ACCELERATORS 2022.

Highlights and Annual Report

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

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Highlights and Annual Report

Upgrading to the next-generation synchrotron

Quadrupole magnet from DESY's synchrotron radiation source PETRA III. Such magnets are used to control the size of the electron beam that zips around the 2.3 km circumference storage ring. In the PETRA IV upgrade, these magnets will be smaller and there will be many more of them to keep the beam size as small as possible throughout the facility. This will result in 500 times brighter X-rays. Stay tuned for the future!
Picture: Michaela Schaumann, DESY

PETRA IV – anchor facility for the Science City Hamburg Bahrenfeld

Setting out into a new era of research and innovation: PETRA IV (see p. 36) is the planned upgrade of DESY’s PETRA III storage ring to the most brilliant high-energy synchrotron radiation source and a key element of the planned Science City Hamburg Bahrenfeld, which is set to foster innovation in Germany and contribute to the solution of grand societal challenges as identified by the Helmholtz Association and the German government. Areas that will particularly benefit from research at PETRA IV are health and drug development, new materials for catalysis and sustainable energy production and storage as well as new functional materials for the next generation of hardware for advanced computing and artificial intelligence.
The Hamburg Senate invited DESY to present the PETRA IV project to numerous representatives from science, politics and industry at the Hamburg City Hall in September 2022.

Picture: Daniel Reinhardt, DESY

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The year 2022 at DESY

Chairman's foreword

Dear Colleagues and Friends of DESY,

The DESY management has been working in crisis mode ever since the outbreak of the COVID-19 pandemic in March 2020. After the strains of the pandemic, the Russian war on Ukraine is now calling into question much of what we have hitherto taken for granted and posing enormous challenges. Our main concern remains the suffering people in Ukraine and the families who have fled the war with its dire human consequences.

This war now also affects research at DESY. Our current problems include the general uncontrolled price development on the energy market and in the construction sector, the enormous inflation trend and the shaky supply chains worldwide. All of these pose unprecedented challenges for the research centre that we have not known before on this scale in Europe and beyond.

In our current deliberations, we assume that we will have another three very difficult years ahead of us and will therefore have to implement massive cost-saving measures. These will include cuts in the operation of our major research infrastructures, if we do not receive financial relief, and painful personnel decisions. The DESY Directorate sees a particularly sensitive area here in the next generation of scientists and engineers, whom we must not abandon under any circumstances. However, we do not give up hope that the German government will also focus more strongly on saving the nation's future innovation potential. The current signals from politics to set up a rescue package also for science make us cautiously optimistic.

In a high-tech nation like Germany, research and innovation are the decisive – if not the only – levers to lead us out of the crisis and secure our long-term sovereignty in key technologies. Against the background of the most acute problems in energy supply, we must not forget that the main threat to our survival on this planet is man-made climate change, which we have to counter with new energy concepts. Nor must we lose sight of the constant threat of viral or bacterial pandemics. At DESY, we are all working at full speed to play our part in solving these complex challenges. This is also reflected in our strategy loop, which we are currently working on intensively – in addition to daily crisis management.

We have identified three pillars for the future development of DESY:

- The cross-divisional DESY Transformation Project (DTP), which is to prepare the future strategy of our "solution ecosystem" and which requires profound conceptual changes in how we organise research and innovation in the future
- The National Analytics Centre (NAC) with the facilities PETRA IV, FLASH2020+ and the Plasma Accelerator as well as an integrated data management structure as the core research infrastructures of DESY
- Increased focus in particle physics on medium-sized dark-matter projects on the DESY campus and exploration of new opportunities in astroparticle physics offered by the Science Data Management Centre (SDMC) of the Cherenkov Telescope Array Observatory (CTAO) and by the German Center for Astrophysics (DZA)

Sustainable concepts play a central role in all our planning. The Directorate has a clear vision for DESY's path to energy-saving and climate-friendly operation. In 2022, we published our first sustainability report, which will appear at regular intervals in the future.

In September 2022, we presented the PETRA IV project – the upgrade of our synchrotron radiation source PETRA III to a 3D X-ray microscope – to a broader public at a major event with representatives from science, politics and industry. I was very pleased that the project was also supported by Stefan Hell from the Max Planck Institutes in Göttingen and Heidelberg, a Nobel Laureate and one of the world's most renowned representatives of new microscopy concepts. On the evening of the event, he gave an impressive lecture in Hamburg's City Hall, demonstrating the innovative power that new types of high-performance microscopes can unleash.

Figure 1

The Hamburg Senate invited DESY to present the PETRA IV project at the Hamburg City Hall. From left: Nobel Laureate Stefan Hell, Hamburg Science Senator Katharina Fegebank and DESY Director Helmut Dosch.

Under the leadership of Harald Reichert and Riccardo Bartolini, the preparation of the PETRA IV project continues to make great progress. The technical design is essentially complete, and the team is currently working on the application for inclusion of the project in the German national roadmap for research infrastructures. PETRA IV will be a key building block in the transformation process of DESY that we have been designing over the past few months. The major impact of the facility will not only be due to its technical design as an interdisciplinary "discovery and solution engine" that includes AI-assisted operations, a new access model and comprehensive involvement of the broad user community. Although these will increase the construction and operational costs of the facility, the expected socio-economic impact will outweigh this investment many times over. In view of the competing Chinese High Energy Photon Source (HEPS) project in Beijing, for instance, which is already at an advanced stage, we must not lose any valuable time now in implementing the PETRA IV project.

We have noted with great pleasure the positive decision of the German Federal Ministry of Education and Research (BMBF) to realise the German Center for Astrophysics (DZA), which was prominently promoted by the European Space Agency (ESA) and DESY. On the DESY side, Christian Stegmann, Director in charge of Astroparticle Physics, and Arik Willner, Delegate of the Directorate for Innovation, were instrumental in the application. This development is a new piece of the puzzle in our 2022/2023 strategy loop, which fits perfectly into DESY's aspiration to build an international beacon in astroparticle physics at its Zeuthen site.

We live in difficult times and so does our research centre. My special thanks therefore go to the DESY staff and all our national and international users and partners for their reliable support at all times. I hope this annual report will show you that, despite the current challenges that occupy us on a daily basis, we are keeping DESY on course for a bright future development!

Yours

Helmut Dosch
Chairman of the DESY Board of Directors

Accelerators at DESY

Introduction

Dear colleagues and friends,

We have had another very productive year in the Accelerator Division. A big thanks to all the staff for their dedication and creativity – as well as their resilience in the face of our yet again highly perturbated society. Just after the worst of the COVID-19 pandemic was over, it was a great shock to all of us that a senseless war broke out in Ukraine in 2022 that continues to cause tremendous human suffering to the population of Ukraine, their families and friends. This attack led by the Russian government has significant impact on our projects and other activities as well, and damages the trustful and successful cooperations that we have had with Russian institutions for many decades. Indeed, despite DESY's long tradition of international cooperation, we have put all collaborations with Russian organisations on hold. Let me underline something that is important to me and to us at DESY: The sanctions are only directed against institutions in Russia, not against individual Russian researchers. They are a clear signal from the research centre, an expression of solidarity with the people in Ukraine and a strong message to Russia to stop the war.

Peaceful cooperation, including across national borders, is a fundamental pillar of research and thus of our work at DESY. The centre is a research innovation ecosystem with a focus on basic research, future technologies and data-based solutions, driven by major challenges to society, including climate change and digitalisation. In the course of updating the DESY 2030 strategy review, adjustments have been made to the strategy compared to the plans outlined in 2018. Our focus is now on developing data-based solutions and creating transformation pathways for a successful implementation of the revised strategy by consolidating our role as the National Analytics Centre, enabling research with X-rays, lasers and electrons, further developing accelerators and detectors and facilitating computing with state-of-the-art systems. Our core large-scale facilities are the synchrotron PETRA III with the planned upgrade PETRA IV as well as the unique hard and soft X-ray free-electron lasers (FELs) in Hamburg, the European XFEL and FLASH with the upgrade FLASH2020+.

Despite the difficult circumstances, the Accelerator Division made key achievements in 2022. The availability of our synchrotron-based light source PETRA III was more than 98% during user operation. This is an excellent result and a testimony to the diligence of the technical teams and operators in maintaining the ageing infrastructure at a very high performance level. Furthermore, PETRA III continues to provide an important prototype test platform for the planned upgrade of the facility, PETRA IV, DESY's top-priority project. The PETRA IV project proposal, which serves as the basis for the technical design report, has made great progress in 2022 and will be finalised in 2023. It includes detailed budget planning for investments and personnel as well as anticipated construction and operation costs. The synchrotron will be a hybrid six-bend achromat (H6BA)-based lattice and provide X-ray beams that are at least a factor of 500 brighter than those delivered by the present facility. This, in turn, will enable *in situ* and *operando* measurements at a rate and scale at least 500 times faster and larger, respectively, thereby strengthening Germany's competitiveness on the international scene. In addition to the technical aspects of PETRA IV relating to the accelerator complex and the beamlines, key points of the project proposal will be new usage options and services with which DESY aims to further open up to users from applied and industrial R&D.

As part of the FLASH2020+ upgrade programme, we completed the first major shutdown phase of the FLASH FEL facility, which started in mid-November 2021 and ended in mid-August 2022. In addition to necessary maintenance and conversion work on the accelerator, many new components were installed to make FLASH fit for the future. The electron energy was increased to 1350 MeV, and FEL wavelengths of 3.8 nm and shorter have been achieved. The upgrade provides many new opportunities for user experiments at FLASH in 2023 and will expand the range of materials and molecules that can be excited and studied in order to better understand catalytic or magnetic processes, for example. In October, Markus Gühr started as leading scientist of FLASH in the Photon Science Division. He was appointed professor jointly with the Department of Chemistry at Universität Hamburg and will be in charge of the scientific programme of FLASH.

European XFEL celebrated its first five years of operation in October 2022 in the presence of Judith Pirscher, State Secretary at the German Federal Ministry of Education and Research (BMBF), and Katharina Fegebank, Hamburg's Second Mayor and Senator for Science, Research, Equality and Districts. The European XFEL X-ray laser is powered by a superconducting linear accelerator operated by DESY's Accelerator Division. Thanks to the dedication of our teams, the accelerator runs very reliably and stably, with high availability, and delivers electrons with energies up to 17.5 GeV to serve the ever-varying operational needs of the facility.

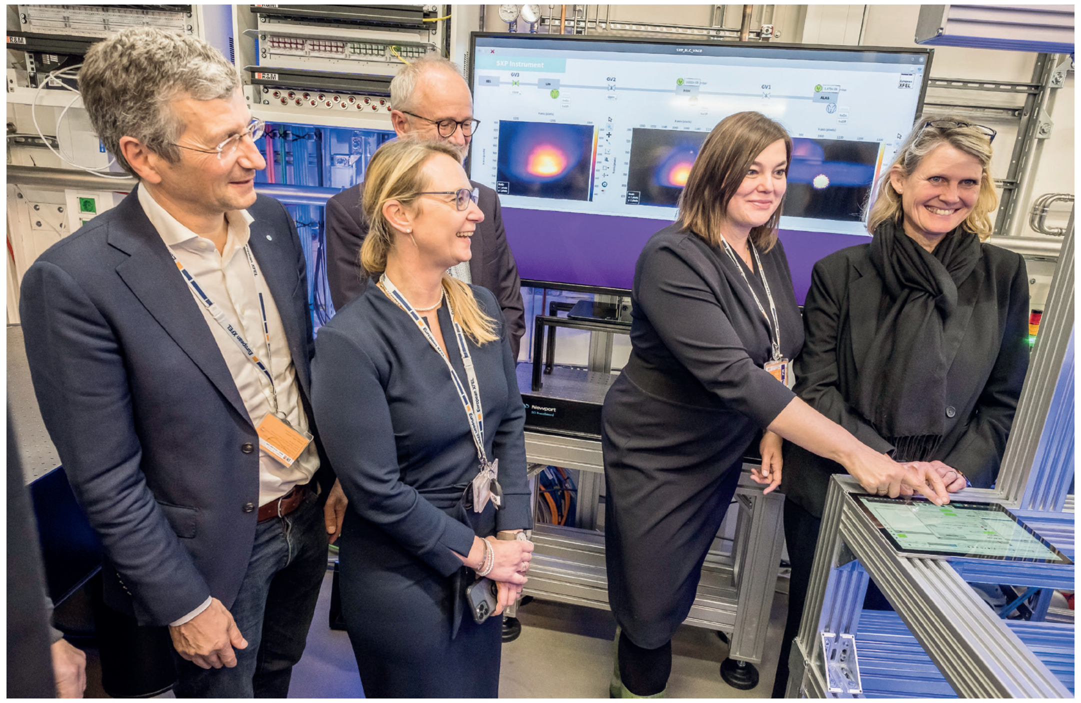


Figure 1
European XFEL celebrated its first five years of user operation in October 2022 and launched the commissioning of its new Soft X-Ray Port (SXP) instrument in the presence of BMBF State Secretary Judith Pirscher and Hamburg's Senator for Science Katharina Fegebank.

In accelerator R&D, we have made significant progress. In plasma acceleration, the focus continues to be on steadily improving the achievable beam quality to bring the technology to application maturity. A long-term plasma strategy for science, technology, applications and spin-offs as a combined approach that benefits the core missions of DESY and prepares the future is currently being developed. Our activities span plasma theory and simulation, beam-driven plasma accelerators and laser-driven plasma accelerators. Beam-driven plasma accelerators may hold the key to the future of high-energy physics and photon science with the promise to accelerate particle bunches to higher energies over shorter distances than conventional accelerators. Other elements of our R&D portfolio include superconducting radio frequency technology, computing and controls (also within the DIGITAL DESY initiative), innovative lasers and photonics, which all feed back into our user facilities.

Our R&D is embedded in national and international partnerships as well as collaborations with industry to foster innovation and attract talent. Our smaller-scale particle-based R&D tools ARES, PITZ and REGAE provide unique facilities and test bed capabilities for accelerator development and training to explore radiation biology for cancer therapy as well as ultrafast electron diffraction for bio- and quantum materials. As an example, the use of very high-energy electron (VHEE, 50–250 MeV) beams for radiotherapy and furthermore involving ultrahigh-dose-rate (≥ 100 Gy/s) delivery or *FLASH* radiotherapy (*FLASH*-RT) is currently an important medical R&D topic in many laboratories and even hospitals around the world. *FLASH* radiation therapy experiments are in preparation at both ARES and PITZ, and a beamline extension for this is being built at PITZ.

One key lesson that we have learned for 2023 and beyond is that the global economic and societal pressures – and the challenges related to our budgets – will further require the setting of priorities. As Europe's energy crisis hit science and the German government considered energy rationing and asking consumers to reduce consumption, DESY has worked on plans to mitigate and deal with a potential energy crunch and the sharp rise in electricity costs, and we have explored options to run our facilities in modes that reduce energy consumption. In addition, we are facing challenges in procuring helium and being able to afford its cost. This noble gas is essential for the operation of our cryogenically cooled superconducting accelerators and of experiments that rely on superconducting components.

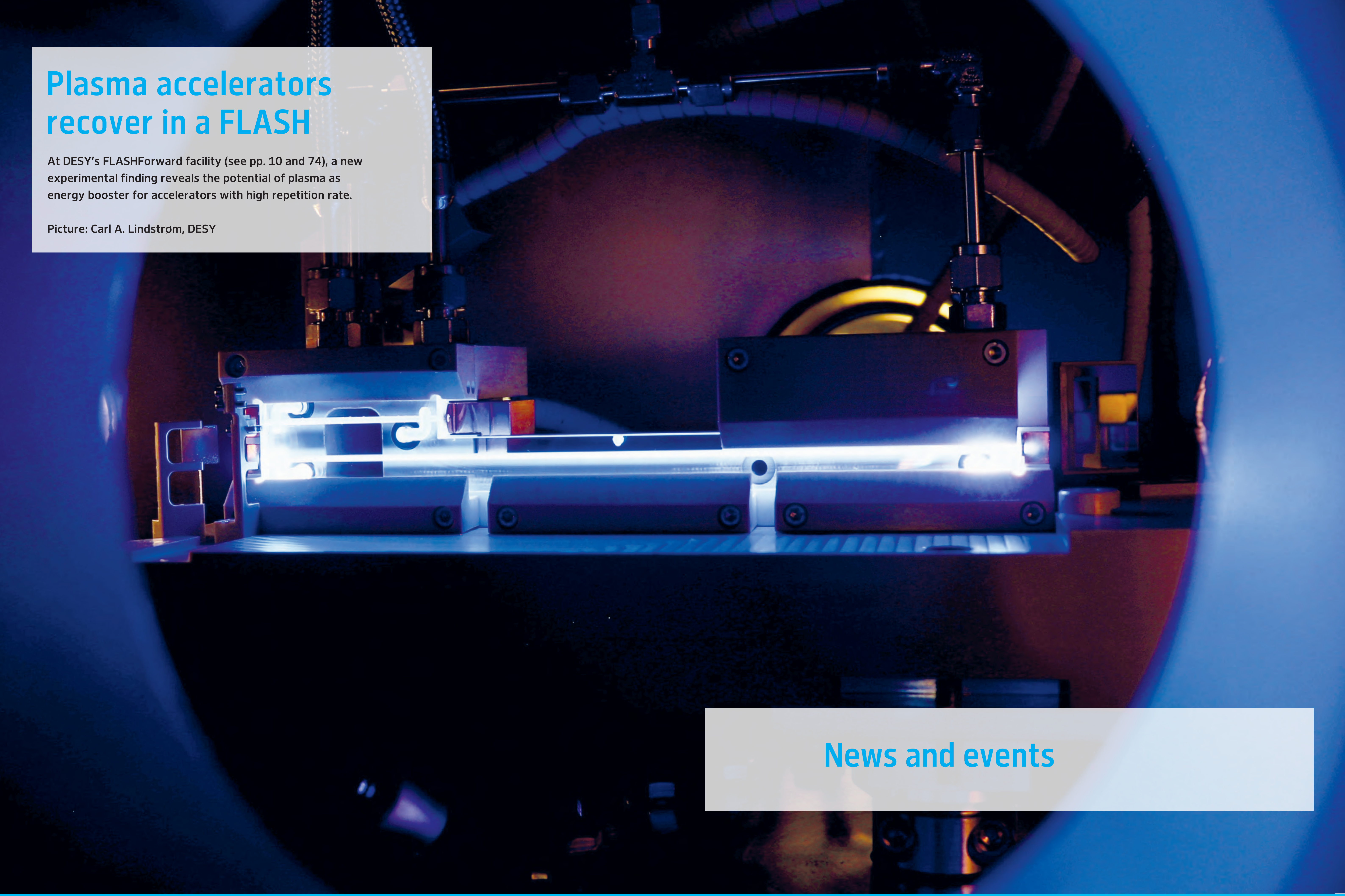
Despite all these challenges, I have full confidence that we as a division and a laboratory can rise to the challenges we face and that, through creativity and perseverance, we will continue to bring science-based solutions to society and make groundbreaking discoveries that will open new horizons.

Wim Leemans
Director of the Accelerator Division

Plasma accelerators recover in a FLASH

At DESY's FLASHForward facility (see pp. 10 and 74), a new experimental finding reveals the potential of plasma as energy booster for accelerators with high repetition rate.

Picture: Carl A. Lindstrøm, DESY



News and events

News and events

A busy year 2022

January

Drivers for cutting-edge research

The benefits of research at DESY's X-ray light sources PETRA III and FLASH and at the European XFEL for the protection of humanity and the environment were highlighted at the annual Users' Meeting, which was held as a virtual meeting in 2022 for the second time in a row. In total, more than 2000 researchers from all over the world joined the online event to discuss latest results and learn about new developments. At the meeting, the directors of DESY and European XFEL presented a joint declaration with which the two research centres intend to put themselves even more strongly at the service of solving acute societal problems, such as climate change or the COVID-19 pandemic.

Experiment at the PETRA III beamline P11

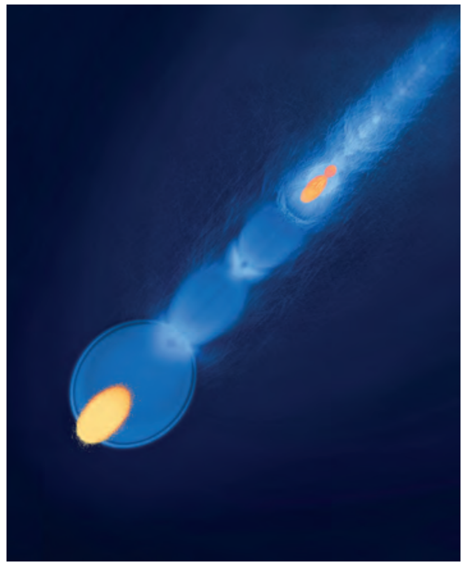
February

Plasma accelerators recover in a FLASH

At DESY's FLASHForward experiment, an international team led by DESY demonstrated for the first time that it is possible in principle to operate plasma accelerators at the repetition rates required for experiments in particle physics and photon science. This opens up the possibility to use such high-gradient accelerators as booster stages in existing high-repetition-rate facilities, such as the X-ray free-electron lasers FLASH and European XFEL, in order to significantly increase the energy of long particle trains over short distances. The team presented their results in the journal *Nature*.

