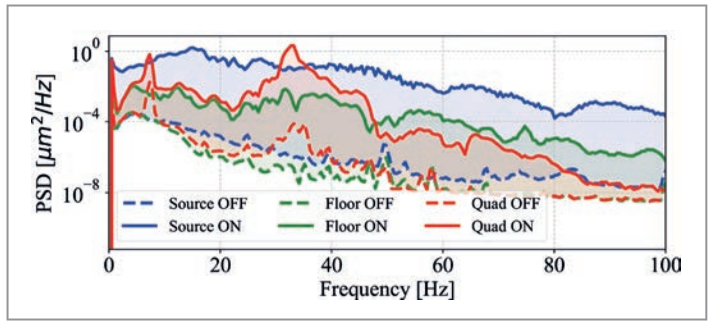

Figure 3

Frequency spectra of ground vibrations during the stone drop experiment measured close to the source (solid blue), on the tunnel floor (solid green) and on top of a quadrupole (solid red). The filling indicates the difference between the spectra with excitation (solid lines) and the quiet spectra without excitation (dashed lines).

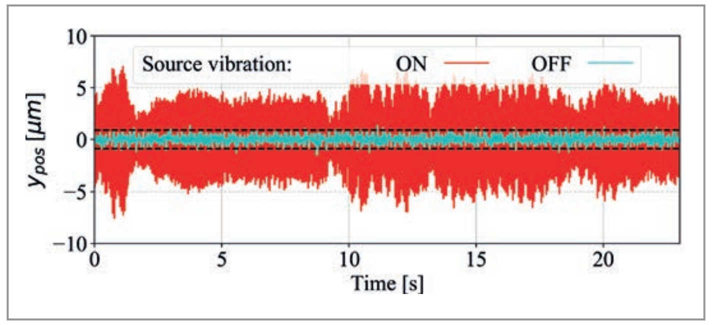

Figure 4

Vertical electron beam position changes at the undulator of the beamline P07 during excitation with a vibrating roller (red) and quiet reference without excitation (light blue). The PETRA III stability goal of 10% of the beam size is marked by the two black dashed lines.

Simulation of construction activity along the PETRA ring – a cross-divisional effort

PETRA III is sensitive to a wide range of frequencies coming from ground motion through the accelerator tunnel floor. Quadrupoles are the main source of beam disturbances due to ground motion, as they introduce an orbit kick when they are displaced. Their individual response induces a range of additional frequency lines on the electron beam frequency spectrum.

Interest in the effects of construction work on beam stability is high. In 2023, four additional study days were dedicated to investigations on this topic. A working group was formed with currently around 50 members from the Accelerator Division, the Photon Science Division, the construction department and the technical groups. The goal is to identify the requirements and capabilities of each party and exchange ideas and expertise in order to make the best use of the given study time and develop a joint plan on how to mitigate the impact of upcoming construction activities.

The planning of the cross-divisional study started in early 2023. After setting up the required data taking and communication between the accelerator control room and the beamlines, a two-day vibration test was conducted in September 2023. A vibrating roller (Fig. 1), normally used for the compaction of loose ground, served as a vibration source at three future construction sites close to the PETRA ring and along the street on top of the European XFEL injector building. In addition, the drop of a 2 t shielding stone from a height of about 5 m (Fig. 2) simulated the impact of a diaphragm wall grab, such as will be used during the construction of the planned new 600 m long PETRA IV experimental hall PXW, which will be excavated during PETRA III operation.

Figure 1

Ground excitation with a vibrating roller in the West area of the PETRA ring. The PETRA tunnel lies only a few metres to the left. The shielding stones in front of the material side entrance are visible on the left.

Figure 2

Dropping a 2 t shielding stone from a height of 5 m in the North area of the PETRA ring. The PETRA tunnel is only a few metres away, below the rising ridge on the left.

Diaphragm wall construction needs further investigation

The results indicate that the construction of two 600 m long diaphragm walls on both sides of the PETRA tunnel during beam operation might have a greater effect on the operating conditions than presently assumed in the construction planning. The ground velocities induced by the dropping stone are of the same order of magnitude as the ones expected from the construction of a diaphragm wall at a comparable distance from the tunnel. Orbit deviations of up to 20% and 110% of the beam size were observed in the horizontal and vertical plane, respectively. This is significantly outside the design stability criterion for vibrations, set at 10% of the beam size. However, it should be noted that the impact was simulated on the ground level of the accelerator. Excitation from excavation is more likely to come from the top, which might lead to a different response due to the different propagation of surface and body waves.

A frequency response spectrum of the floor and quadrupole motion is shown in Fig. 3. Note the broad ground excitation over all frequencies (blue and green lines) and the clear resonant response of the quadrupole at its eigenfrequencies of around 8 Hz and 32 Hz (red). Damped oscillations of this quadrupole and of electron and photon beams at those eigenfrequencies were observed over several seconds after the impact. During the compaction test, the stability limit was also exceeded several times over, especially in the vertical plane (Fig. 4).

Some user experiments impossible under tested conditions

Several PETRA III beamlines were included in the study. The purpose and requirements of the 25 beamlines of PETRA III are diverse, and so is the effect of vibrations on their measurement quality. Both the vibrations transmitted by the electron beam to the photon beam and the direct movement of the photon beamline elements or the sample under investigation are problematic. The sensitivity to either depends on the beamline equipment and measurement method. Analysis is currently still ongoing; however, for most beamlines, certain experiments will be impossible under the tested conditions because the beam quality degradation is too great.

The cross-analysis between beamlines and the understanding of the variety of impacts coming from the same known vibration source provide valuable input for the design of the accelerator and beamline diagnostics and the PETRA IV fast orbit feedback. The observations made during this experiment can be used as a benchmark for PETRA IV simulations. A continuation of these efforts is foreseen for 2024.

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RF energy-saving initiative at the European XFEL

Reducing the energy required for beam acceleration without compromising photon delivery

One third of the energy consumption of the European XFEL accelerator comes from generating the radio frequency (RF) fields required to accelerate the electron beam. Over the last couple of years, multiple efforts to optimise the energy consumption have translated into significant energy and cost savings. A first initiative to lower the high-voltage drive of the accelerator's high-power sources (klystrons) was introduced in 2022, reducing the unused klystron power overhead while preserving enough margin for field regulation. This first step already provided 10–15% savings [1]. As a second step, modifications of the high-power modulator shape combined with a more sophisticated use of the available klystron power allowed savings to be brought up to 30%, without compromising the beam quality required for photon science. This article presents the steps that have led to these savings as well as some insight on their technical implementation.

High-energy and reduced-energy configuration

In its current state, the European XFEL can provide a maximum beam energy of 17.5 GeV, but high-energy user runs typically call for 16.3 GeV beam energy, leaving enough RF reserve to compensate for the failure of a single RF station. This station is kept on, at its maximum gradient, but set off-beam as a hot spare. Some user runs require lower beam energies, ranging from 11.5 to 14 GeV, and special study modes require even lower energies (≤8 GeV). As an example, user runs in 2023 were allocated 8 weeks at energies of 11.5 GeV and lower, 12 weeks at around 14 GeV and 12 weeks at 16.3 GeV.

To simplify the machine setup, it was decided to provide two gradient configurations: a "high-energy" setup for runs of 14.5 GeV and above and a "reduced-energy" setup for all requests below 14.5 GeV. For a given configuration, changing the accelerating phase will allow for beam energy adjustments, scaling with the cosine of the off-crest phase. For reduced-energy runs, up to five RF stations can be left over as reserve, which is more than actually needed. Typically, four out of five are then switched off, saving approximately 200 kW per station. Turning a station back on can be done on demand and takes about half an hour. Reducing the machine repetition rate, for example to 5 Hz instead of 10 Hz, would cut the RF consumption by half but also decrease the production of photons by half. This is certainly not the desired goal.

As a first attempt to save energy, the modulator high voltage was lowered for the reduced-energy configuration, as illustrated in Fig. 1. Note that the RF pulse fits within the flat steady-state zone of the modulator pulse. Depending on the RF stations, this first step already provided 10–15% power savings, essentially removing the unused power overhead, and was successfully implemented in 2022 in the RF stations of the main linear accelerator (L3) of the European XFEL [1].

Optimised use of available RF power

To further save energy, two modifications were introduced to optimise the use of the RF for beam acceleration: (1) The modulator shape was modified by introducing a 15–20% drop in the second half of the pulse where the RF drive level is lower, and (2) the modulator pulse was shortened by 200 μs, forcing the RF to start and finish during the transient time of the modulator pulse, called rising- and falling-edge. These two changes introduce strong variations in the amplitude gain (up to 50%) and phase (up to 360°) of the klystron RF signal, as illustrated in Fig. 2 (in blue). Without compensation, the RF pulse cannot be used for beam acceleration. The low-level RF (LLRF) system was then modified to characterise the newly introduced high-power gain and phase non-linearities and compute the required compensation to be applied to the RF drive signal. Figure 3 illustrates the impact of this optimised use of RF power without and with drive compensation (data taken from station A21 in July 2023).

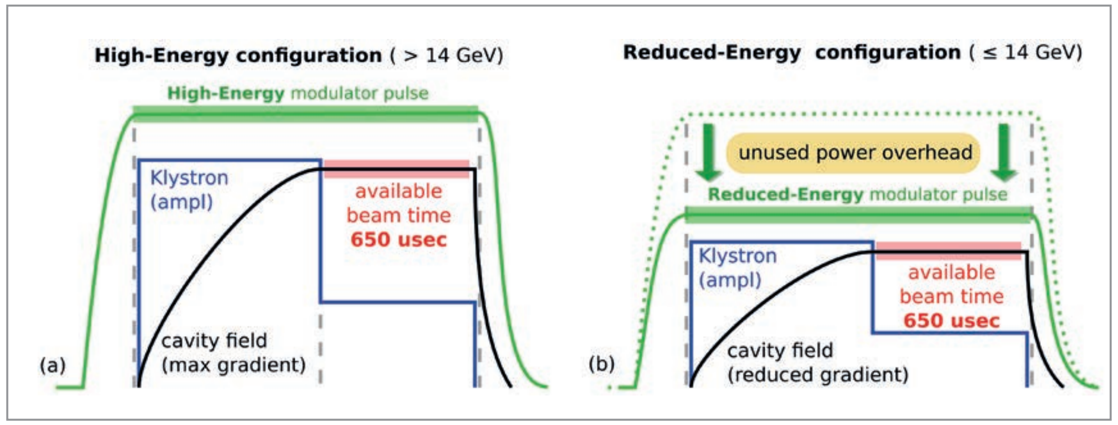

Figure 1

Modulator (green), klystron (blue) and cavity (black) pulse shape in the high-energy (a) and reduced-energy (b) configurations

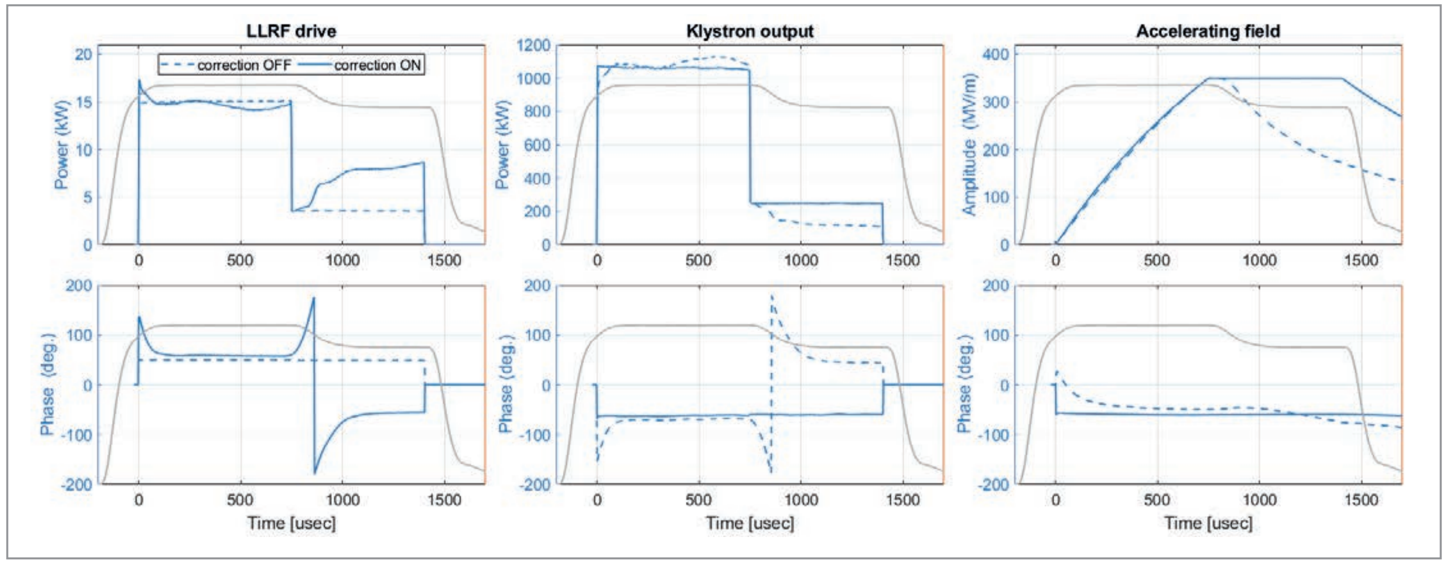

Figure 3

Amplitude (top) and phase (bottom) of the LLRF drive (left), klystron output (middle) and cavity field (right) without (dashed line) and with (solid line) the LLRF corrections. The modulator shape is shown in grey to visualise the time alignment with respect to the RF pulse.

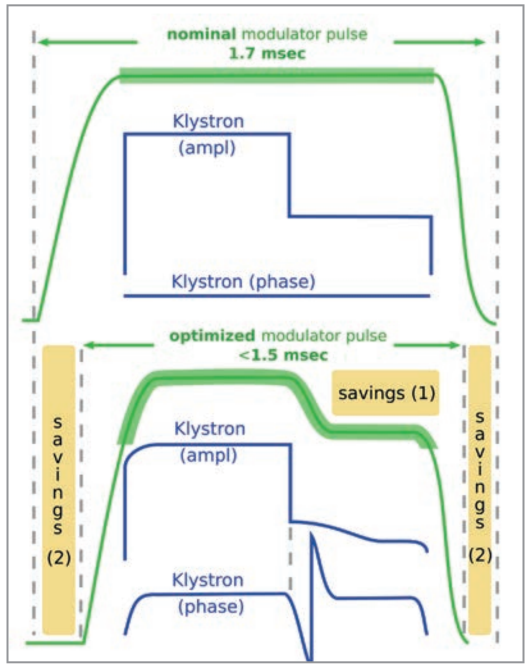

Figure 2

Nominal (top) and optimised (bottom) use of the modulator pulses, shown in green. The modulator pulse shape is shortened and tailored to the RF pulse profile. The impact of these modifications on the klystron output amplitude and phase is shown in blue.

In a test period, 10 out of 20 stations in the main linear accelerator (L3) were configured in this way, providing an approximate saving of 500 kW [2]. During the pilot phase, it could be confirmed that the optimised configuration, while increasing the setup time and the complexity of the LLRF system, did not impact the availability and quality of the beam. Another seven stations in L3 were configured similarly during the startup in January 2024, providing a total saving of 800 kW over the 4.5 MW necessary for RF operation. Some ideas on how to further shorten the modulator pulse (by an additional 90–100 μs) running the klystron in full saturation for the first half of the cavity fill time were successfully tested, but these options come with increased complexity and diminishing returns.

As a side remark, one should emphasise that the techniques developed for optimised RF pulse usage and combined with a shorter modulator pulse in the case of energy saving (as explained in this article) can also be used to extend the available beamtime (without hardware modification) if the modulator pulse length is kept constant. This development perfectly fits with the European XFEL R&D roadmap towards longer pulses and high-duty-cycle operation.

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An XFEL oscillator at the European XFEL

On the way to a true X-ray laser system

Cavity-based X-ray free-electron lasers promise optical-laser-like coherence with high shot-to-shot stability and an order of magnitude higher brilliance than other sources in the hard X-ray regime. A team from European XFEL, DESY and Universität Hamburg has started the construction of the proof-of-concept X-ray Free-Electron Laser Oscillator (XFELO) demonstrator experiment at the SASE1 beamline of the European XFEL. The installation of XFELO began in the winter maintenance period 2023/24.

Motivation

Existing hard X-ray free-electron laser (FEL) facilities suffer from a lack of longitudinal coherence and from high shot-to-shot fluctuations. Cavity-based X-ray FELs (CBXFELs) promise to overcome these issues, providing high-order coherence with high shot-to-shot stability, akin to optical laser oscillators, and an order of magnitude higher peak and average brilliance [1]. CBXFEL schemes are based on trapping the FEL radiation inside an X-ray optical cavity, which entails the use of monochromatising crystals based on Bragg reflection instead of classical total-reflection optical mirrors. As the length of the X-ray cavity needs to match the repetition rate of the electrons, the realisation of a CBXFEL requires the MHz-level repetition rate of superconducting accelerators, such as the one that drives the European XFEL.

The superb characteristics of CBXFELs spurred a team from European XFEL, DESY and Universität Hamburg (Fig. 1) to develop a proof-of-concept experiment at the European XFEL, located at the end of the SASE1 beamline and using the existing undulator cells [2]. The principal goal of the XFELO demonstrator is to prove the working concept – i.e. seeding and increasing the longitudinal coherence by several orders of magnitude over subsequent round trips, from synchrotron radiation to almost monochromatic FEL amplifier radiation. The first results of the experiment are expected in 2024.

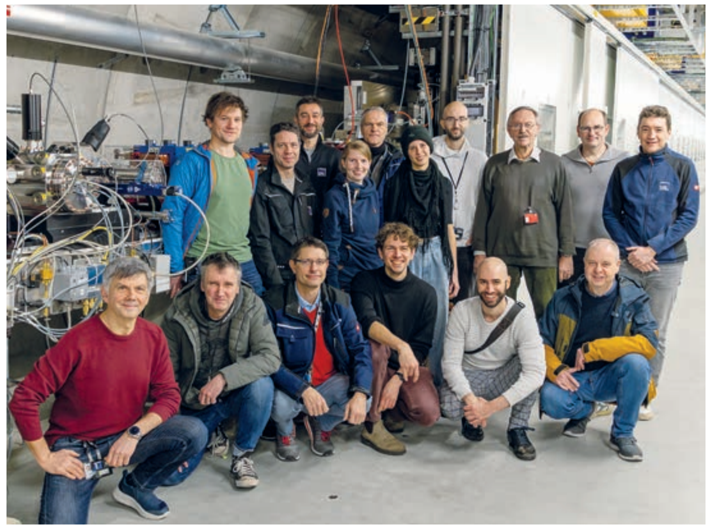

Figure 1

The XFELO team in front of the newly installed magnetic chicane and crystal chamber at the SASE1 beamline of the European XFEL

Demonstrator setup

As sketched in Fig. 2, the demonstrator is designed in a simple two-crystal backscattering geometry. Diamond crystals have been chosen due to their high tolerance for heat load. Four 5 m long undulator cells are located inside the cavity. Chicanes and correctors are used to couple the electrons in and out, respectively. The crystal-to-crystal distance is fixed at LC−C ≈ 66.42 m, which matches the commonly used electron bunch repetition rate of 2257 kHz and agrees well with the spatial constraints in the tunnel. The crystals are offset by some milliradian from nominal backreflection by additional total-reflecting Kirkpatrik–Baez (KB) mirrors, which furthermore enable focusing with a numerically optimised focal length of 30 m. In addition, the diamond crystals are planned to be cooled down to around 70 K using pulse tube coolers.

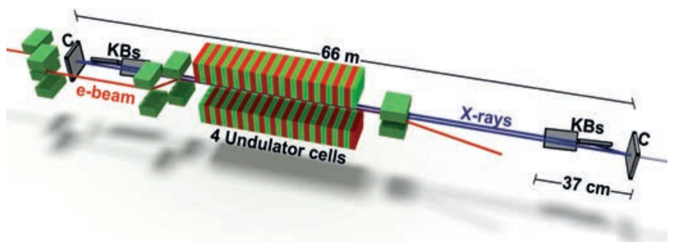

Figure 2

Sketch of the demonstrator setup (the illustration is not to scale; in addition, the undulator cells are not centred in the cavity, as it appears, but much closer to the upstream mirror, and the crystal and mirror assembly is only about 50 cm in size)

Working principle and simulation

The initially weak X-ray pulse generated by the four undulator cells will be partially recirculated through the cavity and serve as seed for the subsequent electron bunch after 444 ns. This seed will then be amplified, resulting in an exponential rise of the X-ray power in the cavity and the development of an intense X-ray field after some dozens of round trips, as depicted in Fig. 3.

Unlike classical laser resonators in the optical regime, though, X-ray cavities have the important difference of being based on the principle of Bragg reflection. Bragg reflection can provide very high reflectivity up to 99%, which is however restricted to a very narrow bandwidth centred around the crystal- and incident-angle-dependent Bragg wavelength. For the diamond reflection under consideration, the resulting bandwidth is around one permille of the initial self-amplified spontaneous emission (SASE) bandwidth at 7 keV photon energy. As such, the reflection effectively acts as a spectral filter, enabling spectrally very pure seeds. This spectral purity is imprinted on the subsequent radiation pulses, leading to a decrease in bandwidth with the number of round trips (Fig. 4, a–c) and a high degree of coherence. A prerequisite for this gain is the spatial matching between the few tens of micrometre sized electron bunches and the X-ray pulses of the same size. This requires not only a positional accuracy on the order of 5 µm, but also a very demanding angular accuracy of the crystals and mirrors on the order of 100 nrad.

For all cavity-based radiation sources, the method used to couple out the radiation is an integral part of defining the output characteristic. Due to its evident simplicity, direct transmission through the downstream crystal has been chosen for the XFELO demonstrator project. Because of the high peak reflectivity (~99%), only the side wings of the spectral profile will actually be transmitted (Fig. 4d). Still, the peak spectral density remains orders of magnitude higher than for SASE (see inset) and has an integrated pulse energy on the hundred microjoule level, making it perfectly suitable for the demonstrator.

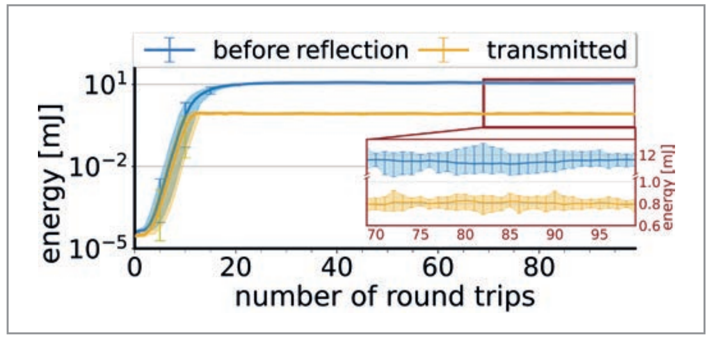

Figure 3

Evolution of the circulating and transmitted X-ray pulse energy as a function of the number of cavity round trips, showing exponential gain

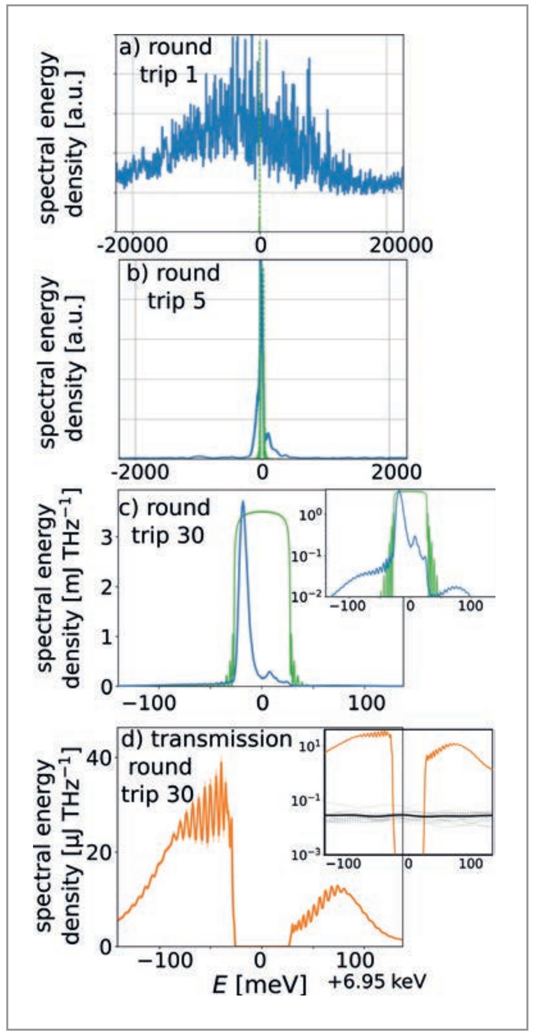

Figure 4

(a–c) Spectral representation of the X-ray pulse before reflection for different numbers of round trips (1, 5 and 30, respectively). The blue line denotes the X-ray field spectrum and the green line the crystal reflectivity. (d) Transmitted X-ray pulse in saturation. In the inset, the spectral energy density of a typical SASE pulse is shown on a logarithmic scale for reference.

Status and outlook

By the end of winter maintenance period 2023/24, the undulator cell 33 of the SASE1 beamline was shifted to the beginning of the line and replaced with a magnetic chicane. The up- and downstream diamond crystals in their respective vacuum chambers and their high-precision mechanic stages were also installed, allowing for the required very precise movement accuracy. To enable the transverse alignment of the X-ray pulse in the cavity, two diagnostic stations with fluorescent YAG screens and a scientific 10 Hz camera were added to the beamline inside the cavity. Using these components, first tests will be carried out, including transverse calibration of the crystals and probing the stability of the cavity. The KB mirrors and the linear movement stage for the matching of the cavity length will be installed in the summer maintenance period 2024. These installations can then be used to prove seeding in an X-ray cavity for the first time.

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APPLE-X undulator radiation study

Ensuring safe operation of the European XFEL APPLE-X undulators

At the European XFEL X-ray laser, the SASE3 soft X-ray beamline can provide photons with energies ranging from 300 eV to 3 keV. These photons are linearly polarised in the horizontal plane, fixed by the orientation of the tuneable-gap undulators. During the winter shutdown 2021/22, four stations of APPLE-X undulators had been installed downstream of SASE3 as an afterburner to be able to control the polarisation of the X-ray beam. The APPLE-X undulators could also be operated in combination with the current SASE3 undulator for harmonic lasing and for the generation of photons carrying orbital angular momentum. Although first lasing of the APPLE-X undulators was achieved quickly during commissioning, radiation-related problems also appeared.