Plasma acceleration is an innovative technology for the next generation of particle accelerators thanks to both its compactness and versatility, with the aim to utilise the accelerated electrons for various applications in science, industry and medicine. The acceleration takes place in an extremely thin channel – typically only a few centimetres long – filled with an ionised gas, the plasma. A high-energy laser or particle beam fired through the plasma can excite a strong electromagnetic field – a kind of "wake" – that can be used to accelerate charged particles. In this way, plasma accelerators can achieve accelerating gradients up to a thousand times higher than the most powerful accelerators in use today. They could thus drastically reduce the size of kilometre-scale facilities, such as particle colliders or free-electron lasers.

Modern accelerators for cutting-edge science must meet high requirements in terms of efficiency, beam quality and number of bunches accelerated per second. To generate a particularly large number of light flashes or particle collisions in the shortest possible time, thousands or even millions of densely packed particle bunches must be propelled through accelerators in a single second. Plasma accelerators would therefore have to achieve a similar repetition rate to be competitive with state-of-the-art particle accelerator technology. Current test facilities for plasma acceleration are usually operated at much slower repetition rates in the range of one to ten accelerations per second. The team led by DESY researchers has now proven that much higher repetition rates are possible.



Slava Ukraini!

Ever since the Russian invasion of Ukraine, DESY staff members have been very willing to help Ukrainian refugees. DESY employees got involved in many ways, e.g. by helping with administrative matters, doing shopping for the International Office, providing laptops for school classes, doing translation work or simply providing space and time for talking. DESY employees also helped by contributing money to the GoFundMe pot, from which many needed things and activities are being financed.

Horst Klein Research Award for Ferdinand Willeke

Together with the Horst Klein Foundation of Physikalischer Verein Frankfurt, the Working Group on Accelerator Physics of the German Physical Society (DPG) awarded Ferdinand Willeke the Horst Klein Research Prize 2022 for outstanding scientists in accelerator physics. Willeke was a leading scientist in the Accelerator Division until 2007.

Ferdinand Willeke

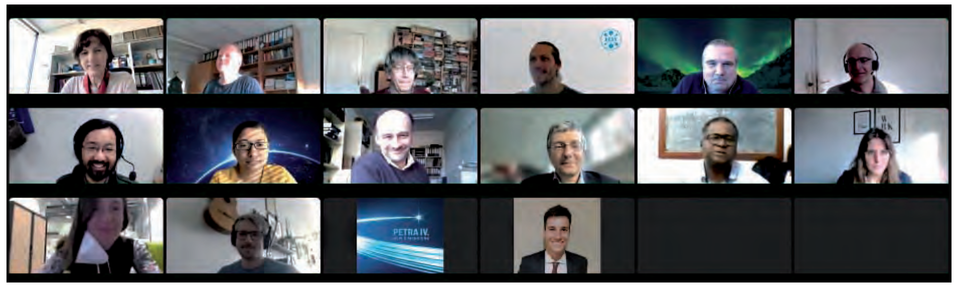
Reinforcement for DESY's future project PETRA IV

DESY arranged with the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, for Harald Reichert to further strengthen the PETRA IV project, the planned upgrade of DESY's PETRA III synchrotron radiation source. Harald Reichert was Director of Research in Physical Sciences at ESRF from 2009 until the end of 2021. He now supports the PETRA IV team in the creation of the technical design report for the project.

From left: Edgar Weckert, Riccardo Bartolini, Harald Reichert, Christian Schroer and Wim Leemans

WE-Heraeus seminar on novel light sources

More than 90 scientists from universities and research institutions from many countries around the world attended the 762^{nd} WE-Heraeus seminar on "Diffraction Limited Synchrotron Light Sources and Next Generation Free Electron Lasers". It took place at the Physikzentrum in Bad Honnef in Germany from 7 to 11 March. This WE-Heraeus seminar – in a hybrid format – addressed the scientific opportunities opened by modern accelerator-based light sources as well as the technical issues, on the side of both accelerators and experiments, to develop this field even further. The scientific organisers were Robert Feidenhans'l (European XFEL), Wim Leemans and Edgar Weckert (DESY).



April

Brandenburg's Research Minister Manja Schüle visits Hamburg campus

The good relationship between the Ministry of Science, Research and Culture of the German federal state of Brandenburg and DESY became even closer in April. After visiting DESY in Zeuthen in Brandenburg, Research Minister Manja Schüle came to Hamburg to learn more about research at DESY in an exchange with the DESY Board of Directors and during a tour of the research facilities.

Brandenburg's Research Minister Manja Schüle on her tour of the DESY campus in Hamburg

Three research ministers open Centre for X-ray and Nano Science at DESY

Research Ministers Katharina Fegebank, Karin Prien and Bettina Stark-Watzinger at the opening of the CXNS at DESY

It's a symbol of cutting-edge research: No fewer than three research ministers opened the Centre for X-ray and Nano Science (CXNS) at DESY on 12 April. German Federal Research Minister Bettina Stark-Watzinger, Hamburg's Senator for Science Katharina Fegebank and Schleswig-Holstein's Minister of Education Karin Prien handed over the keys to the new research building to its new occupants: Kiel University (CAU), the Helmholtz Centre Hereon and DESY.

The CXNS is a one-of-a-kind, multi-institutional, interdisciplinary platform for research using X-rays in combination with nano and materials sciences. The centre benefits from its proximity to the high-brilliance X-ray source PETRA III and will provide a home for further collaborative projects. The CXNS also houses the DESY NanoLab, DESY's centre for nano research, whose technically sophisticated laboratories provide ideal conditions for structuring, manufacturing, characterising and labelling nanospecimens. These are then studied with the high-intensity X-rays of the light sources PETRA III, FLASH and the European XFEL.

How inspiration by nature can help us improve vibration properties

Marine biologist Simone Andresen was awarded the Helmholtz Doctoral Prize for mission-oriented research in the Helmholtz research field "Earth & Environment" for her PhD work at the Alfred Wegener Institute (AWI), Helmholtz Centre for Polar and Marine Research in Bremerhaven, in cooperation with DESY's Accelerators and Experiment Setup group. She was honoured for her work on the influence of bio-inspired structures on the vibrational properties and the development of the girder structure for DESY's future project PETRA IV.

The team of physicists, biologists and engineers developed various novel girder prototypes inspired by nature, based on the structural principles of tiny aquatic plankton organisms, for low-vibration, lightweight constructions as support frames for the PETRA IV magnet optics. However, the shape of the prototype ultimately depends on the magnet optics that are being developed in parallel, and manufacturing costs also play a role.

Multiple awards for accelerator physicist Sarah Schröder

For her excellent PhD thesis in plasma accelerator physics, DESY scientist Sarah Schröder was awarded the Doctoral Prize of the German Physical Society (DPG) in the section "Matter and Cosmos" as well as the Helmholtz Doctoral Prize for mission-oriented research in the Helmholtz research field "Matter". The Helmholtz Association awards the prize to young scientists who combine the search for knowledge and possible applications in their research.

Helmholtz President Otmar Wiestler handing over the award to Sarah Schröder

May

Andreas Maier becomes leading scientist at DESY

Laser plasma acceleration is a disruptive technology for a new generation of particle accelerators that will not only be very compact, and therefore economical to build, but also highly versatile. To drive the development of laser plasma acceleration and get it ready for practical applications, DESY appointed the physicist Andreas Maier as leading scientist in the field of lasers and secondary sources. The KALDERA project headed by Maier aims to build a new high-power laser to pave the way for plasma acceleration applications. The main focus is on a particularly high repetition rate of up to 1000 laser pulses per second. This will make it possible to quickly detect any deviations in performance and to actively counteract them.

Andreas Maier and colleague Kaja Schubert in the tunnel of the LUX laser plasma accelerator at DESY

Intelligent control of accelerators

DESY and the Hamburg University of Technology (TUHH) have been cooperating for a long time in many different research areas. The joint appointment of DESY researcher Annika Eichler for a W2 professorship at TUHH consolidates and expands this cooperation to include a new research topic: data analysis and control of accelerator systems with the help of artificial intelligence. This is the second joint appointment with TUHH and the first from DESY's Accelerator Division.

Since 2019, Annika Eichler has been a member of DESY's Beam Controls group, which is responsible for the fast control of various accelerator parameters, the synchronisation of all components and special systems for beam diagnostics.

DESY control theorist Annika Eichler now also holds a professorship at the Hamburg University of Technology.

WE-Heraeus seminar on plasma-based accelerators

From 15 to 18 May, over 90 researchers from universities and research institutions across the world attended the 767th WE-Heraeus seminar on "Science and Applications of Plasma-Based Accelerators" at the Physikzentrum in Bad Honnef. The participants reviewed and discussed recent breakthroughs and the applications to which the various plasma-based acceleration systems can contribute, as well as the main technological challenges for which solutions must be found to make these systems viable. The scientific organisers were Allen Caldwell (Max Planck Institute for Physics, Munich), Wim Leemans and Jens Osterhoff (DESY).

Innovation and research for breakfast with members of the Federal Parliament

Together with the Helmholtz Centres Berlin (HZB) and Dresden-Rossendorf (HZDR), DESY devised a national strategy for the further development of accelerator-based light sources. The directors of the three centres presented their strategy to invited members of the German Federal Parliament in the rooms of the German Parliamentary Society in Berlin on 13 May.

May

Measuring WAVEs for science

For the first time, researchers from Universität Hamburg, DESY and the Helmholtz Centre Potsdam (GFZ) used a fibre-optic network to measure ground vibrations and oscillations on the DESY campus in Hamburg-Bahrenfeld and analyse their causes. In their demonstration study of the novel measurement method, the researchers from the WAVE collaboration describe how sensitively such a seismic network can measure the effects of seismically transmitted disturbances. The study also includes ideas for building a seismic network as part of the research infrastructure on campus.

Using a fibre-optic network, the WAVE collaboration measured vibrations caused by a vibrotruck on the DESY campus.

First Diversity Day at DESY

After signing the Diversity Charter in 2021, DESY celebrated its first Diversity Day on 31 May – a nationwide day of action launched by the "Charta der Vielfalt" association. For DESY, diversity in the work context means an appreciative and conscious approach to difference and individuality with regard to factors such as gender, origin, age, sexual orientation as well as physical and mental abilities.

June

Colloquium in honour of Albrecht Wagner's 80th birthday

Albrecht Wagner at the colloquium held in his honour

Happy birthday, Albrecht Wagner! On 16 June, DESY celebrated the 80th birthday of its long-time director with a scientific colloquium. In his many years at DESY, Wagner contributed significantly to the scientific successes and the national and international reputation of the research centre. In 1991, he was appointed Director of Research at DESY. From 1999 until 2009, he served as Chairman of the DESY Board of Directors.

Wagner played an important role as leader of several international consortia, e.g. as Chairman of the TESLA Technology Collaboration Board and of the International Committee for Future Accelerators (ICFA). The landmark decisions on the TESLA superconducting accelerator technology and the European XFEL X-ray free-electron laser were made under his leadership.

Science on tap – return to the pubs!

How loud was the big bang? Man flu – fairy tale or truth? Or: What does the dosage of drugs have to do with beer foam? At the "Science on tap" event, researchers from Universität Hamburg and DESY give answers to exciting questions from their research. After a pandemic-related break, the entertaining lectures finally took place live again in more than 20 Hamburg pubs. Cheers!

July

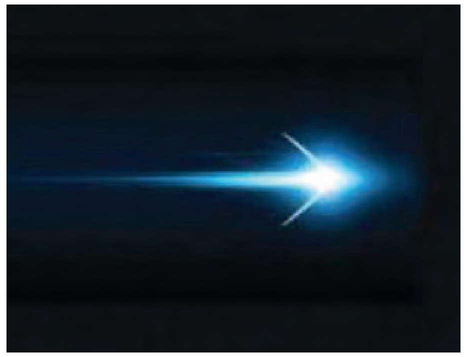
DESY wins Hamburg 2040 award

DESY received the first Hamburg 2040 award at the premiere of the Hamburg Business Summer Festival. With this award, the Hamburg Chamber of Commerce honours companies, institutions or individuals who are actively shaping the future of the city of Hamburg, demonstrating innovative strength and advancing the region in line with the Hamburg 2040 location strategy developed by the Chamber of Commerce.

The DESY Board of Directors at the Hamburg 2040 Award ceremony, together with Norbert Aust, President of the Hamburg Chamber of Commerce (left), and Andreas Dressel, Finance Senator of the City of Hamburg (right)

Strategy update: DESY gets fit for the future

With a first meeting on 4 July, DESY started a comprehensive update of its DESY 2030 strategy, setting the course for a successful future at the forefront of research. The goals fixed in the DESY 2030 strategy in 2018 needed to be sharpened to incorporate current challenges – such as advancing climate change, the new threat to society from pandemics and the digital transformation – even more strongly and visibly into future planning. The strategy update is to be presented in autumn 2023. For DESY, this will form the basis for the scientific planning and application for the fifth round of the Helmholtz Association's programme-oriented funding (PoF V).



August

Summer students from around the world try their hands at research

Ever wanted to characterise digital cameras for beam diagnostics? Get functional cellulose lignin coating on porous materials underway or work on machine learning techniques for laser plasma acceleration? These were just a few examples of the many different hands-on research experiences that were possible in the 2022 DESY summer student programme. After cancellation in 2020 due to the pandemic and one year of very restricted hybrid summer student programme in 2021, a total of 84 students from around the world took part in the 2022 DESY summer student course, working on real research projects either in person or remotely.

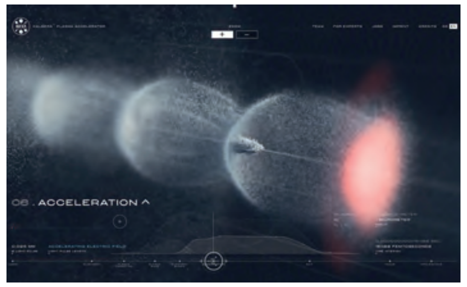
First lasing of THz free-electron laser at PITZ

The PITZ photoinjector test facility at DESY in Zeuthen reached a major milestone: A free-electron laser (FEL) driven by the photoinjector generated its first laser light in the terahertz (THz) wavelength regime. Pulses with a wavelength of about 0.1 millimetres were produced with a repetition rate of up to one megahertz. The laser is the first high-power THz FEL worldwide working according to the SASE principle, the self-amplification of spontaneous emission. It will now be used to characterise the properties of the intense radiation for a possible future application at the European XFEL X-ray laser.

PITZ facility at DESY with the new terahertz FEL

Lightspeed at a mouse click

Besides operating various accelerator facilities, DESY is also working on promising concepts for the future, such as laser plasma acceleration, in order to build facilities that are significantly more compact, space-saving and cost-effective than today's large-scale accelerators. An elaborate visual animation of the KALDERA project demonstrates how this innovative technique works: Viewers can watch interactively and in detail how powerful laser pulses are used to generate electron beams that travel at nearly the speed of light and are tremendously useful in research. *https://kaldera.desy.de/*



September

Record: Electronic noise measured more precisely than ever before

Louise Springer and Uroš Mavrič with their prototype for testing electronic components

A team from DESY's Beam Controls group measured phase noise for the first time with 500 times greater precision than was achievable in this frequency range before. This will enable breakthroughs in medicine, telecommunications and accelerator technology.

Our world would be unthinkable without radio frequency (RF) technology – everywhere, these short-wavelength electromagnetic oscillations ensure that information is transmitted and processed. With increasing information density, however, susceptibility to interference such as noise – "impurities" in the oscillations caused by electronic components, for example – increases. The RF oscillations used in particle accelerators must be as low-noise as possible to make the acceleration as efficient and reproducible as possible.

The team designed a prototype detector that is able to measure the electromagnetic field of superconducting cavities, such as those used in the European XFEL accelerator, with an unparalleled time resolution of 10 attoseconds, thus determining the noise in the fundamental frequency more than 500 times more accurately than possible before. The group plans to further develop its detector together with an industrial partner in order to improve RF electronic components, which are used not only in science but also in industry, telecommunications, radar applications and space exploration.

PETRA IV – Setting out into a new era of research and innovation

How can we preserve our ecosystems and save resources? How can we fight infectious diseases? To help us answer such questions, the world's best X-ray microscope is to be built on the DESY campus in Hamburg. The upgrade of DESY's PETRA III synchrotron radiation source to PETRA IV will provide 3D images of the nanocosm and offer insights into materials and biological structures with unprecedented precision – from the structure of pathogens through catalysts to innovative microchips and quantum materials. PETRA IV will also be an anchor facility for the Science City Hamburg Bahrenfeld. The Hamburg Senate invited DESY to present the project to representatives from science, politics and industry at the Hamburg City Hall on 13 September.

Before the reception, a symposium attended by around 150 guests was held at DESY to mark the kick-off of the PETRA IV campaign. The talks and roundtable discussions illustrated how PETRA IV's outstanding analytical facilities will provide researchers from a wide range of disciplines – from physics, chemistry and biology through medicine, engineering and geosciences to art and cultural research – with unprecedented insights and help companies develop their innovations. Scientists discussed how the planned 3D X-ray microscope will help solve global challenges. The analytical research carried out at PETRA IV is expected to contribute decisively to identifying solutions for a climate-friendly and sustainable economy that preserves natural resources.

In a recent study, DESY examined which technology trends are expected in the coming decades. Together with extensive workshops with scientists, these will serve as guidelines for tailoring the analytical methods and tools provided by PETRA IV to the needs of research and industry. For example, it will be possible to study catalysts, functional materials or the emergence of corrosion under natural and near-natural conditions in 3D, live and on all relevant space and time scales. DESY will offer researchers from science and industry additional services associated with the available analytical techniques, such as sample preparation, data storage and analysis.

The symposium was followed by the Senate reception at the Hamburg City

Hall, in the presence of Katharina Fegebank, Hamburg's Second Mayor and Senator for Science, and Nobel Laureate Stefan Hell, Director at the Max Planck Institute for Multidisciplinary Sciences in Göttingen and the Max Planck Institute for Medical Research in Heidelberg, who emphasised the role of science as a driver for innovation and transfer in his keynote address.

PETRA IV symposium at DESY with representatives from science and industry

Senate reception at the Hamburg City Hall to present the PETRA IV project, with Hamburg's Senator for Science Katharina Fegebank and Nobel Laureate Stefan Hell as keynote speaker

FLASH shutdown successfully completed

The nine-month shutdown of DESY's FLASH free-electron laser (FEL) facility was completed in August with warm commissioning of the superconducting accelerator modules, followed by cooldown to 2 K to be ready for operation. In parallel, the radio frequency (RF) electron source (gun) was restarted, and first beam for accelerator commissioning was achieved on 3 October.

The first phase of the FLASH2020+ upgrade project and other important refurbishments resulted in a new layout of the cryogenics, the injector and linear accelerator section. Two new superconducting accelerator modules increased the electron beam energy by 100 MeV. The bunch compression system was upgraded to improve the electron beam parameters. A refurbishment of the master RF oscillator, the synchronisation and phase stabilising system and the longitudinal diagnostics significantly improved the stability of the beam. A new laser heater system was installed to smooth the electron beam phase space as required for the next FLASH2020+ project step, external seeding. The commissioning phase to recover the FEL radiation in both beamlines, FLASH1 and FLASH2, was tense, but thanks to the enormous efforts of the FLASH crew, first photon science experiment could start as planned on 7 November.

A barbecue lunch party was organised to thank all those who contributed to the success of the FLASH shutdown work.

Carl Lindstrøm receives Simon van der Meer Accelerator Award

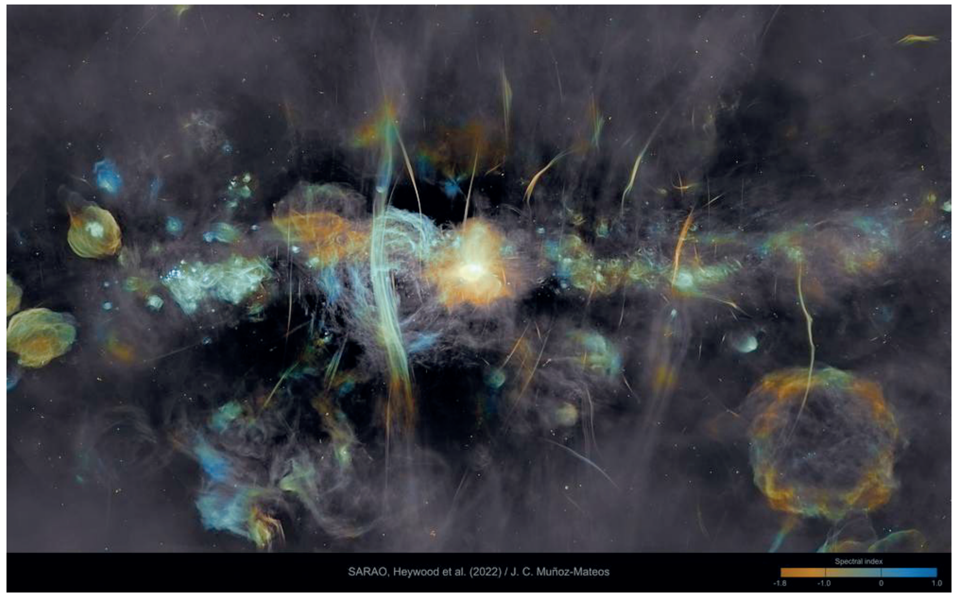
Carl A. Lindstrøm was awarded the Simon van der Meer Early Career Award in Novel Accelerators. The young accelerator physicist, who worked as a postdoctoral researcher in DESY's FLASHForward project, was honoured for "numerous outstanding experimental and theoretical contributions to the field of beam-driven plasma accelerators, including the demonstration of beam quality preservation and efficient acceleration, the investigation of advanced beam transport concepts, and the invention of self-stabilizing multistage acceleration".

Simon van der Meer Early Career Award winner Carl Lindstrøm

BMBF State Secretary Judith Pirscher visits DESY

BMBF State Secretary Judith Pirscher (left) and Hamburg's State Councillor for Science Eva Gümbel (right) at DESY's PETRA III synchrotron radiation source

Judith Pirscher, State Secretary at the German Federal Ministry of Education and Research (BMBF), accompanied by Hamburg's State Councillor for Science Eva Gümbel, visited DESY in Hamburg to learn about the research centre's current projects and plans for the future. Her conclusion after the visit: "Basic research on large-scale facilities, such as that carried out at DESY, is an innovation driver and a source of impetus, for example in climate protection or the development of new therapeutic agents. In view of today's pandemic, geopolitical and economic challenges, we need it more than ever."

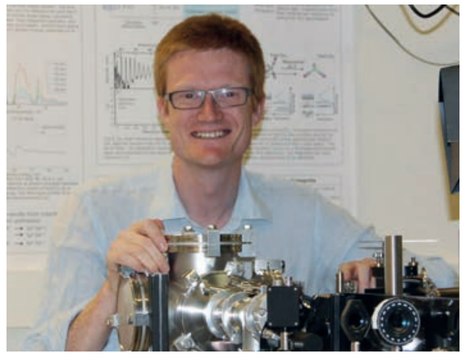


German Center for Astrophysics to be built in Lusatia

The German Center for Astrophysics (DZA) will be located in the Lusatia region in the German federal state of Saxony. Together with the Center for the Transformation of Chemistry, the DZA proposal won the competition "Knowledge Creates Perspectives for the Region" of the German Federal Ministry of Education and Research (BMBF) and the federal states of Saxony and Saxony-Anhalt. DESY played a key role in preparing the initiative: The project office was based at DESY and Astroparticle Physics Director Christian Stegmann was one of the DZA's applicants. The DZA is a joint initiative of astronomy and astroparticle physics in Germany.

October

Markus Gühr becomes leading scientist of FLASH



Markus Gühr, the new head of FLASH

On 1 October, Markus Gühr started as leading scientist of DESY's FLASH facility. The X-ray laser expert, who was appointed professor jointly with the Department of Chemistry at Universität Hamburg, is in charge of the world's first self-amplified spontaneous emission (SASE) X-ray laser, which has been in operation as a user facility since 2005 and is currently being made fit for the future with the FLASH2020+ upgrade project.

Volker Soergel

Volker Soergel (1931–2022)

DESY mourns the death of Volker Soergel, long-time Chairman of the DESY Board of Directors and pioneer of the united DESY with its locations in Hamburg and Zeuthen. Soergel passed away on 5 October at the age of 91. He was one of the great visionaries of the research centre and key in shaping DESY as it is known today.

Under his 12-year leadership, the electron–proton collider HERA progressed from a proposal to a funded project and was completed on time and within budget. At the time, HERA was the largest basic-science project in Germany. Soergel and his successor Bjorn H. Wiik launched the "HERA model" of international cooperation – a major breakthrough in the financing and organisation of large-scale research projects that became a model for the implementation of many other international facilities.

Soergel was also a driving force behind the successful merger of the Institute for High Energy Physics (IfH) of the Academy of Sciences of the GDR in Zeuthen with DESY on 1 January 1992 after the end of the German Democratic Republic (GDR). The institute thus became the DESY site in Zeuthen with its unique research profile centring on astroparticle physics with a focus on gamma-ray and neutrino astronomy, parallel computing for theoretical particle physics as well as the development and construction of electron sources for X-ray lasers.

European XFEL celebrates five years of user operation

European XFEL celebrated its fifth anniversary of user operation and launched the commissioning of its new SXP instrument in the presence of BMBF State Secretary Judith Pirscher, Hamburg's Senator for Science Katharina Fegebank and around 150 guests and staff members. The facility was officially opened to operations on 1 September 2017 and has since been the most technologically advanced X-ray laser worldwide, with users from across the world taking advantage of its unique research opportunities.

The European XFEL delivers high-energy X-ray flashes at a repetition rate of 27 000 pulses per second in an X-ray laser beam that can be focused down to a diameter of just 11 nanometres, roughly the size of a protein molecule. The large number of pulses per second makes the European XFEL currently unique in its class, enabling a higher rate of data acquisition than at any other large X-ray FEL.

European XFEL and guests celebrated five years of user operation and started the commissioning of the new SXP instrument.

In the five years since user operation began, the European XFEL community has had to deal with numerous challenges, the war in Ukraine and the COVID-19 pandemic being just two. But the collaboration and trust of the users, partners, staff members and the entire European XFEL community has been one of the major strengths of the company. After reaching the milestone of five years of operation, the facility will continue to grow. European XFEL is now entering a phase of "harvesting" – i.e. reaping the rewards of many years of ramp-up. It will produce an increasing number of exciting experimental results and continue to expand its instrumentation and capabilities so that even more users can benefit from the facility. The company will also sharpen its strategic focus towards science that addresses society's biggest challenges – from climate and energy through digitalisation to the environment, sustainability and health.

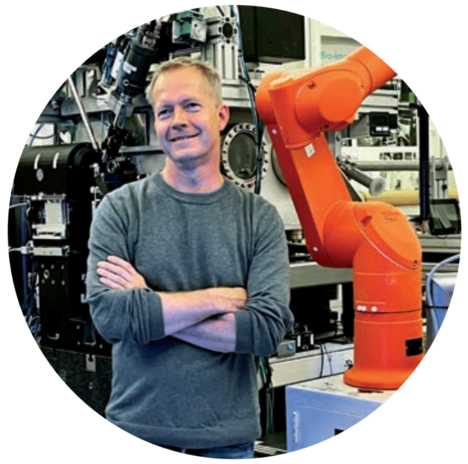
November

Strengthening international ties

On 31 October and 1 November, leaders in scientific research and government, mainly from Europe and the USA, came together in Washington, DC, for the Transatlantic Big Science Conference. At the initiative and invitation of DESY and the US research foundation Carnegie Science, participants discussed highly topical issues relating to international research cooperation in order to jointly develop solutions for the challenges of our time.

Alke Meents receives Bjørn H. Wiik Prize

During the early stages of the COVID-19 pandemic, DESY physicist Alke Meents launched a promising and internationally acclaimed research project at DESY's PETRA III X-ray source in search of a drug against the new coronavirus. By April 2021, 37 active substances had been identified, a result that was published in the journal *Science*. In November 2022, Alke Meents was awarded the Bjorn H. Wiik Prize for his outstanding achievements, which go far beyond this project. Meents is now putting a lot of energy into his new project: the electron accelerator REGAE, whose ultrashort electron pulses are used to examine various samples.



Alke Meents at the PETRA III beamline P11

November

DESY Science Day 2022

On 23 November, DESY celebrated excellent research, outstanding developments and lifetime achievements, welcomed newly appointed staff members and recognised long-time personal merits of its employees.

The new DESY Exceptional Achievements Award, which recognises outstanding accomplishments in engineering and technology, went to Burcu Yildirim, Yasmin Nachtigal and Valery Katalev from the Radiofrequency Technology for Accelerators group. In exemplary teamwork, they contributed to the success of the European XFEL X-ray laser by developing innovative and world-leading RF technology, the "waveguide tailoring" method, in particular with regard to achieving the 17.5 GeV design energy of the facility. A second award went to Frauke Poblotzki for her work on a CO_2 cooling method for silicon detectors.

Some of the award winners at the DESY Science Day 2022

Ke Li represented the Accelerator Division in the scientific highlights session.

Alke Meents received the Bjørn H. Wiik Prize (see previous page), and the PhD Thesis Prize of the Association of the Friends and Sponsors of DESY (VFFD) was awarded in equal parts to Sarah Schröder for her thesis on the external injection of electron beams into plasma wakefield accelerators and to Andrea Cardini for his thesis with the CMS experiment at the LHC particle collider.

For the second time, four scientists from DESY's research divisions presented the scientific highlights of the year. For the Accelerator Division, Ke Li, a PhD fellow of the DASHH data science graduate school programme working in a collaboration between the Human–Computer Interaction group at Universität Hamburg and the Accelerator Control System group at DESY, presented her work on novel mixed-reality technology and 3D user interfaces for operating particle accelerators and high-power laser facilities.

No violence!

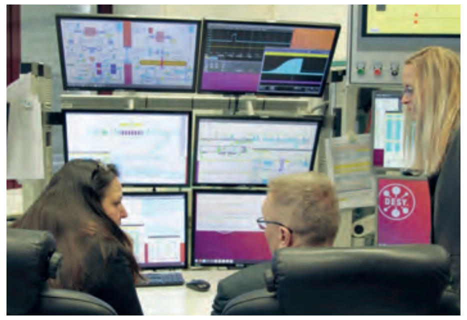
It is appalling that this is still an issue – violence against women. On the International Day for the Elimination of Violence against Women on 25 November, DESY set a sign by making the campaign colour orange the colour of the campus.

FLASH experimental hall illuminated in orange on the International Day for the Elimination of Violence against Women

Official opening of terahertz free-electron laser at PITZ

Brandenburg's Research Minister Manja Schüle officially opened the new terahertz free-electron laser (THz FEL) at the PITZ photoinjector test facility at DESY in Zeuthen on 28 November. The THz FEL could pave the way for new research in a variety of scientific fields, from studies of quantum materials to investigations of biomolecules, for example at the European XFEL X-ray laser. Minister Schüle was joined by Christian Stegmann, Head of DESY's Zeuthen site, Thomas Tschentscher, Scientific Director at European XFEL, and other partners of the project.

Research Minister Manja Schüle (centre) opened the new terahertz FEL in the tunnel of the PITZ facility.



Manja Schüle (left) in the PITZ control room at DESY in Zeuthen

The new THz FEL generated its first light in August. It delivers wavelengths around 0.1 millimetres, about 100 times longer than the wavelengths of visible light. The next step will be to show that it is possible to develop and install a similar THz FEL at the European XFEL. This would enable new experiments that combine the long-wavelength THz radiation with the European XFEL's short-wavelength X-rays. The THz radiation would be used to transform or "pump" matter, including single molecules, into new states that are otherwise not accessible. These would then be probed with the European XFEL's X-ray pulses, revealing how they evolve over time.

December

IEEE Laser Award for Franz Kärtner

DESY researcher Franz Kärtner was awarded the Laser Instrumentation Award by the Institute of Electrical and Electronics Engineers (IEEE) Photonics Society. The group leader at the Center for Free-Electron Laser Science (CFEL) at DESY was recognised for the development of laser technology that uses ultrashort laser flashes to synchronise large-scale research facilities, such as DESY's FLASH and the European XFEL X-ray laser, with femtosecond precision, even over kilometre lengths. This extremely high accuracy is required, for example, to record movies of chemical reactions at such facilities.

Franz Kärtner (left) received the IEEE Laser Instrumentation Award.

DESY publishes its first sustainability report

DESY's first sustainability report entitled "Providing impulses. Doing sustainable research." for the period 2019–2021 was published in December. In addition to presenting reliable figures, concrete activities, interim goals and interesting ideas, the 36-page document features inspiring stories about the people on the campus who are behind the main projects and sustainable strategies. The clear message is: DESY is on the right track.

Keeping DESY´s facilities at the forefront

Two new superconducting accelerator modules installed in the FLASH linear accelerator provide enhanced overall performance.

Picture: Siegfried Schreiber, DESY

Accelerator operation and construction

PETRA III

User operation with high availability and studies for PETRA IV

In 2022, DESY's synchrotron radiation source PETRA III achieved a very high availability of more than 98% during user operation. In total, 4896 h of beamtime were scheduled for the user run, complemented by 1040 h of beamtime for setting up user experiments. In addition, studies were conducted to improve user operations and support the technical design of the upgrade project PETRA IV: In the winter shutdown, a method was tested to improve the mechanical stability of the accelerator tunnel, and prototype diagnostic equipment for PETRA IV was installed and tested in the summer shutdown. Furthermore, a series of tests was performed to reduce the electric power consumption of the PETRA III accelerator complex.

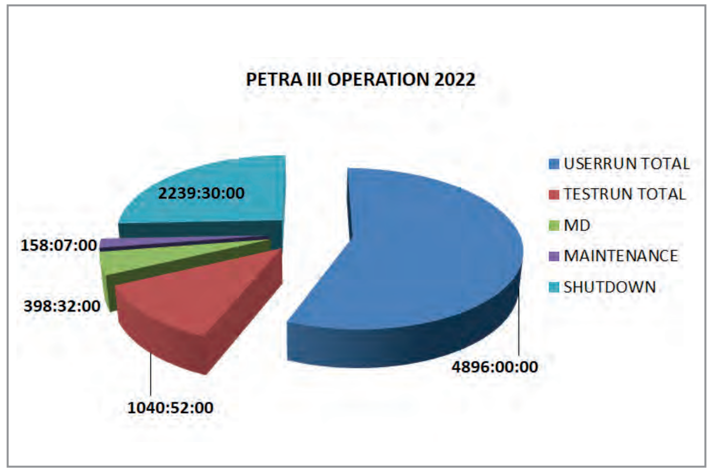


Figure 3

Distribution of the different PETRA III machine states in 2022

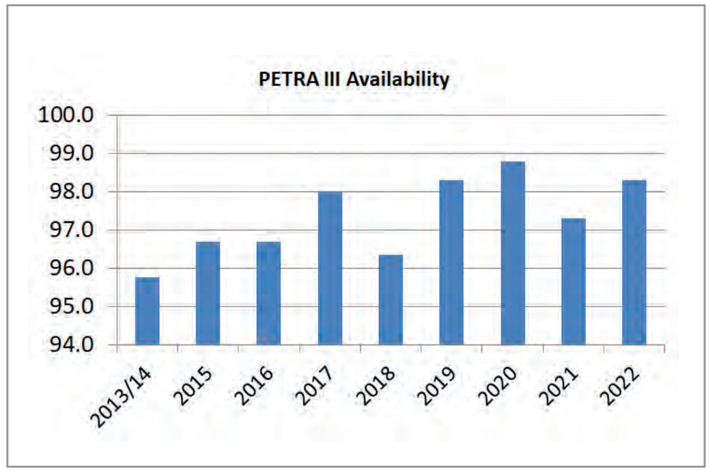


Figure 4

Long-time development of the availability of PETRA III

Studies for the technical design of PETRA IV

In 2022, several activities at PETRA III aimed to support the technical design of PETRA IV, including beam dynamics studies, tests of new equipment as well as improvements and tests of the stability of the existing PETRA III tunnel. The PETRA tunnel, constructed in 1976, is made of individual tunnel segments of mostly 24 m in length. Today, cracks in the walls and floor mark the connection points of the tunnel segments, clearly indicating that the segments move against each other. In several places, the displacement is monitored by special movement sensors. In the winter shutdown 2021/22, the connection between segments in the south-west of the tunnel was stabilised by reinforcement rods and injection of a special resin through the tunnel ground plate into the soil underneath. A view of the stabilised segment transition is shown in Fig. 1. Thirty sealed holes housing the reinforcement rods are still visible in the tunnel floor. First measurements with the movement sensors indicate that the motion of the tunnel segments could be significantly reduced, from 80 µm to 20 µm in the vertical plane.

In the summer shutdown 2022, a new vacuum chamber was installed in the straight section in the south of the PETRA III ring to enable tests of prototype diagnostic equipment for PETRA IV. Two beam current monitors were installed in this new section (Fig. 2). Furthermore, the installation of a new single-cell cavity was prepared. At the end of the 2022 beam operation period, three study days were dedicated to a girder movement test to inform the design of the PETRA IV girder alignment system. The beam orbit response due to girder movement was studied, and technical requirements and limitations for the planned new system at PETRA IV could be identified.

Figure 1

Stabilisation of the transition between two PETRA III tunnel segments

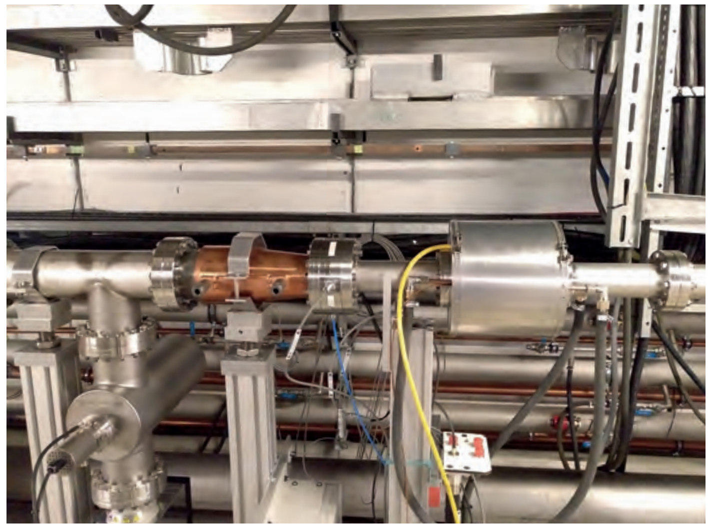


Figure 2

Test of new current monitors in PETRA III

User operation

Regular user operation resumed on 18 February 2022 after a short commissioning period of about two weeks. In total, 4896 h of beamtime were scheduled for the user run, which were complemented by 1040 h of test run time used to set up user experiments. Necessary maintenance was done in six dedicated service periods distributed over the year and additionally during the 3.5-week-long summer shutdown, which was also used to refurbish a cooling tower. 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 2022 is shown in Fig. 3. During user runs, the storage ring was operated in two distinct modes, characterised by their bunch spacing of either 16 ns (480 bunches) or 192 ns (40 bunches). In 2022, 51% of the user time was allocated to the 480-bunch mode and 49% to the 40-bunch mode.

In 2022, the average availability was 98.3%, which is a very good achievement and an improvement compared to 2021. The long-time development of the availability of PETRA III during user runs is shown in Fig. 4. The average mean time between failures (MTBF) in 2022 was 58 h, and the mean time to recover (MTTR) was about 1 h. All faults were carefully analysed as part of an internal review process based on an essential effort from all the technical groups involved.

Several measures to save electric energy were studied in order to cope with the skyrocketing electricity market in 2022. In October 2022, operation of PETRA III at a beam energy of 5 GeV was set up for a test run to verify the energy saving of about 20% compared to 6 GeV operation and investigate the conditions at the beamlines. Unfortunately, the 5 GeV operation mode impairs the experimental opportunities due to lower brilliance and photon flux for hard X-rays. Nevertheless, several energy-saving measures could be implemented at the PETRA III injector complex. Furthermore, it was decided to reduce the test run time to the absolutely necessary minimum in 2023.

Plans for the next operation period

During the winter shutdown 2022/23, it is planned to install a new undulator for Beamline P25 in the "Ada Yonath" experimental hall and a PETRA IV prototype single-cell cavity in the long straight section in the south of the PETRA III ring.

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FLASH back to the future

Spot landing in time for first photon user experiment in 2022

DESY's FLASH free-electron laser (FEL) facility features two undulator beamlines, FLASH1 and FLASH2, operated in parallel as a tandem. The FLASH3 beamline is used by the FLASHForward plasma wakefield acceleration experiment. The first shutdown for large-scale refurbishments and the first phase of the FLASH2020+ upgrade project began on 16 November 2021 and was completed on time on 14 August 2022. After a commissioning phase, the first scheduled photon science experiments started on 7 November 2022, as scheduled in 2021, profiting from the enhanced overall performance of the electron accelerator.

First phase of FLASH2020+ upgrade with improved accelerator performance

The FLASH2020+ project aims to provide greatly improved experimental capabilities. It therefore encompasses many major changes and upgrades to almost all sections of the accelerator, undulators, photon beamlines and photon diagnostics, including substantial work in the experimental halls.

The FLASH accelerator team, together with the FLASH2020+ team and colleagues from the Accelerator and Photon Science support groups, worked hard to successfully realise the major refurbishments and upgrades required to complete the first phase of the FLASH2020+ project in a nine-month shutdown from mid-November 2021 to mid-August 2022. A key feature of the upgrade was to increase the electron beam energy by 100 MeV to 1350 MeV. In the FLASH linear accelerator, two superconducting accelerator modules of the old TTF type were replaced by modern prototype modules of the type installed in the European XFEL X-ray laser (Fig. 1). From the start, these two modules were operated with the projected beam energy increase of 100 MeV. An important refurbishment of the cryogenic system that keeps the superconducting modules at 2 K, with a newly developed low-pressure scheme of less than 0.5 bar overpressure, was successfully put into operation.