Radiation issues of the APPLE-X undulators

First lasing with the APPLE-X undulators (Fig. 1, left) was achieved in April 2022. Shortly after the first lasing, however, errors began to occur in the readings of the linear and rotary encoders (Fig. 1, right), which provide the position of the magnetic structures and movers. In addition, the radiation level measured by the radiation monitor (Radfet) in the area of the APPLE-X undulators was 100 times higher than in the SASE3 planar undulator. It was suspected that the encoders were damaged by spontaneous synchrotron radiation from the planar undulator. To prevent further damage, it was decided to take out all the APPLE-X undulators from the tunnel during the summer shutdown 2022. After the removal of the undulators, the damaged linear encoders were replaced and the damaged motors were sent for repair. Fortunately, magnetic measurements did not reveal any damage to the permanent magnets. In the meantime, simulation and experimental studies were carried out to understand the cause of the radiation damage and plan possible mitigation measures to allow the reinstallation of the APPLE-X undulators.

Simulation and measurement results

Simulations were performed using the BDSIM tracking code with the initial photon distribution calculated with SPECTRA [1]. Radiation dose rate measurements were made using the MARWIN robot, which can be driven along the accelerator tunnel, equipped with a PANDORA box radiation detector system. The measurements and simulation results showed that the encoders were most likely damaged by back-scattered high-energy photons from the absorbers,

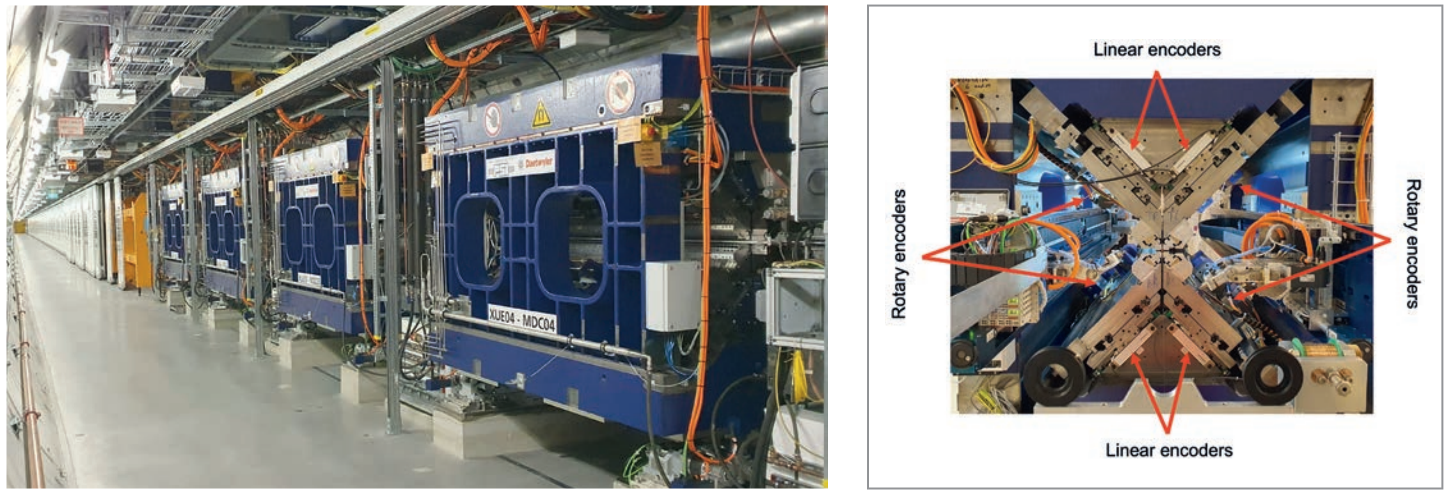

Figure 1

Left: APPLE-X undulators installed downstream of SASE3. Right: Location of the encoders on the APPLE-X undulators. Linear encoders are situated on the downstream side of the undulators, around 30 cm away from the electron beam. Rotary encoders are mounted on the motors located on the sides of the undulators at a distance of 30–40 cm from the electron beam.

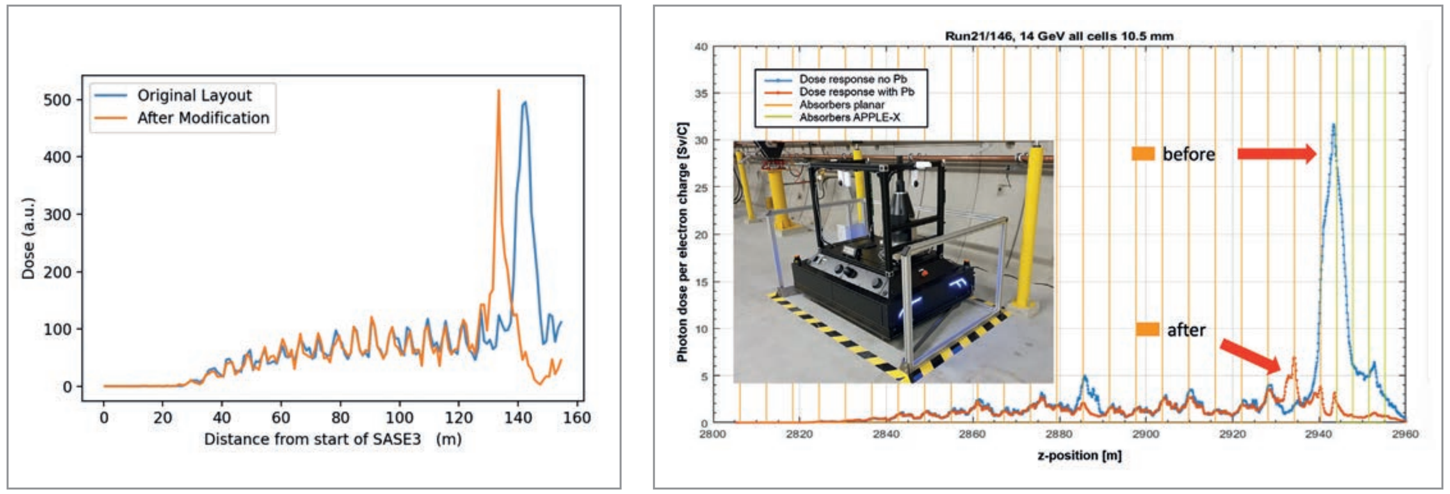

Figure 2

Simulation (left) and measurement (right) results before and after changing the aperture of the absorbers. In the simulation, no lead (Pb) shielding was added after the modification, which resulted in a higher radiation dose compared to the measurements.

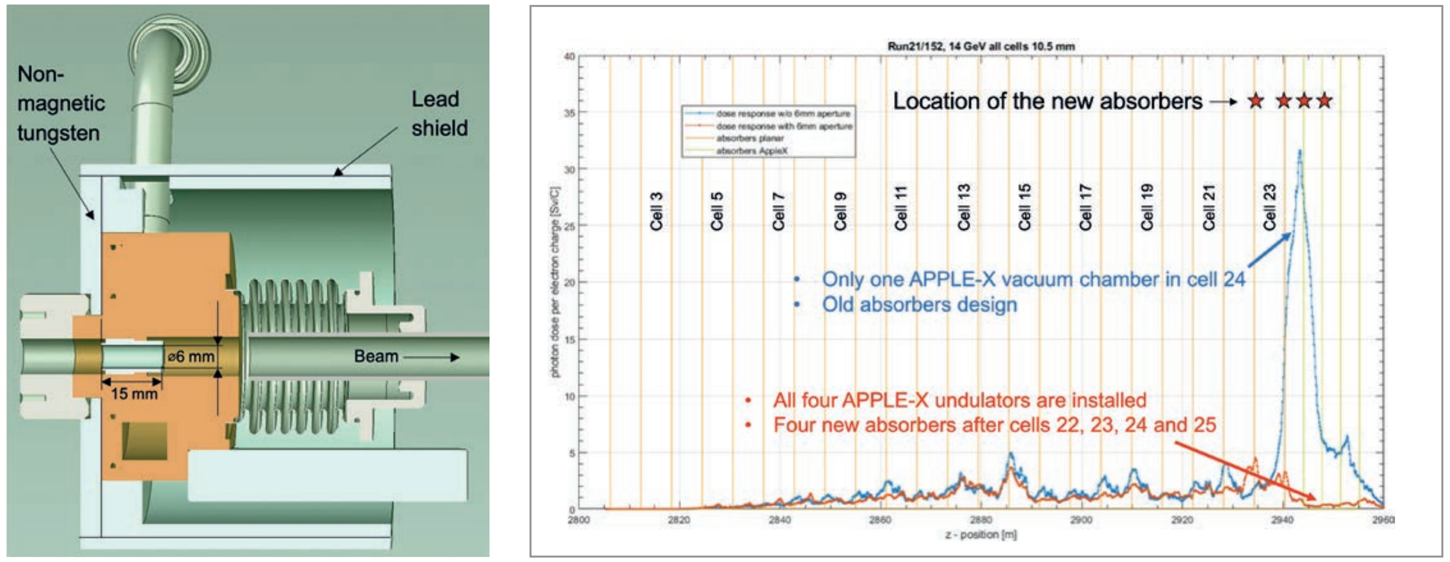

Figure 3

Left: Design of the new absorber. Right: Radiation dose measurements performed after reinstallation of the APPLE-X undulators.

which could be avoided by improving the design of the absorbers and by adding proper shielding to the components, e.g. using lead.

During the summer shutdown 2023, two absorbers with a diameter of 6 mm and a length of 15 mm were replaced behind the last two planar undulators of SASE3. An additional 3 mm thick temporary lead shielding was fitted around these absorbers. Afterwards, the radiation measurements showed a reduction in radiation by a factor of 10 (Fig. 2).

Upgrade of absorber design and reinstallation of the APPLE-X undulators

To further improve the situation, two additional absorbers of a new design (Fig. 3, left) were installed in the area of the APPLE-X undulators during the winter shutdown 2023/24. In addition, the linear and rotary encoders of the undulators were covered with a lead shield, and all absorbers in the SASE3 tunnel were equipped with protective shields made of lead and non-magnetic tungsten. Afterwards, all four APPLE-X undulators were reinstalled in the tunnel. Recent measurements of the radiation dose after reinstallation showed a reduction in radiation dose by a factor of 100 (Fig. 3, right) compared to the radiation dose from four vacuum chambers without modified absorbers.

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Magnetic flux expulsion and trapping

Impact of external magnetic fields on the performance of superconducting accelerators

Optimum performance of superconducting accelerator cavities is achieved by proper surface cleaning, but also by heat treatments of the cavities prior to their installation in the linear accelerator. Reaching ever lower cryogenic losses is desirable, as this enables improved accelerator performance at potentially lower operation costs. New methods for cavity preparation are therefore being developed, which require detailed studies and measurements of cavities under realistic operating conditions. One aspect is the presence of external magnetic fields. As part of a PhD project, a dedicated measurement system using a large number of magnetometric sensors was developed and commissioned. Initial results are already available.

Negative impact of magnetic fields

Medium temperature (mid-T) heat treatments at about 300 °C are used to reduce thermal losses, i.e. enhance the intrinsic quality factor of superconducting radio frequency (SRF) cavities. Unfortunately, such treatments potentially increase the sensitivity to trapped magnetic flux and consequently the surface resistance of the cavity. For this reason, it is crucial to maximise the expulsion of magnetic flux during cooldown. In addition to the heat treatment, the flux expulsion behaviour is mainly determined by the crystallographic structure and defects of the niobium material. However, it is also affected by the parameters of the cavity performance tests, such as the cooldown velocity, the spatial temperature gradient along the cavity surface and the magnetic flux density during the critical-temperature transition.

To improve the flux expulsion behaviour and hence the efficiency of future accelerator facilities, the impact of these adjustable parameters and of the mid-T heat treatment on 1.3 GHz TESLA-type single-cell cavities is being investigated using a new magnetometric mapping system approach, which was developed as part of a PhD thesis project. The system is based on previous work published by Helmholtz-Zentrum Berlin (HZB) [1].

Figure 1 shows the experimental setup: A superconducting single-cell cavity (here 1DE26) is surrounded by 23 magnetic sensor boards and one board for the thermocouples to control the cooldown velocity (using sensor Temp. 2) and the spatial temperature gradient ((Temp. 1 – Temp. 3) / sensor distance). Two heaters mounted on the cavity's upper and lower drift tube are used to adjust and control

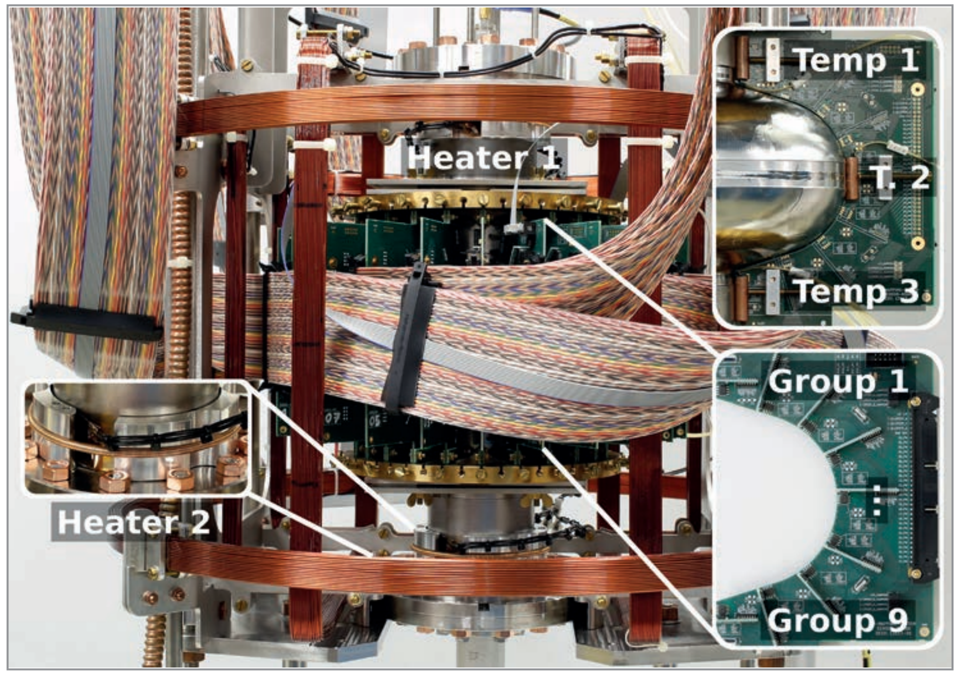

Figure 1

View into a vertical test stand for superconducting cavities. A single-cell niobium cavity is located in the centre, surrounded by a large number of electronic boards, each equipped with magnetic sensors (nine groups) or thermocouples. The complete setup is cooled in a vertical dewar using liquid helium. The cavity performance (accelerating field and thermal losses) is measured at 2 K together with a magnetic field mapping performed using the installed sensors of the system.

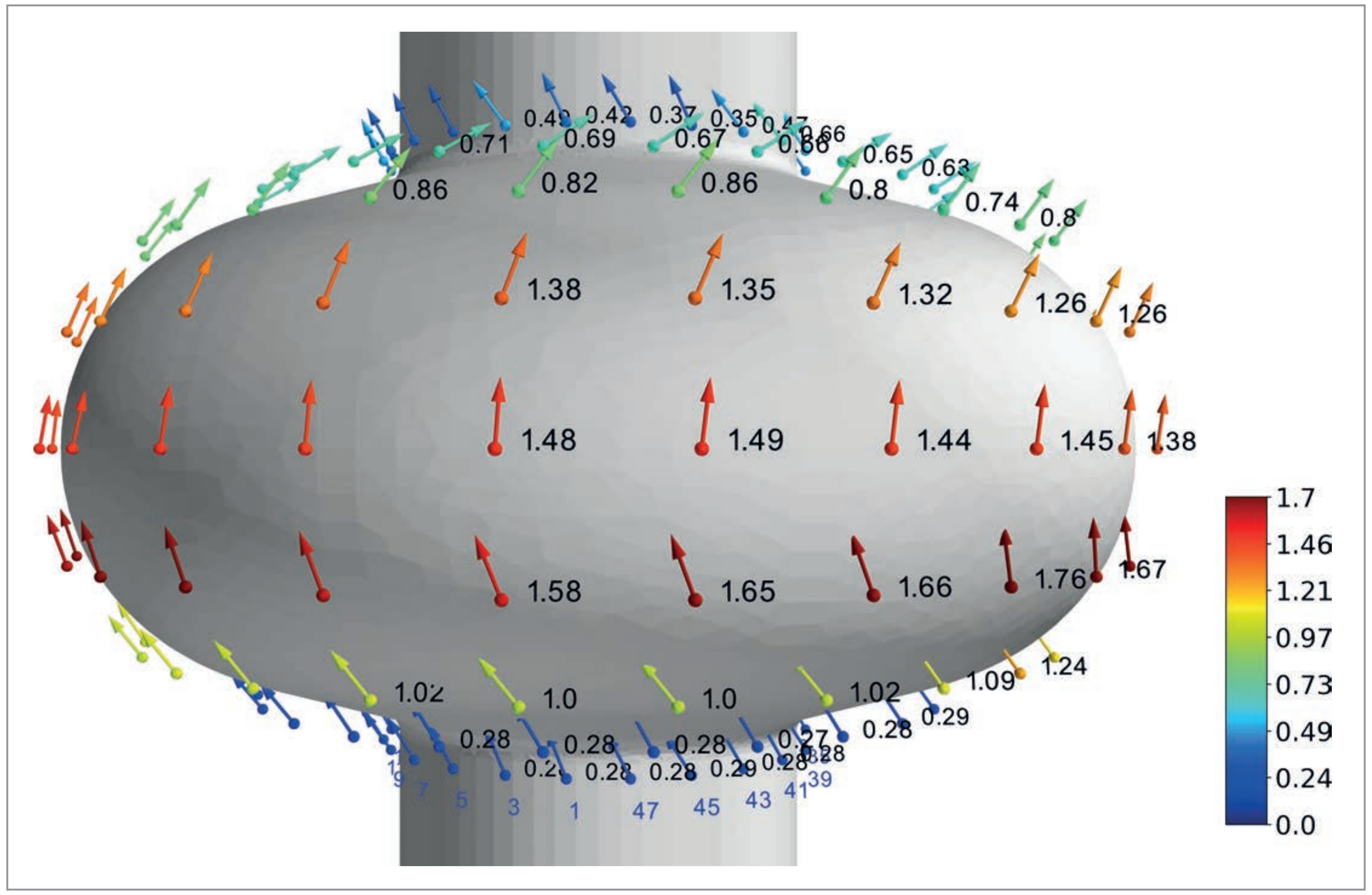

Figure 2

Magnetic flux distribution snapshot of the cavity 1DE26 recorded before mid-T heat treatment in the superconducting state for a cooldown velocity of -5 K/h and a spatial temperature gradient of 4 K over the complete cavity cell. The given numbers indicate the fraction of magnetic flux expelled. An inclined transition from the normal-conducting to the superconducting state of the cavity material at 9.2 K led to an asymmetrical magnetic flux expulsion.

the temperature gradient. The large number of magnetic sensors (27 per board) makes it possible, to a certain extent, to detect grain-boundary-dependent differences in flux expulsion behaviour as well as the potential formation of normal-conducting "islands".

To study the impact of the cooldown velocity on flux expulsion, a well-defined procedure was developed that includes the cooldown of the entire insert to 2 K prior to the actual measurement. Fixing the initial conditions is necessary in order to take into account the temperature dependence of the permeability of the local magnetic shielding. During the flux expulsion measurement, the target temperature is reached by varying the helium pressure and controlling it using the local heaters. The coils (copper wires) visible in Fig. 1 are used to apply a defined magnetic field during cooldown.

After commissioning of the setup, first measurements were started in 2023 (Fig. 2). No significant changes in the flux expulsion behaviour related to the cooldown velocity or the mid-T heat treatment were noted. However, an extensive dependence of the used spatial temperature gradient on the flux expulsion behaviour could be observed. In all cases, a higher temperature gradient was linked to an improved expulsion of magnetic flux. The sensitivity to trapped magnetic flux increased by a factor of 5 from 3.1 nΩ/μT to 15.7 nΩ/μT for the higher temperature gradient and from 3.5 nΩ/μT to 17.7 nΩ/μT for the lower temperature gradient after mid-T heat treatment.

Consequently, it can be concluded that only the sensitivity to trapped magnetic flux increases due to the heat treatment and that the flux expulsion behaviour of cavities made of large-grain material likely remains unaffected. More details were published in [2] and will finally be documented in Jonas Wolff's PhD thesis in 2024.

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FLASH2020+

Between the shutdowns

The FLASH2020+ project consists of a series of upgrades to DESY's FLASH free-electron laser (FEL) facility that will enable new, eagerly anticipated beam properties in the soft X-ray regime for next-generation user experiments. Most of the upgrades are concentrated in two long shutdown periods to ensure the availability of the facility for users, reduce the overall downtime and gain experience with operation. The shutdown 2021/22 focused on improving the linear accelerator and enabled user experiments to be conducted already in 2023 while simultaneously commissioning and tweaking the properties of the electron bunches to fully support externally seeded operation. The upcoming shutdown 2024/25 will be fully devoted to implementing a new externally seeded FLASH1 beamline. Additional parts of the project, to be realised after 2025, will further broaden the facility portfolio and make it possible to tackle an even wider range of scientific problems of our time.

Project progress

With the successful upgrades of the last shutdown, the accelerator now features a broader accessible energy range with improved control and beam quality. This has already been of benefit to various user experiments in 2023. While the new accelerator modules ACC2&3 performed as expected directly after the shutdown, the old modules have now also been brought up to their design gradient. This has enabled stable operation of the facility again, with energies of even more than 1.35 GeV and thus delivery of photon wavelengths of 3.43 nm and below in the fundamental. To increase the performance of the beams even more, the newly added laser heater makes it possible to mitigate the so-called microbunching instability and thus achieve a more homogeneous electron beam with minimised sliced energy spread arriving at the undulators.

The combined benefit of these two upgrades is an integral part of e.g. generating the shortest possible FEL pulses. To this end, a small fraction of the original electron beam is prepared for lasing by means of a scheme that uses a reverse taper and a short undulator section. Pulses as short as 1.26 fs [1] have been measured and backed by simulations. With minor changes in the settings and further tweaking, even shorter pulse durations on the attosecond level are expected at FLASH. A complementary approach, which uses sophisticated bunch modification based on a two-laser-pulse scheme in the laser heater, pursued by the ErUM-Pro project FLARE, is currently also being investigated and has led to promising first results.

For operation with multiple electron bunches at MHz repetition rate, as is standard at FLASH, the newly added fast orbit correctors have successfully demonstrated that they enable the manipulation of existing intra-bunch-train trajectory deviations and, most importantly, substantially reduce them. This benefits self-amplified spontaneous emission (SASE) operation and is a necessity for future seeded operation in order to achieve a stable overlap between electrons and seed laser and generate stable photon pulses with percent-level intensity.

Regarding installations, two valuable additions were made to the FLASH facility in 2023: an afterburner in the FLASH2 beamline and new photoinjector lasers. Owing to the pandemic and the geopolitical situation, various components of the afterburner, which was originally also planned for installation in the last shutdown, had been delayed. Through sophisticated scheduling of experiments in 2023, a dedicated installation slot could be generated to facilitate the afterburner installation in the FLASH2 tunnel while FLASH1 was operated for users at the same time – thus maximising the scientific output of the facility. In a series of commissioning shifts, the afterburner, which is delicate to set up and benefits greatly from the upgrades made to the linear accelerator, was first put into operation at longer wavelengths. Since then, continuous development toward operation at 1.4 nm wavelength (much shorter than what FLASH can conventionally generate in the fundamental) has been ongoing, ensuring the delivery of the requested beam parameters for two scheduled short-wavelength user experiments in 2024.

In addition to shortest wavelengths, the afterburner also allows for adjustable polarisation of the emerging photon pulses. While the polarisation can in fact be continuously adjusted by sliding half of the undulator magnet structure in the propagation direction of the electron beam, commissioning focused on preparing four distinct polarisation states – linear horizontal and vertical as well as circular left and right – which were successfully demonstrated with only minor impurities. While this was already a great success, the reduction of the impure components down to noise level is subject to further commissioning.

Thanks to tremendous efforts by a large number of people across the DESY campus in parallel to commissioning, preparations for the next shutdown are progressing as planned. The machine design for the new FLASH1 beamline is finished. The full CAD model of the beamline, e.g. the complex seeding section as displayed in Fig. 1, is nearing completion with only a few open points. The latter are being reduced on a weekly basis, thanks to the great support of everyone involved. The continuous stream of components, fabricated both externally and on site, is being processed internally at DESY using specially developed procedures to enable fast and timely installation, as prepared to meticulous detail in the shutdown plan. The shutdown will result in a new FLASH1 beamline optimised for externally seeded operation by means of high-gain and echo-enabled harmonic generation (HGHG and EEHG, respectively). The unique beam properties will facilitate the next generation of user experiments, for which community-wide planning has started.