Figure 1
Two new superconducting accelerator modules after installation in the FLASH linear accelerator

A new laser heater system was mounted upstream of the first bunch compressor (Fig. 2). The laser heater modifies the longitudinal phase space of the electron bunches in such a way as to improve the self-amplified spontaneous emission (SASE) properties and to make the seeding scheme of the FLASH2020+ upgrade possible.

The FLASH2 beamline will be equipped with a variable-polarisation third-harmonic afterburner undulator of APPLE III type, optimised to provide photon energies around the L-edges of iron, chromium and nickel, thus paving the way for studies of ultrafast magnetisation dynamics. Due to delays in the delivery of key components of the undulator, its installation was postponed to 2023. However, the beamline was prepared to quickly include the undulator as soon as it would be available.

Beamtime for accelerator R&D efforts concentrated on preparing the external seeding scheme Xseed and on FLASHForward. The plasma acceleration experiment had a very productive year. In particular, FLASHForward demonstrated for the first time that the initial transverse emittance of a particle bunch could be preserved on the micrometre level whilst undergoing acceleration in plasma. Xseed is a unique tool to study the interaction of the electron bunch with external laser fields and dispersive beamline components and how these can generate an optimally tailored charge density distribution to imprint real laser-like properties onto FEL radiation. The focus of Xseed shifted from purely academic studies towards experimental efforts to pave the way for FLASH to become the world's first megahertz repetition rate FEL user facility.

Photon beamline R&D concentrated on upgrading the beamlines and experimental stations. One example is the setup of a new beamline, FL23, which includes a time-delay-compensating monochromator as a key element. This beamline saw its first beam in January 2023. Terahertz streaking has been further developed to measure photon pulse durations on the femtosecond scale. The data are compared to the electron beam phase space measured with PolariX, a transverse deflecting structure that provides femtosecond-scale resolution.

Operation after the shutdown

Photon-science-related experiments by internal and external users started, as scheduled, on 7 November 2022, with 838 operating hours until the end of December 2022. A total of 501 h of user experiments were realised at the FLASH1 beamline, and 473 h at FLASH2. Due to the short beam commissioning time in autumn 2022, tuning for photon beam properties turned out to be difficult and thus took a significant amount of time: 17% on average, with a downtime during experiments of 2.5%.

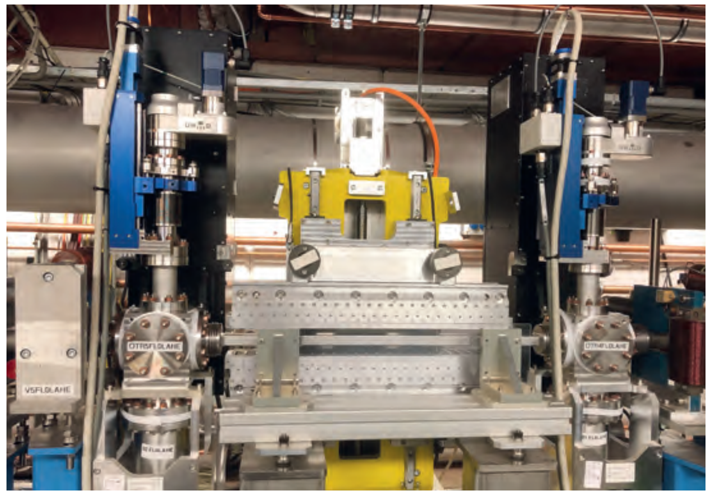

Figure 2
New laser heater undulator mounted upstream of the first bunch compressor

In 2023, as much beamtime as possible will be scheduled for user experiments, accelerator R&D and FEL-related studies to improve and further develop the facility. The first weeks of user operation in 2023 have already shown a trend towards a significant reduction in setup and tuning times, combined with low downtime, indicating the possibility of achieving an availability of 99%.

A remarkable improvement in long-term stability was realised by upgrading the master radio frequency (RF) oscillator system and the laser-based synchronisation systems and by introducing a reference system for the low-level RF system to stabilise the RF phase of the accelerator modules (REFM-Opt) in the long term. The enormous efforts of the Accelerator and Photon Science division staff, which make even tricky experiments at the edge of the facility's capabilities possible, are highly acknowledged.

Further extending the capabilities of FLASH

A key upgrade of FLASH2020+ is the realisation of external seeding in order to provide longitudinally coherent photon pulses with 1 MHz beam repetition rate in the 10 Hz burst mode. Seeding is being designed, prepared and finally supported by a coordinated effort to create a multi-scale framework for realistic modelling in a start-to-end approach – from the electron source to the photon experiment. The second phase of the upgrade will be completed in 2024/2025 to include the FLASH1 external seeding, the new photon beamlines and diagnostics as well as substantial work in the "Albert Einstein" experimental hall.

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European XFEL accelerator

Efficient and reliable operation for an increasing number of experiments

In 2022, the European XFEL accelerator complex – which is run by DESY – was in reliable and stable operation. The superconducting accelerator and its handling have largely matured, and the accelerator delivers electrons with energies up to 17.5 GeV to serve the ever-varying operational needs of the European XFEL X-ray laser facility. In addition to regular photon delivery, important developments have been pursued both on the accelerator and the free-electron laser (FEL) sources, yielding record FEL photon energies and intensities. New installations include the addition of a corrugated structure upstream of the SASE1 undulator and first diagnostics for the X-ray Free-Electron Laser Oscillator (XFELO) demo experiment.

Operation summary

In 2022, the European XFEL accelerator complex – consisting of the injector, the 17.5 GeV superconducting linear accelerator, the electron beam distribution and the beam transport system through the three undulators to the beam dumps – was operated for more than 7000 h (Fig. 1). Of these, about 4500 h were spent on experiment operation, during which almost 100 user experiments were performed at the three undulators. The availability of the facility was excellent (92.8% averaged over all FELs), but slightly below our self-imposed goal of 95%. The reasons were already well-known sporadic failures of bearings in the cold compressors of the cryogenic plant. With test operation of active magnetic bearings in one of the cold compressors now under way, we hope to have this spook behind us soon.

Several improvements, extensions and European XFEL "firsts" were realised in 2022. For example, a new electron beam power record of 120 kW was established, from which up to 120 W of X-ray radiation can be generated. Incidentally, the European XFEL facility as a whole consumes about 12 MW of electricity. In recent months, many groups have been working intensively on ways to reduce energy consumption. Infrastructures have been optimised, and the radio frequency (RF) system is now being operated in a more adapted and thus more economical way. On average, it should be possible to save between 5 to 10% of the electricity.

The spectrum of the X-rays generated – and transported to the experiments – now ranges from 300 eV at 8 GeV beam energy with the SASE3 undulator to 30 keV at 16.5 GeV with SASE2. In addition to the standard FEL operation, more and more special operation modes are being introduced and established. For example, hard X-ray self-seeding at SASE2 and the generation of two different wavelengths (two-colour mode) at SASE2 and SASE3 are now almost standard. The need for even shorter photon pulses is met by various methods, and the newly installed wave structure ("corrugated structure") upstream of SASE2 helps with the adjustment here. At SASE3, photon pulses with a duration below 1 fs could be produced and detected.

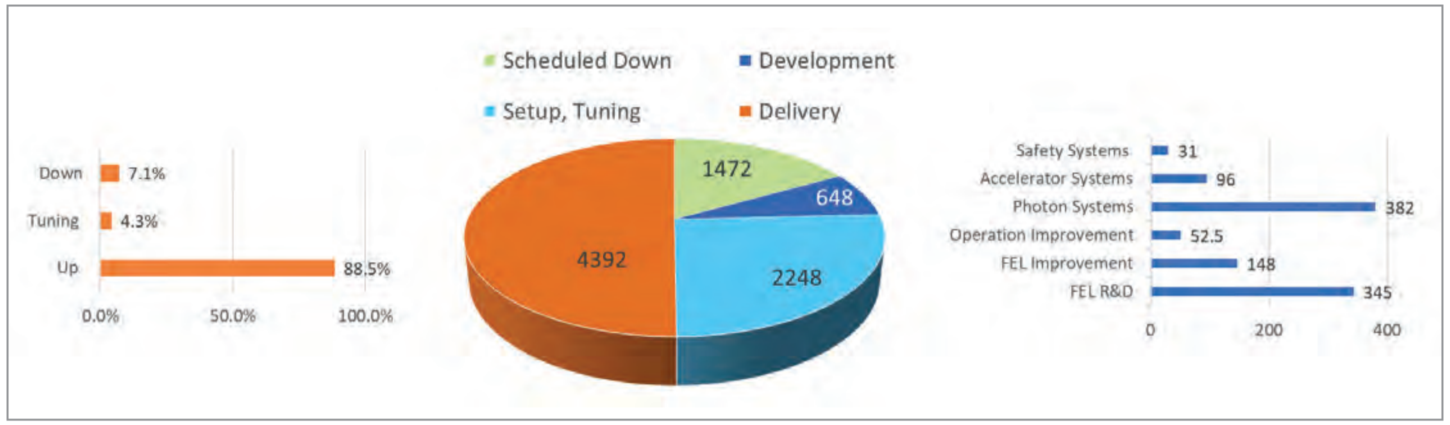

Figure 1

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

Maintenance work in the European XFEL accelerator tunnel

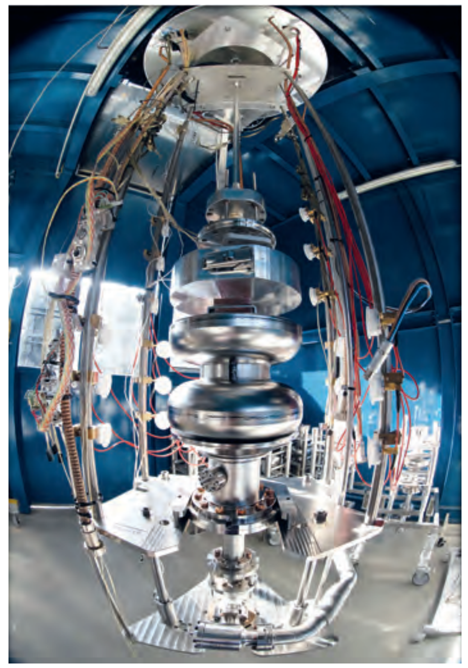

Figure 3

As part of the R&D work for future high-duty-cycle operation of the European XFEL, a superconducting photocathode injector is being developed. Shown here is a prototype of the 1.5-cell superconducting cavity in the Accelerator Module Test Facility (AMTF).

A challenge that will keep us busy in the coming years is to provide these operation modes in parallel to standard operation at the other undulators. We have taken a significant step towards easing this issue with the introduction of the Beam Regions concept, which allows the greatest possible flexibility in setting the RF parameters within an RF pulse. Additional kicker systems in the injector and routine operation of the fast longitudinal feedback system stabilise the long beam trains better and better.

Installations

A regular operating year includes two maintenance periods totalling about six working weeks, which are used for new installations in the accelerator system in addition to the standard preventive maintenance and repair (Fig. 2). The APPLE-X undulators installed in the winter maintenance period 2021/22 had to be uninstalled again in summer 2022, because the spontaneous synchrotron radiation generated in the upstream SASE3 undulator was not sufficiently shielded and led to damage of the actuators. Nevertheless, it could be shown that the undulators work in principle as calculated.

During the winter maintenance period 2022/23, major work was performed upstream of the SASE1 undulator, where the electron beamline was modified on a length of 50 m to install another corrugated structure for phase space manipulations of the bunches that will later lase in SASE1 or SASE3.

New developments

Preparations for the long maintenance period in the second half of 2025 are in full swing. Large installations will be made again – for example, everything downstream of the SASE2 undulator will be prepared for the installation of superconducting undulators, and the ASPECT project for generating attosecond pulses will be set up upstream of SASE1 and in the shaft XS1 at the end of the accelerator tunnel. By then, the new electron source, Gun 5, and a corresponding replacement gun must also be fully conditioned and characterised. For this, the completion of the gun conditioning facility FALCO in 2023 is of crucial importance.

For the long term, European XFEL is currently working out a strategy for the 2030s. One pillar will be the upgrade of the accelerator to high-duty-cycle operation. The preparatory developments for this upgrade are already under way (Fig. 3).

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PITZ

20 years of successful accelerator R&D at the photoinjector test facility in Zeuthen

Despite the difficult circumstances, 2022 was a very successful year for PITZ, the photoinjector test facility at DESY in Zeuthen. It started with the high-power conditioning and operation of the new electron source Gun 5.1. In summer, DESY celebrated 20 years of fruitful PITZ operation and first lasing of the world's first high-power terahertz self-amplified spontaneous emission free-electron laser (THz SASE FEL) at PITZ. Later in the year, the PITZ team installed a first, preliminary beamline for studies of *FLASH* radiation therapy of tumours and prominently presented the first experimental results at the international 2022 *FLASH* Radiotherapy and Particle Therapy (FRPT2022) conference.

High-power long-pulse operation of Gun 5.1

Gun 5.1, the first radio frequency (RF) electron source, or gun, of the new type of L-band RF guns designed for up to 1 ms RF pulse duration, was successfully operated at PITZ in 2022. Conditioning was performed up to the full RF pulse length of 1 ms – which is about 50% longer than what was possible before – at the required accelerating gradient of 60 MV/m. The low-level RF regulation using the RF pickup newly implemented inside the gun cavity resulted in a much better stability than typically obtained for the previous gun generation (e.g. Gun 4.2): The stability is improved by a factor of around 12 along the RF pulse and drift versus temperature is improved by a factor of about 30. The detuning within the RF pulse (per pulse length) is about 24% lower than typical values for the Gun 4 generation. The dark current, which is an important issue when using a normal-conducting gun in a superconducting linear accelerator environment, was found to be more than a factor of 3 lower than typical Gun 4.2 values. This is of major importance for the user facilities FLASH and European XFEL, as both will later be equipped with copies of this gun.

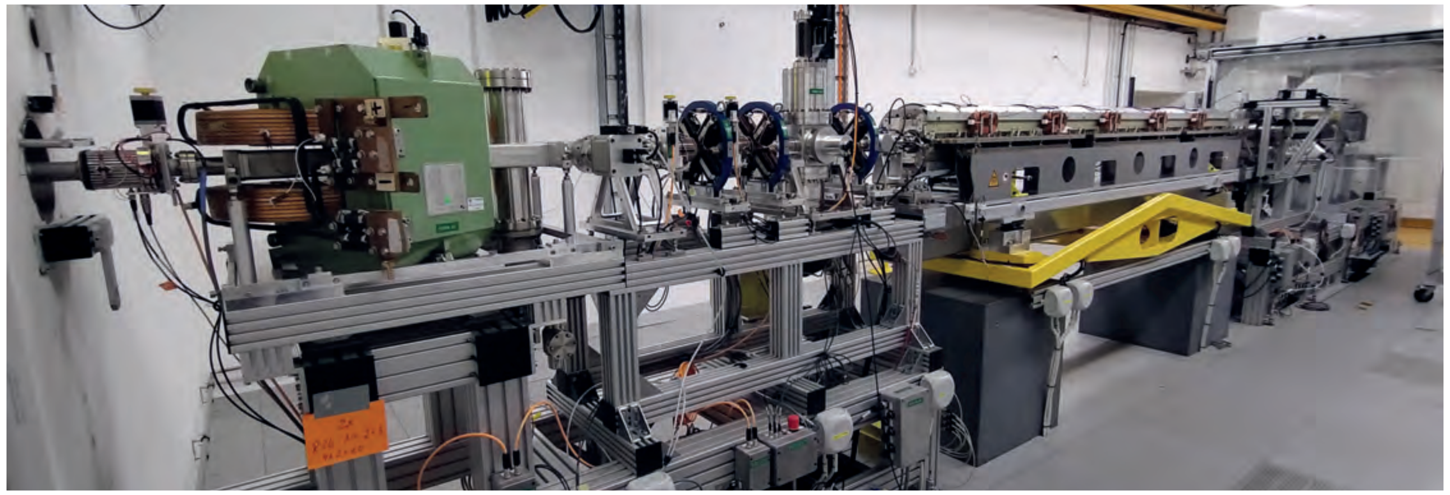

Figure 1

THz SASE FEL installations in the PITZ tunnel extension

Figure 2

Inauguration of the THz SASE FEL by Brandenburg's Minister for Science, Research and Culture Manja Schüle (centre) and European XFEL Scientific Director Thomas Tschentscher (left) in November 2022

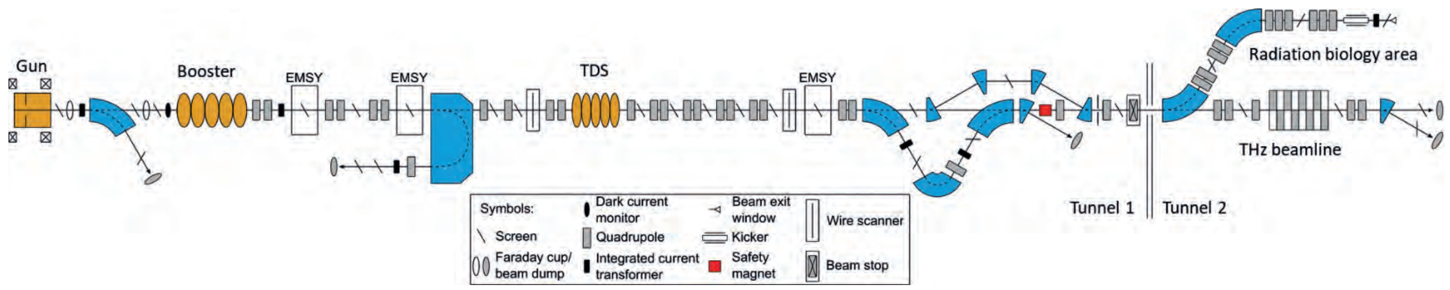

Figure 3

Schematic of the extended PITZ facility with the beamline for the THz SASE FEL and a separate new beamline for radiation biology studies

First lasing and inauguration of the THz SASE FEL

In the framework of an R&D project co-funded by European XFEL, a prototype of an accelerator-based high-power high-repetition-rate THz source for users of the European XFEL was set up at PITZ (Fig. 1–3). Both PITZ tunnels were connected at the end of April 2022, and later the beamline was closed to connect the installations in both tunnels. The first electron beam was sent through the undulator in July, and first THz light was detected three weeks later in August. SASE lasing and then saturation could be proved a few days later, and these great results were immediately presented at the FEL2022 conference in Trieste, Italy [1].

In August 2022, the ceremony marking 20 years of successful PITZ operation could therefore also celebrate the first SASE light from the THz FEL. The facility was then officially inaugurated in November together with Manja Schüle, Minister for Science, Research and Culture of the German federal state of Brandenburg, and Thomas Tschentscher, Scientific Director at European XFEL (Fig. 2). The event marked the transition from the facility construction phase to the second phase of the project, which comprises the optimisation of THz light generation, the characterisation of the THz light properties and the proof of the proposed parameters. These measurements will be part of the PITZ operation programme for 2023. At the end of 2023, a conceptual design report will be provided to European XFEL.

Towards *FLASH* radiation therapy studies: *FLASH*lab@PITZ

Recent observations show that radiation therapy (RT) treatments of tumours with ultrahigh dose rate (UHDR) and sufficiently high total dose applied in very short time intervals lead to considerably less toxicities in healthy tissue than conventional radiation therapy, while showing equal therapeutic response of the tumour. The discovery elicited enormous resonance in the radiation oncology community, and radiation oncologists around the globe now strive for rapid clinical exploitation of the differential response of tumour and normal tissue, which has been termed the "*FLASH* effect".

With the extension of the PITZ facility by a separate beamline for radiation biology, called *FLASH*lab@PITZ [2], many of the UHDR and *FLASH* RT community's recommendations on future research focus areas could be addressed in the coming years. The extremely wide parameter range accessible at PITZ, together with its full flexibility and tight beam control capabilities, provides worldwide unique opportunities to advance the understanding, optimisation and application of UHDR and *FLASH* RT. The installation of such a dedicated beamline in the PITZ tunnel extension is currently in the design phase (Fig. 3).

As a first step towards exploring this interesting topic at PITZ, a preliminary beamline for first experiments was built in the tunnel extension of the PITZ accelerator in October 2022. First trials began in November 2022 and have continued since then. The developments for *FLASH*lab@PITZ were prominently presented with an invited talk at the international FRTP2022 conference with 650 participants in Barcelona, Spain, and received a lot of attention.

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REGAE

First 3D structure determination at atomic resolution with MeV electrons

A new high-precision diffraction setup was installed at DESY's ultrafast electron diffraction facility REGAE. In a first demonstration experiment with the setup, the REGAE team was able to determine the 3D structure of the layer silicate mica at atomic resolution. Diffraction data were recorded with very high sensitivity with the Jungfrau 1M detector. Standard software commonly used in X-ray structure determination was modified and successfully applied for data analysis. These studies pave the way for future time-resolved experiments at REGAE aiming at high-resolution structure determination of excited and transient states of quantum materials, such as transition metal dichalcogenides (TMDs). These typically consist of 2D-layered structures similar to mica, and thus similar sample preparation techniques can be used. For this purpose, different laser excitation schemes ranging from ultraviolet to terahertz excitation are currently being implemented at REGAE.

New diffraction setup for solid-state samples

A new compact crystallography goniometer, which was specially designed for operation in the ultrahigh-vacuum environment of REGAE, was installed and commissioned. The goniometer allows the sample to be rotated by ±180° in order to collect information from it in all directions. A three-axis centering stage on top of the goniometer with travel ranges of ±6 mm in all directions makes it possible to also scan larger samples or even multiple samples on different holders. For sample alignment with respect to the incident beam, the sample can be visualised with visible light with an inline sample viewing microscope. In combination with a Jungfrau 1M detector, this setup enables the acquisition of high-quality diffraction data from solid-state samples.

3D structure determination from mica

Mica is a naturally occurring layer silicate, which has been used as a very thin insulator in electrical devices and also as window material for experiments with X-rays (Fig. 1, left). It provides very good cleavability between the individual layers, which makes it possible to generate laterally extended samples with dimensions of several hundred micrometres and, at the same time, a thickness of only a few hundred nanometres. This makes mica the ideal sample for experiments at REGAE. Thin sheets of mica were prepared with the exfoliation technique, which is also used to create thin layers of quantum materials, such as TMDs. For the experiment, thin mica sheets were glued over an aperture of a silicon support frame (Fig. 1, right).

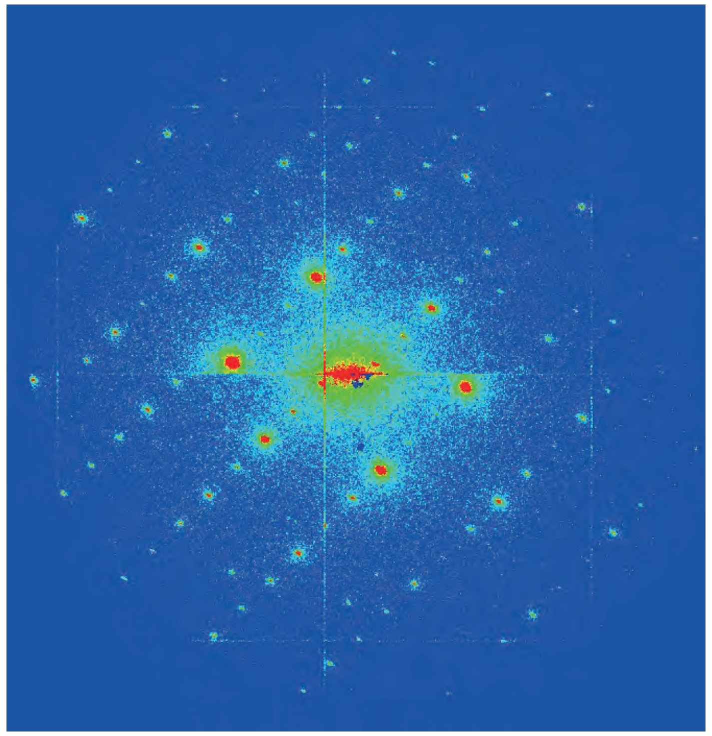
Figure 1

Left: Mica bulk material. Right: Ultrathin sheets of mica with a thickness of a few hundred nanometres glued onto a silicon support frame with three rectangular apertures for mounting on the REGAE goniometer.

For structure determination at REGAE, the samples were mounted on the goniometer. Data were collected at an electron energy of 3.3 MeV at a bunch repetition rate of REGAE of 50 Hz. For data collection, the sample was rotated over a total angle of 96.6° in rotation increments of 0.01°. For every rotation increment, 20 images were recorded on the Jungfrau 1M detector (Fig. 2, top). For data processing, all 20 images per rotation increment were summed up and then processed with an X-ray Detector Software (XDS) program package. Subsequent structure refinement with the *SHELXL* program yielded the three-dimensional structure of mica, as shown in Fig. 2 (bottom). The data are of good quality for electron diffraction experiments, comparable to data obtained with lower-energy electrons available from laboratory-based devices.

Future: 3D time-resolved structure determination of excited and transient states

In the present work, we have performed a static structure determination of the mineral mica without utilising the pulse structure of REGAE and the resulting time resolution.



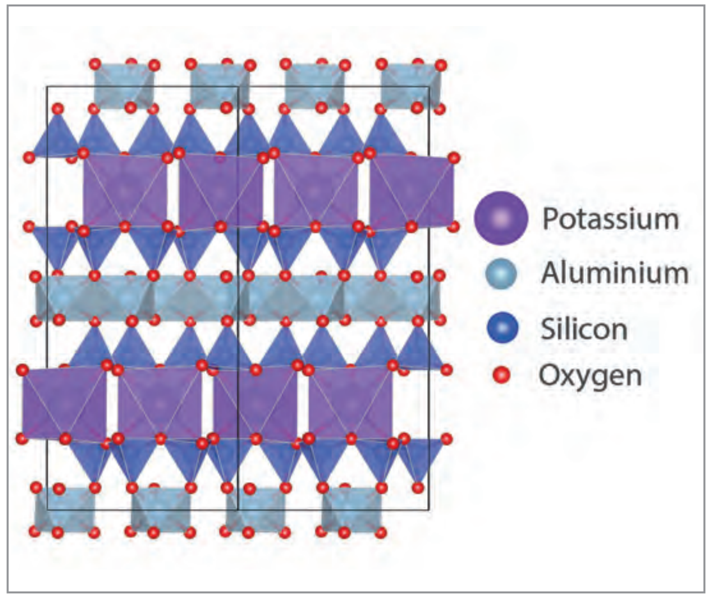


Figure 2

Top: Diffraction pattern recorded from a thin mica sample at an electron energy of 3.3 MeV at REGAE with the newly installed diffraction setup and the Jungfrau 1M detector. Bottom: Layer structure of mica determined with MeV electron diffraction at REGAE.

For the future, we plan to conduct pump–probe experiments with laser excitation – taking advantage of the outstanding short electron pulse duration of down to 20 fs enabled by the buncher cavity. Similar to mica, thin-layered 2D materials such as TMDs with potential as quantum materials are ideal first candidates for such experiments. We are currently implementing a variety of laser excitation schemes at REGAE, ranging from ultraviolet over infrared and terahertz radiation, for such experiments.

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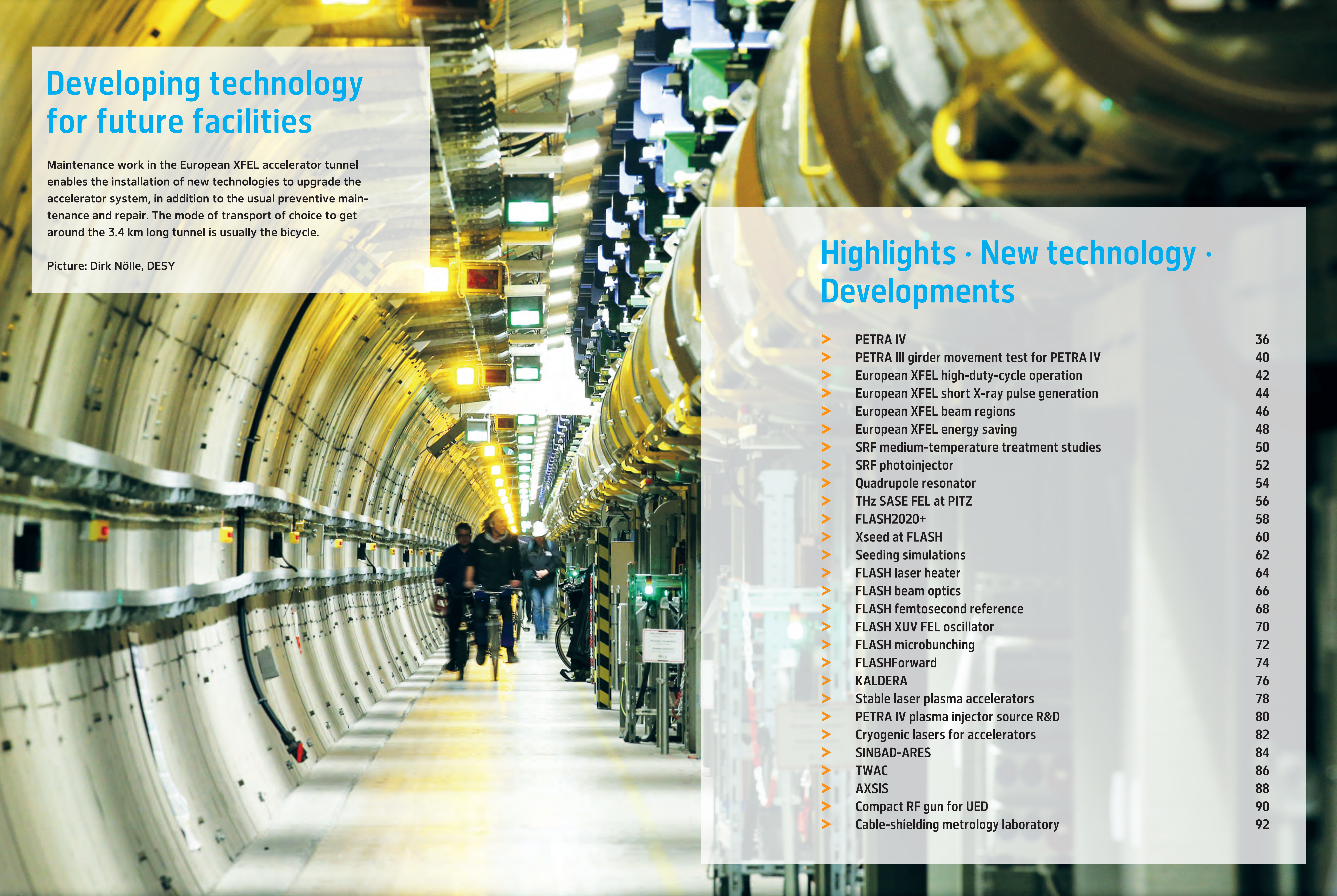


Developing technology for future facilities

Maintenance work in the European XFEL accelerator tunnel enables the installation of new technologies to upgrade the accelerator system, in addition to the usual preventive maintenance and repair. The mode of transport of choice to get around the 3.4 km long tunnel is usually the bicycle.

Picture: Dirk Nölle, DESY

Highlights · New technology · Developments

PETRA IV – the ultimate 3D X-ray microscope

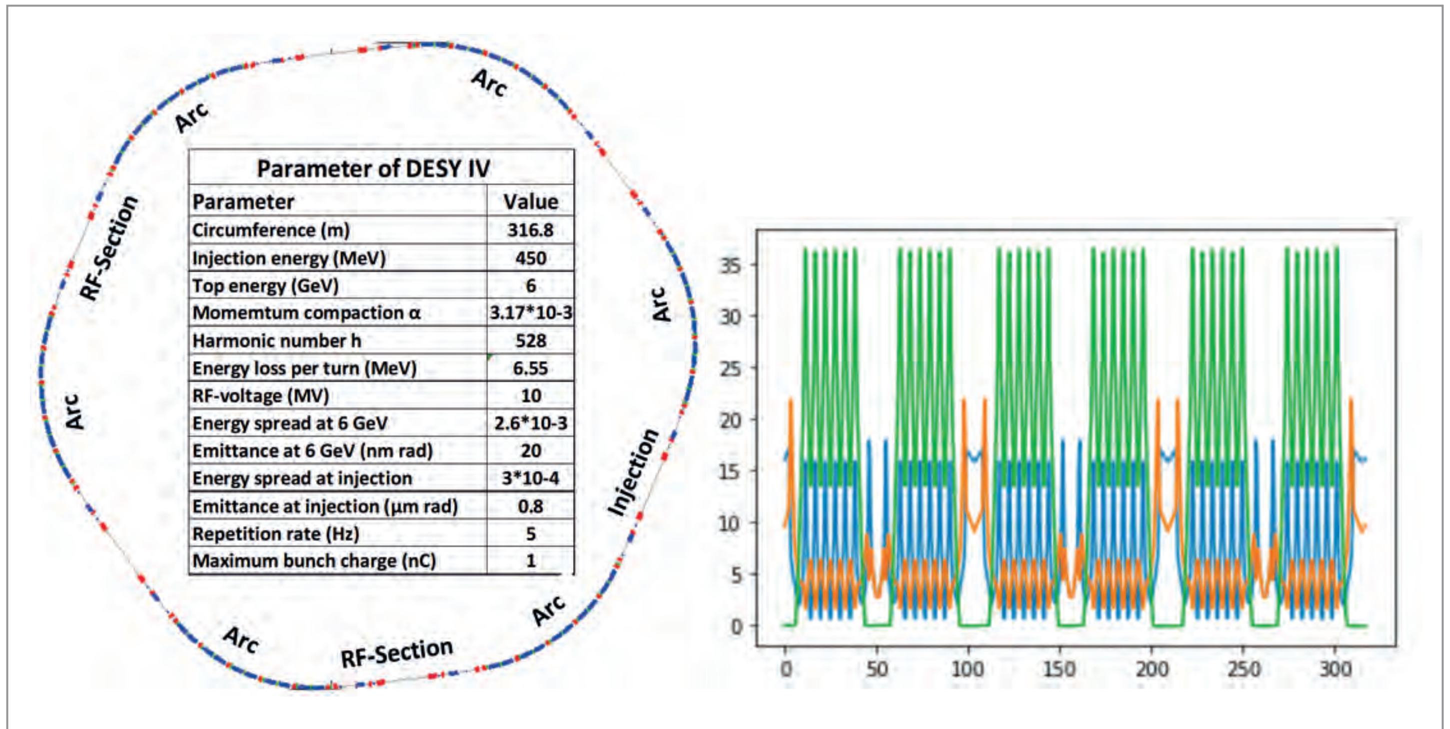
Plans for the new light source PETRA IV are taking shape

PETRA IV is the planned upgrade of DESY's PETRA III storage ring to the most brilliant high-energy synchrotron radiation source, which will be diffraction-limited up to a photon energy of 5 keV. It will push imaging techniques into the single-digit nanometre regime with sufficient brightness to enable time-resolved measurements from nanoseconds to seconds. The extreme brightness will be achieved by introducing a hybrid six-bend achromat (H6BA) magnetic lattice for the electron storage ring with a targeted horizontal emittance of 20 pm·rad. PETRA IV is a key element in the plans for a unique scientific environment far beyond the current capabilities on the DESY campus – the Science City Hamburg Bahrenfeld.

Envisioned novel user operation

Besides the technical upgrade of the PETRA III facility, the PETRA IV project aims to improve the experimental infrastructure to enable the full exploitation of the capabilities of the new light source. This includes a new experimental hall (PXW) in the western area of the PETRA IV complex to increase the range of experimental techniques and to provide laboratory space for new services to the user community.

The new services will increase both capacity and capabilities for ground-breaking research and innovation, not only for the existing large community of academic users, but also for non-experts in the use of synchrotron radiation mainly from the area of applied and industrial research and development.



Parameter	Value
Circumference (m)	316.8
Injection energy (MeV)	450
Top energy (GeV)	6
Momemtum compaction α	3.17*10-3
Harmonic number h	528
Energy loss per turn (MeV)	6.55
RF-voltage (MV)	10
Energy spread at 6 GeV	2.6*10-3
Emittance at 6 GeV (nm rad)	20
Energy spread at injection	3*10-4
Emittance at injection (µm rad)	0.8
Repetition rate (Hz)	5
Maximum bunch charge (nC)	1

Figure 1

Layout of the 20 nm·rad booster synchrotron DESY IV. Left: Performance parameters. Right: Lattice function. An option for a test beam facility can be included in the design. The new transfer line (see Fig. 2) allows for a future upgrade and electron injection into PETRA IV with a 6 GeV laser plasma accelerator.

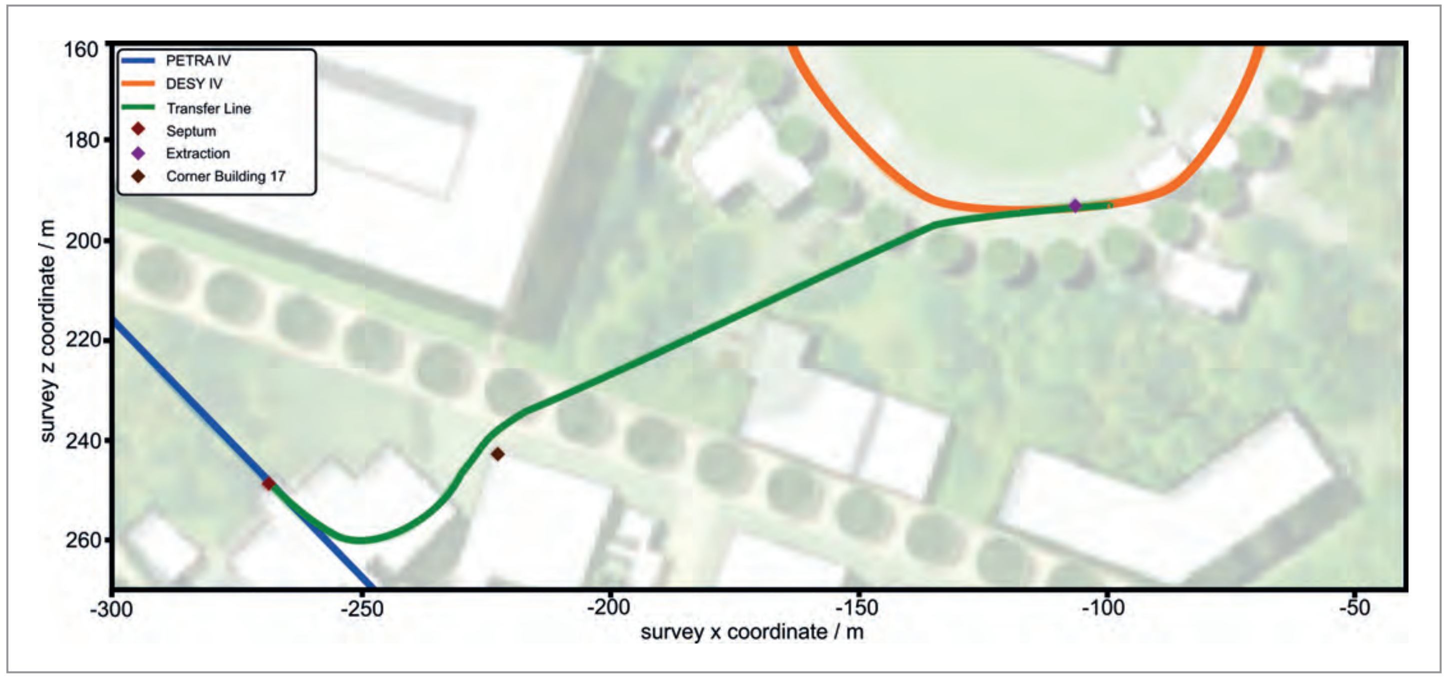


Figure 2

Layout of the new transfer line between the DESY IV booster synchrotron and the PETRA IV storage ring

It is planned to increase the responsiveness to the demands of PETRA IV users by providing faster access to beamtime and dedicated laboratories, such as wet chemistry, nanosample preparation, cryofacilities and complementary light and electron microscopes. The other important element is an integrated data handling concept, spanning from data acquisition to storage, analysis and archiving. This will be complemented by the establishment of a support team to assist non-expert users from the planning of experiments to data analysis and the extraction of solutions to their problems.

Continued design of the accelerator complex

The planning for the electron storage ring and the new accelerators is already well advanced. The conceptual design of the optical lattice was "frozen" in spring 2022. The main activities now focus on the engineering design for the accelerator complex. In the "Max von Laue" experimental hall, it was possible to maintain the canting of the sectors currently housing Beamlines P11–P14 (canting angle of 5 mrad) in order to preserve the existing experimental and infrastructural installations. This also applies to the Swedish Materials Science Beamline in the "Ada Yonath" experimental hall. Here, a total canting angle of 1 mrad is required to preserve the current setup.

Prototyping of the main technical subsystems is key to reducing project risks. In 2022, the prototype programme made essential progress in many areas. A single-cell, high-order-mode- (HOM)-damped, 500 MHz radio frequency (RF) cavity was procured and will be installed in the PETRA III ring for testing. It will be powered by solid-state amplifiers, which are also part of the prototype programme. Delivery is expected in early 2023. In collaboration with ALBA in Spain and HZB/BESSY II in Germany, a prototype of the single-cell HOM-damped third-harmonic cavity was built and installed for testing at BESSY II, with encouraging results on bunch lengthening. A prototype of the high-gradient quadrupoles (115 T/m) will be in production by the French company Sigmaphi from January 2023, while a prototype of a sextupole magnet is in the call for tender process.