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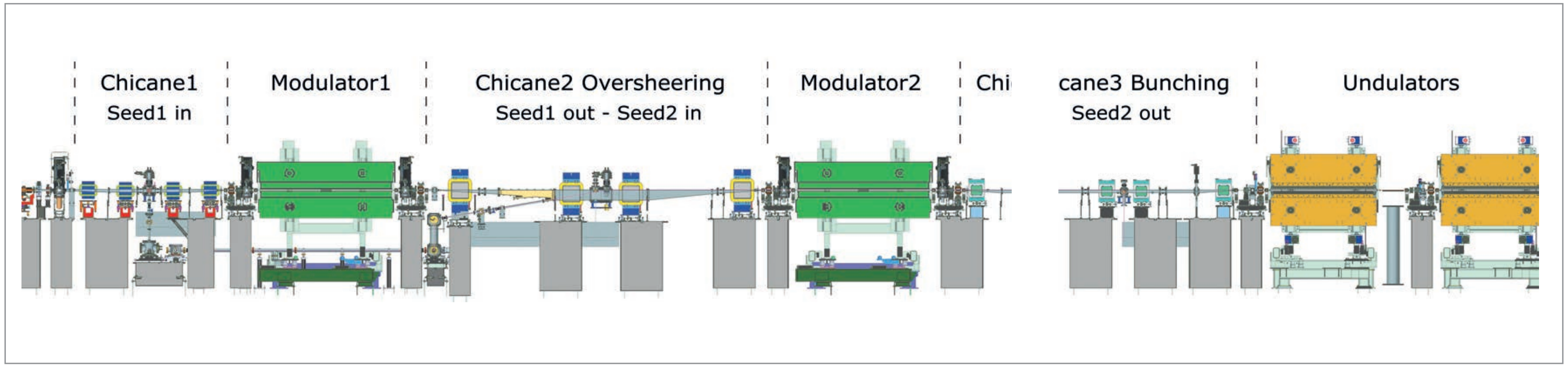

Figure 1
Excerpt from the full CAD model of the new FLASH1 beamline, showing the seeding section with the electron and laser beam propagating from left to right. The seeding section consists of three chicanes and two modulators to prepare a bunched electron beam so as to efficiently generate stable soft X-ray beams in the downstream undulators, two of which are displayed on the right. For shortest wavelengths, echo-enabled harmonic generation (EEHG) is used, where a laser beam is coupled in within the first chicane to be overlapped with the electron beam in the first modulator (green). Here, energy from the laser is transferred to the electron beam. The second chicane makes it possible to remove the first laser, couple in a fresh laser beam and simultaneously redistribute the energy-modulated electron beam to generate multiple slices with low energy spread. In the second modulator, a sinusoidal energy modulation is imprinted on the electron beam by the laser. Finally, in the third chicane, a very subtle rearrangement of the beam "bunches" the electron beam, meaning that sharp current spikes develop in the beam propagation direction. These spikes then allow for very stable lasing in the subsequent radiators (orange).

Xseed demonstrates EEHG seeding

Critical milestone towards FLASH2020+

External seeding via echo-enabled harmonic generation has been established for the first time at DESY's FLASH facility. This is a major step towards external seeding as foreseen in the FLASH2020+ upgrade, achieved thanks to the considerable effort of the Xseed team and the support of many FLASH experts. Compared to standard self-amplified spontaneous emission (SASE) operation, the spectral quality and the longitudinal coherence of the generated photon beam are drastically improved and will ultimately enable the next generation of user experiments.

Introduction

Single-pass free-electron lasers (FELs) can deliver high-power femtosecond pulses in the extreme-ultraviolet (XUV) and X-ray spectral regions. Moreover, they are characterised by a high degree of coherence, offering the opportunity to combine the advantages of X-ray sources and lasers. The FEL process can be initiated by the density noise that is naturally present in the electron beam distribution, producing SASE. The SASE process is inherently stochastic and characterised by poor longitudinal coherence.

Another possibility is to seed the FEL process using an external seed laser and generate radiation at harmonics of the seed laser wavelength itself, either through the high-gain harmonic generation (HGHG) scheme [1], in which a seed laser is overlapped with the electron beam in a single stage, or through a more complex two-stage process known as echo-enabled harmonic generation (EEHG) [2], in which two seed lasers are used to carefully tailor the longitudinal phase space of the electron beam by means of magnetic chicanes. Both seeding techniques can be used to generate highly stable and reproducible FEL pulses with laser-like longitudinal coherence, reduced bandwidth and constant central wavelength. However, the pulses generated with EEHG generally offer better photon beam performance, especially at higher harmonics.

First EEHG at FLASH

In March 2023, the FLASH seeding team succeeded for the first time in demonstrating EEHG seeding at a dedicated setup installed in front of the main undulator of the FLASH1 beamline. In parallel to the FLASH1 seeding operation, the FLASH2 beamline was set up to deliver SASE radiation at 30 nm with intensities above 100 µJ and an excellent transverse mode (Fig. 1e). This is a world first in parallel operation and a crucial milestone, as it demonstrates the feasibility and efficacy of the future FLASH operational concept. The requirements placed on the electron beam for seeding and SASE operation are very different. The team took full advantage of FLASH's flexibility and tuned the properties of the electron beam differently for FLASH1 and FLASH2.

Comparison of the radiation properties

Seeded radiation is only possible at an integer harmonic of the seed laser wavelength. While various harmonics have been investigated, the examples presented here are all from the 12th harmonic at 22.1 nm, as displayed in Fig. 1, where EEHG and HGHG performance are compared. Figure 1a shows a comparison of the average spectrum for HGHG and EEHG when lasing at 22.1 nm (h = 12), together with an example of single-shot spectra, as well as false-colour plots of 30 consecutive normalised spectra for EEHG (b) and for HGHG (c). The stability of the spectral bandwidth for 90 shots for EEHG and HGHG is also shown (d).

At these wavelengths, an improvement by a factor of 2 can be seen for EEHG compared to HGHG. In addition, Fig. 1 also shows a comparison of the spectral properties – the spectral intensity (f), the central wavelength (g) and the bandwidth (h) – as a function of the dispersive section strength for EEHG and HGHG. Here again, the improvement in the central wavelength stability of EEHG compared to HGHG is evident. Compared to SASE, both seeding techniques offer significantly improved stability and reproducibility and provide photon beams of superior quality for future user experiments.

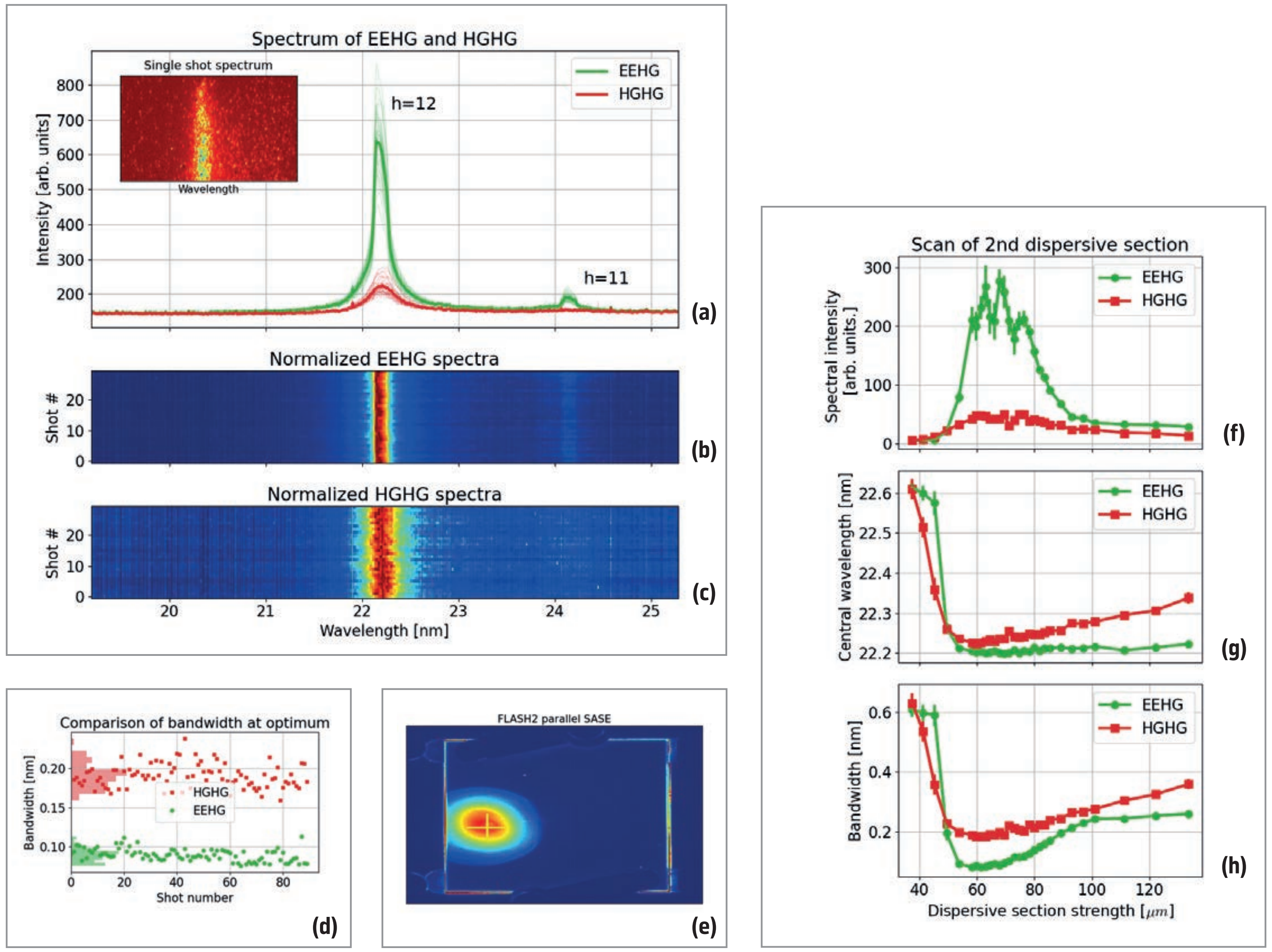

Figure 1

Parallel operation of seeded FLASH1 together with SASE in FLASH2. (a) Comparison of the average spectrum for HGHG and EEHG when lasing at 22.1 nm (h = 12). The inset shows an example of a single-shot spectrum in false colours. (b, c) Single-shot spectra shown in narrower lines for 30 consecutive shots and in false-colour scale. (d) Comparison of the spectral bandwidth stability for 90 shots for EEHG and HGHG. Here, the beamline was optimised for EEHG, hence the relatively larger bandwidth and reduced spectral intensity of HGHG compared to EEHG (see also: a). (e) Transverse mode for SASE radiation at 30 nm with about 100 µJ pulse energy. (f, g, h) Comparison of the spectral properties – intensity (f), central wavelength (g) and bandwidth (h) – as a function of the dispersive section strength for EEHG and HGHG.

Reproducibility of the setup and next steps

One week after the first demonstration, the Xseed team was able to re-establish the EEHG seeding conditions within four hours after accelerator maintenance. In this case, the signal was optimised at the 15th harmonic of the seed laser, which corresponds to seeded radiation at 17.8 nm. Among other things, this time two electron bunches were distributed on the FLASH1 beamline, mimicking the shortest possible bunch train. This is a crucial step on the way to FLASH2020+, where it is planned to seed bunch trains with up to 500 bunches at MHz repetition rate.

In the following months, the team improved the operational procedures, achieved seeding under different machine conditions, e.g. at higher electron beam energies, and explored seeding in parallel to FLASH2 photon delivery for users. The experience gained during these experiments will be crucial for the commissioning and operation of the new seeded FLASH1 beamline as part of the FLASH2020+ project, which will be installed during the upcoming shutdown and should provide "first light" before the end of 2025.

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Data-driven FEL quality and coherence control

Highlights of simulation studies and sustainable software development for FLASH2020+

The simulation team of the FLASH2020+ project has made considerable progress in its studies and sustainable software development in 2023. Integrating comprehensive and easily expandable simulation tools to enhance start-to-end simulation-based research capabilities was central to our initial efforts. The more recent focus and ongoing activities are now directed at creating a synthetic data set designed to augment experimental data and facilitate coherent control studies. This achievement will be significant for FLASH after its upgrade to FLASH2020+. Our developments are underpinned by a commitment to sustainable software practices, ensuring efficiency and long-term usability.

Sustainable and user-centric simulation strategies for FLASH2020+

The coherence properties of a free-electron laser (FEL) are critical to the sharpness and clarity of the images and data it produces, much like a high-resolution camera captures finer images than its standard counterpart. Echo-enabled harmonic generation (EEHG) allows for high flexibility and precision in adjusting the spatial and temporal coherence. The seeding section's unique interaction involves two crucial modulation and dispersion stages for generating high-harmonic content. The quality of the FEL light hinges on the precise synchronisation and alignment of the laser and electron beam, which requires meticulous control of these parameters.

In preparation for the FLASH shutdown in 2024, we are harnessing our experimental expertise, simulation resources and data insights to evaluate and enhance the coherence and overall quality of the future seeded FEL. This approach has led to two significant outcomes: the development of the Genesis Elegant Interfacing Simulation Toolset (GEIST) and the creation of extensive and reusable data sets that model the chirped electron beam of FLASH and its interaction with the Seed1 and Seed2 lasers in the designed FEL beamline, incorporating predicted beamline tolerances. This approach prepares us for exploring potential advancements in FLASH's capabilities and performance.

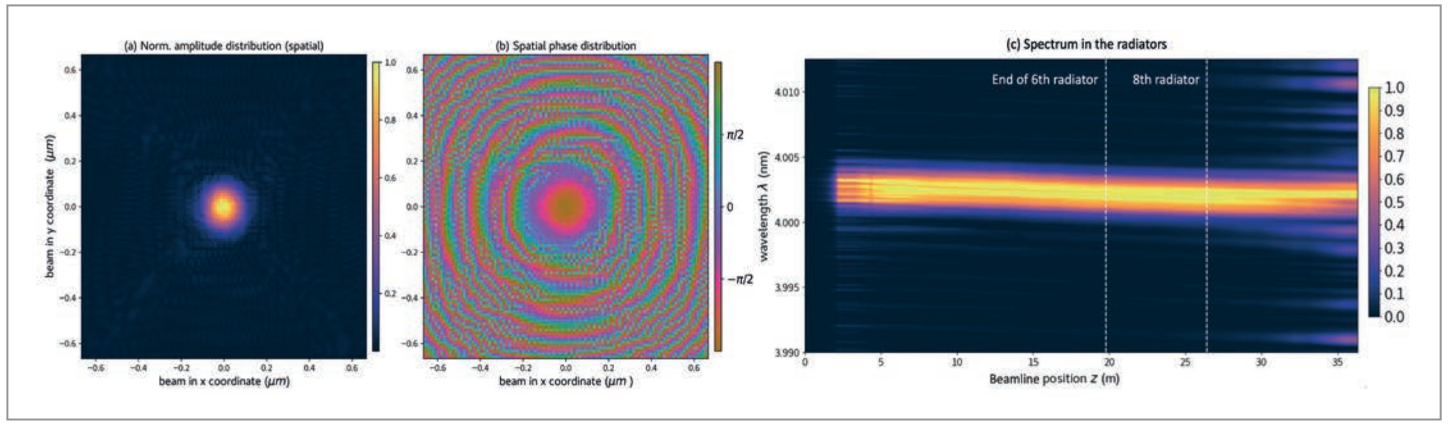

Figure 1

Transverse field (spatial) and longitudinal (temporal) properties of a simulation optimised for a 1.35 GeV electron beam with a chirp of 19 MeV per picosecond (highest value foreseen for the chirp at FLASH) with tapered circularly polarised radiators. (a) Amplitude and (b) phase of the projected FEL field after the sixth radiator. (c) Evolution of the spectrum along the beamline.

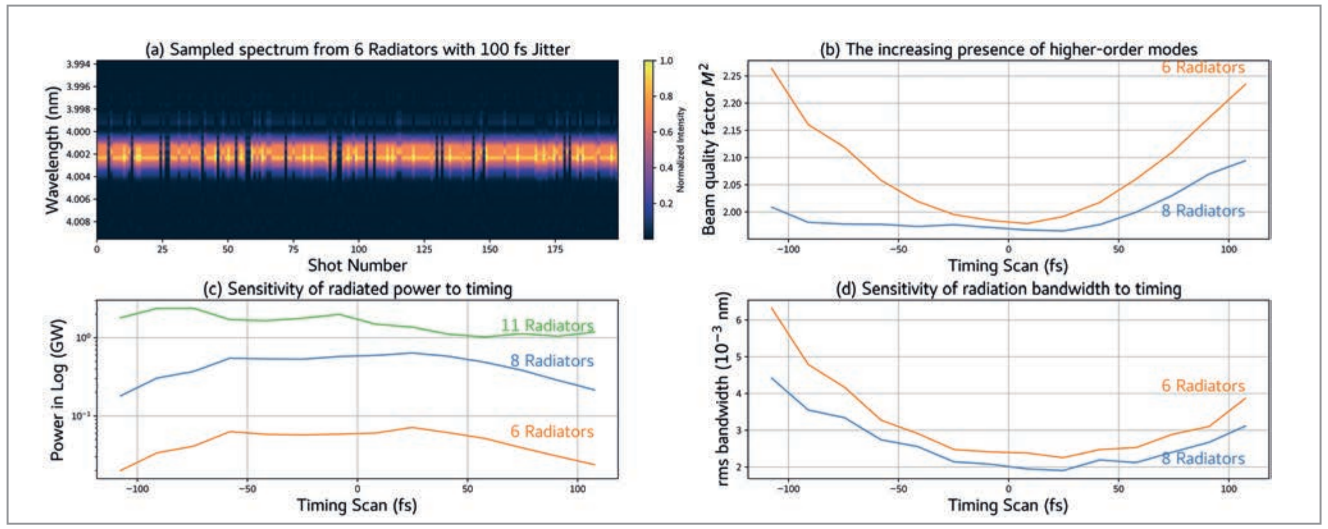

Figure 2

Example tolerance study data set. The optimised working point corresponds to a 1.35 GeV electron beam with linear chirp. (a) Photon beam spectra for 100 random samples. A shift in the central wavelength can be seen, which is due to the different beam energies involved in the FEL process. (b) Impact of timing on the transverse quality factor (M^2) of the beam: As the quality factor increases, the FEL beam is composed of more transverse modes with higher divergence. (c, d) Illustration of the impact of timing changes on the spectral properties power (c) and bandwidth (d).

Optimising for EEHG at FLASH

One of the unique features of FLASH is the capability to supply electron beams with tailored properties to the FLASH1 and FLASH2 beamlines simultaneously, enabling parallel self-amplified spontaneous emission (SASE) and seeded operation. This versatility requires optimising the seeding section for an electron beam characterised by linear energy variation in time (chirp). The optimisation of the EEHG process is then a delicate balance of bandwidth against power.

Fine-tuning the dispersion of the second chicane mitigates overbunching and, when combined with adequate tapering, enables us to achieve output powers around 1 GW for 4 nm wavelength when an undulator chain composed of 11 undulators is considered. However, this optimisation can lead to a bandwidth broadening by a factor of 2 above the Fourier limit. Reducing the energy of the Seed2 laser narrows the bandwidth while simultaneously reducing the modulation amplitude in the second stage. This reduces the output power at high harmonics, e.g. for 4 nm (75th harmonic).

As mentioned above, the optimisation was performed for the final FLASH2020+ design, featuring 11 radiators. In Phase 0, i.e. "first light" operation after the 2024 shutdown, fewer undulators are planned. To ensure the success of the FLASH2020+ "first light", our optimisation efforts have prioritised the FEL beam quality, focusing on bandwidth and coherence, reducing the presence of higher-order modes. As illustrated in Fig. 1, this optimisation results in a beam with high transverse coherence and a bandwidth that is 1.7 and 1.6 times the Fourier limit after passing through six and eight radiators, respectively, yielding reduced power in the range of hundreds of megawatts.

Sensitivity to timing jitter

Precise synchronisation and alignment of the laser and electron beam are essential to the EEHG setup. Several parameter scans were therefore performed at each optimised working point to investigate the tolerance of the setup to machine fluctuations. An example is shown in Fig. 2, which illustrates the effects of timing jitter between laser and electron beam on an EEHG setup over a range of 200 fs. This is the worst-case scenario, as we expect the synchronisation performance to be on the order of tens of femtoseconds. The data were generated for helical radiators in circular polarisation, where a beam quality factor of 2 is due to the inherent helical features of the Gauss Laguerre modes.

Figure 2a shows a random sampling of the 15 timing points in (b–d), revealing a frequent shift of the central wavelength due to the different electron beam energies involved in the FEL process. Figures 2b and 2d show that the setup can tolerate a maximum of 60 fs mismatch in timing, especially with only six radiators. When power is the most critical metric, Fig. 2c suggests that the setup is more forgiving and can tolerate 100 fs of timing variation.

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FLASH accelerator modules

High-gradient operation of refurbished FLASH accelerator modules

One of the main goals of the FLASH2020+ upgrade project at DESY was to increase the electron beam energy of the FLASH facility to 1.3 GeV. Two accelerator modules were therefore replaced in 2022. The new accelerator modules, which were installed with a specially adapted, well-tailored waveguide radio frequency (RF) power distribution to achieve highest total energy, have successfully met the energy upgrade goal. After commissioning and proper tuning, both modules are being operated routinely. Since May 2023, this enhancement has noticeably improved user operations, with the modules running at nearly 250 MeV each.

New accelerator modules for FLASH

The FLASH linear accelerator uses superconducting radio frequency (SRF) accelerator modules developed by the TESLA Collaboration. Currently, seven of these cryomodules are installed in different sections separated by warm beamlines. Each of the cryomodules houses eight SRF cavities, which were all qualified in vertical test cryostats in the Accelerator Module Test Facility (AMTF) at DESY. For the FLASH2020+ upgrade, two prototype modules were refurbished. Following successful testing, again in the AMTF, the modules PXM2.1 and PXM3.1 are now installed in the positions ACC2 and ACC3, right between the bunch compressors shown in Fig. 1. The unprecedented energy gain is 400 MeV for both modules.

RF test results

Cryomodule tests are performed in pulsed operation mode, and the maximum and operational gradient limits as well as the limitation mechanism of the individual cavities are determined (Fig. 3). Three cases can be distinguished: thermal or magnetic breakdown (BD, quench) with $E_{acc.oper} = (E_{max} - 0.5$ MV/m), field emission (FE, with measured gamma radiation value above a threshold of 10^{-2} mGy/min, measured at one of the cryomodule ends), and reaching the RF power limit (PWR).

Commissioning and operation of the new accelerator modules

The cryomodules were installed with a specially adapted, well-tailored waveguide RF power distribution to achieve highest total energy. The adaptation is required as all 16 SRF cavities are fed by one single RF station. After conditioning of the SRF cavities, both modules (ACC2&3) met the FLASH beam energy upgrade goal of 200 + 200 MeV. The RF station could be operated up to a set point of 450 MeV, with routine operation at 400 to 450 MV since October 2022.

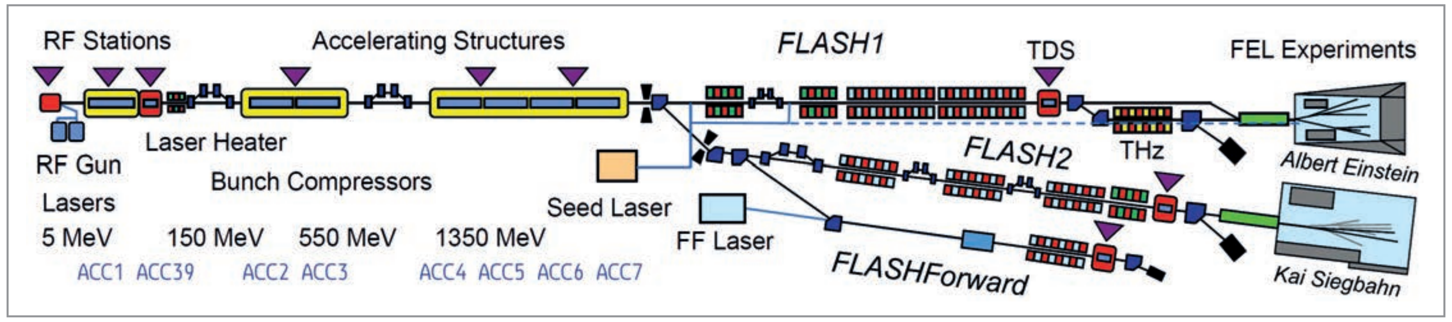

Figure 1
FLASH facility layout after the upgrade in 2022

Figure 2
Module PXM3.1 (ACC3) installed in FLASH in 2022

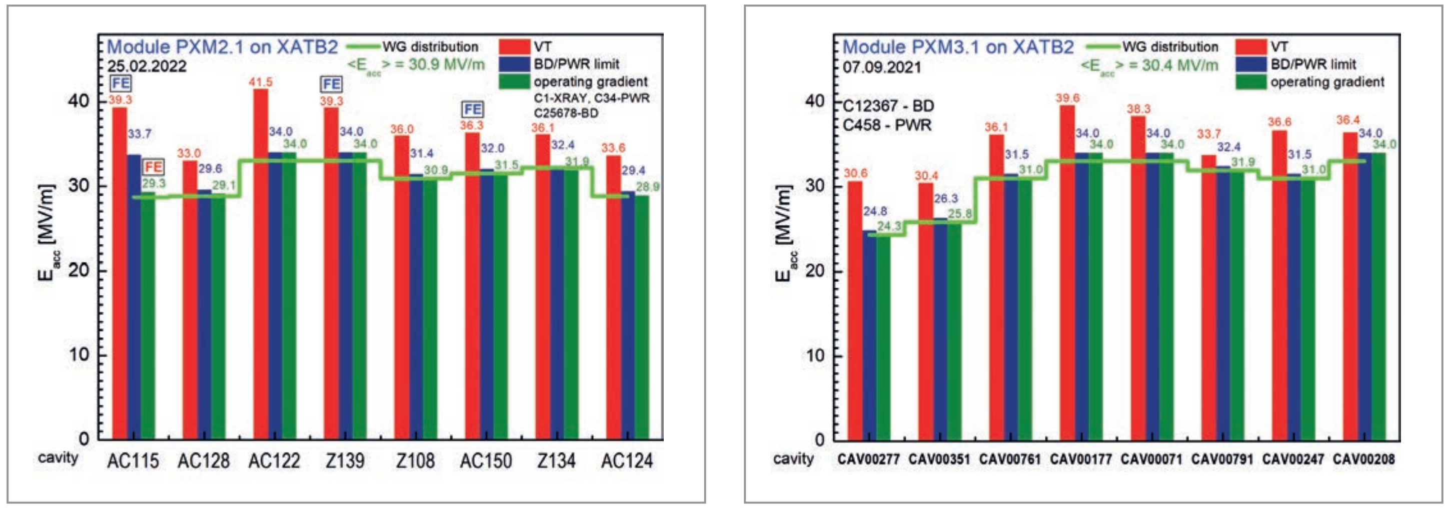

Figure 3
PXM2.1 and PXM3.1 cavities: Comparison of maximum gradients in vertical tests (VT, red) and cryomodule tests (blue). The operating gradient is indicated in green; the green line gives the gradients with an adapted RF power waveguide distribution.

Figure 4
FLASH ACC2&3 RF station set point operating history from September to December 2023

Figure 4 shows the operation history during the last quarter of 2023. Before the replacement of the cryomodules, ACC2&3 were operated at ~300 MeV, so the two renewed modules contribute to increasing the maximum electron beam energy of FLASH to 1.3 GeV. Since May 2023, user operation has visibly benefited from this increase. The beam operation of the two modules close to 250 MeV each is unique worldwide and comparable to the European XFEL.