Non-evaporable getters (NEG) coating tests of long, small-aperture vacuum chambers continued with a successful test of NEG activation of a 5 m stainless steel (316L) chamber with a 7 mm full vertical aperture. Kapton heater foils will be tested in early 2023. Concerning beam diagnostics, tests of beam position monitor (BPM) readout electronics progressed with the installation of a µTCA crate in PETRA III, with eight BPMs operating in parallel to the existing Brilliance Libera system. The external crossbar switching concept was tested, confirming performance within the PETRA IV specifications. On the power supply front, the hot-swap scheme was tested in the laboratory with a seamless transition of the output current between two power supplies. Tests on magnetic elements in PETRA III are planned for early 2023. Finally, stripline kickers and fast high-voltage pulsers were produced and tested on site with excellent results, demonstrating that the pulse amplitude and shape meet the requirements of the PETRA IV injection. A complete

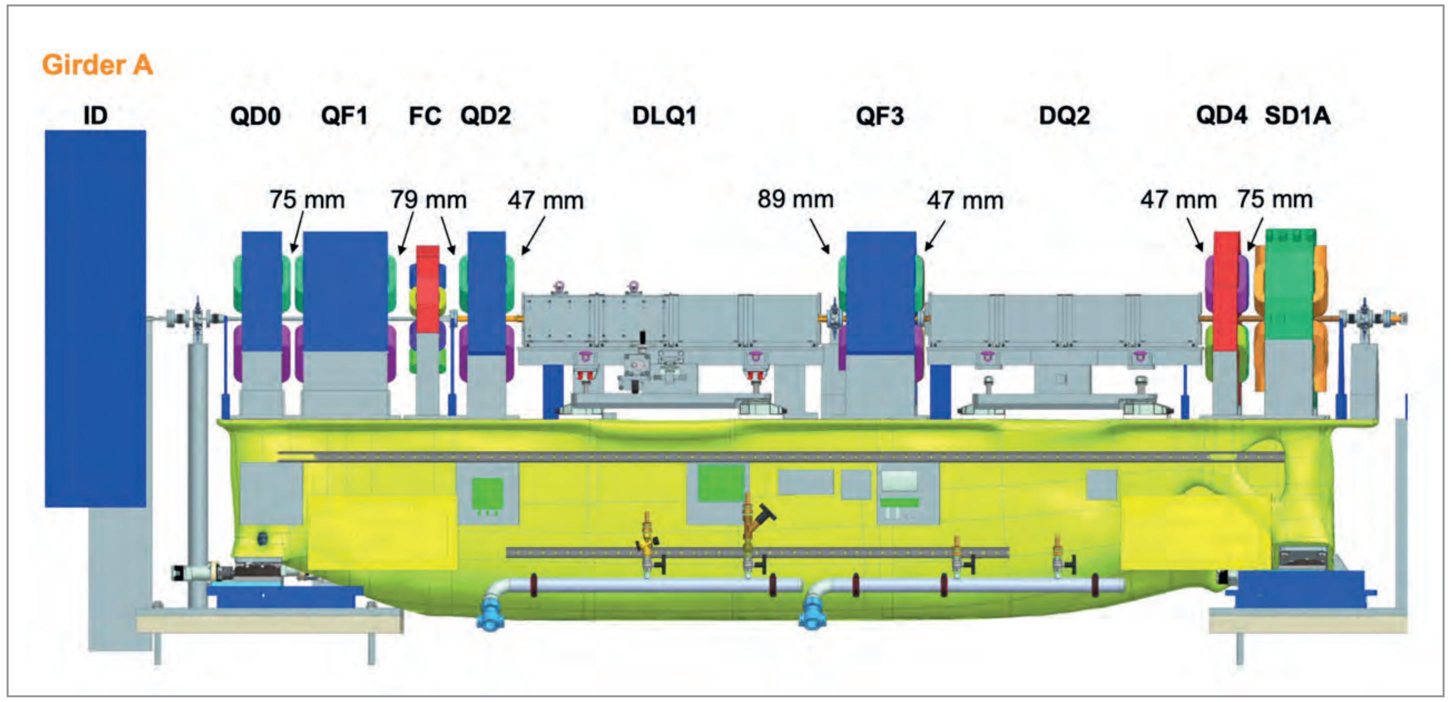


Figure 3

CAD design of the newly developed topological girder for the storage ring. Using computer simulations, the design was optimised in terms of its eigenfrequency spectrum to minimise vibrations disturbing the stored electron beam.

Figure 4

The Hamburg Senate invited DESY to present the PETRA IV project to numerous representatives from science, politics and industry at the Hamburg City Hall in September 2022

system will be installed and tested at MAX IV in Sweden in 2023.

The optical lattice for the new DESY IV booster synchrotron (Fig. 1), which is part of the pre-accelerator chain for PETRA IV, was "frozen" in 2022 as well. The next steps include the engineering integration into the existing building complex. Owing to its particular topology, the synchrotron DESY IV will be mounted on the ceiling of the already existing DESY tunnel. By placing it at the same height as the storage ring, unnecessary bends in the transfer line (Fig. 2) can be avoided, which might otherwise spoil the quality of the electron bunches before injection into the PETRA IV storage ring. DESY II, the current booster synchrotron for PETRA III, will be decommissioned before the installation of DESY IV.

At the same time, R&D on a possible upgrade of the PETRA IV injector to a laser plasma accelerator is ongoing, with 6D simulations showing that a high-quality beam suitable for injection into PETRA IV can be produced with (i) novel schemes for the laser guiding in the plasma channels and (ii) an energy compression beamline employing an X-band cavity dechirper. Further tests of such schemes using an existing S-band cavity are being discussed.

In order to achieve the world's smallest horizontal emittance of any storage-ring-based source (20 pm·rad) and subsequently a focal spot size of the X-ray beams in the range of a few nanometres, all components of the accelerator and photon science complex must be designed for maximum stability. Therefore, a topologically optimised design for the girders of the storage ring was chosen to minimise vibrations of the frame and the components mounted on it (Fig. 3). This design features higher stiffness at lower weight. Another advantage is that this geometry can be readily adjusted to external constraints while maintaining the superior vibrational response of the system. Moreover, this approach will help to tackle a specific issue in the northern part of the storage ring, where the beamlines of the FLASH free-electron laser cross the PETRA IV storage ring, and space for the various beam pipes of FLASH has to be made available in the PETRA IV girders. The design of the regular girders for the storage ring is now finished, and a prototype of a cast iron girder will be procured at the beginning of 2023. Alongside tests on the vibration behaviour of the naked girder, a complete mock-up girder will be produced. It will be populated with prototype magnets or realistic dummy magnets in order to test both the vibration response of the whole system and the assembly and alignment procedures.

The project team plans to finalise the PETRA IV project proposal in spring 2023 for eventual submission to the funding agencies. In addition to the accelerator and photon science complex, the proposal includes the required infrastructure modifications on the DESY campus as well as the logistics required for the realisation of PETRA IV.

Plans for new buildings, including the PETRA extension hall West (PXW), the girder assembly building (GAB), a new RF hall in the northern straight section of the storage ring and a set of smaller support buildings, have been further developed. In parallel, the necessary refurbishment of existing structures, such as the DESY pre-accelerator complex and the corresponding beam transfer lines, has been assessed.

All these activities are integrated into the larger campus development plans, which include the new visitor centre DESYUM, the new DESY Innovation Factory and others. Further elements to be considered in the planning for PETRA IV are the parallel upgrade programmes of existing facilities: the second shutdown of FLASH as part of the FLASH2020+ programme and the maintenance shutdown of the European XFEL X-ray laser. Both are planned for the middle of the decade.

Project activities on and off campus

After more than two years of planning in mostly online meetings due to the COVID-19 pandemic, it was finally possible to bring together the entire PETRA IV project team on campus for an all-hands meeting in summer 2022. In September 2022, the project office moved into its own office premises, bringing together core members of the team from different DESY divisions. Being able to work closely together is crucial for the preparation of the PETRA IV project proposal and the technical design report (TDR).

PETRA IV is a key element of the planned Science City Hamburg Bahrenfeld, which is set to foster innovation in Germany and contribute to the solution of grand societal challenges as identified by the Helmholtz Association and the German government. Areas that will particularly benefit from research at PETRA IV are health and drug development, new materials for catalysis and sustainable energy production and storage as well as new functional materials for the next generation of hardware for advanced computing and artificial intelligence.

Raising awareness of PETRA IV is the goal of a campaign that held its kick-off event in September 2022, with a round-table discussion on the DESY campus followed by a reception hosted by the Senate of the City of Hamburg (Fig. 4). Hamburg's Deputy Mayor Katharina Fegebank welcomed the DESY project team in the Hamburg City Hall together with representatives from science, politics and industry. The highlight of the event was an inspiring talk by Nobel Laureate Stefan Hell on the importance of applied science and R&D for industry and innovation in Germany.

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Girder movement test at PETRA III

Contributing to the design of an automatic girder alignment system for PETRA IV

The tight alignment tolerances in the design of PETRA IV – the upgrade of DESY's synchrotron radiation source PETRA III – will pose challenges for the commissioning and operation of the storage ring. An automatic girder alignment system is foreseen for fine control of the girder position, benefitting the design beam performance. At PETRA III, the girders in the "Max von Laue" experimental hall are also equipped with a motorised alignment system, which is not used during regular operation, however. To study the technical requirements for the system foreseen for PETRA IV, a movement test of one of the PETRA III girders was performed in December 2022.

Beam-based girder alignment to achieve design performance

The next-generation light source PETRA IV is to be built within and extend the existing infrastructure of PETRA III, keeping a significant part of the old tunnel, which is made of individual tunnel segments. Owing to the lower emittance, PETRA IV will have lower alignment and aperture tolerances by a factor of 2 to 10 compared to PETRA III. Investigations at PETRA III regarding the long-term beam orbit stability and its correlation with environmental parameters, including tunnel temperature and the mechanical movement of different tunnel segments relative to each other, revealed that the expected ground motion could potentially impact the performance of PETRA IV [1, 2].

Similar to other light sources, the storage ring elements in the magnetic lattice of PETRA IV will be placed on girders that mechanically connect and carry a group of elements so that they can be assembled, transported and aligned as a unit. In order to counteract the misalignment introduced by ground motion and temperature effects, the girders will feature a remote-controlled alignment system. Based on the corrector strength patterns and a response matrix, alignment corrections will be applied to individual girders and so provide an alignment stability within the required tolerances.

At PETRA III, the "Max von Laue" experimental hall is equipped with girders that have a remote-controllable alignment system (Fig. 1). These girders are not moved during beam operation, however; the system was only used during the initial installation of the storage ring elements in the tunnel in 2009. Thanks to the moderate tolerances at PETRA III, potential movements or drifts are well compensated by the orbit correction system.

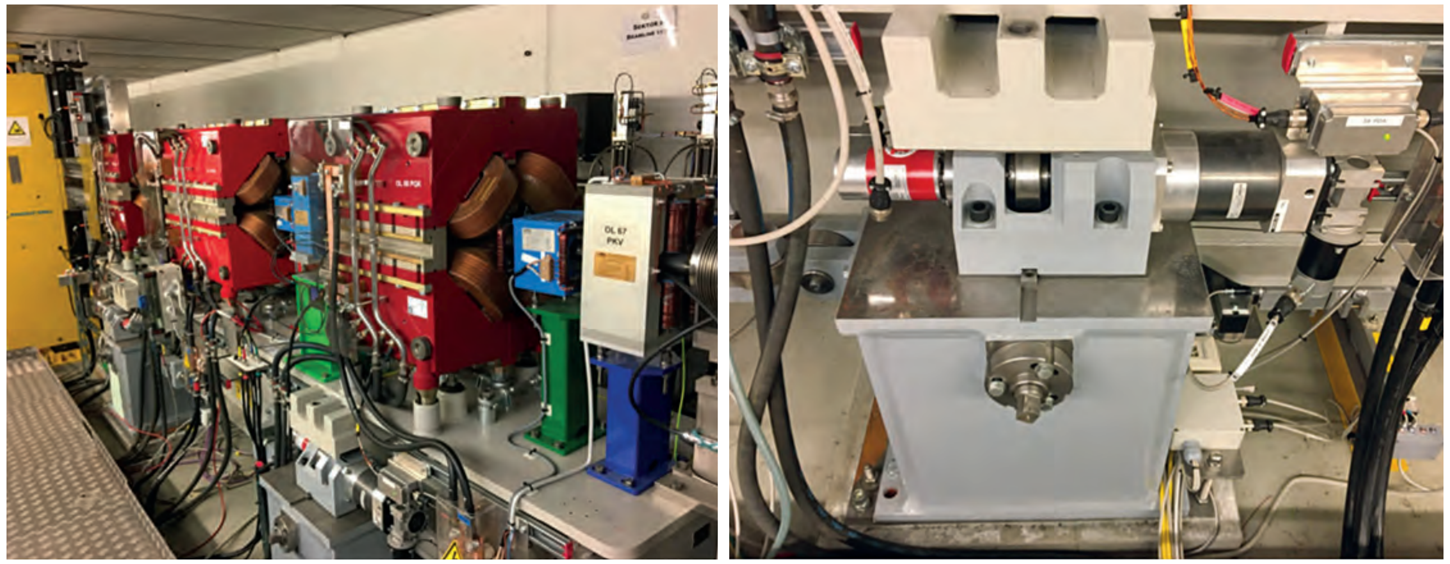

Figure 1

Left: View of a movable girder installed in the PETRA III tunnel downstream of the undulator PU14 (yellow element on the left), carrying three quadrupole magnets. Right: Zoom in on the motor and encoders installed on the cam-mover-based alignment system that connects the supporting feet to the girder table.

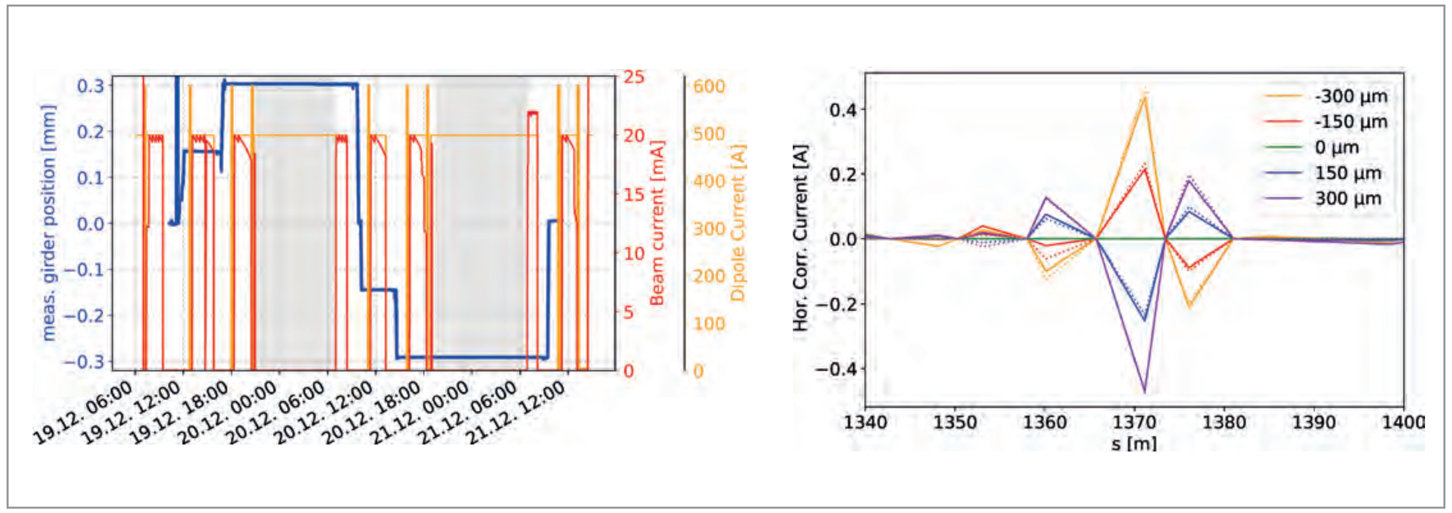

Figure 2

Left: Time evolution over the three-day experiment. The left axis (blue) shows the measured horizontal girder position, the right axes display the beam (red) and dipole magnet (orange) currents, showing the time periods during beam operation and tunnel access for girder movement. Right: Measured (solid) and simulated (dotted) horizontal corrector currents for the five girder positions as a function of corrector location.

It is of crucial importance for the PETRA IV performance prospects to understand the limits of the girder response matrix model and the accuracy with which this procedure can be performed. Therefore, a girder movement test was performed at PETRA III in December 2022.

First motorised girder displacement since the installation of PETRA III

The PETRA III girder alignment system in the "Max von Laue" hall is not built to perform automatic girder displacements remotely controlled from the accelerator control room. Movements can only be initiated when locally connected to the motor controls in the tunnel. This implies that girders cannot be moved while the beam is circulating. A time-consuming experiment procedure with alternating periods of tunnel access for girder movement and beam operation to observe the beam orbit response was therefore necessary. During three days, five girder positions between ±300 µm shift in the horizontal plane were evaluated, as can be seen in the time evolution shown in Fig. 2 (left). The most extreme position was kept overnight without circulating beam, but with the magnet current set to operational values. This kept the tunnel temperature relatively constant and so guaranteed compatible experimental conditions through all steps of the experiment.

It was known that the transverse rigid vacuum joints in particular would make this test in PETRA III challenging. To cope with this issue, the maximum movement range was limited and drifts of the vacuum chamber at both ends of the girder were carefully monitored along with the overall girder position. The displacement was performed with the expected precision. However, about 20% of the girder movement was also observed as shift of the undulator vacuum chamber upstream of the girder and on the beam position monitor in the centre of the girder. Taking this into account, the corrector currents are in good agreement with expectation, as shown in Fig. 2 (right). The photon beam position drifted locally with the girder movement, which is directly related to the drift of the undulator chamber.

The good collaboration and high commitment of the involved colleagues from several groups of the Accelerator and Photon Science divisions made this experiment a success. As described, the technical circumstances in PETRA III are not optimal for this kind of experiment. Nevertheless, the ability to safely and precisely remote-control the equipment was demonstrated, and the accuracy of the optics model that describes the effect of the girder movement on the beam orbit was evaluated.

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Exploring high-duty-cycle operation at the European XFEL

Upgrade options for the accelerator operation

While the European XFEL strategy wishes to maintain the unique advantage of providing high-energy electrons (27 000 electron bunches per second at energies up to 17.5 GeV), an ongoing R&D effort at DESY aims at exploring options for upgrading the accelerator towards long-pulse and up to continuous-wave (CW) operation in order to increase the effective bunch rate and bunch separation. This article presents these modes of operation, referred to as high duty cycle (HDC), and the associated technical challenges.

High-duty-cycle operation

In its current mode of operation, the superconducting accelerator of the European XFEL X-ray free-electron laser (FEL) is pulsed at 10 Hz, with each radio frequency (RF) pulse lasting about 1.4 ms, while the accelerated burst beam is confined within 650 µs at a bunch repetition rate of up to 4.5 MHz. The remainder of the RF pulse is used to fill and discharge the superconducting radio frequency (SRF) cavities. Effectively, this mode of operation generates up to 27 000 electron bunches per second, at beam energies up to 17.5 GeV, hence making the facility the FEL with the highest brilliance worldwide.

Other large-scale FELs (LCLS II in the USA, SHINE in China) have followed a different approach, where the RF system is on all the time (CW), allowing for more relaxed beam injection rates (kHz instead of MHz). This approach also avoids beam gaps between RF pulses, possibly increasing the overall bunch throughput and simplifying the requirements for photon detectors. On the other hand, CW operation increases the load on the cryogenic system and the stress on SRF cavities and power couplers, so that today's CW SRF accelerators operate in a lower energy range of 4–8 GeV. A strategic upgrade of the European XFEL would preserve the production of high-brilliance photons while increasing the effective number of bunches (Fig. 1).

Upgrade scenarios

In the short term (2025), the RF flat-top duration will be increased from 650 µs to 1 ms, in readiness for the new RF electron gun. This *extended burst mode* will also optimise the RF pulse to make more efficient use of the energy in the existing modulator pulses while increasing the length of the RF pulse flat-top. Extending the flat-top to 2–3 ms, the so-called *ultimate burst mode*, requires further study to understand its limits (with respect to a new gun, new power sources, cryoplant upgrade, new timing etc.).