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Shortest wavelength with variable polarisation at FLASH2

Amplification of the third harmonic and control of polarisation using an APPLE-III undulator

To generate extreme-ultraviolet (XUV) and soft X-ray radiation with tuneable polarisation at the third harmonic of the main undulator wavelength of the FLASH2 beamline, an additional APPLE-III type undulator was installed downstream adjacent to the FLASH2 self-amplified spontaneous emission (SASE) undulator section. This afterburner allows the wavelength range to be extended down to 1.33 nm so that the L-edges of iron, cobalt and nickel can be reached at FLASH2. It also serves as a full-scale prototype for the FLASH2020+ seeding radiators to be installed in the FLASH1 beamline. After installation and commissioning, amplification of the third harmonic and generation of different polarisations have been demonstrated.

Introduction

Undulators are magnetic structures that force an electron bunch, aligned along the undulator axis, to radiate photons of a certain wavelength along that axis. The most simple – planar, horizontal – undulators consist of two long stretches of alternating strong permanent magnets above and below the beamline that produce vertically oriented dipoles of alternating polarity along the axis, which make the electrons inside the bunch "wiggle" periodically from left to right and back. Seen from the front of the undulator onto the beam direction, the wiggling bunch resembles a horizontally oscillating Hertzian dipole that radiates horizontally polarised light. When certain conditions on the bunch are met, the free-electron laser (FEL) instability creates a substructure of FEL-microbunches in the incoming bunch. These FEL-microbunch structures have a characteristic length comparable to the radiation wavelength. As a consequence, the electrons contained in these FEL-microbunches radiate coherently, i.e. with a pulse energy that is proportional to the square of the number of electrons involved rather than proportional to their plain number. In saturation, this easily produces an energy enhancement of several orders of magnitude and explains the high pulse energies delivered by FEL sources.

However, the FEL process involves more than just the linear theory and planar undulators. Firstly, the non-linearity of the FEL-microbunching process also creates higher-order (mostly odd) harmonics in the bunching. When a well FEL-microbunched bunch enters a subsequent undulator, called the afterburner, which is tuned to a higher harmonic, e.g. the third one, the bunch will radiate at a three times shorter wavelength with enhanced pulse energy. Secondly, modern undulators, such as the APPLE-III, may contain more sophisticated magnetic structures that make it possible (mostly by mechanically shifting parts of the magnets) to vary the wiggling plane of the electrons, thereby enabling variable planar polarisation, and/or even to transform the planar wiggling into a corkscrew-like helical trajectory that produces circularly polarised light. Many experiments benefit from controllable polarisation achieved in this manner.

Figure 1

Installed APPLE-III undulator

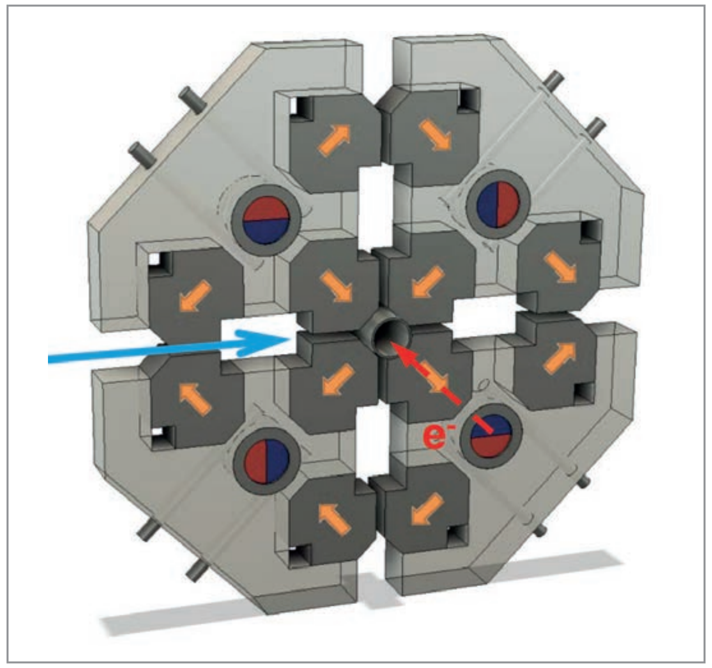

Figure 2

Different segments of the APPLE-III undulator

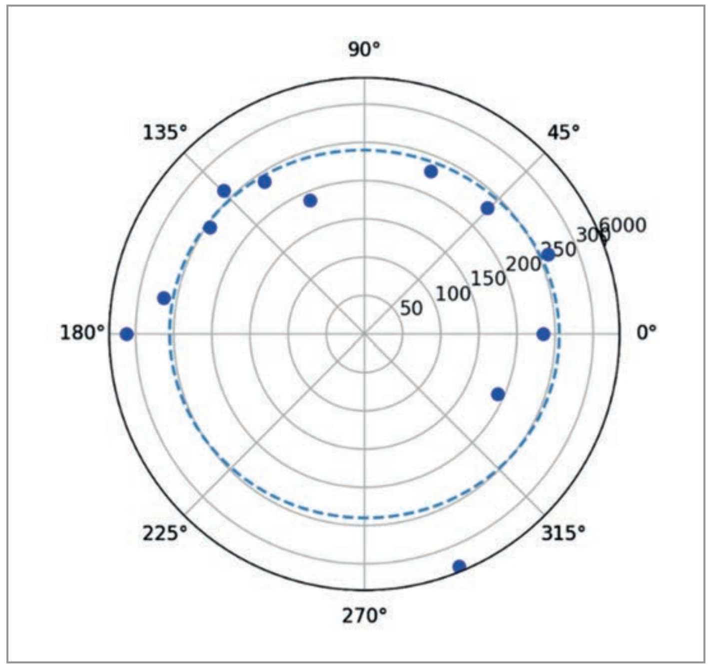

Figure 3

Measurement with the "ballchamber" when the APPLE-III undulator was set up for circular polarisation

APPLE-III undulators at FLASH

The FLASH2020+ upgrade project includes the installation of a tuneable afterburner undulator with variable polarisation at the end of the undulator section of the FLASH2 beamline. FLASH2 has 12 planar, horizontal, variable-gap undulators used to accommodate the FEL process in SASE mode. The undulator located at the downstream end of the section had been moved towards the upstream end to make room for the afterburner in the shutdown 2021/22, the first of two shutdowns for FLASH2020+. The afterburner was then installed during a one-week-long FLASH2 shutdown in September 2023.

The afterburner for FLASH2 was designed as an APPLE-III undulator. The magnet structure of an APPLE-III undulator consists of four permanent magnet arrays. The period length of the APPLE-III undulator at FLASH is 17.5 mm. It contains 20 x 20 mm^2 NdFeB magnets with cut-outs and clipped edge. The undulator can be closed to a very small gap. The vacuum chamber (the beampipe) inside the afterburner is therefore extremely fragile and only has a small free aperture for the beam. The inner aperture is round with a diameter of 6 mm, and the diamond-shaped chamber has a side length of 7 mm, resulting in a minimum wall thickness of 0.5 mm. To stabilise the extremely fragile chamber, thin metal plates are attached to it, which reach through the undulator gap towards a massive aluminium beam that supports the chamber with an accuracy of better than 0.5 mm over 2.40 m. Figure 1 shows the opened APPLE-III afterburner undulator in its position as the last of the FLASH2 undulators, with the support for the undulator vacuum chamber. The different segments of the undulator can be seen in Fig. 2.

Commissioning of the afterburner undulator and first measurement results

A first measurement was performed in parallel with FLASH1 user operation at a beam energy of 430 MeV. The main FLASH2 undulator was set up for lasing at a wavelength of 45.6 nm, and a strong increase in the intensity of the third harmonic was observed on a spectrometer when the afterburner was tuned to the appropriate undulator gap. Control of the polarisation of the FEL radiation was demonstrated using an angle-resolving spectrometer setup, called the "ballchamber" [1]. Figure 3 shows a polar plot of a measurement carried out with the APPLE-III undulator tuned for circular polarisation. Each blue dot represents the measurement of one spectrometer. Setting up the afterburner for different polarisation clearly changed the intensities at different angles.

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Beating the coherence time

New method for generating ultrashort pulses in XUV and X-ray FELs successfully tested

Ultrashort pulses generated by free-electron lasers (FELs) have revolutionised various fields of science and technology. Researchers can now observe and control phenomena such as electron movements, chemical reactions and phase transitions with unprecedented temporal resolution. The pulse duration in short-pulse schemes for self-amplified spontaneous emission (SASE) FELs is limited by the so-called FEL coherence time. However, a recently proposed concept makes it possible to overcome the coherence time barrier and generate much shorter pulses.

Challenges in generating sub-femtosecond pulses in SASE FELs

The possibilities to generate few- and sub-femtosecond pulses in extreme ultraviolet (XUV) and X-ray FELs have been studied theoretically over the last 20 years, and experimental demonstration of the production of sub-femtosecond FEL laser pulses was recently achieved at different facilities. For SASE FELs, the shortest pulses that can typically be generated are limited by the FEL coherence time. This longitudinal coherence of the photon pulses is formed due to slippage effects in the undulators, where the emitted electromagnetic wave advances the electron beam by one wavelength while the electron beam passes one undulator period. Thus, the coherence time is given by the slippage of the radiation with respect to the electron beam on the scale of the FEL gain length.

Proposed methodology to overcome coherence time limitations

A method to beat the coherence time limit in SASE FELs was proposed in [1]. In a first step, one can create a short lasing slice – much shorter than the FEL coherence time – within the electron bunch. Due to the SASE process in the long main undulator, a microbunching, i.e. a density modulation at the resonance wavelength, is generated within that short slice. However, the radiation pulse is still much longer – on the order of the coherence time – due to the mentioned slippage in the undulator. In a second step, the modulated electron bunch produces a short radiation pulse in a short radiator, while the long radiation pulse from the main undulator is suppressed or separated from the short pulse. Different methods of suppression (separation) are discussed in [1], one of them being the application of an excessive reverse taper in the main undulator. In fact, strong reverse undulator taper is used to suppress the radiation in the main undulator while keeping the microbunching as suggested in [2].

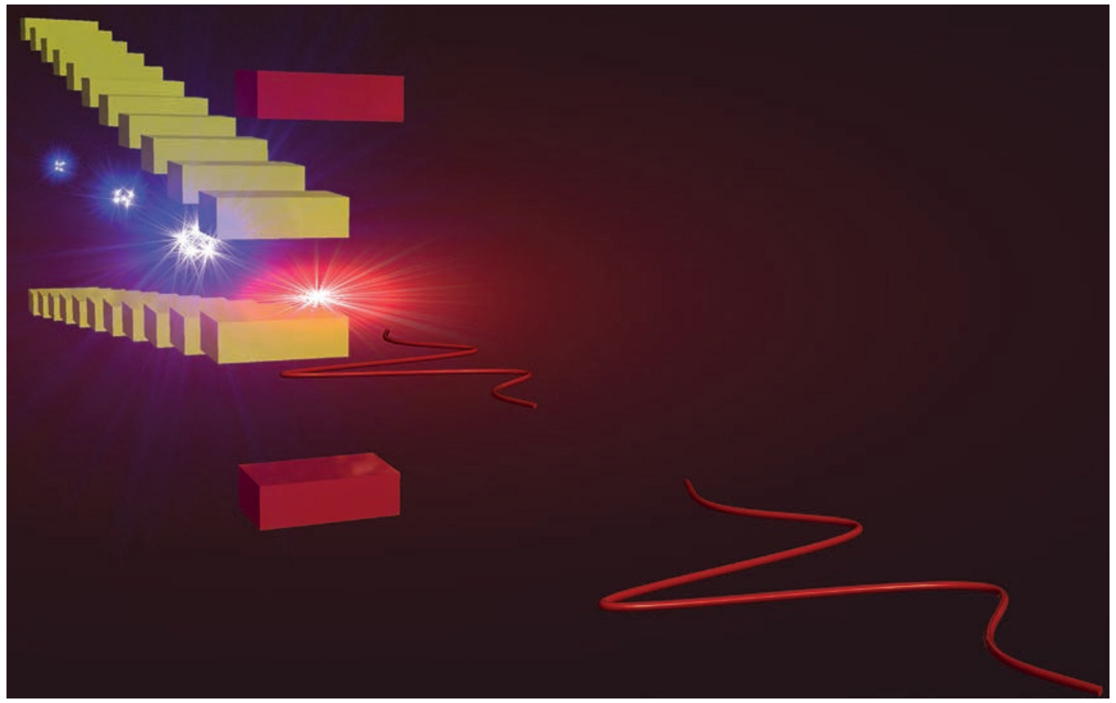

Figure 1
Schematic illustration of the new short-pulse scheme. The gaps of the magnetic segments of the undulator structure are decreasing along the undulator length, which changes the resonance conditions for the SASE lasing process. In this way, the long radiation pulse is suppressed, while the microbunching within the electron bunch is maintained. The last undulator segment – called the radiator – is then tuned to resonance with the incoming microbunching, resulting in the emission of ultrashort pulses that are not limited by the coherence time.

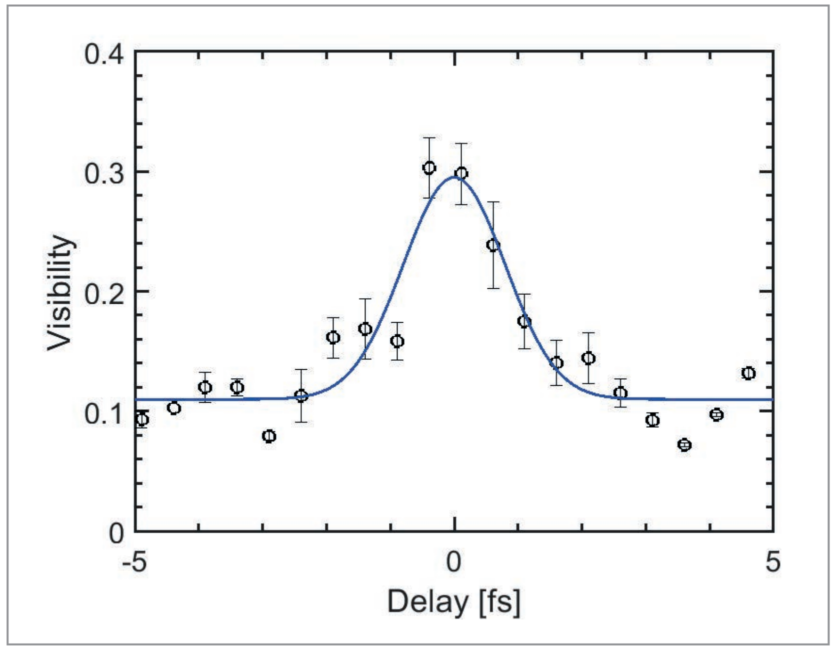

Figure 2
Field autocorrelation (AC) trace. The change in the interference fringes depends on the delay of the two overlapping photon pulses created using the split-and-delay unit at FLASH2. In the case of single-spike SASE pulses, the width of the AC trace is directly related to the photon pulse duration. The conversion factor was determined by modelling and leads to a measured photon pulse duration of 1.26 ± 0.37 fs.

Experimental implementation and validation at FLASH2

The scheme is illustrated in Fig. 1. The main undulator consists of many segments (shown in yellow), the gaps of which are decreasing along the undulator length, i.e. the undulator parameter *K* is increasing. The ultrashort radiation pulse is produced in a short radiator (shown in red), tuned to resonance with the incoming microbunching.

The experimental test of this concept was performed at the FLASH2 beamline of DESY's soft X-ray FEL user facility FLASH. The electron energy was 1.2 GeV, and the FEL wavelength was set to 5 nm. A photoinjector laser with 1 ps pulse duration was used to generate an electron bunch with a charge of 80 pC. Non-linear compression was applied to the electron bunch in order to generate a short high-current leading peak for the production of ultrashort photon pulses. The gap-tuneable undulator of FLASH2 consists of 12 segments. First, single-spike operation of a SASE FEL in standard configuration was established, where only one longitudinal spectral mode is generated (this was validated at the FLASH2 spectrometer). Then, the following configuration was applied: The first 11 undulator segments were strongly reverse-tapered, while the 12th segment played the role of the radiator. To effectively reduce its length – and thus the length of the radiated photon pulse – an ambient field correction coil was activated to steer the beam inside the radiator.

The photon pulse duration was measured with the autocorrelation method. The split-and-delay unit at the beamline FL24 [3] with a time resolution of 120 attoseconds was used to spatially split the incoming FEL beam into two partial beams. The two split beams were recombined spatially and temporally on a screen at the beamline focus, creating interference fringes. By scanning the delay and measuring the visibility of the fringes, one can measure the field autocorrelation, which is shown in Fig. 2 [4]. The full width at half maximum (FWHM) of this trace is 1.88 ± 0.21 fs. Based on extensive FEL modelling of the generation process, a conversion coefficient of 0.67 to the FWHM of the pulse intensity distribution was obtained. Thus, the estimated photon pulse duration was 1.26 ± 0.37 fs, and the measured pulse energy was 1.5 μJ at a wavelength of 5 nm. This pulse duration of close to 1 fs FWHM sets a new record for FELs operating at this wavelength. The short gigawatt-level pulses with a potentially high repetition rate (up to several thousand pulses per second) can make FLASH a unique source within its wavelength range.

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Short FEL pulse generation by laser heating at FLASH

FEL pulse length control by tailoring the energy distribution of electron bunches with a laser heater

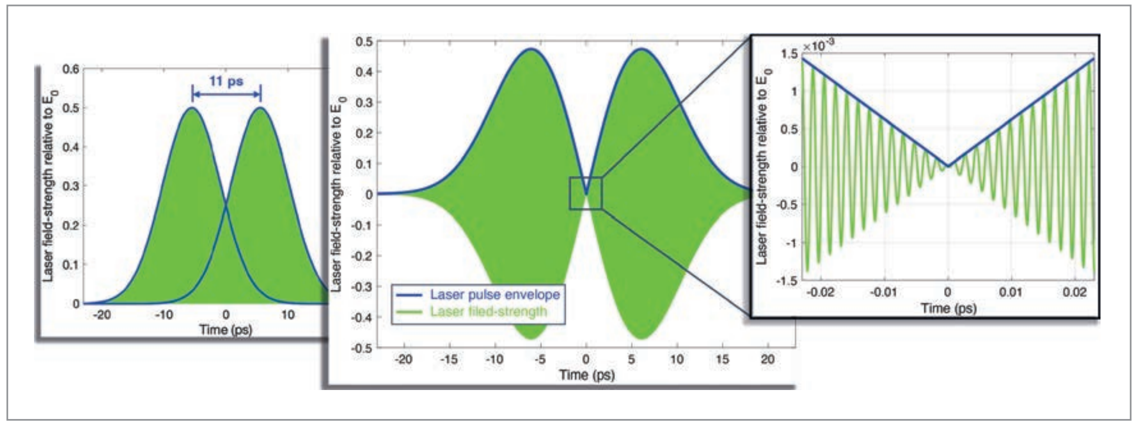

Figure 2
Left: Two laser pulses separated in the interferometer by 11 ps (without interference effect). Centre: Recombined laser pulse at destructive interference (i.e. the laser pulses have a phase difference of 180°). Right: Centre region enlarged to resolve individual laser wavelengths.

FLASH Laser-Assisted Reshaping of Electron bunches, or FLARE for short, is a project funded by the German Federal Ministry of Education and Research (BMBF) and carried out in collaboration with TU Dortmund University. FLARE investigates possible electron beam manipulation schemes using a laser heater to facilitate the generation of short FEL pulses at DESY's free-electron laser (FEL) facility FLASH. One scheme is based on partial overheating, where the FEL process is limited to a short longitudinal region of the electron bunch while the rest of the bunch is heated to such a degree that FEL amplification is suppressed. As the longitudinal structure of an electron bunch is directly inherited from the laser field that drives the heating process, partial overheating can be achieved by means of adequately shaped laser pulses in the laser heater.

Impact of laser heating on FEL performance

A laser heater was recently installed in the injector of FLASH [1]. The laser heater is used to intentionally "heat" the beam, i.e. to increase the uncorrelated energy spread of the electron bunches. Depending on the amount of additional energy spread, the resulting impact on the electron bunch and FEL performance can differ significantly. A small amount of heating is generally beneficial, as it suppresses the microbunching instability (MBI), which can otherwise lead to fragmentation of the longitudinal phase space and thus to an increase of the energy spread before the electron bunch reaches the FEL undulators. Hence, suppression of MBI can improve the FEL performance. On the other hand, if the bunch is "overheated", i.e. too much energy spread is added by the laser heater, both the MBI and the FEL process – which is itself a longitudinal instability – are suppressed. As the amount of heating can be controlled through the laser power, the laser heater makes it possible to directly influence the FEL process.

Tailoring of the FEL process

The FLARE project investigates two schemes that use the laser heater at FLASH to facilitate short FEL pulse generation by means of longitudinal phase space manipulation of the electron bunches. To that end, an interferometer was added to the laser heater: The initial laser pulse is separated into two pulses, which are then recombined with a certain time delay (Δt) (Fig. 1). The resulting laser pulse is then overlapped with the electron bunch in the undulator, where the electron bunch acquires a longitudinal energy modulation at the wavelength of the laser pulse (532 nm). This optical-scale energy modulation is then smeared out by the longitudinal dispersion of the subsequent bunch compression chicane, which leads to an energy spread distribution that mimics the envelope of the electric field strength of the recombined laser pulse.

By tailoring the laser pulse envelope, partial overheating can be achieved, where the FEL process is limited to a short, "cooler" region of an otherwise overheated bunch [2] (Fig. 2). In the FLARE mode, the two laser pulses are separated in the interferometer by a time delay of about Δt = 11 ps and recombined with a phase difference of 180° of their carrier waves. This results in destructive interference in the region where both laser pulses overlap: The laser field envelope vanishes in the centre of the pulse, increases nearly linearly in a significant region around the centre and reaches the maxima at about half the initial laser field strength E_0. The enlarged part of the centre region in Fig. 2 (right) shows individual laser wavelengths (solid green line). For a sufficiently large laser field strength, this pulse structure leaves only a small gap where the imprinted energy spread is small enough so that the FEL process is not suppressed but rather enhanced. As the width of this gap depends on the optical path length difference and the laser field strength, these parameters can provide a fast and flexible way to tune the FEL pulse duration.

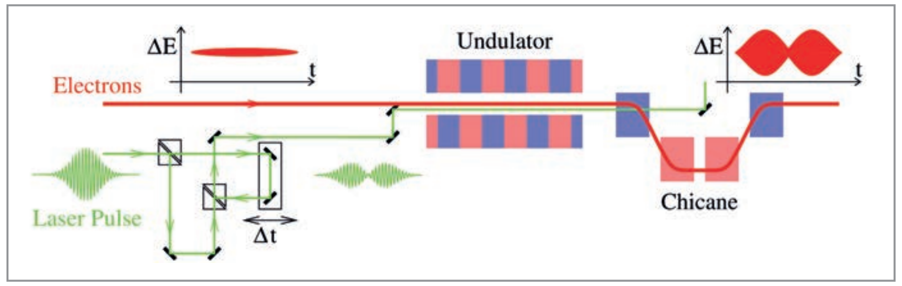

Figure 1
FLARE setup: An interferometer is used to control the shape of the laser pulse via the time delay (Δt) and thus the energy modulation that is transferred to the electron bunch in a undulator. This energy modulation is then transformed into an energy spread modulation in the subsequent chicane.

Time-resolved measurement

The effect of partial overheating has been studied with the transverse deflecting structure PolariX located downstream of the FEL undulators in the FLASH2 beamline. PolariX enables the measurement of the longitudinal phase space density, i.e. the energy distribution at all longitudinal positions (time axis) within the electron bunch, by observing the electron bunch on a view screen further downstream in a dispersive section. The beam images shown in Fig. 3 correspond to two such measurements of the longitudinal phase space density for two different settings of the laser heater.

When the laser heater shutter is closed (Fig. 3a), no heating occurs and most parts of the electron bunch clearly exhibit spikes in the longitudinal phase space, which can be attributed to the energy loss of the electrons in the FEL process. When the interferometer is set up in a configuration with two laser pulses in destructive interference (Fig. 3b) – the FLARE mode as described above – it becomes apparent that only a much shorter part of the bunch takes part in the FEL process, which clearly demonstrates the viability of the partial overheating scheme. For the measurements shown in Fig. 3, FLASH was intentionally operated in a regime where the FEL process is particularly susceptible to the overheating effect. The exact determination of the resulting FEL pulse durations from these measurements of the longitudinal phase space and a comparison with the results from THz streaking measurements are the subject of ongoing investigations.

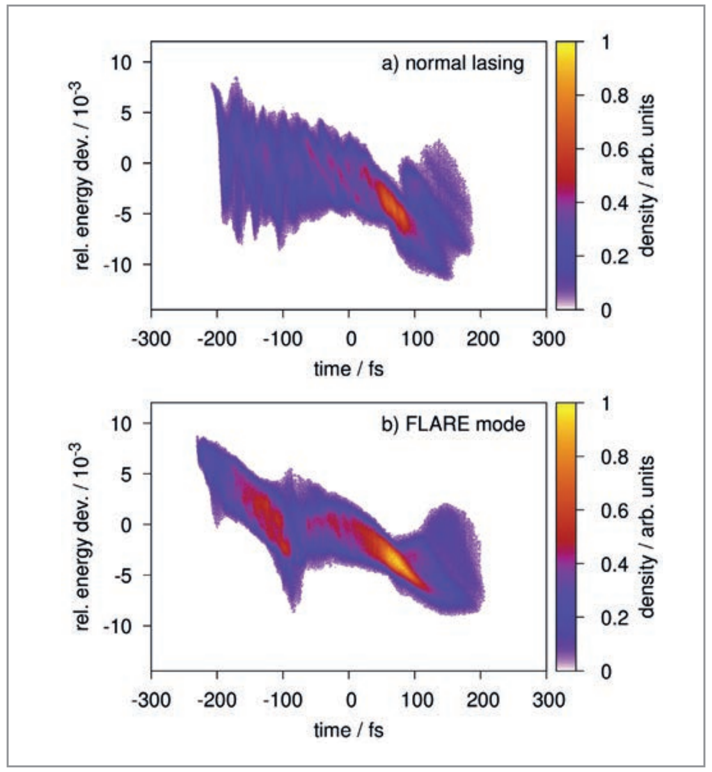

Figure 3
Measurements of the longitudinal phase space after the FLASH2 undulators: (a) Laser heater turned off: The spiky structure in the range from -200 fs to 0 fs is a strong indication for the FEL process. (b) Partial overheating with the FLARE setup: Suppression of the FEL process in a major part of the bunch. The characteristic spiky FEL structure is only present around -90 fs with a significantly reduced FEL pulse length.

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Discharge plasma development at DESY

Work in the ATHENA Discharge plasma deVelopment ANd Characterisation Experiments (ADVANCE) laboratory

Plasma sources are rapidly becoming an important tool in particle acceleration. They provide the acceleration medium for plasma wakefield accelerators, promising more compact, cost- and energy-efficient accelerators while also having applications in the focusing of charged particles through very strong, radially symmetric focusing fields. Although plasma sources can take many forms, one of the most experimentally successful sources is the capillary discharge cell. Such sources discharge a high-voltage current pulse through a thin capillary, typically made of sapphire. The pulse ionises the gas within the cell, generating a stable and longitudinally uniform plasma. To develop such discharge plasma cells, a dedicated infrastructure has been established at DESY in the form of the ATHENA Discharge plasma deVelopment ANd Characterisation Experiments (ADVANCE) laboratory.

The ADVANCE laboratory

Experiments with discharge plasmas require specific infrastructure and diagnostic systems to characterise the plasma. A versatile vacuum chamber and a pumping system capable of handling high gas load are essential for hosting the cells. High-voltage pulse modulators and various gas species are necessary for plasma generation, and high-resolution spectrometers and/or high-quality diagnostic lasers are required for plasma characterisation.

Basic investigations had been done at DESY in the laser plasma laboratory in Building 28m, but this quickly became unsustainable. The growing demand on the number of plasma sources and the required quality of investigation necessitated a dedicated test environment. The ADVANCE laboratory [1] was therefore established at DESY through collaborative efforts of different groups, with funding provided by the ATHENA project. The first plasma was produced in November 2021. Diagnostics and additional infrastructure in the form of various high-voltage pulsers were installed and commissioned throughout 2022 and 2023.

Plasma sources for wakefield acceleration at FLASHForward

One of the main fields of application for discharge plasma sources at DESY is the acceleration of particles in wakefields excited by a particle or laser beam driver in a plasma. The FLASHForward experiment [2] at DESY's FLASH free-electron laser operates mainly using plasma sources based on high-voltage discharges. To make use of the microsecond-spaced electron bunches the FLASH linear accelerator can generate, a plasma source was developed that is capable of providing identical plasma profiles at MHz repetition rates. The left picture in Fig. 1 shows such a high-repetition-rate plasma cell. Different cell designs were thoroughly characterised, paving the way for the installation of the depicted model in the FLASHForward beamline in 2023. First high-repetition-rate acceleration experiments with electron beams took place in July/August 2023, with very promising results, enabled by the reliable operation of the plasma source.

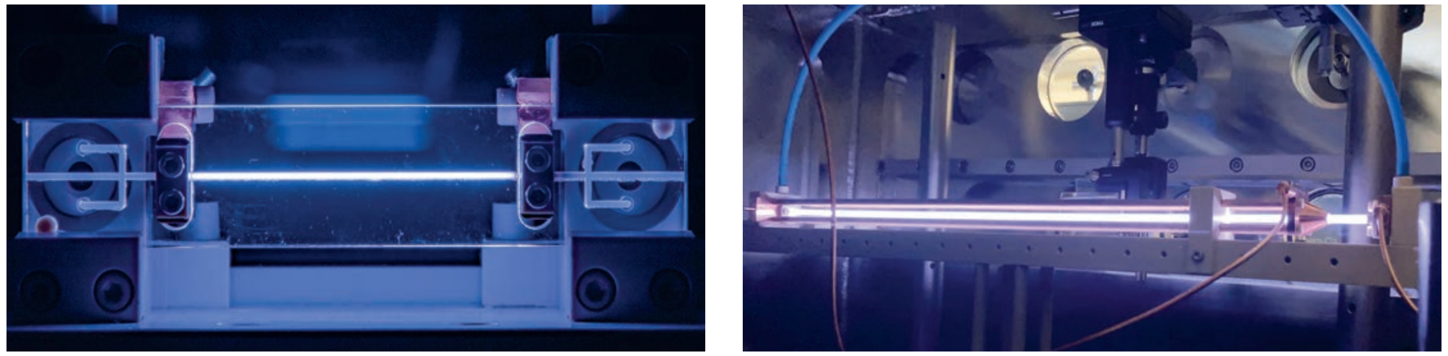

Figure 1

Plasma cells developed in the ADVANCE laboratory for the FLASHForward experiment. Left: Plasma cell optimised for operation at MHz repetition rates. The central plasma channel has a length of 50 mm. Right: 500 mm long plasma cell developed for large energy gain.

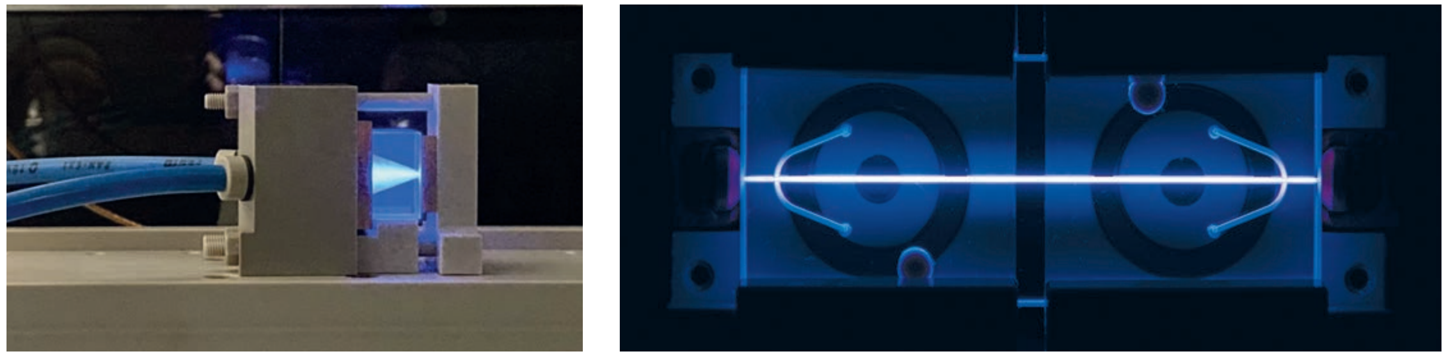

Figure 2

Left: Prototype of an active plasma lens for focusing highly divergent positron beams. Right: Discharge plasma for guiding light.

Another focus of the FLASHForward experiment is the demonstration of acceleration with a larger energy gain of the accelerated particles of hundreds of MeV while preserving the beam quality. As the acceleration gradient at FLASHForward is usually in the 1–2 GV/m range, plasma sources with metre-scale lengths are required. A first prototype of a 500 mm long plasma source was built and successfully tested in the ADVANCE laboratory, with first plasma achieved in November 2023 (Fig. 1, right). Stable plasma operation was achieved, and detailed optimisation of the cell design and its operational parameters is currently ongoing.

Active plasma lenses for positron focusing

Besides providing the plasma media for wakefield acceleration, plasmas can also be used to focus charged particle beams. By driving a current through a plasma during the passage of charged particles, the magnetic field of the current exerts symmetric focusing forces on the particles that are an order of magnitude higher than what is achievable with conventional focusing magnets. These properties of active plasma lenses allow for more compact focusing devices and can provide better beam quality. An interesting plasma lens application is the focusing and capture of strongly divergent positron beams generated in a converter target. For such purposes, a prototype plasma lens was designed and produced [3] in a collaboration between Universität Hamburg and DESY. A picture of the prototype, which is now being studied in the ADVANCE laboratory, is shown in Fig. 2 on the left.

Plasma cells for guiding light

Finally, discharge plasmas designed for guiding light have also been investigated in the ADVANCE laboratory. Due to the temperature gradient across the plasma, an inverse parabolic density profile is created, which establishes a parabolic refractive index profile. Such a profile is capable of guiding high-intensity light in a way similar to optical fibres. This technique has already proven to be very successful in laser-driven wakefield acceleration, as the guiding structure is able to both withstand and maintain the high laser intensity required for long acceleration lengths and high electron energies. The plasma cell shown in Fig. 2 on the right has a diameter of 500 µm and is being studied for such an application in collaboration with the Max Born Institute in Berlin.

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Tuning laser plasma accelerators

Fine-tuning LUX beam parameters with machine learning assistance

The inherent compactness of laser plasma accelerators introduces a complex challenge – a delicate balance of many tuning parameters is critical for optimal performance. Recent advancements at DESY's LUX experiment have highlighted the effectiveness of machine learning in navigating these complexities. By employing machine learning strategies, the LUX team has successfully identified tuning curves that enable precise control over electron beam parameters while maintaining good beam quality.

Controlling laser plasma accelerators

Laser plasma accelerators are maturing towards compact sources of relativistic electron beams. However, for these accelerators to successfully drive a wide array of applications, they must offer flexible control over an extensive range of beam parameters. The dynamics inside a laser plasma accelerator are inherently complex and exhibit high coupling among all parameters, meaning that adjustments to one beam property can have unforeseen effects on others. Specifically, fine-tuning one parameter, such as the charge, to a target value can unintentionally affect another, such as the energy spread, underscoring the critical need for a careful balance of all parameters of the laser–plasma interaction. Finding this balance is therefore an intricate task when manually operating a laser plasma accelerator.

To facilitate the identification of optimal tuning curves, the LUX team recently showcased the application of multi-objective Bayesian optimisation, a machine learning method [1].

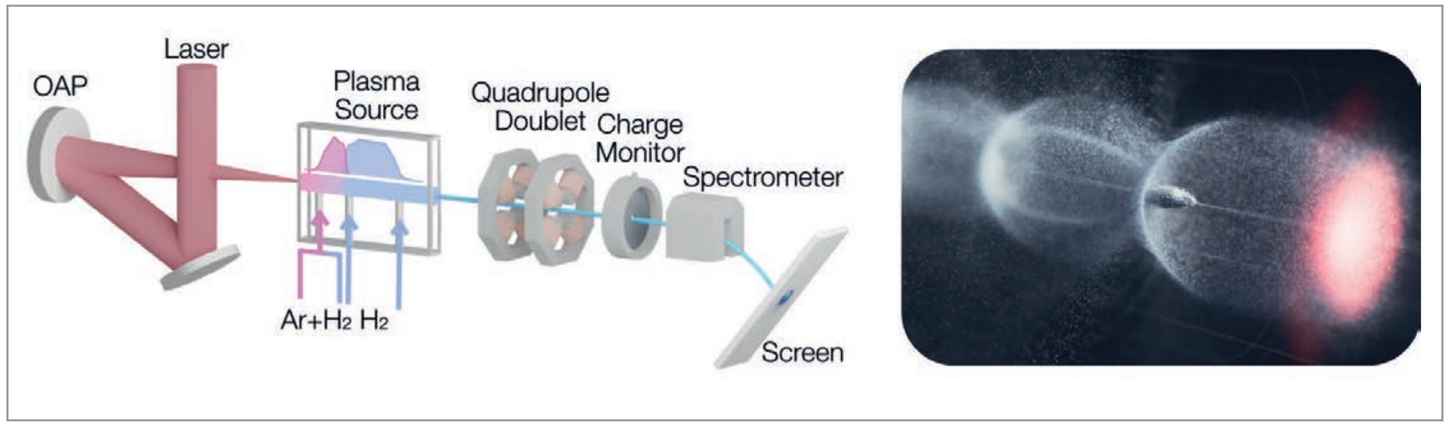

Figure 1

Schematic of the LUX accelerator (left) [2]: Laser pulses with 100 TW peak power are focused into a plasma source, where they drive a plasma wave (simulation on the right) and accelerate electron bunches to around 300 MeV. The accelerated electron bunches are focused into a set of diagnostics to measure, among other parameters, the charge and energy spectrum. To find optimal ways of tuning the beam parameters, the vast parameter space of the experiment is explored using a machine learning method called Bayesian optimisation. Adapted from [1] and Science Communication Lab [5].

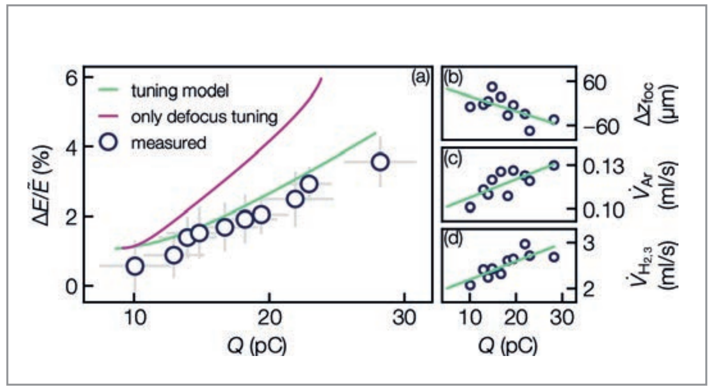

Figure 2

Tuning of the beam charge (left) at LUX, exploiting the tuning curve using the most relevant parameters (right) found through multi-objective Bayesian optimisation (green) and simple single-parameter tuning (red). Adapted from [1].

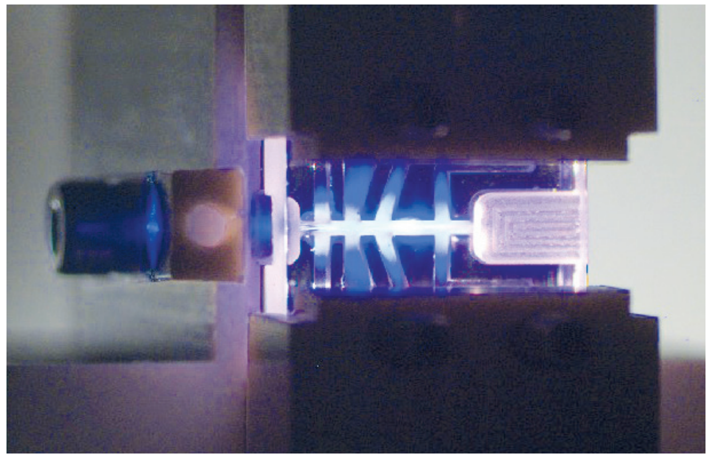

Figure 3

Plasma glow in the LUX plasma source

Finding optimal tuning curves

The LUX facility at DESY (partially shown in Fig. 1) provides extensive monitoring and control capabilities across a wide range of machine parameters and environmental conditions. This aspect of LUX is crucial for stable operation of the accelerator over extended periods [2]. Moreover, the comprehensive data sets generated at LUX enable the deployment of advanced machine learning methods to decode and fine-tune the complex dynamics between the laser and the plasma [3, 4].

One of these methods is Bayesian optimisation, which applies machine learning to create a model of the accelerator based on the collected measurement data. This model, continuously refined with new data, guides the subsequent exploration and optimisation of the machine.

Adopting this approach to simultaneously optimise multiple conflicting properties of the electron beam, the LUX team used Bayesian optimisation as a tool to identify machine configurations that increase the charge while ensuring that the energy spread remains as low as possible. To achieve this, the optimiser autonomously adjusted important parameters of the accelerator, such as the laser energy and focus position as well as the composition and distribution of the gas that forms the plasma. This strategy resulted in the discovery of various working points that cover a broad range of beam energies and charges, with minimal effect on the energy spread, as shown for example in Fig. 2. In a subsequent step, the discrete working points were generalised into continuous tuning curves. These now grant the machine operators precise control over the electron bunch parameters while providing optimal energy spread trade-offs.

With the current trend towards high-repetition-rate laser plasma accelerators, exemplified by DESY's KALDERA project [5], the machine learning methods demonstrated at LUX are set to play an important role in unlocking the full potential of these pioneering facilities.

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Laser pulse compressor

Out-of-plane femtosecond pulse compressor with multilayer dielectric gratings

Short-pulse, high-peak-power titanium–sapphire (Ti:Sa) lasers are important tools for various research areas. Many applications, however, require ever-higher pulse repetition rates from these systems. For example, DESY's new flagship laser KALDERA aims for 3 J, 30 fs pulses with kHz-level repetition rates to drive a next-generation plasma accelerator. This kW-level average power requires advances in laser architecture, in particular in optical grating technology for the final pulse compressor. New multilayer dielectric gratings for Ti:Sa lasers, which can in principle support very high average powers, have recently been developed with industry partners and tested at DESY in an out-of-plane geometry. In a proof-of-principle setup, the Lasers and Secondary Sources group at DESY achieved compression of sub-30 fs pulses with such gratings and demonstrated the feasibility of the concept for future high-repetition-rate, high-average-power Ti:Sa systems.

Design and setup of MLD compressor and matching stretcher

Ti:Sa laser technology can readily reach terawatt to petawatt peak powers, corresponding to joule-class pulse energies at few-10 fs pulse lengths. Typically, such high-intensity lasers are limited to repetition rates of a few hertz. KALDERA, DESY's laser plasma drive laser currently under development, aims for repetition rates of up to 1 kHz to enable fast feedback control and increased data rates for experiments, benefiting many new applications.

However, this push towards higher repetition rates with several kilowatt average laser power significantly increases the thermal load on many laser components. This heat load issue is especially prevalent in the final laser pulse compressor, in particular its optical gratings, where the full laser (peak) power is reached. Conventional Ti:Sa lasers use gold-coated gratings for their large spectral bandwidth, but these gratings suffer from absorption of the laser energy at a level of some percent (≈ 4%). The resulting heating can lead to their deformation and consequently to an undesirable degradation of the laser pulse [1]. To avoid this heating problem, multilayer dielectric (MLD) gratings with significantly reduced absorption had been proposed [2, 3]. First prototype gratings and their subsequent tests [3, 4] already showed promising spectral properties. We implemented such gratings in an energy-scaled out-of-plane pulse compressor to validate this concept for the future KALDERA compressor design [5].

Figure 1 shows the general layout of the MLD grating compressor. Due to the structure of their coating, MLD gratings can only be used in the so-called Littrow configuration [2–4]. This means that the diffracted beam would overlap with the incoming beam. The gratings therefore have to be tilted to separate the diffracted beam from the incoming beam (Fig. 1, left), resulting in an out-of-plane geometry.

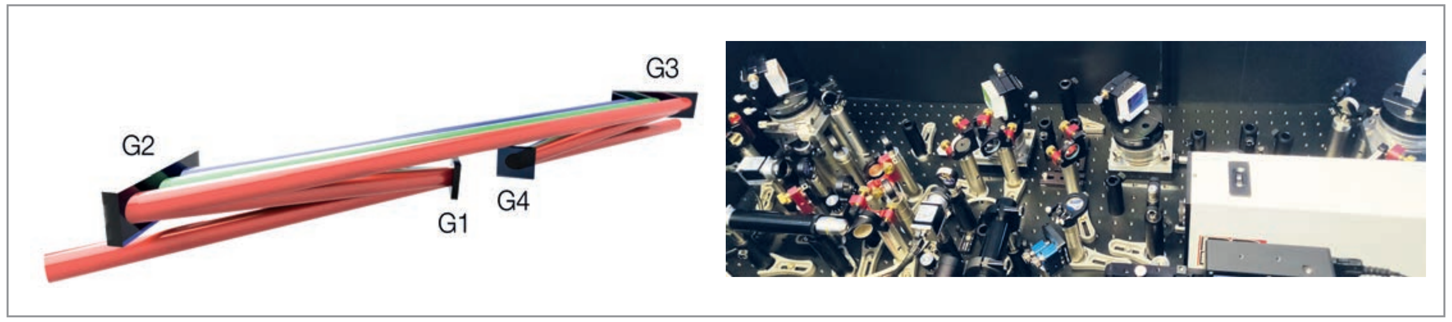

Figure 1
Left: Iso view of the out-of-plane compressor geometry. From [5]. Right: Energy-scaled test compressor.

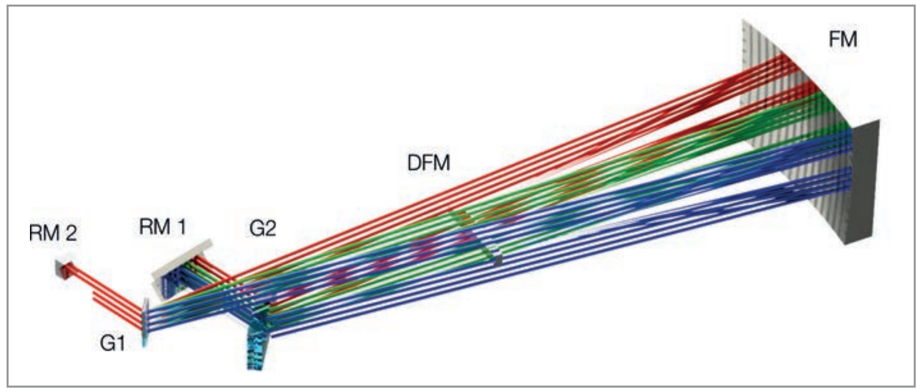

Figure 2
Left: Iso view of the two-transmission-grating stretcher including simulated beam paths. From [5].

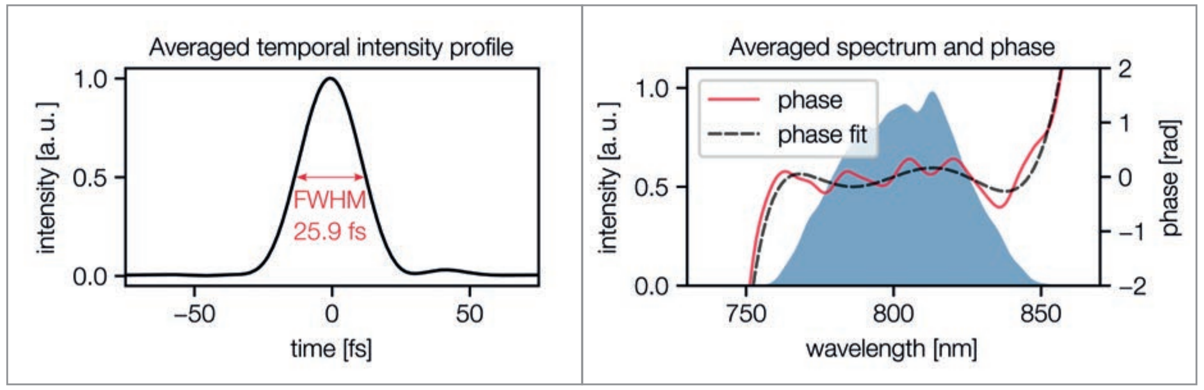

Figure 3
Measured pulse length of the compressed pulse. Left: Temporal intensity profile of the compressed pulse. Right: Measured spectrum and spectral phase. Both figures adapted from [5].

To fully compress the laser pulses to few-10 fs length, the dispersion of the initial pulse stretcher has to match the compressor. Thus, in our case, the stretcher gratings also need to be operated at the Littrow angle. We have developed a custom stretcher by adapting the common Oeffner design and using a pair of transmission gratings designed for Littrow operation (Fig. 2). A first version of this stretcher was built for the initial grating tests and is now being used as the main pulse stretcher for KALDERA.

Demonstration of sub-30 fs compression with MLD gratings

To demonstrate the stretching and compression with the setups described above, an on-air test setup (Fig. 1, right) was built and characterised [5]. As sufficiently large MLD gratings were not available, two of the four gratings had to be replaced by gold gratings for the compression experiment. Measurements of the spectral efficiency of the MLD gratings, however, clearly showed that the results would have been very similar with a pure MLD compressor. Stretcher and compressor were both aligned with a custom-built multicolour laser combining three laser diodes of different wavelengths in one optical fibre. With this device, which is also being used to align the full-size setups in KALDERA, the grating angles in both setups were carefully adjusted to ensure proper recombination of the whole spectrum.

For the compression tests, pulses of 800 nm central wavelength, 60 nm FWHM bandwidth and 40 µJ pulse energy from the KALDERA seed laser [6] were sent through the stretcher and compressor. After recompression, the pulse length was measured to be 25.9 fs (Fig. 3, left). The phase (Fig. 3, right) was flat over the full spectrum except for a small fifth-order modulation. This confirms that compression to sub-30 fs is possible with an MLD-grating-based compressor, making it a viable option for the KALDERA laser and future lasers of similar specifications.

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The SINBAD-ARES linear accelerator

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

In 2023, the construction of the Accelerator Research Experiment at SINBAD (ARES) linear accelerator was successfully finished. Outstanding electron beam parameters (energy spread and bunch length) and all design beam parameters were demonstrated and measured with the newly installed PolariX transverse deflecting structure (TDS). ARES also delivered more than 170 days of beamtime for DESY-internal and external accelerator R&D and medical application users. For the first time, the energy modulation of an electron bunch with a dielectric structure was shown with record-high intensity. Medical experiments with living cells irradiated by a 155 MeV electron beam were performed on a regular basis with the collaboration partners at the University Medical Center Hamburg-Eppendorf (UKE) and the University of Manchester, UK.

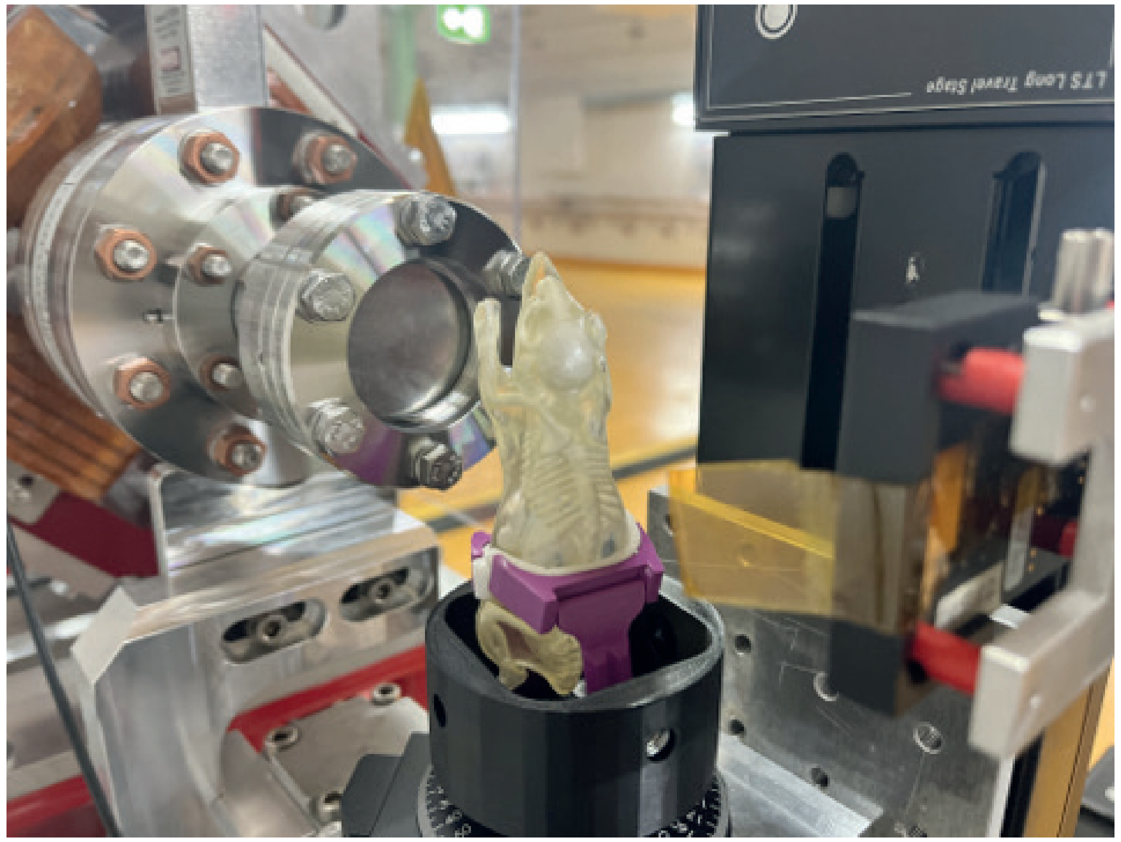

Figure 2
Experimental setup of the "electron CT" experiment. The titanium foil at the end of ARES is located on the left, the mouse phantom from UKE in the middle and the detector from the DESY Particle Physics Division on the right.