Upgrade scenario	Energy	Duty cycle	Bunch/s	Comments
Burst mode	17.5 GeV	0.6%	27k	Today's operation, baseline reference
Extended burst mode	17.5 GeV	0.9%	40k	Expected 2025, with new Gun 5 upgrade
Ultimate burst mode	17.5 GeV	2.3%	104k	Exploring current system limits
Long-pulse mode	12 GeV	13.5%	152k	Major upgrade, 100 ms at 1 Hz for beam acceleration
Long-pulse high-energy mode	17 GeV	5.0%	56k	Major upgrade, 50 ms at 1 Hz for beam acceleration
CW low-energy mode	4.7 GeV	100%	1129k	Full CW operation, but no change to SRF cryomodules
CW (canonical) mode	7 GeV	100%	1129k	Full CW operation with major upgrade

Table 1

Non-exhaustive list of HDC upgrade scenarios

In its present form, the upgrade to make the European XFEL linear accelerator fully CW-capable consists of substituting the first 16 cryomodules (i.e. up to Bunch Compressor 2) with CW-modified cryomodules while installing the refurbished ones at the end of the accelerator, increasing the number of RF stations from 25 to 29. CW-optimised cryomodules will have cavities that can sustain high CW gradients with minimal heat load dissipation (quality factor Q_0 > 3 x 10^{10}), modified input power couplers that can sustain higher average power (up to 4–5 kW) and an improved cooling system to support higher cryogenic helium flow. The cavities in these CW cryomodules would operate CW at gradients up to 25 MV/m to meet the design bunch compressor energy. The rest of the cryomodules in the main accelerator (accounting for 768 SRF cavities) would need to be operated at a moderate gradient (up to 7 MV/m per cavity) to accommodate for the fact that they were optimised for pulsed and not CW operation. The low gradient is constrained by both the dynamic cryogenic heat load at 2 K and the RF forward power per cavity. This upgrade scenario, called *canonical CW upgrade*, could provide an estimated final energy of 7 GeV.

Between the extended burst mode (RF on for up to 2–3%) and the full CW upgrade (RF on 100% of the time), the so-called *long-pulse operation* offers an interesting compromise. Keeping the dynamic heat load constant, the RF pulse can be scaled up in amplitude by accordingly shortening the time the RF is on, i.e. the RF duty cycle (Fig. 2). While it is not full CW operation (100% duty cycle), this long-pulse operation (5–15% duty cycle) offers a unique perspective for a European XFEL upgrade, increasing the effective photon delivery while keeping a relatively high final beam energy.

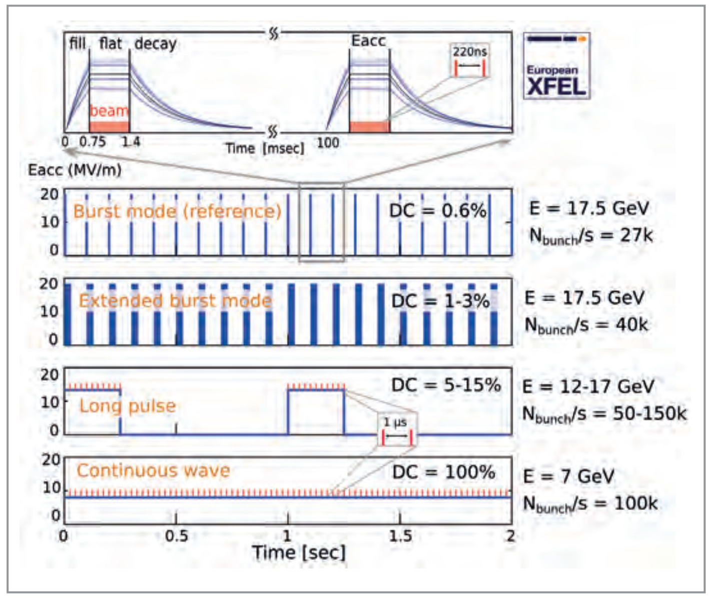

Figure 1

Current burst mode of operation of the European XFEL compared to long-pulse and continuous-wave RF operation (DC: duty cycle)

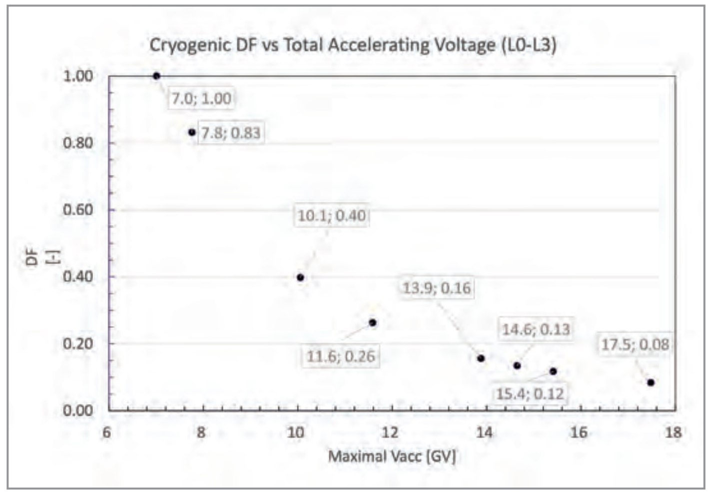

Figure 2

RF duty cycle (box, number on the right) vs. maximum beam energy (box, number on the left) for constant heat load (Courtesy J. Sekutowicz)

Long-pulse and CW operation upgrades require replacing the present power sources (klystrons) with CW-capable ones (inductive output tubes or solid-state amplifiers). Increasing the loaded quality factor Q_L of the cavities by a factor of 10 (corresponding to bandwidths < 10 Hz) is also necessary to allow for higher RF-to-beam power efficiency. Total cryogenic load, average and peak coupler power, tunnel space requirements and microphonics mitigation are among the numerous challenges currently being looked at. Possible upgrade scenarios are summarised in Table 1.

Outlook

The various upgrade scenarios and HDC modes of operation are currently being studied in detail. Specific topics related to the technical challenges associated with the upgrade options are the focus of dedicated workshops held twice a year and monthly seminars to find the best ways to address the challenges and determine the concrete strategy.

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Short X-ray pulse generation at the European XFEL

Hardware-less methods enable (sub-)femtosecond pulses in the soft and hard X-ray regions

One of the main goals of the FEL R&D group at DESY and European XFEL in 2022 was the production of X-ray pulses with durations in the few-femtosecond range in the hard and soft X-ray regions of the spectrum covered by the self-amplified spontaneous emission (SASE) undulators of the European XFEL. Variable charge and non-linear bunch compression were employed both separately and in combination to produce pulse durations below 10 fs at all three SASE undulators. Aggressive compression settings, together with the use of transverse dispersion in the undulator, enabled the generation of sub-femtosecond pulses at energies of around 1 keV at the SASE3 undulator. The duration of the pulses was confirmed by direct measurements in the time domain using angular streaking techniques.

Introduction

There are many important scientific applications of ultra-short X-ray pulses [1, 2], including research into ultrafast atomic processes and charge migration mechanisms in molecules. Therefore, state-of-the-art free-electron laser (FEL) facilities worldwide aim to produce powerful, ultra-short X-ray pulses. The European XFEL strategy to achieve this goal includes enabling zero-cost solutions that exploit the flexibility of the baseline SASE setup. This will be followed by *ad-hoc* installation of dedicated hardware that allows for the best possible control of the bunch lasing window below the coherence time limit. These efforts are bundled in the Attosecond Pulses with Enhanced SASE and Chirp/Taper (ASPECT) project.

This article discusses the experimental results obtained by the virtual FEL R&D group at DESY and European XFEL in 2022 to implement this strategy. The need for simultaneous operation of the three SASE undulators was always taken into account: SASE1 and SASE2 in the hard X-ray region and SASE3 in the soft X-ray region, with minimal cross-talking.

Variable charge with non-linear compression

We have implemented and combined two methods for X-ray pulse duration control at the European XFEL in a customised way at different undulators (Fig. 1). The first method exploits an acousto-optic modulator (AOM) in front of the amplifier of the electron gun laser [3]. It allows the generation of electron bunches with variable charge along the bunch train with minor restrictions. As the AOM is able to react on a 4.5 MHz scale, the system can customise the bunch length for all three undulator lines even if SASE1 and SASE3 are operated in an interleaved mode.

The second method for longitudinal bunch shaping along the train exploits the radio frequency (RF) system instead, which makes it possible to modulate both the amplitude and the phase of the wave in the cavity along the bunch train [4], thereby effectively changing the energy chirp and thus the compression of the bunches. The high quality factor of the superconducting RF system gives a lower limit for transition times on the order of tens of micro-seconds, which in turn limits the interoperability with the other beamlines. However, work to reduce this limitation is ongoing.

The combination of these two techniques allows for very short pulses (Fig. 2). The simple methods enable individual pulse duration control for each undulator. We have never experienced any interference with the operation of the other undulators [5], and the methods were implemented during user operation.

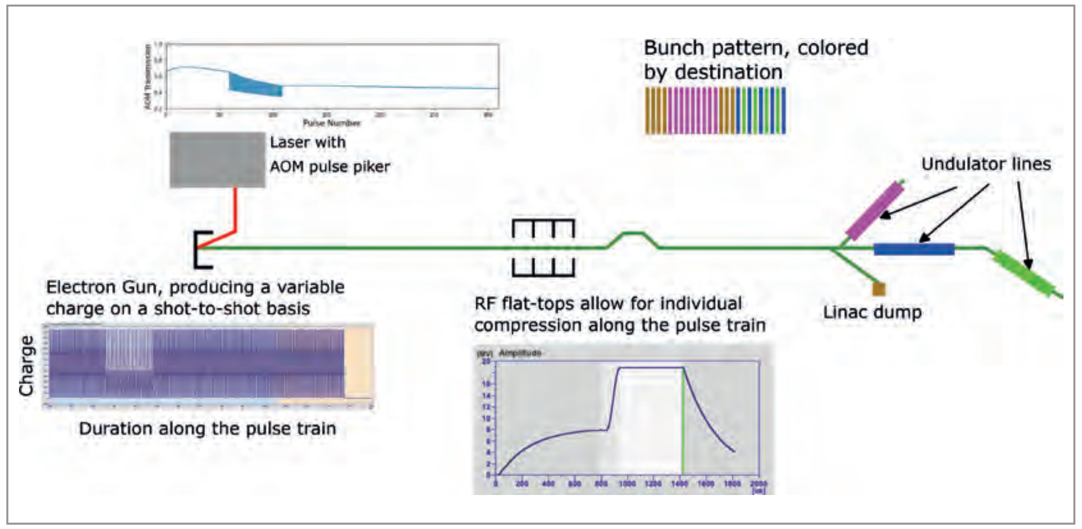
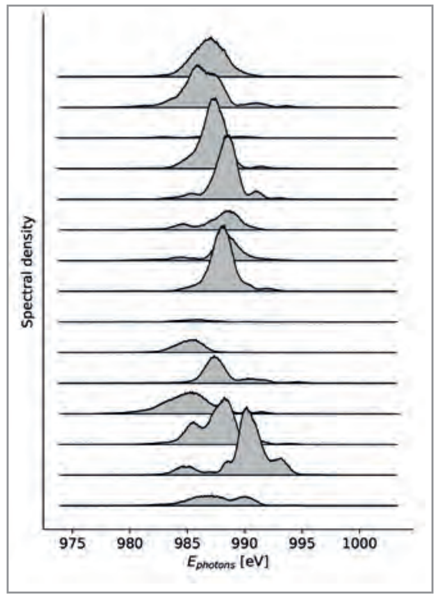


Figure 1
Schematic layout of the European XFEL with its electron bunch trains feeding the three undulator lines. The laser AOM absorber located close to the electron gun makes it possible to arbitrarily shape the charge profile of the electron bunches. The modulated RF flat-top enables individual bunch compression along the train. Note the different time scales of the two options, which make them appropriate for different delivery modes (depending on the destination of the bunches).



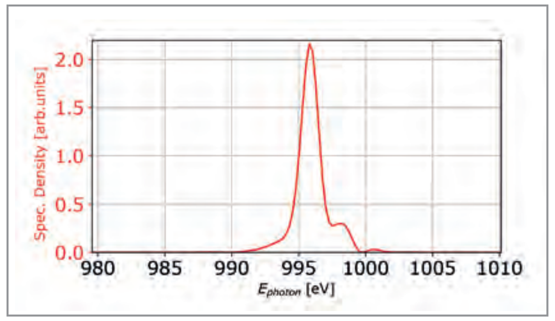


Figure 3
Left: Ten consecutive measurements of nearly single-spike X-ray spectra at an averaged pulse energy of about 600 µJ. Right: Simulations reproducing the experimental results.

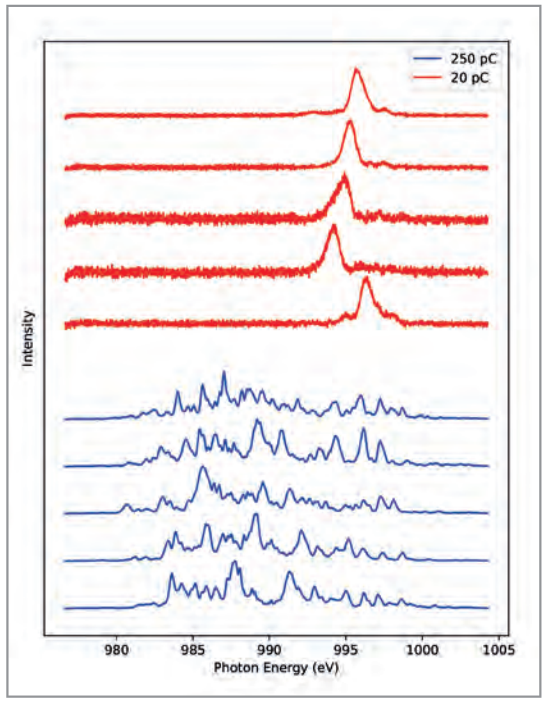


Figure 2
Selected X-ray spectra for nominal (250 pC) and low-charge (20 pC) electron bunches with optimised compression

Dispersion-based techniques at SASE3

The low photon energies at SASE3 allow for lasing with relaxed electron beam characteristics compared to SASE1 and SASE2. At around 1 keV photon energy, lasing can be supported by electron beams with higher peak currents than in the nominal case. These are obtained by more aggressive compression settings, which also result in a complicated longitudinal phase space. When dispersion is added in the undulator, electron trajectories start to depend on the electron energy, leading to a straight trajectory through the FEL for a small slice of the electron beam only. As a result, short X-ray pulses with high energy are produced, as shown by spectral measurements in an experimental setup (Fig. 3, left) and by simulations (Fig. 3, right).

Nearly single-mode spectra suggest a short pulse duration, but since information about the spectral phase was missing, a direct measurement was needed in order to actually confirm the pulse duration. During a dedicated measurement campaign based on angular streaking, full width at half maximum (FWHM) pulse durations were confirmed to be less than 1 fs.

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European XFEL Beam Regions

Flexible intra-pulse operation at the European XFEL

Beam Regions are flexible adjacent segments of the 600 µs beam pulse of the European XFEL accelerator to which arbitrary radio frequency (RF) amplitude and phase settings can be applied, making it possible (for example) to change the bunch compression delivered to each experiment. The new concept supports arbitrary RF settings as a function of time along the beam pulse, limited by klystron power and RF bandwidth. Its successful implementation in 2022 required significant upgrades to both the low-level RF systems, including the fast intra-bunch longitudinal feedback, and the high-level control systems.

What are Beam Regions?

A major upgrade to the RF control and beam pattern timing systems has provided greater flexibility in fine-tuning the European XFEL beam parameters within a single 600 µs pulse. The original system, effectively inherited from DESY's FLASH facility, supported three so-called flat-top regions, which could be assigned to deliver self-amplified spontaneous emission (SASE) radiation to each experiment. Each of the subsequent flat-top regions could have a small relative phase and amplitude offset with respect to the first flat-top. This has allowed each of the three SASE undulators to be supplied with bunches with slightly different bunch compressions, including chirp (adjusted by the 3.9 GHz system in the injector). The magnitude of the relative offsets is ultimately limited by the ~800 Hz bandwidth of the 1.3 GHz superconducting cavities, the available klystron power and limits on the RF power waveguide distribution system. Typically, the "transitions" between flat-tops are limited to 1–2% in RF amplitude and a few degrees in phase over tens of microseconds.

In 2021, it was agreed that a more sophisticated control of the beam pulse characteristics would be operationally advantageous. Typical use cases identified were the ability to fine-tune measured variations in energy across the pulse or the possibility to "modulate" bunch parameters such as compression and chirp. The result was the concept of Beam Regions (BR), where the beam pulse could be divided into a maximum of 16 adjacent regions, each of which could be arbitrarily manipulated and offset, within the limits of the cavity bandwidth and RF power constraints.

Figure 1 illustrates the concept of Beam Regions for three regions. Figure 2 shows an experimental demonstration of the new system for RF Station A2, where only the amplitude of the RF pulse flat-top is displayed. A total of five

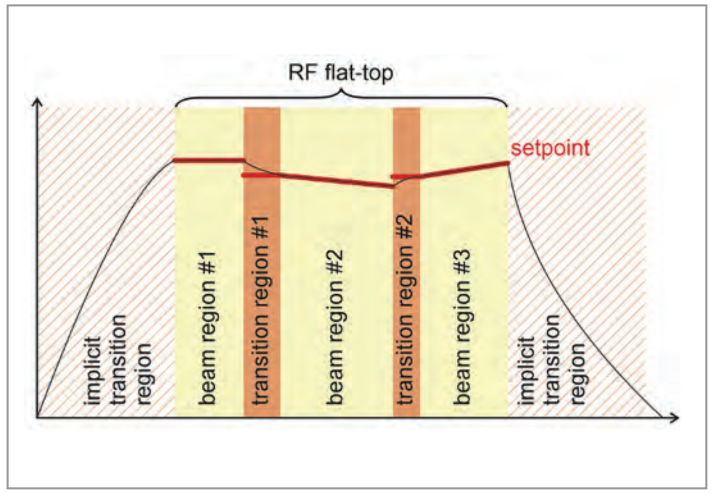

Figure 1

Sketch of the typical RF pulse form, showing the Beam Regions concept

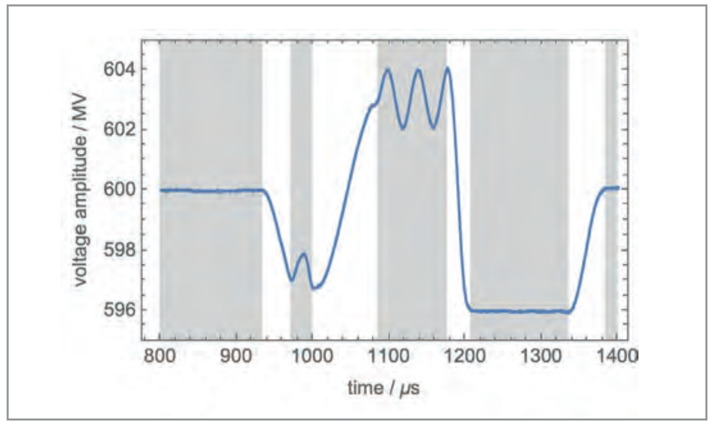

Figure 2

Demonstrated voltage amplitude (RF pulse flat-top, Station A2) with five Beam Regions (grey zones). BR 2 and BR 3 have arbitrary modulation. The white zones are the so-called transitions.

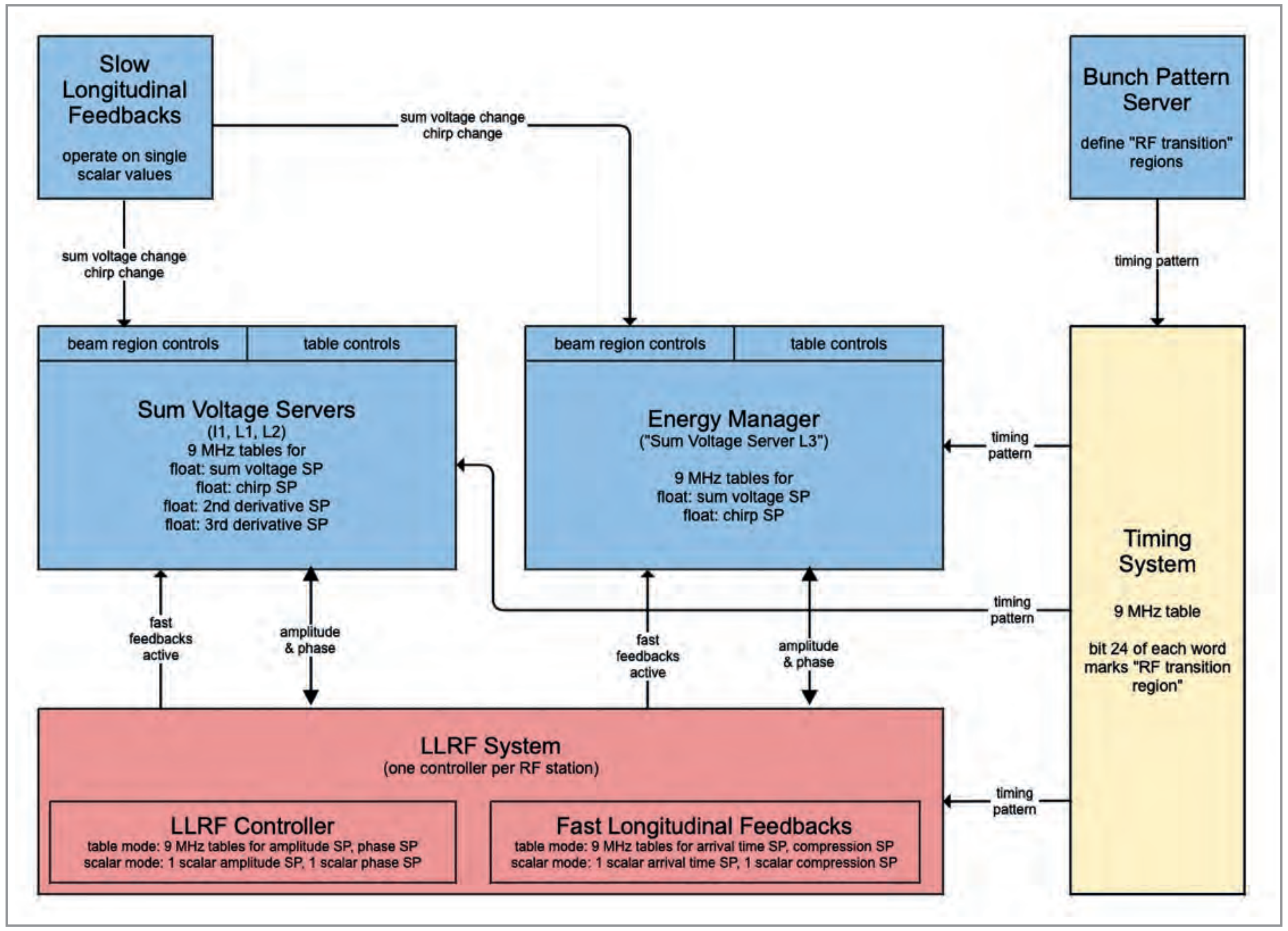

Figure 3

Control system architecture to support Beam Regions

Beam Regions were requested with amplitude offsets. In addition, an arbitrary modulation of the amplitude in BR 2 and BR 3 was made, in this case a simple sine wave. The required transitions between regions (white zones) are automatically calculated by the low-level RF (LLRF) system. If the rate of change in amplitude, which is proportional to the requested klystron forward power, exceeds predetermined limits, the requested waveform is rejected.