The R&D linear accelerator ARES

In 2023, the ARES construction was successfully finished (Fig. 1) and all design beam parameters were reached. As one of the Helmholtz test facilities, ARES has since been frequently used for various internal and external accelerator R&D projects. Internally, the DESY Accelerator Division used ARES to advance the development of beam position monitors, intensity measurement devices, beam loss monitors and fibres as well as to optimise synchronisation. The facility was also used by the Particle Physics Division for component and detector R&D (Cherenkov detector tests and strip sensor development), by the Photon Science Division for laser development and by the Radiation Protection team for dose rate monitor system development. For the first time, ultrashort electron pulses with a length of 3.7 fs (rms) were measured with the polarisable PolariX TDS, and the first successful 5D beam tomography using the PolariX TDS was demonstrated. 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. More than 1300 h of beamtime were dedicated to these studies (see p. 70). The development of novel compact bunch length diagnostic methods within the European EIC Pathfinder Project TWAC also continued with regular beamtimes at ARES.

DESY-external users came from UKE and the University of Manchester mainly to perform medical experiments, such as cell irradiation and dose monitoring. During a shutdown in the second quarter of 2023, a magnetic chicane and a small undulator were installed to perform microbunching experiments at ARES, which are foreseen in 2024.

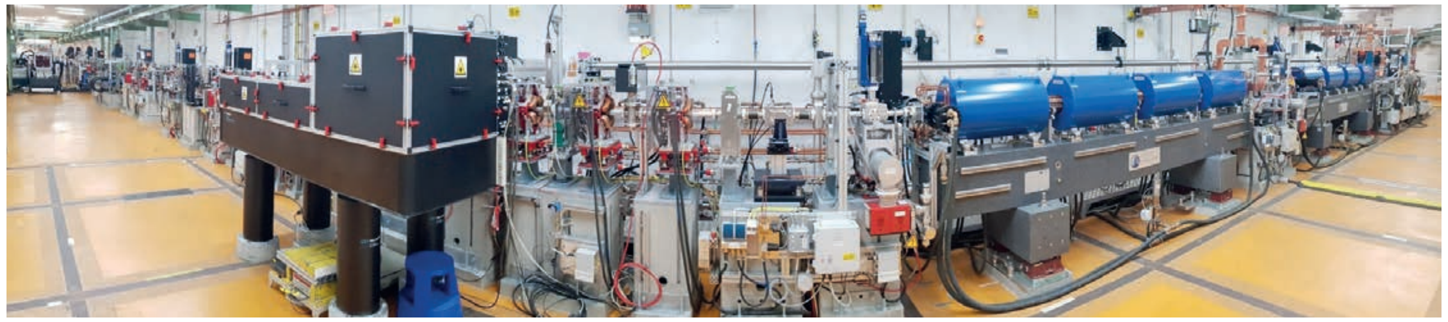

Figure 1
Fish-eye view of the fully installed ARES accelerator. The electron source (gun) can be seen on the right, the experimental area with the laser table in the middle and the PolariX TDS on the left.

VHEE conference at DESY and medical applications

In July 2023, the ARES team hosted the international Very High-Energy Electron (VHEE) Radiotherapy Conference at DESY. With 125 participants and more than 50 presentations, discussions and a poster session for young researchers, the workshop was a full success. VHEE is a novel method to treat cancer with high-energy electrons above 100 MeV. ARES is a worldwide unique accelerator to study VHEE in combination with *FLASH* radiotherapy. ARES also serves as a hub to connect medical users and accelerator and detector experts from DESY and industry in beamtimes for medical experiments. One example is the medical imaging experiment "electron CT", with a realistic mouse phantom from UKE, supported by the detector and tomography experts from the DESY Particle Physics Division. This project is also funded through the DESY Innovation and Technology Transfer channel. In 2023, several beamtimes at ARES were used to perform a full, high-resolution computed tomography (CT) of the mouse phantom (Fig. 2).

ACHIP – first energy modulation

As part of the Accelerator on a Chip (ACHIP) project, dielectric laser accelerators (DLAs) are being studied at ARES for use as compact beam manipulators and diagnostics. In 2023, the momentum modulation of a relativistic electron beam using a 2050 nm laser was demonstrated. A record charge transmission of up to 60 fC was achieved, and the entire transmitted charge was modulated. This represents an order of magnitude improvement over previous DLA-related work, with an acceleration gradient of 100 MV/m achieved. A microwire scanner from the Paul Scherrer Institute in Switzerland was used to verify the transverse electron beam sizes.

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AI for autonomous accelerator tuning at ARES

Developments at ARES for transfer to the DESY user facilities

The tuning of particle accelerators is often time-consuming, reducing the amount of time available to the users of these cutting-edge facilities. Recent developments in artificial intelligence (AI) have the potential to tune particle accelerators autonomously. The ARES team together with the Beam Controls group leverages DESY's R&D facility ARES to develop a number of AI-based methods towards autonomous accelerator tuning. In more than 1300 h of beamtime, we demonstrated in practice that reinforcement-learning-trained optimisers can outperform human operators. We further conducted a comprehensive study comparing reinforcement-learning-trained optimisation and Bayesian optimisation for accelerator tuning. Moreover, this work resulted in a differentiable high-speed beam dynamics simulator that enables various novel possibilities.

AI-based optimisation

As confirmed by the programmable humanoid Nao robots that visited the DESY R&D accelerator ARES [1, see p. 68] in April 2023 (Fig. 1), the facility provides an excellent platform to develop AI-based algorithms for accelerator operation. As part of the Helmholtz AI project Autonomous Accelerator, we used reinforcement learning (RL) to show that AI tools such as RL can outperform human expert operators, using the example of transverse beam parameter tuning [2].

The setup considered is shown in Fig. 2. To provide guidance on when to use which AI-based method for accelerator tuning, a comprehensive study was conducted that compared RL-trained optimisation and Bayesian optimisation (BO) with standard methods for accelerator tuning [3]. RL and BO were tested and compared for 22 random setups. RL was found to achieve consistently faster convergence to lower objective values than any other algorithm (Fig. 3), making it advantageous for repeatable, high-precision tasks.

Figure 1
Nao robot visiting the ARES accelerator, which enables AI for particle accelerator developments

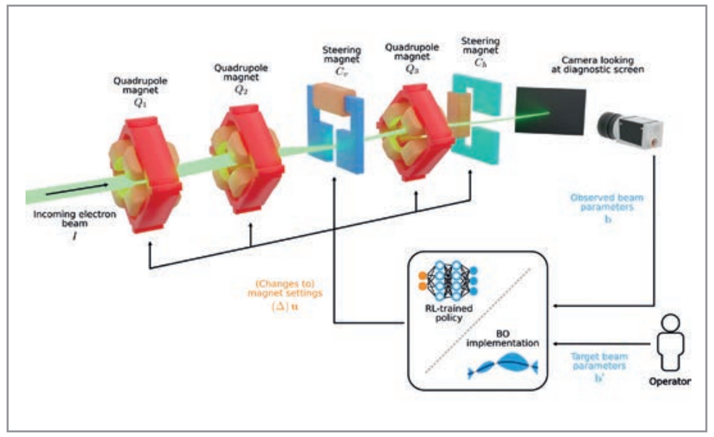

Figure 2
Control loop for reinforcement learning and Bayesian optimisation for transverse beam parameter tuning in the experimental area section of ARES

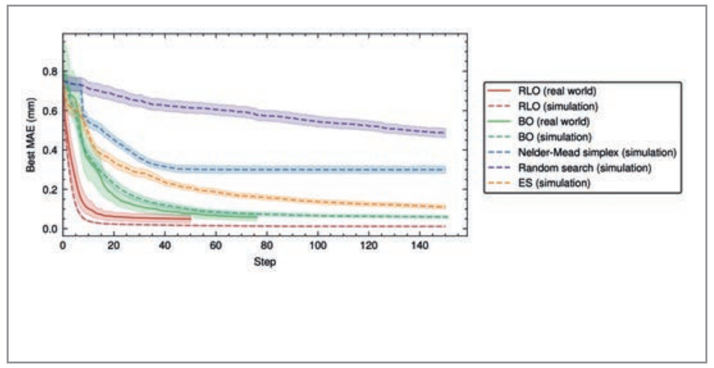

Figure 3
Averaged tuning objectives over time for different algorithms. Reinforcement learning (RL) achieves faster convergence to lower objective values than any other algorithm, while Bayesian optimisation (BO) is convincing in terms of ease of setup and engineering effort.

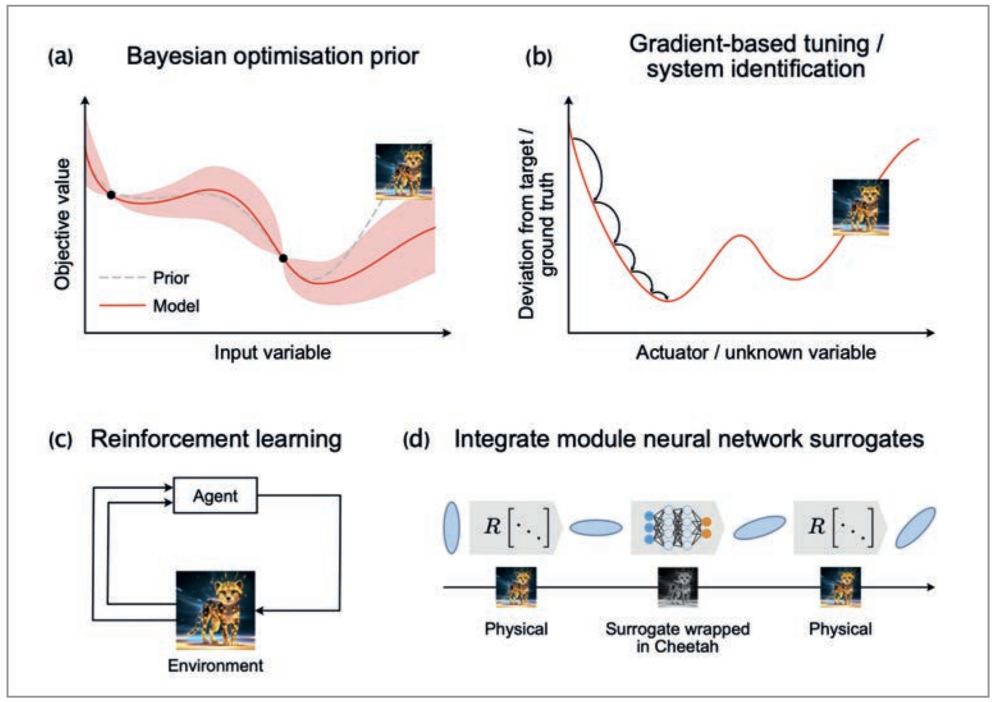

Figure 4
Overview of application examples for the Cheetah simulation code, illustrating where it is applied in each respective application

BO, on the other hand, was found to require significantly less engineering effort, making it perfectly suited for out-of-the box use in less frequently performed tuning tasks.

Fast differentiable simulations bridging accelerators and machine learning

To answer the need for bringing RL to accelerators, the high-speed simulation environment Cheetah [4] for beam dynamics has been developed in PyTorch. This side product by itself opens the door to many new applications of AI for accelerators. By reducing computation times by several orders of magnitude compared to existing beam dynamics codes, Cheetah can be used to overcome the challenges of generating the data required to train state-of-the-art machine learning models. Being based on PyTorch, Cheetah also inherits its automatic differentiation features, which enables efficient gradient-based optimisation for accelerator tuning and system identification. Thanks to its modularity, Cheetah also allows the integration of surrogate models based on neural networks with hand-crafted beam dynamics models. Examples of Cheetah use cases to date are shown in Fig. 4.

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Cryogenic lasers for accelerators

Application of technologies developed at DESY

DESY is developing new laser technologies to break through the current limitations of solid-state lasers. The applications of these new technologies can be far-reaching. The lasers, which achieve pulse energies in the joule range and average powers in the kilowatt regime, will be used to generate high-energy terahertz radiation as a future laser-driven electron source within the AXSIS project. The other promising area of application is high-energy and high-power pump–probe lasers, which will provide the accelerator user community with access to advanced capabilities at experimental stations. The complex technological development cycle includes advances in related fields. For example, the development of low-noise fibre lasers, which are required for cryogenic lasers, also opens up new opportunities for applications in non-linear microscopy.

Figure 2

Left: Development of a high-power fibre laser seeding source. Centre: Installation of the newly developed beam spatial filter. Right: Multiphoton microscopy platform using an ultrashort-pulse low-noise fibre laser source.

Cryogenic laser development

One of the main challenges in laser development is the thermal management of the laser gain material, which is the main limitation in reaching higher energies and power. Especially under cryogenic conditions, where the operating temperature of the gain crystal is around 100 K, thermal management is crucial. The Ultrafast Optics and X-rays (UFOX) group at the Center for Free-Electron Laser Science (CFEL), a joint enterprise of DESY, the Max Planck Society and Universität Hamburg, has recently advanced the technique of crystal to heat spreader bonding, which has enhanced the laser amplifier output by more than 30%. This opens up the possibility of creating a compact and powerful laser amplifier unit that can deliver an average power of 450 W from a 1 W seed laser. We envision the compact and reliable unit as a prototype for a next-generation pump–probe laser.

Another important development is the construction of a high-power fibre laser seed source for the next generation of Yb:YLF cryogenic amplifiers. The laser pulses from this source will provide a 10 nm bandwidth at the input of the main amplifier laser system, resulting in a 350 fs, 450 mJ output pulse. This pulse will be compressed in a newly designed Treacy compressor.

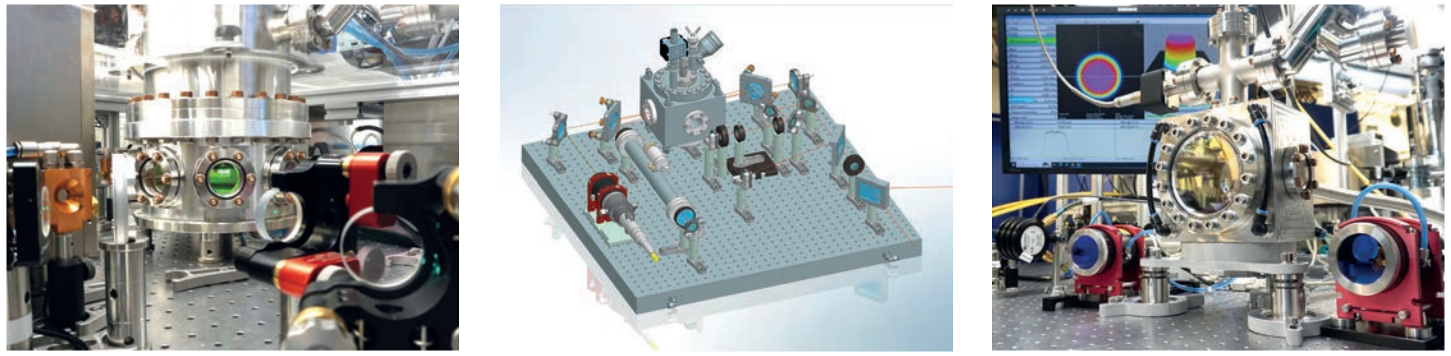

Figure 1

Left: Yb:YLF crystal bonded with a new bonding technique. Centre: 3D prototype design of a 450 W compact Yb:YLF laser unit. Right: Installation of a 2 J module for a Yb:YAG system

In the meantime, the previously developed 100 mJ, 100 W [1] Yb:YLF laser system has been used for experiments for almost 18 months, demonstrating its reliability and performance. Spectral broadening and pulse compression from 1 ps to 110 fs at high average power have been reached.

The cryogenic Yb:YAG system is in the next stage of advancement. The 2 J amplification stage is currently being installed. Together with the new concept of beam relaying and spatial filtering, it will provide a diffraction-limited 2 J beam for the AXSIS Compton inverse scattering station.

Some of these recent developments are shown in Fig. 1.

Low-noise fibre laser development

By controlling diverse non-linear light–matter interactions in optical fibres, we have developed a set of new technologies for the versatile generation of ultrashort optical pulse trains with an intensity noise so low that it approaches the standard quantum limit (Fig. 2). Such exceptionally low-noise pulsed fibre laser systems [2] have a number of cutting-edge applications in the fields of high-resolution non-linear biological imaging, quantum information processing and frequency metrology. To demonstrate the potential of these ultralow-noise non-linear fibre technologies, we are currently exploring their usefulness in a versatile multiphoton microscopy platform suited for performance-enhanced high-resolution imaging in fields such as neuroscience, structural biology, biomedical imaging and oncology.

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AXSIS – the THz accelerator lab at DESY

THz photogun experiment approaches first electrons

The aim of the AXSIS project is to develop a new terahertz (THz)-driven accelerator technology that harnesses the ultrahigh fields and field gradients possible at millimetre wavelengths. This mesoscale is a nearly unexplored regime for accelerator development, with many unique possibilities for acceleration and manipulation, leading to low-emittance femtosecond electron bunches. Development of the multiple layers of required technology, including joule-scale high-repetition-rate lasers, millijoule-scale THz sources and novel, millimetre-scale accelerator structures, is in full swing at the recently constructed AXSIS facility in the SINBAD hall at DESY. A new experiment is now being put into operation, which represents a key milestone: a THz-driven MeV photogun, with the first electrons anticipated in the kinetic energy range of multiple 100 keV.

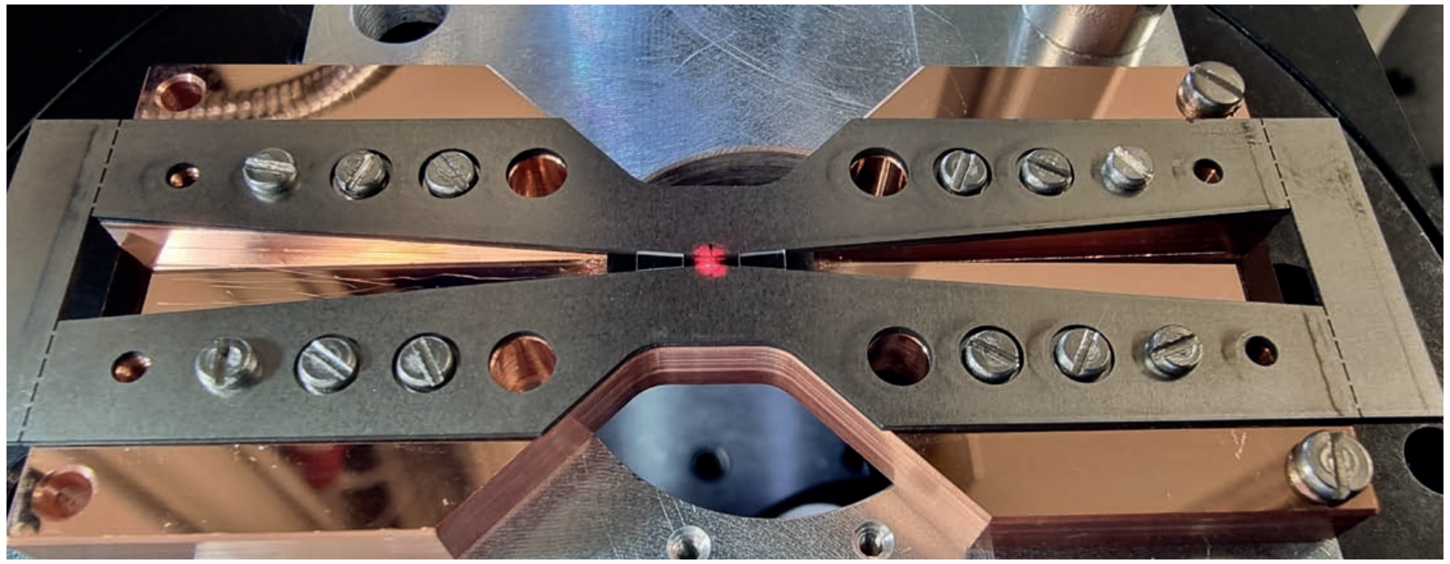

Figure 2

Three-layer THz photogun under assembly. The copper base forms the support structure, the photocathode as well as half of the horn antennae used to couple in the THz energy. Two tungsten "spacers", a steel divider and two dielectric trapezoids, which are used to construct the layered interaction region, can also be seen. A red helium–neon beam is used for alignment.

Twin high-energy single-cycle THz sources

The power plant for the THz photogun is a matching pair of millijoule-scale (0.4 mJ) single-cycle THz pulses with a centre frequency of ~300 GHz (Fig. 1). The twin THz sources are based on the well-established tilted pulse front scheme [1] of laser-driven non-linear downconversion, but have been scaled up to handle 2 x 100 mJ, 0.4 ps drive pulses from a commercial 52 Hz laser system. With a precision optimisation strategy developed in house [2], peak conversion efficiencies near 1% (internal to the crystal) could be achieved. Beamlines are currently being developed to efficiently transport the THz pulses and shape them for coupling into the THz photogun structure.

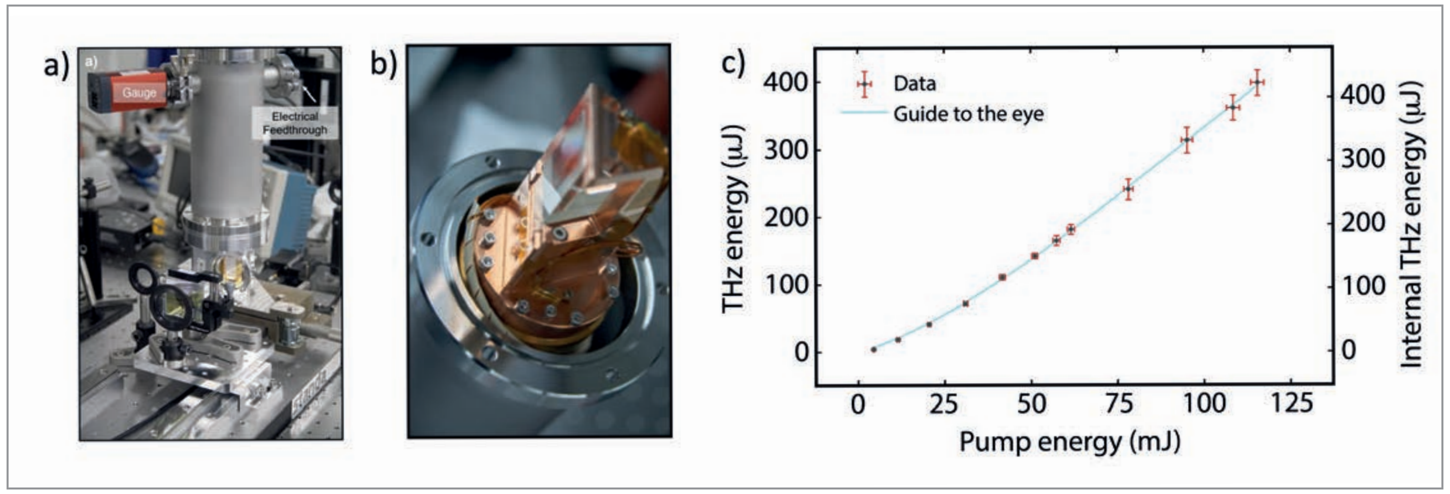

Figure 1

(a) Cryostat and imaging system for the tilted pulse front setup. (b) Large-aperture lithium niobate conversion medium, accepting drive beams of more than 100 mJ. (c) THz yield from one of the twin setups. 400 µJ of usable energy were collected, indicating that up to 800 µJ were generated within the crystal and can be collected with improved output coupling methods.

Multi-100 keV THz-driven photogun

The single-cycle THz sources described above enable the development of a THz-driven photogun that can reach electron kinetic energies in the range of multiple 100 keV, i.e. one to two orders of magnitude higher than previously achieved. Accelerating from zero to the relativistic (MeV) range is arguably the greatest technical challenge, due to the rapid change in velocity of the electrons during the initial phases of acceleration and the resultant dephasing of the electrons from the electromagnetic wave. This difficulty is heightened in the case of the THz-driven photogun by the millimetre-scale THz wavelengths, which are 100 times shorter than those in a radio frequency (RF) gun.

To overcome this issue, the interaction region is divided into multiple layers, allowing repeated rephasing of the electrons with the THz wave in a transversely pumped geometry [3]. The structure is pumped by twin, counter-propagating THz pulses, which has the dual purpose of enhancing the accelerating electric field and minimising the magnetic field that would otherwise produce an unwanted deflection of the beam. As has already been demonstrated [4], electric fields in excess of 3 GV/m – i.e. two orders of magnitude higher than typically used in RF photoguns – can be applied to the interaction, largely due to the short pulse duration and high frequency of the THz pulses. Such field strengths are highly desirable, especially during acceleration from rest, as they enable a rapid transition to relativistic energies where the negative effects of space charge can be mitigated. Electron beams of exceptionally low emittance are therefore possible.

The hardware of the THz photogun – including the gun itself (Fig. 2) and a custom-designed, single-shot broadband energy spectrometer – is currently being assembled, and the first experiments coupling high-energy THz pulses into the gun structure are expected in the coming months.

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First light from a compact RF gun for UED

Progress towards structural dynamics with ultrabright electron bunches from a table-top system

Ultrafast electron diffraction (UED) is an attractive and cost-efficient alternative to time-resolved X-ray techniques in the field of structural dynamics. To capture the fastest structural rearrangements on the angstrom scale, a temporal resolution on the order of 10 fs is needed, which requires the generation of electron pulses with matching duration and sufficient brightness. While such parameters are already reached in large MeV facilities, such as DESY's UED facility REGAE, most DC table-top variants fall short of these requirements. We have designed, built and tested a sub-relativistic radio frequency (RF) electron source (gun) in the Ultrafast Optics and X-rays group at the Center for Free-Electron Laser Science (CFEL) in collaboration with the Accelerator Physics and Beam Controls groups at DESY. The pin cathode RF gun concept has a projected capability of reaching 100 MV/m peak photocathode extraction fields, resulting in 160 keV, 100 fC self-compressing electron pulses with sub-100 fs pulse duration that require only 10 kW RF driving power.

The photogun characterisation setup

The RF cavity, which was developed specifically for UED applications, has been described in the DESY Accelerators 2022 annual report. In 2023, the laser beamline, including mode-locked oscillator to cavity synchronisation and streak camera trigger, was completed and characterised. The synchronisation scheme relies on the established μTCA technology provided by DESY and a low-noise Rohde & Schwarz RF signal generator combined with a Balanced Optical-Microwave Phase Detector (BOMPD) purchased from Cycle GmbH. The cavity amplitude response becomes unstable and breaks down at a driving power below 2 kW (Fig. 1). A sharp rise in the extracted dark charge suggests that this breakdown occurs at the pin cathode itself. Further increase to the maximum driving power (9 kW) results in a semistable regime capable of producing consistent electron bunches, albeit with a relatively large root mean square (rms) amplitude fluctuation of 0.05% despite active amplitude stabilisation by the low-level radio frequency (LLRF) system. Examining the estimated pin cathode field distribution for these parameters, we find peak fringe fields of 83 MV/m, close to the expected maximal vacuum breakdown field of 95 MV/m at 3 GHz (inset Fig. 1, right).

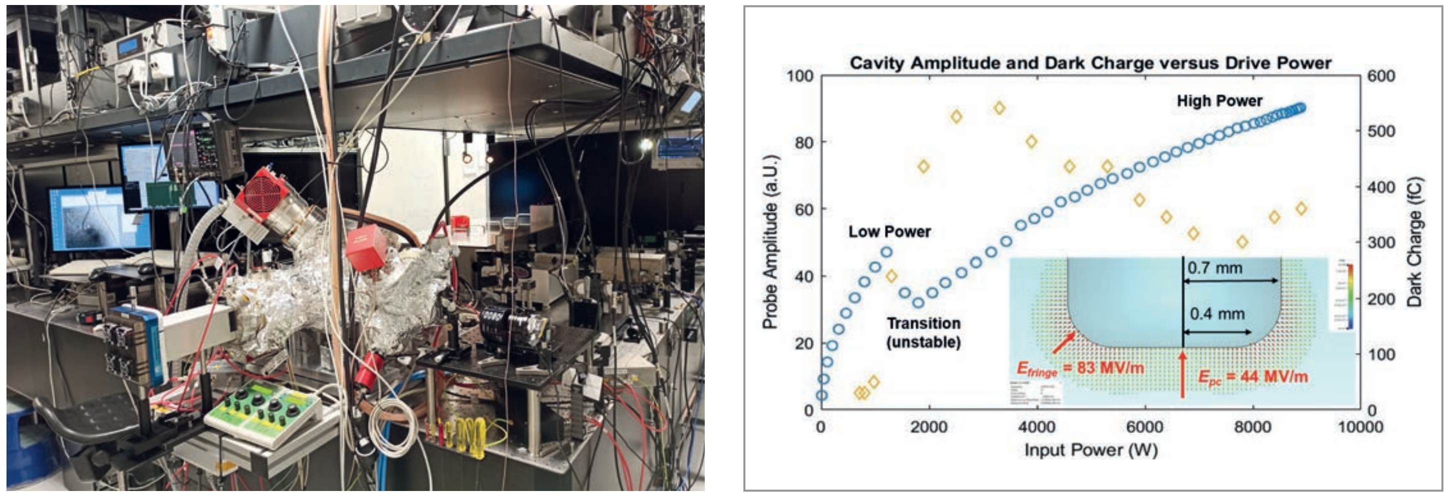

Figure 1

Left: UED RF gun test setup as currently installed in the CFEL building. Right: Cavity amplitude and dark charge emission response as a function of driving power. Inset: Electric field distribution of the pin cathode for a measured electron acceleration energy of 62 keV.

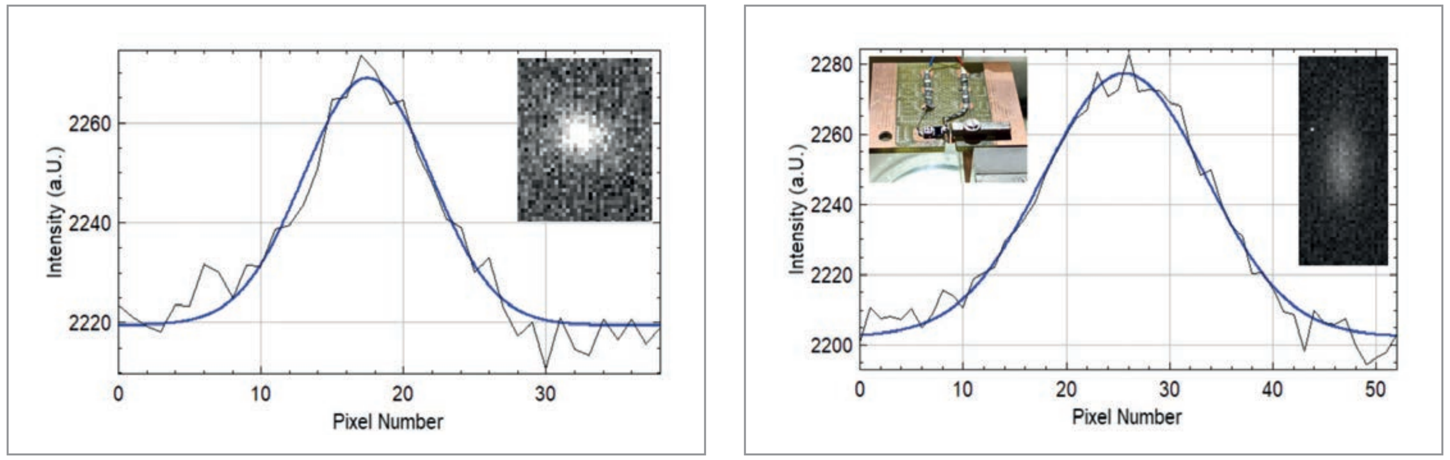

Figure 2

Left: Beam profile at the detector corresponding to an accumulated 30 μm aperture raster scan of the beam at the target position. Right: Profile of the streaked electron beam at optimal compression phase. Insets: Image of the streak camera and recorded streak image.

Electron beam characterisation

Central to our beam characterisation efforts is a home-built streak camera featuring a gallium arsenide photoconductive semiconductor switch that has been developed in collaboration with the Max Planck Institute for the Structure and Dynamics of Matter (MPSD). This device is demonstrably capable of electron bunch profiling and bunch arrival time jitter measurement with 100 fs and 30 fs rms resolution, respectively. Measurements of bunch arrival times at different beam path positions allowed us to accurately determine the electron beam velocity $v_z = 1.36 \times 10^8$ m/s, corresponding to a beam energy of 62 keV.

Figure 2 on the right shows the measured streak profile with optimised phase at the temporal focus over an accumulation period of 5 s. Gaussian subtraction of the unstreaked profile results in an rms pulse duration of 170 fs. Our characterisation of the sensitivity of the bunch arrival time to amplitude fluctuations suggests that this temporal dispersion is almost entirely attributable to the currently measured relative rms amplitude jitter of 0.05%, while the cavity phase jitter, laser to RF synchronisation jitter and single-shot pulse duration are much smaller. Raster scanning of a 30 μm aperture over the entire beam resulted in the beam profile at the detector shown on the left in Fig. 2. Together with a virtual slit aperture scan for on-target beam size profiling, we obtain an rms beam size of 200 μm with an rms angular spread of 0.43 mrad. The corresponding transverse normalised emittance is 16 nm, yielding an on-target transverse coherence length of 5 nm, which meets the requirements for high-quality diffraction of metallic and small molecule-based crystals to be considered in upcoming experiments.

Summary and outlook

We have achieved a milestone with the first production and characterisation of bunched femtosecond electron pulses from a novel pin cathode electron gun. Although the measured bunch parameters fall well short of the gun's simulated performance predictions, they are already approaching the state of the art for table-top UED systems. Moreover, our detailed measurements point to specific measures that are expected to significantly improve the gun's performance. Installation of a larger pin cathode with a diameter of 3 mm is planned for spring 2024, which is expected to increase the extracted pulse energy to above 100 keV while reducing the pulse duration to below 100 fs by mitigating field-emission-induced instabilities and damping the time-of-flight sensitivity at higher electron energies. Further improvements are planned by implementing fast intra-pulse amplitude stabilisation capabilities of the LLRF system.

Preparations for first time-resolved diffraction experiments are under way. We plan to conduct UED studies of phonon dynamics in lithium niobate to improve THz generation for the AXSIS project and eventually use a clone of this electron gun as a photoinjector for the AXSIS source.

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DESY FPGA firmware framework

Towards open source and collaboration

Developing field-programmable gate array (FPGA) firmware is a complex task that requires the integration of various technologies into a single design. This process, which often involves numerous developers and the use of multiple tools, is challenging, especially for long-term maintenance and reproducibility in scientific institutions such as DESY. To address these challenges, the DESY Beam Controls group has developed an open-source FPGA firmware framework (FWK) that streamlines development, facilitates collaboration and reduces complexity.

FPGA firmware framework

The FPGA firmware development process at DESY presents a set of significant challenges. The institute's facilities, including FLASH and the European XFEL, demand long-term support and maintenance, spanning up to 20 years. Over such extended periods, many features evolve or undergo modifications, tool chains are updated or replaced, and hardware experiences changes or upgrades. What further complicates the process is the involvement of numerous developers and collaborations, with projects transitioning between responsible persons.

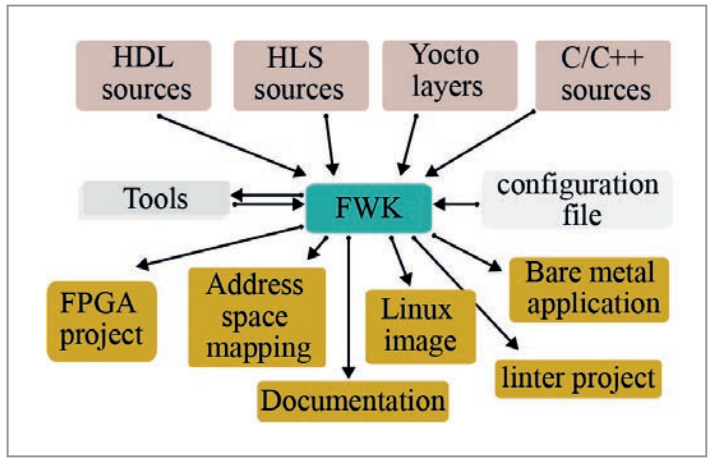

Figure 1
Framework concept

These firmware development challenges intersect with the management of multiple projects, often handled by small teams, and run in parallel with a continuous stream of new developments and rapid prototyping efforts. To further complicate matters, the most recent developments encompass a convergence of various technologies, entailing the integration of code written in Hardware Description Language (HDL), High-Level Synthesis (HLS), Embedded C/C++ and Embedded Linux into a unified and coherent design. To address these challenges of FPGA firmware development head-on, we have developed a dedicated firmware framework. It can be defined as an abstraction that provides particular functionality, is universal and re-usable. It is a set of rules, scripts, functions and procedures required to build the project. The main concept is presented in Fig. 1 [1].

In the firmware framework, there are a few major components: framework module, source modules, main project and vendor tools (Fig. 2.). The main concept behind the framework is that it provides abstraction layers that allow various project sources to be integrated independently on the FPGA vendor tool. These sources are placed in separate repositories, which can be an open or closed source. The only requirement is that they follow the interface specified by the FWK, which is one Tcl file included into the design. This simplifies and enables the exchange of intellectual property (IP).

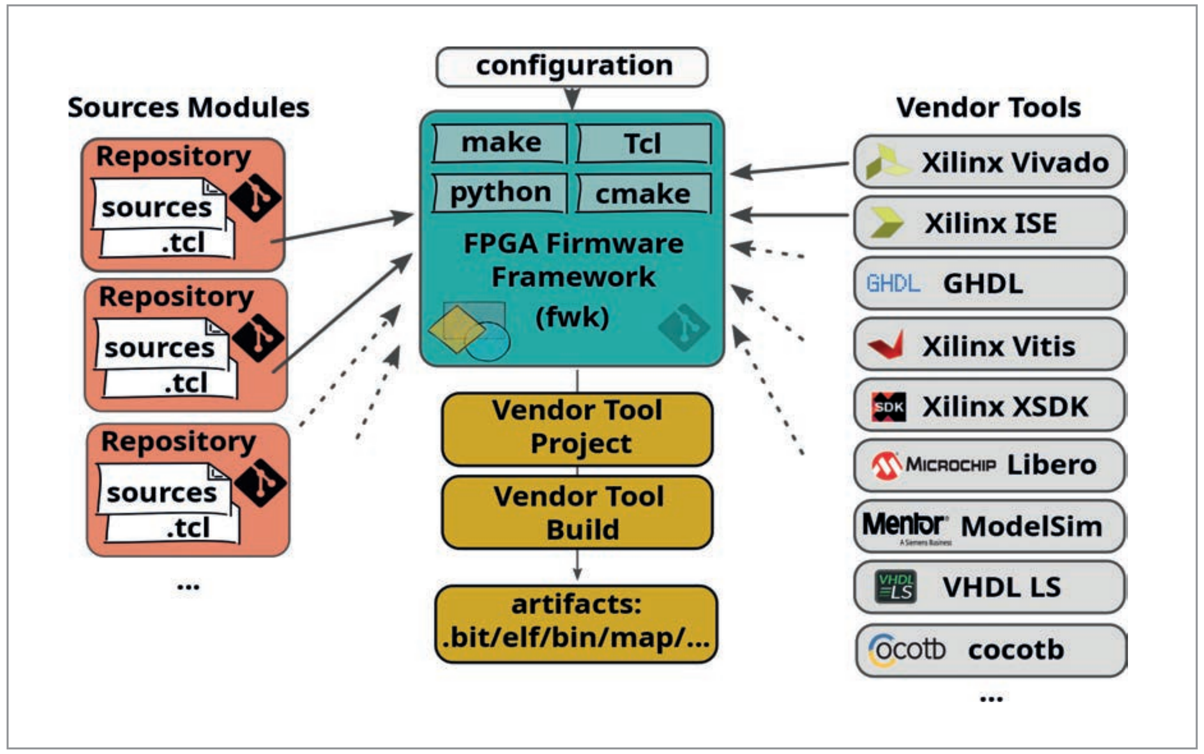

Figure 2
Major components of the FPGA firmware framework

Towards open source

The initial version of the firmware framework was developed in 2013 specifically for MTCA.4 systems at the European XFEL [2]. Initially, the framework was tightly integrated with the code within a monolithic repository, leading to challenges related to sharing and scalability as project numbers grew. To tackle these issues, the decision was made to decouple the framework from the code, restructure it and subsequently release it as an open-source project. The motivation behind this transition was to not only assist other institutions but also foster collaboration through open sourcing. Given that we often share projects or seek to enhance collaboration, accomplishing this through closed-source internal repositories proves to be challenging.

While opening up the framework, we encountered various challenges, including determining where and how to publish it as well as deciding on the appropriate license. Ultimately, our framework, along with example designs, was officially released in 2022 on the DESY GitLab instance under the Apache 2.0 license. The framework was presented at several conferences, including the ICALEPCS 2023 conference, the MTCA.4 workshops in 2022 and 2023 and the Helmholtz ARD-ST3 workshop in 2022.

Results

The FWK has been successfully used in the DESY Beam Controls group for more than ten years. This framework has empowered a team comprising three to seven members to effectively manage approximately 40 projects, involving 15 distinct hardware boards. With contributions from around 50 developers to the code base, the FWK has exhibited notable improvements in collaboration, code quality, reproducibility and change traceability.

Currently, in addition to DESY, other institutes and companies such as HZDR, HZB, SOLEIL, BNL, CERN, Uppsala University, MYRRHA and Struck GmbH are either using or evaluating the described framework.

Further information

The framework is available on the DESY GitLab instance: https://gitlab.desy.de/fpgafw/fwk. Refer to the GitLab https://gitlab.desy.de/fpgafw group description for documentation.

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Moving with the times

Are progressive web apps suitable for the operation of accelerators?

Web-based applications are ubiquitous these days, and the Google and Apple download portals are overflowing with applications for all sorts of purposes. The question is whether web-based applications, built with HTML, CSS and JavaScript/TypeScript, are also suitable for operating accelerators. An attempt has been made by the DESY Accelerator Control System group to understand the pros and cons of this technology by implementing sample applications. It turns out that it depends on what you use web apps for.

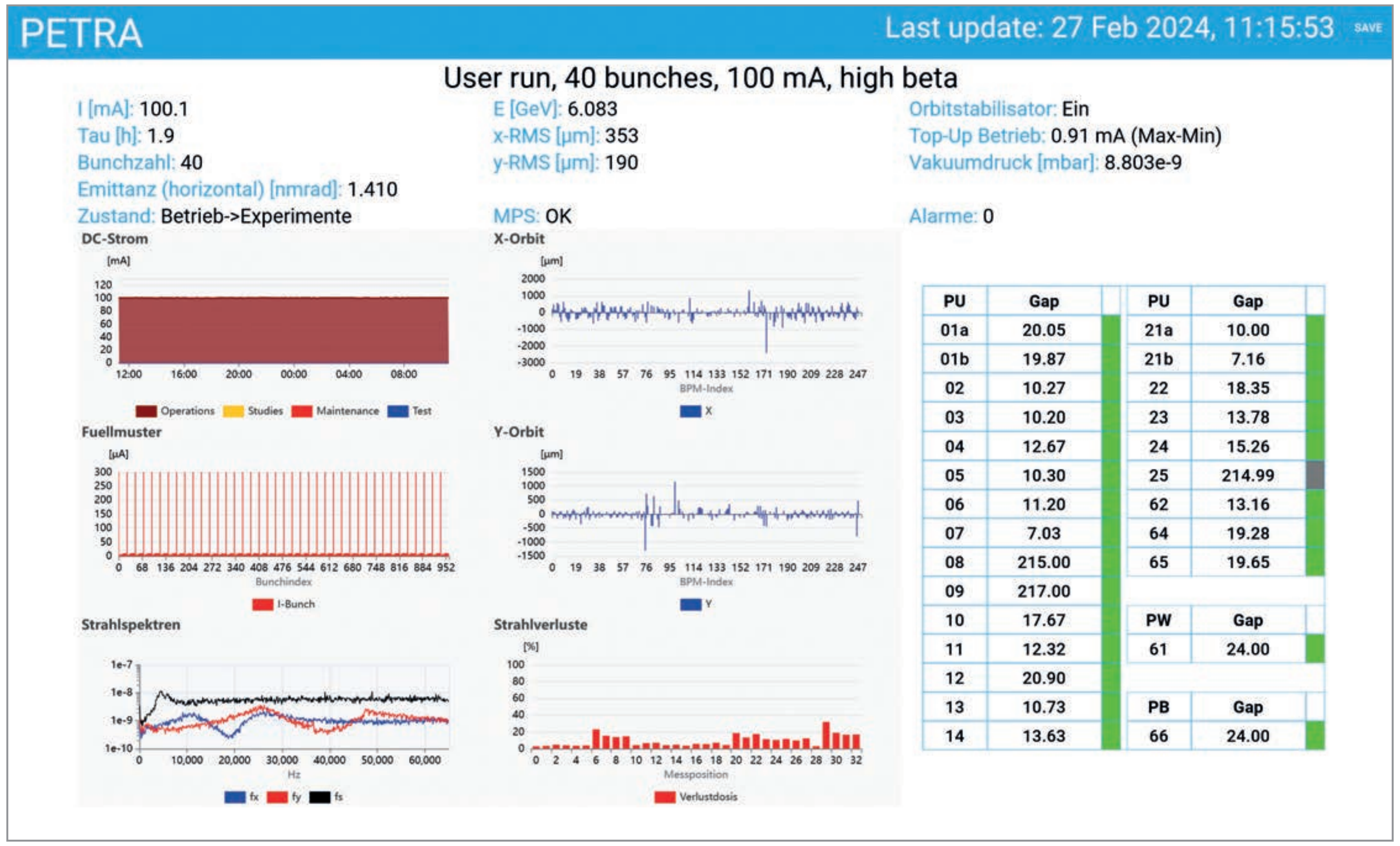

Figure 1

Snapshot of a live display showing the operating status of the PETRA III accelerator

Overcoming the legacy

In many accelerator labs, graphical user applications for accelerator operation have traditionally been implemented in Java, either as custom-built rich client applications or as thin client applications that can be easily created in an integrated development environment without knowledge of a programming language, using a functional and extensive set of configurable widgets. In recent years, it has become increasingly popular to use Python instead of Java, especially for scientific applications. But if you look at other areas, such as social media, you will see that completely different technologies have been introduced, and the download portals of Google or Apple are practically overflowing with web-based applications. A huge number of software developers around the world are offering amazing applications for all sorts of purposes. These so-called progressive web apps are intuitive to use. As if by magic, they adapt to any screen size and orientation, and you will not want to miss the option to zoom with a simple finger gesture. Web apps are available for all types of devices, be they smartphones, tablets or laptops, regardless of the underlying operating system. This article discusses whether web applications are able to deliver what they promise, also with regard to the operation of accelerators.

Insights into progressive web apps

Progressive web apps are implemented using HyperText Markup Language (HTML), Cascading Style Sheets (CSS) and JavaScript/TypeScript. The interaction between the app and its host environment is based on the open WebAssembly standard. Powerful, freely available frameworks such as React or Angular, or other frameworks based on them, facilitate software development. Web apps are downloaded from a web server and run in a browser engine, either embedded in the browser window or as stand-alone applications added to the user's home screen. They have a responsive design and look like native applications.

In order to control accelerators, web applications need to communicate with a web server that acts as a gateway to the control system of the accelerator.

Web application development is also very popular. Unlike for Java or, to a lesser extent, Python, skilled software developers with knowledge of web technologies are widely available on the job market.

Are progressive web apps suitable for the operation of accelerators?

We have implemented sample applications to understand the advantages and disadvantages of this technology. It turns out that it depends on what you use web apps for.

The graphical user applications that are used in an accelerator control centre tend to be highly complex and carefully designed screens that consist of many interactive, often multi-functional, graphical widgets. This design pattern obviously conflicts with the responsive nature of a progressive web app. Web technologies have undoubtedly already reached a high level of maturity today, but frameworks such as React are still subject to rapid change. The typically multi-year lifecycle of applications for the operation of accelerators does not fit well with this. Applications for accelerator operation rely on high-performance and reliable network protocols. A protocol such as Hypertext Transfer Protocol (HTTP) may not be the first choice here. For maintenance reasons, the IT environment in an accelerator control centre is very uniform in terms of computer and monitor hardware and operating systems. The fact that web apps can be run on a variety of different devices would not be an advantage in this respect.

However, there are many use cases where applications are also used outside the accelerator control centre and by a wide range of people, such as the management and technical staff or the scientific users of the accelerator facilities. Examples include all kinds of dashboard applications, status information pages, applications that visualise trends of operating parameters over time or simple, dedicated control applications that are preferably operated by finger gestures and used for maintenance purposes on site. In these cases, it pays off that web apps can be used literally anywhere a mobile data network is available, and universally on all types of devices, irrespective of the underlying operating system.

In summary, while web-based applications offer cross-device compatibility and ease of use, their responsive nature and rapid framework changes pose challenges for complex, long-lifecycle applications in accelerator control centres. However, web-based applications are beneficial for external applications like dashboards, status pages and maintenance tools, providing flexibility and universal device compatibility.

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Taskomat

A powerful tool for automating processes in accelerators and laboratories

The new Taskomat software, developed in a joint effort between the DESY groups MCS, MXL and FS-FLASH-D, makes it easy for users to automate processes in control systems. Operators or system experts can define individual process steps, arrange them into a sequence, execute it and follow its progress. If desired, sequences can be enhanced with flow control via constructs such as "if" or "while". Individual steps are fully programmable in the simple Lua scripting language, which is known from computer games and commercial applications. Taskomat installations are already in use at the European XFEL, the DESY facilities FLASH, PITZ, DESY II, LINAC II and LEAP as well as in several laboratory and simulation settings.

Automating processes

The operation of a particle accelerator, like any complex system, is governed by processes of various kinds. These processes can be implicit ("we usually do it like this"), explicit (checklists, step-by-step instructions) or automated (implemented in hard- or software). Automated processes have several advantages over their manual counterparts, such as faster execution, better reproducibility, reduced work load for operators and improved documentation of what happened when.

Software tools to execute process steps automatically, so-called sequencers, have a long history both at DESY and in other laboratories [1]. Due to the growing need for automation and the ever-increasing complexity of our controls landscape, existing solutions have failed to meet the expectations of accelerator operation teams for a while. Therefore, we started discussions about designing a new sequencer from scratch in late 2021.

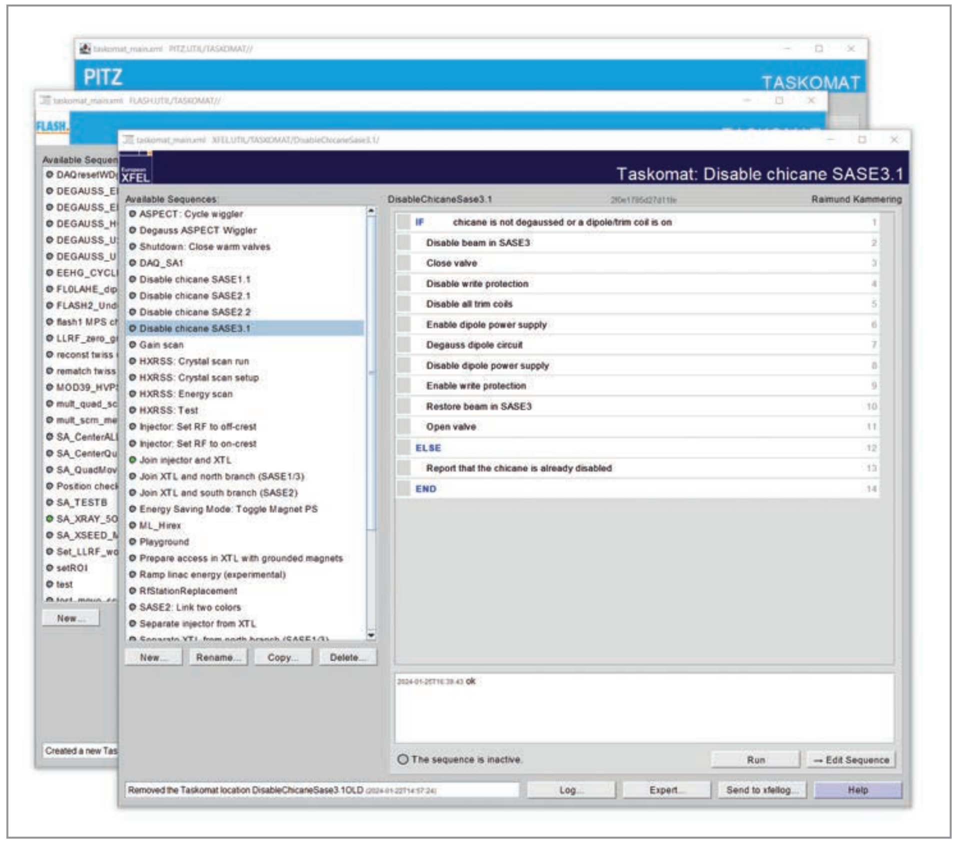

Figure 1

Taskomat sequence selectors for the European XFEL, FLASH and PITZ

Design

The new Taskomat sequencer is designed around the following goals:

- Integration into the control system: Sequences can be started, controlled and manipulated from the control system.
- Control flow: Sequences can contain control flow constructs such as "if" or "while".
- Programmability: Where necessary, users can program the functionality they need.
- Ease of use: The barriers for users to create, edit and test sequences are as low as possible.
- Separation of control-system-dependent and -independent code: Most of the code has no dependency on a specific control system.

Processes are modelled as sequences of individual steps. On the highest level, only the overarching control flow and user-defined step descriptions are visible, providing a clear and unobstructed outline of the sequence. For instance:

```
WHILE hungry
    IF fridge empty
        Go to supermarket
        Buy food
        Go home
    END
    Eat food
END
```

What each individual step actually does is defined by a script written in the lightweight Lua extension language [2, 3], which is known from many computer games and commercial applications. Unlike most general-purpose programming languages, Lua has a clear and simple syntax that is easy to handle even for occasional users:

```
addr = "SOME/CONTROL/SYSTEM/ADDRESS"
for i = 1, 10 do
   print("Writing", i, "to", addr)
   dset(addr, i)
   sleep(0.5)
end
```

Implementation

Most of the functionality is implemented in an open-source library called Taskolib [4]. The library is written in platform-independent C++ and carries no dependency on any specific control system. Its features include classes for modelling sequences and steps, custom commands for Lua (e.g. "sleep", "print"), executing sequences asynchronously and aborting them at any time, receiving status updates and output from running sequences, saving and loading sequences as well as version control via git.

On the basis of this library, we have developed an implementation for the DOOCS control system, the Taskomat server [5]. This server is already in use at the European XFEL, FLASH, LINAC II, DESY II, PITZ and LEAP for the automation of dozens of accelerator-specific tasks (Fig. 1). In addition, a number of laboratory installations support the operation of lasers and other equipment. Taskomat implementations for other control systems, such as Karabo, Tango or EPICS, require no changes to Taskolib and could therefore be realised with relatively little effort.

Outlook

The Taskomat has already become an integral part of daily operation in some of our accelerator environments, most notably at the European XFEL and FLASH. We hope to make use of its full potential by putting it in the hands of more technical and domain experts to automate their tasks.

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Blending realities

Immersive neural graphics for accelerator inspection and robot teleoperation

A virtual reality (VR) system that can quickly replicate real-world environments to provide users with a high level of spatial and situational awareness is crucial for facility maintenance and inspection. However, the exact 3D shapes of these facilities are often too complex to be accurately modelled with traditional meshes or point clouds. To address this problem, the Accelerator Control System group at DESY and the Human–Computer Interaction (HCI) group at Universität Hamburg develop VR systems based on neural graphics, which can compress complex 3D volumetric information as neural network weights and enable the appearance of the physical realities of complex particle accelerators to be accurately and rapidly replicated, stored and rendered through VR head-mounted displays. The neural graphics system enables numerous futuristic applications, ranging from virtual accelerator inspection to robust immersive robot teleoperation during accelerator runtime.

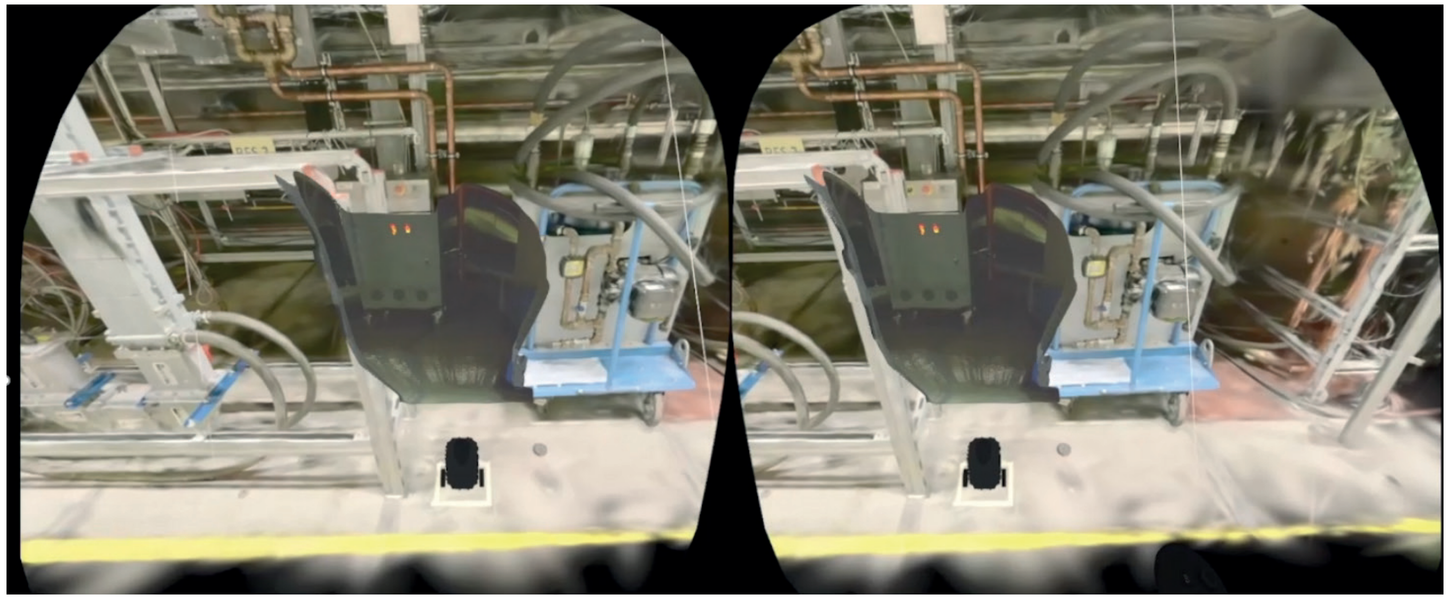

Figure 2

Screenshot from our neural graphics robot telepresence system running in real-time VR in the European XFEL accelerator tunnel [4]

Magic NeRF Lens: virtual accelerator inspection through the eyes of a neural network

Large-scale physics facilities, such as the particle accelerator of the European XFEL, are complex systems with more than ten million control system parameters and tens of thousands of components that require frequent inspection and maintenance. However, the accelerator must operate continuously for more than 5000 hours per year, during which time on-site human access is not possible and any unexpected interruptions to operation result in high energy and setup costs. As a result, a virtual inspection system where accurate 3D representations of the complex conditions of the facility can be viewed and updated frequently is critical for maintenance planning to reduce maintenance windows.

The rapid development of novel 3D representations using neural radiance fields (NeRF) [1] and 3D Gaussian splattings (3DGS) [2] introduces a paradigm shift in how the appearance of our physical realities can be replicated, stored and rendered by computers. A neural graphics 3D model can be trained with low costs from just a set of 2D images, with the complex information about our physical realities efficiently compressed into the parameters of a neural network [1] or a set of universal function approximators, such as 3D Gaussians [2].

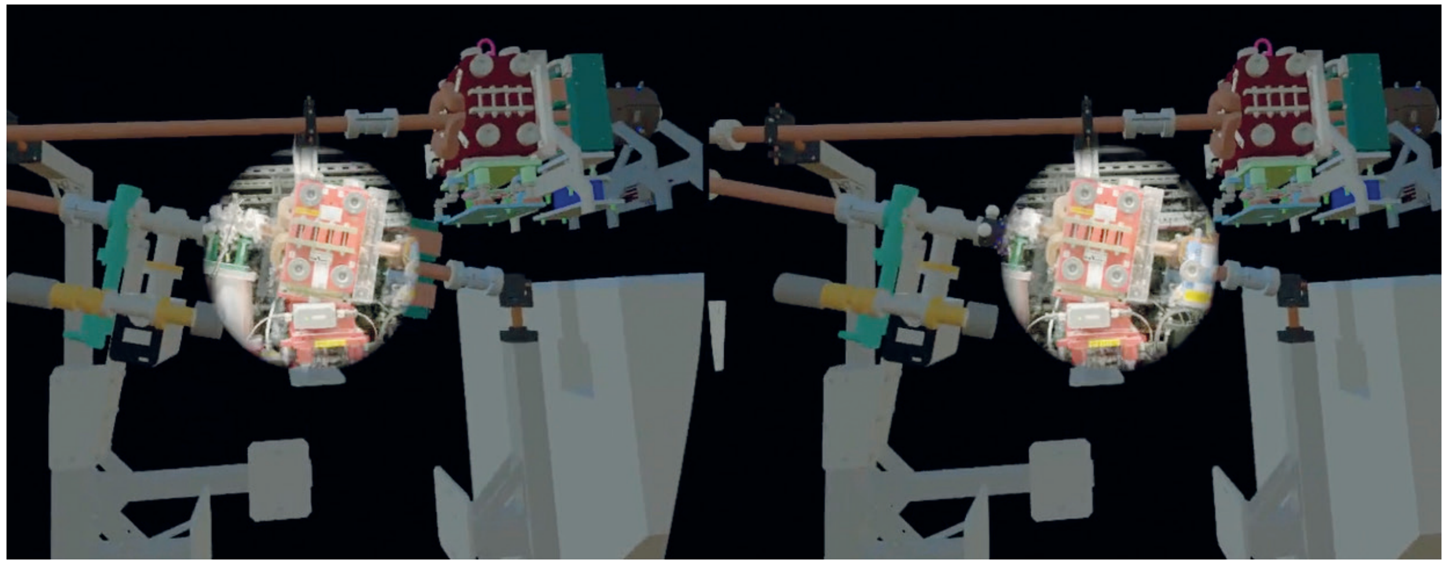

Figure 1

Screenshot from our immersive neural graphics VR system for virtual accelerator inspection, where the NeRF 3D model representing the physical reality of the European XFEL linear accelerator is merged with the virtual CAD model of the accelerator

As Fig. 1 illustrates, our Magic NeRF Lens work brings such novel neural graphics representations of physical reality to immersive VR [3]. In Fig. 1, a NeRF model converts around 40 2D images of a section of the European XFEL linear accelerator captured by a mobile phone into a photorealistic 3D model that faithfully replicates the physical appearance of the complex accelerator facility. Moreover, the NeRF model is merged with its corresponding CAD model in VR, helping operators reveal the difference between the initial CAD design and the actual facility.

The immersive neural graphics system was evaluated through user studies and expert reviews at DESY. Experts leading the design and upgrade of particle accelerators mentioned the benefits of our system: “With this system, I see the possibility to test something in theory before you build it in practice. For example, when you have a machine, and you want to test if you have enough space for installing it, it is quite nice that you could test everything in the virtual area before you do it in reality.”

Reality fusion: robust robot teleoperation in VR with 3D Gaussian splattings

The application of immersive neural graphics systems goes beyond virtual facility inspection. Figure 2 demonstrates a VR application built with neural graphics for remote controlling robots in the European XFEL tunnel. Teleoperation of robots in complex remote environments like particle accelerators is a challenging task. While operators require high situational awareness of the remote environment for safe and accurate task planning, the conventional user interfaces for robot teleoperation based on 2D displays and video feedback can only provide limited spatial understanding and fields of view (FoV).

To address this challenge, we propose reality fusion, a novel robot teleoperation framework that can localise, stream, project and merge the typical depth sensor of the robot with a photorealistic, high-resolution, high-framerate and wide-FoV rendering of the complex remote environment represented as 3DGS. Our framework allows for robust robot teleoperation in immersive VR in complex particle accelerator environments, with the 3DGS model effectively extending the FoV of the robot depth sensor and balancing the trade-off between data streaming costs and data visual quality. The robot teleoperation system was already successfully tested in the European XFEL tunnel, with a wide range of future work planned to support more efficient and intuitive human–robot collaboration with more advanced robotic systems at particle accelerators.

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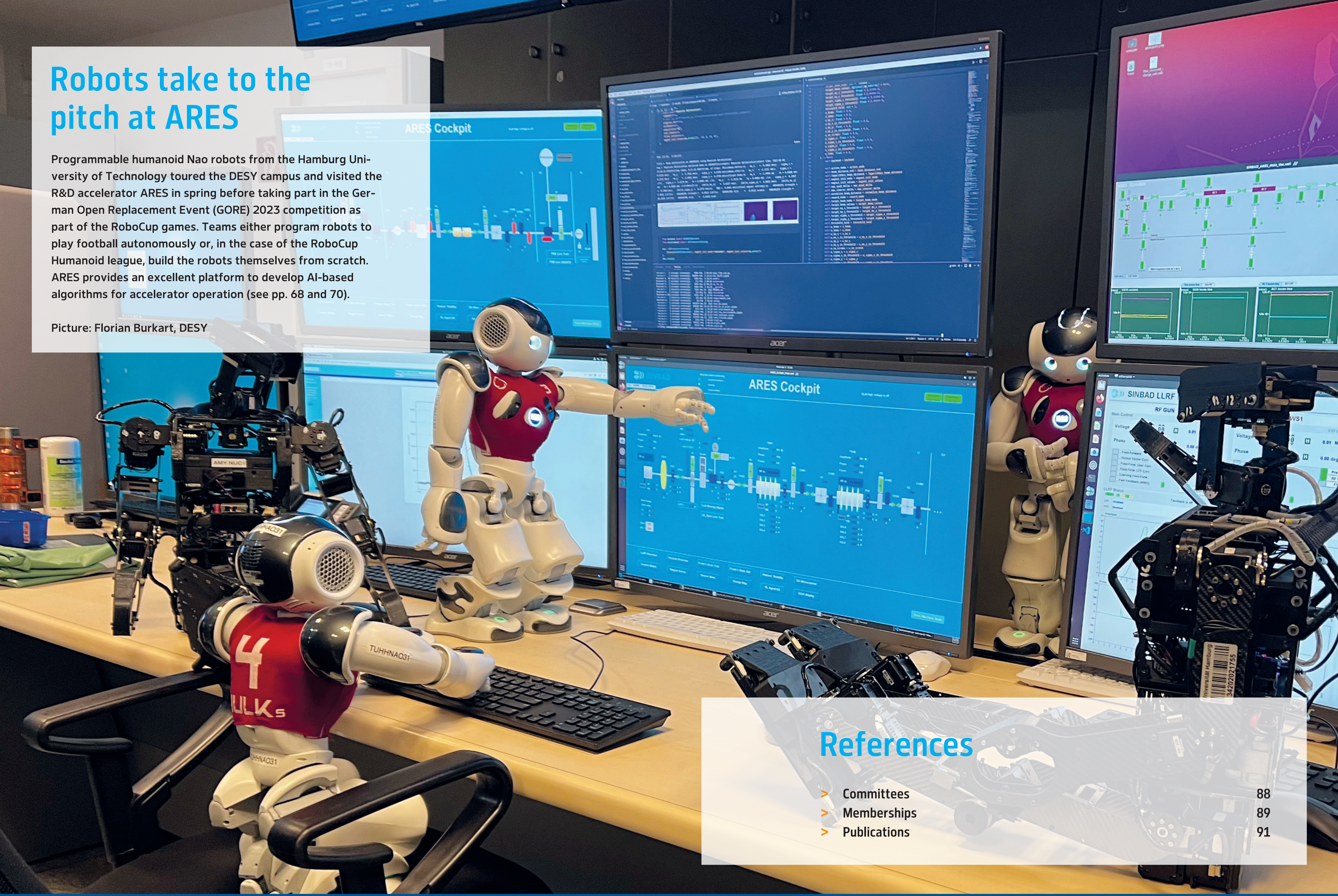
Robots take to the pitch at ARES

Programmable humanoid Nao robots from the Hamburg University of Technology toured the DESY campus and visited the R&D accelerator ARES in spring before taking part in the German Open Replacement Event (GORE) 2023 competition as part of the RoboCup games. Teams either program robots to play football autonomously or, in the case of the RoboCup Humanoid league, build the robots themselves from scratch. ARES provides an excellent platform to develop AI-based algorithms for accelerator operation (see pp. 68 and 70).

Picture: Florian Burkart, DESY



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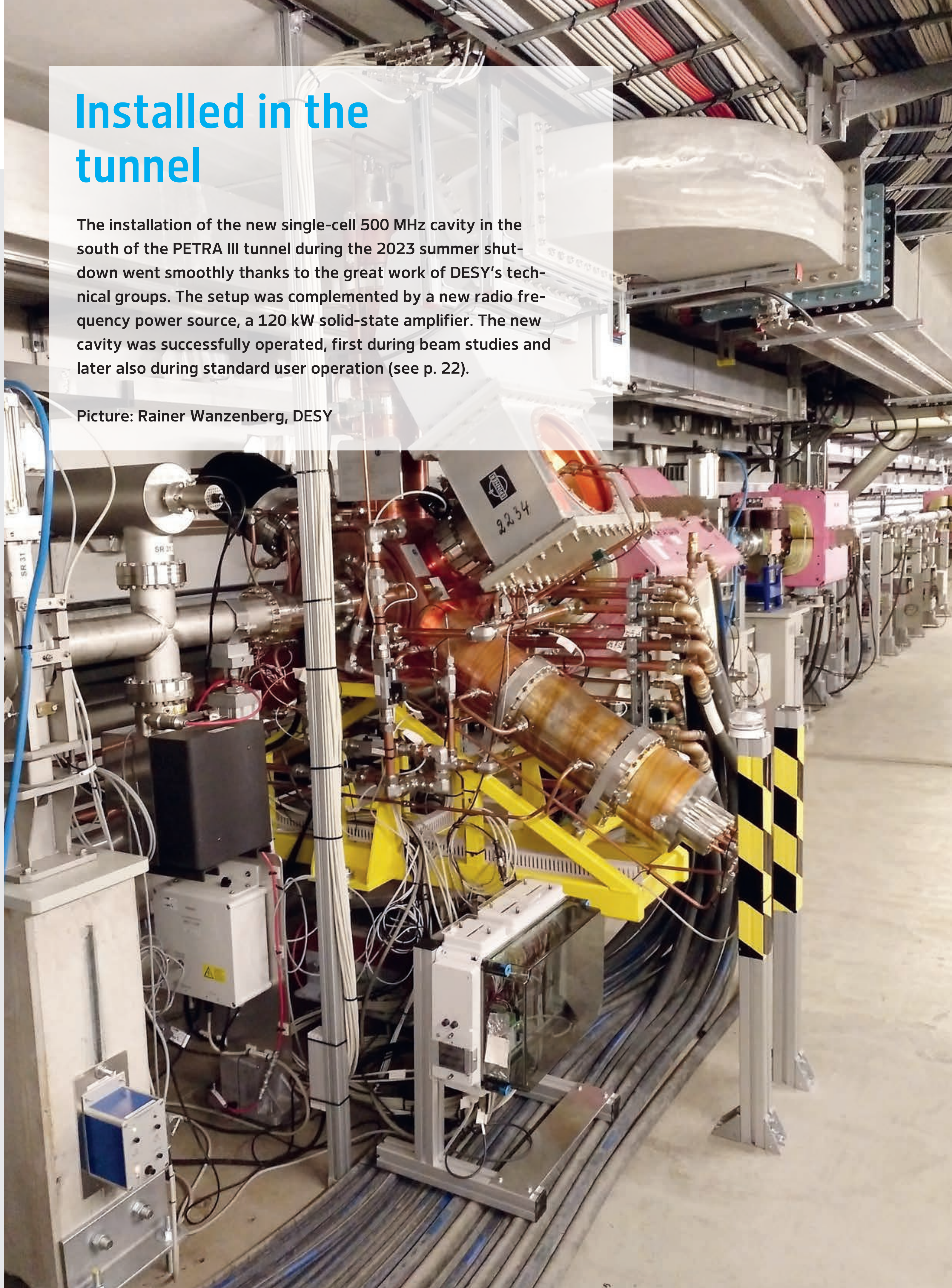


Installed in the tunnel

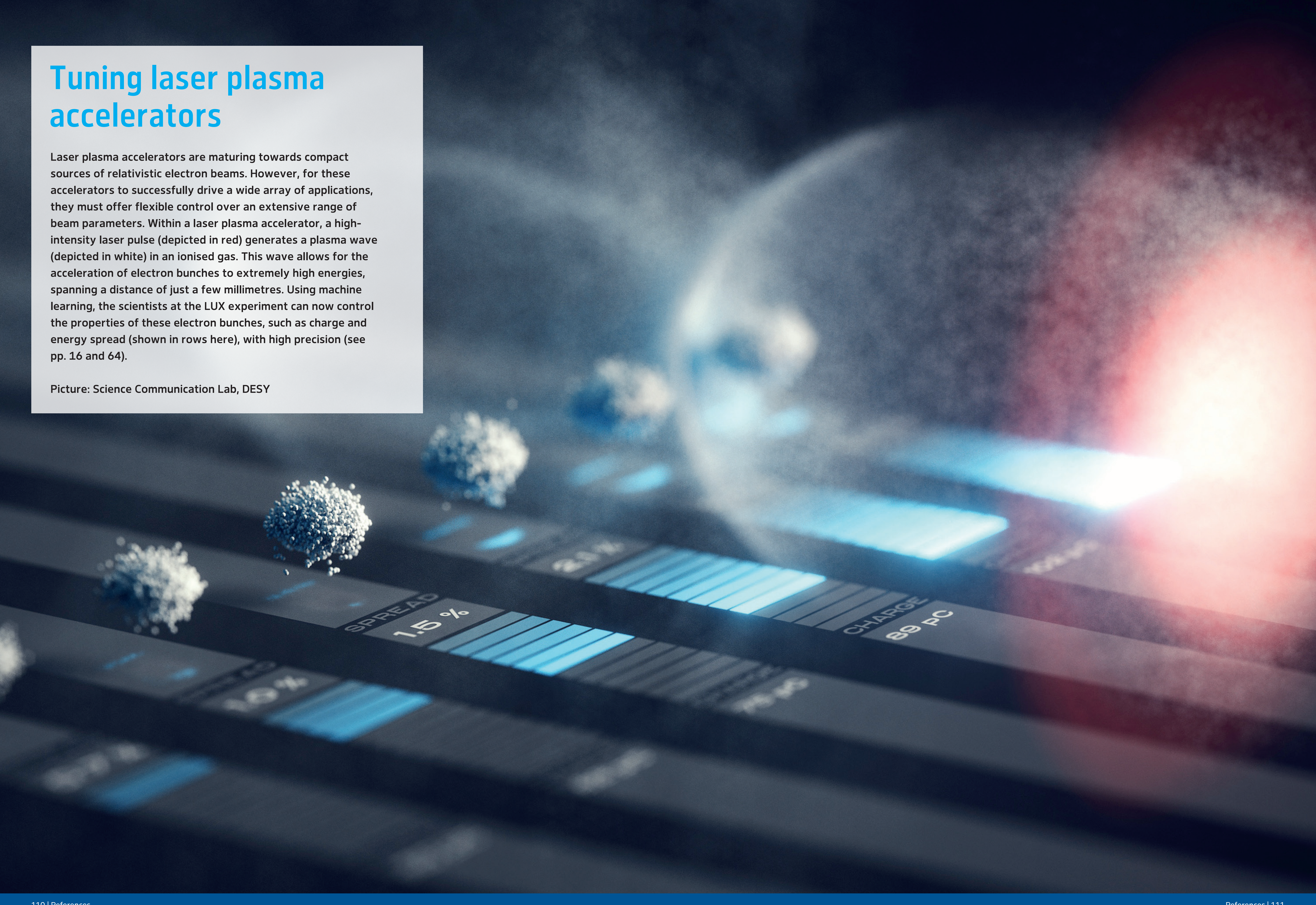
The installation of the new single-cell 500 MHz cavity in the south of the PETRA III tunnel during the 2023 summer shutdown went smoothly thanks to the great work of DESY's technical groups. The setup was complemented by a new radio frequency power source, a 120 kW solid-state amplifier. The new cavity was successfully operated, first during beam studies and later also during standard user operation (see p. 22).

Picture: Rainer Wanzenberg, DESY

Tuning laser plasma accelerators

Laser plasma accelerators are maturing towards compact sources of relativistic electron beams. However, for these accelerators to successfully drive a wide array of applications, they must offer flexible control over an extensive range of beam parameters. Within a laser plasma accelerator, a high-intensity laser pulse (depicted in red) generates a plasma wave (depicted in white) in an ionised gas. This wave allows for the acceleration of electron bunches to extremely high energies, spanning a distance of just a few millimetres. Using machine learning, the scientists at the LUX experiment can now control the properties of these electron bunches, such as charge and energy spread (shown in rows here), with high precision (see pp. 16 and 64).

Picture: Science Communication Lab, DESY



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