Implementation

Figure 3 shows the overall systems architecture supporting Beam Regions. Although each of the subsystems already existed, all of them required significant upgrades. Major upgrades were made to several key software and in some cases firmware systems, including the LLRF controller, the longitudinal intra-bunch feedback system, the timing system (bunch pattern generator) and the high-level control systems (specifically those controlling the bunch compressor RF systems via the LLRF).

Implementation began in the spring of 2022, with systems ready for initial testing in July. A complete roll-out of the new systems in the bunch compressor linear accelerators (first four RF stations) was made during the summer shutdown, and the systems have since been in successful operation. While the primary goal was to implement the required Beam Regions functionality, there were also several other benefits in terms of system implementation, interface definition and overall "operability". Although driven by European XFEL requirements, the Beam Regions concept was also successfully introduced at FLASH.

Next steps

In 2023, Beam Regions will be implemented in the European XFEL main linear accelerator (L3). Furthermore, more advanced use of the functionality is planned (for example 100 kHz modulation of chirp), as well as other studies to understand the operational limits and potential novel applications.

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Energy saving at the European XFEL

Adapting the high-power RF system operation to different electron beam energies

The European XFEL can accelerate electrons to high energies of 17.5 GeV. To achieve this, 5 MW of electrical power must be applied to generate the radio frequency (RF) power required for electron acceleration. However, there are also long operating phases at significantly lower beam energies of typically 14 GeV and 11.5 GeV. In these operating phases, less RF power is required and the power consumption could be reduced by up to 1 MW. This was achieved by adapting the voltages of the klystrons to the various operating states of the accelerator. If the maximum possible RF power is not required, the operating voltage and thus the energy consumption of the klystrons can be significantly reduced.

How much RF power is needed

In the European XFEL, 97 accelerator modules and one electron source (gun) are supplied by 26 RF stations with an RF power of 0.7 to 6.5 MW. Figure 1 shows an RF station in the European XFEL tunnel with exemplary, approximately correct and easily comprehensible parameters. The provided input signal with a frequency of 1.3 GHz is amplified to 100 W by a preamplifier and then fed to the klystron. The klystron then amplifies this signal to 5 MW, which is transmitted via two waveguide arms. A waveguide distribution then feeds the RF power to the 32 cavities that accelerate the electron beam.

To generate this RF power, the klystron needs a high operating voltage. In our example, 8 kV are generated by a high-voltage modulator and then raised up to 96 kV by a pulse transformer. Thus, 10 MW of electrical power must be made available for the operation of the klystron (96 000 V x 104 A ≈ 10 MW). However, this is only done ten times per second for a period of 1.7 ms each, so the average power required is only 170 kW. In order to achieve the maximum possible beam energy, slightly more power is required on average and power losses of the overall system must be compensated. Therefore, the total power requirement for all 26 RF stations is 5 MW.

What klystron power consumption depends on

As illustrated in Fig. 2, the power is provided by the high-voltage modulator, which generates square-wave voltage pulses that are fed into the tunnel via a cable. The matching network ensures that the pulse is not reflected during the rising edge. The transformer raises the voltage by a factor of 12 and feeds the power to the klystron. The current in the klystron depends on the klystron voltage, but unlike a resistive load, the current increases disproportionately with the voltage. Ultimately, the power requirement of the modulator can be represented in an expression that depends directly on the modulator voltage (Fig. 2, bottom right). It is important to note that the power requirement does not only decrease quadratically when the voltage is reduced, but with the exponent 2.5. So, lowering the modulator voltage drastically reduces the power consumption.

Reducing the power consumption

If the modulator voltage and thus the klystron voltage is reduced, less RF power can of course be produced. However, if the European XFEL is operated at lower beam energies, less RF power is actually needed to drive the electrons. Therefore, in mid-2022, the voltages of 13 RF stations were lowered during 14 GeV operation in order to save energy. This reduced the power consumption by 0.5 MW. As an additional measure, it was decided to completely switch off three of the RF stations during 11.5 GeV operation, which reduced the power consumption by a further 0.5 MW.

No investments had to be made to implement these energy-saving measures, and they do not restrict the performance of the European XFEL. There are also two positive side effects for the klystrons when the voltage is reduced: They run more stably and their lifetime is extended.

For the next years, it is planned to operate the European XFEL accelerator at a beam energy of 16.5 GeV for one third of the operating time, another third at 14 GeV and the remaining time at 11.5 GeV. The measures presented here will then lead to energy savings of about 3.6 GWh per year.

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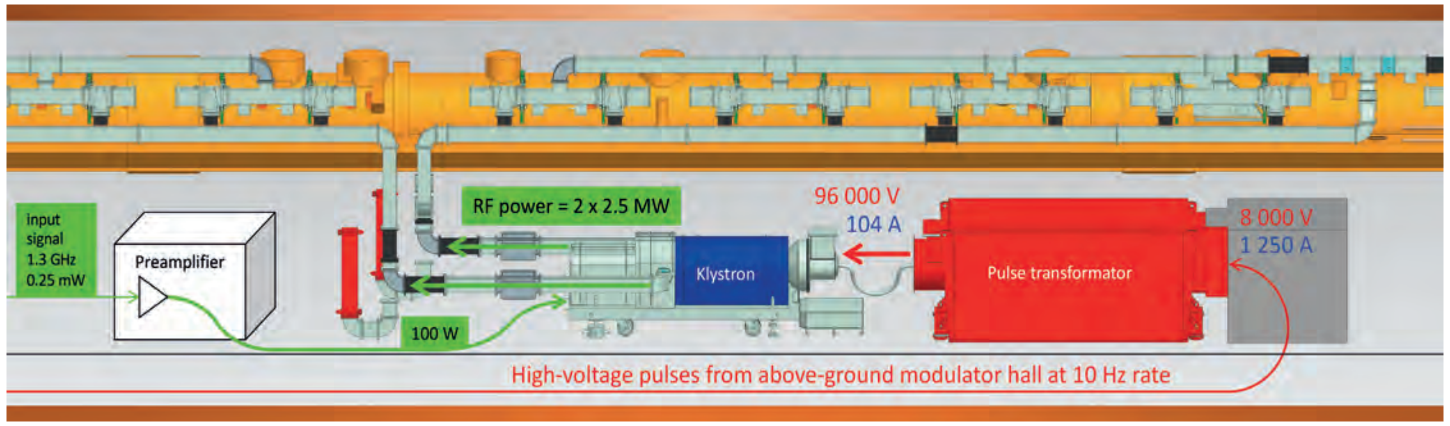

Figure 1

Power supply of the klystron and generation of the RF power

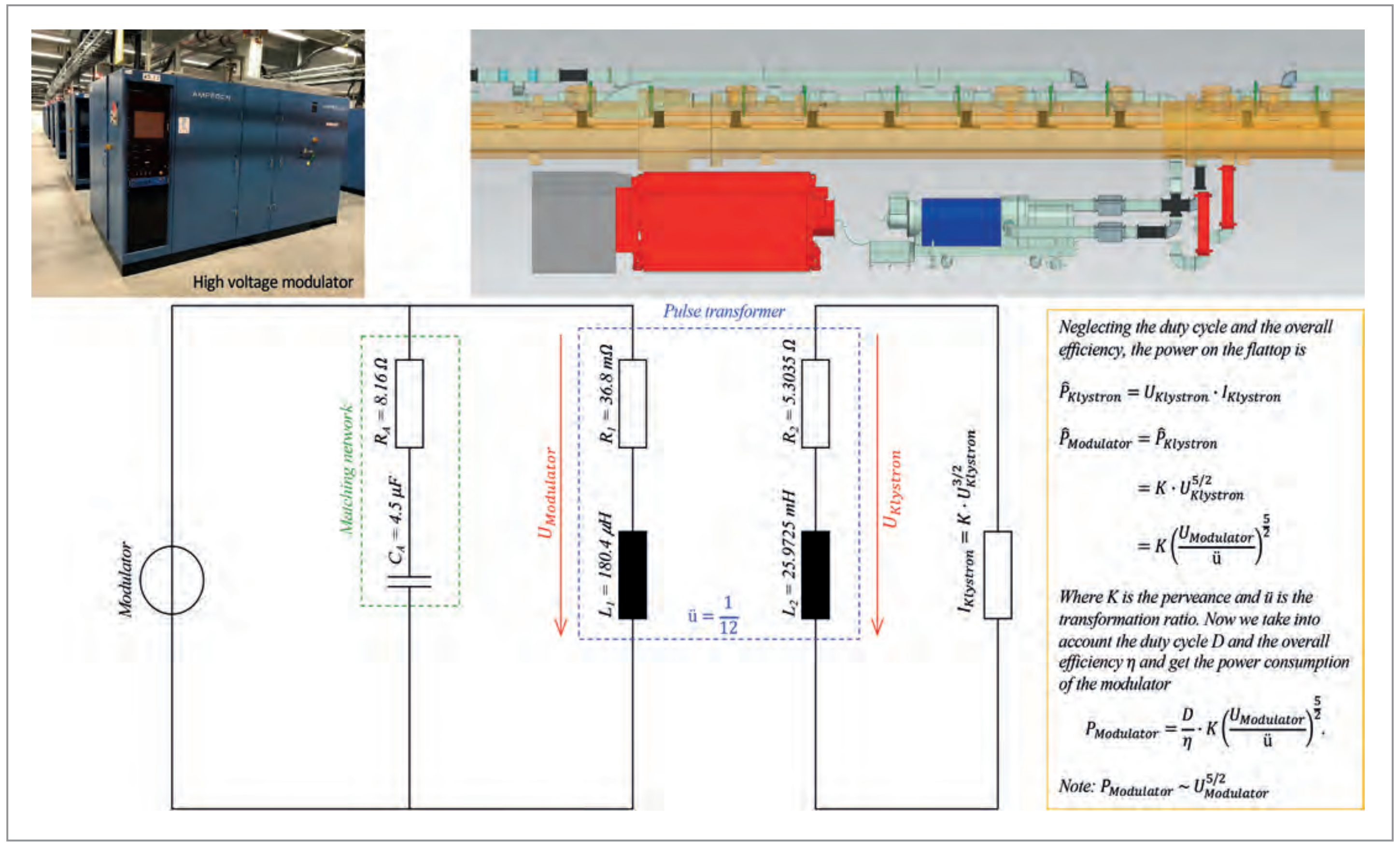

Figure 2

The power requirement of the klystron depends directly on the modulator voltage.

Medium-temperature treatment studies of superconducting cavities

Refurbished niobium retort furnace allows promising first studies

The hunt for superconducting radio frequency (SRF) cavities with unprecedented performance began at DESY in 2022, using a refurbished niobium retort vacuum furnace. DESY's SRF group, whose members were responsible for the development and production of all 800 very successful niobium cavities at the heart of the European XFEL accelerator, started to explore treatment options to achieve even better accelerator structures for an upgrade of the European XFEL. In the last few years, the worldwide SRF community has tried out different surface treatment recipes based on sophisticated heat procedures in order to push the cavity quality factor in particular into new regimes. A clearly reduced cryogenic load during accelerator operation can thus be expected. For the time being, a baking procedure in ultrahigh vacuum at temperatures of about 300°C seems to be very promising for this purpose and is therefore being investigated in more detail at DESY.

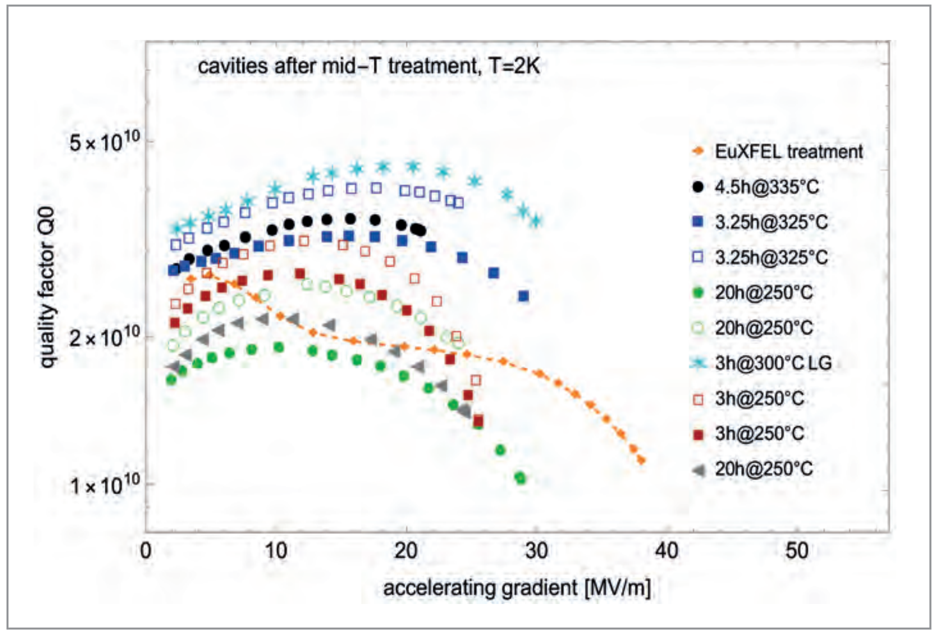

Figure 2

Performance of different single-cell cavities after medium-temperature baking, given as quality factor versus accelerating gradient. A test-to-test uncertainty of about 10% for the accelerating gradient and 20% for the quality factor has to be assumed for the shown results.

SRF cavity R&D towards a European XFEL upgrade

Upgrading the European XFEL to enable high-duty-cycle or even continuous-wave operation requires a partial replacement of the linear accelerator modules. For the new operation modes, the injector and the first 16 modules need to be rebuilt with SRF cavities that provide an enhanced quality factor. This parameter can be understood as something like the efficiency of the accelerator. The higher the quality factor, the lower the losses in the cavity walls and the less cryogenic power is required for cooling. The second figure of merit for cavities is the accelerating gradient, which is also part of the accelerator efficiency, as it describes the field strength in the cavity and thus the possible energy gain per metre. A large accelerating gradient is needed for the standard short-pulse operation of the facility in order to reach high energies.

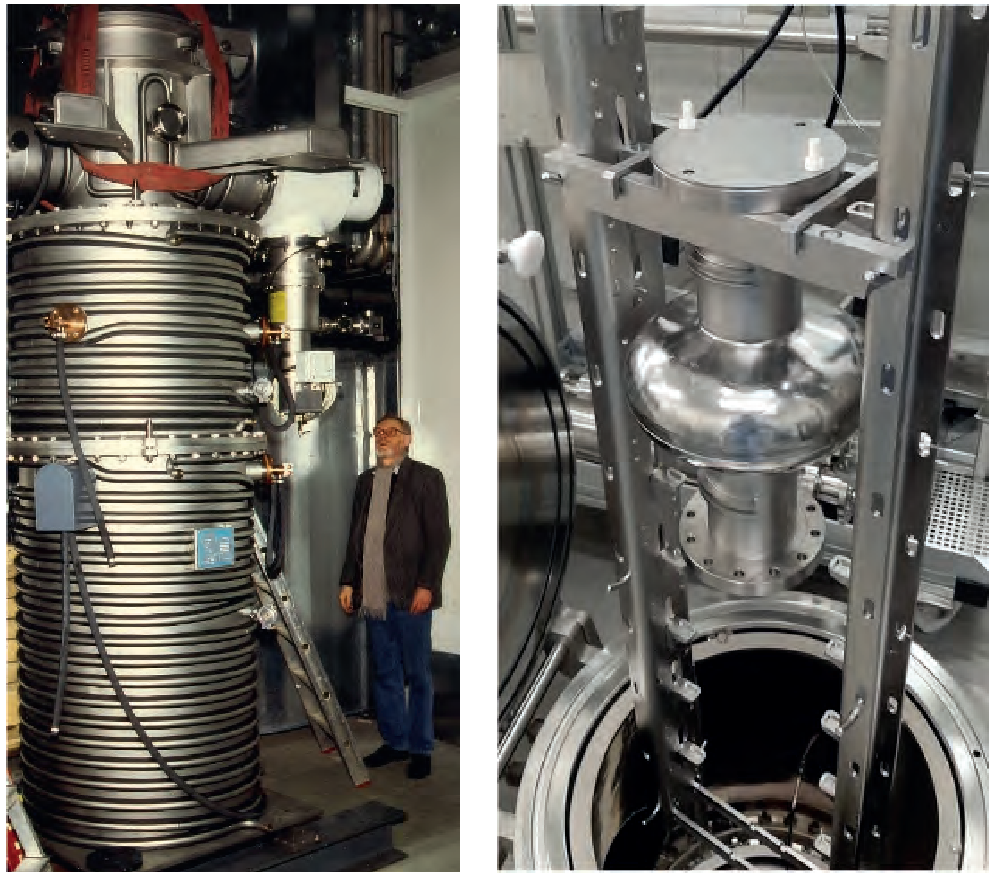

Figure 1

The niobium retort furnace. Left: During installation in the 1990s. Right: During insertion of a single-cell cavity for a medium-temperature treatment run in 2022.

Cavity treatment campaign in newly refurbished vacuum furnace

The upcoming challenge is to define a new gold standard surface treatment recipe for the well-established niobium cavity structures. The aim by applying this treatment is to allow for cavity operation with an enhanced quality factor while maintaining a large accelerating gradient. For this purpose, the SRF community has developed different recipes, all based on heat treatments in very clean ultra-high-vacuum furnaces.

As the furnace available so far at DESY could not fulfil the requirements, an all-niobium retort furnace – last used in the 1990s and shown in Fig. 1 – was completely refurbished and became available by the end of 2021. This furnace is directly attached to the ISO4 cleanroom and hence perfectly suited for treatment studies. It is operated by two cryogenic pumps and, as the vacuum systems for the heater and the niobium retort are separated, it reaches a starting pressure of 2×10^{-8} mbar at room temperature and about 3×10^{-7} mbar at 300°C. The reference residual gas spectra are very clean and underline the very good condition of the furnace.

First promising cavity results and supporting sample studies

Taking advantage of this new infrastructure, many different versions of medium-temperature treatments around 300°C have been performed on single-cell cavities in 2022 [1]. Such cavities are used as workhorses for R&D activities in cavity research. The goal of the campaign is to find a parameter set for the treatment that allows for a large quality factor while maintaining accelerating gradients above 30 MV/m. The latter seems to be a challenge, but will be important for a possible European XFEL upgrade.

Many medium-temperature treatments yield extraordinarily high quality factors (Fig. 2) compared to the "European XFEL treatment" cavities (orange diamonds), but the reduction in accelerating gradient is obvious as well. So what are the optimum treatment parameters? A better understanding of the underlying physics will be reached through studies of small niobium samples treated in the same furnace runs. The samples will be analysed using modern surface characterisation methods, such as electron microscopy or X-ray reflectivity measurements. This will help to identify which treatment is the most promising in order to develop a stable recipe for a cavity series that can be used in industry for the next step towards very high-performance superconducting accelerators.

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SRF photoinjector

New-technology photoinjector for the European XFEL

Figure 1

Intermediate components of the next two cavity prototypes (16G09/10) before final welding

An upgrade of the European XFEL foresees high-duty-cycle (HDC) operation ranging from continuous-wave (CW) mode and 100% duty cycle for maximum timing flexibility to about 8% duty cycle for the high-energy electron beam. This requires a photoinjector operating in CW mode. Using L-band superconducting radio frequency (SRF) technology for the electron gun is preferred in order to maintain the present "pancake" electron emission scheme [1]. In 2022, surface treatments of 1.6-cell SRF gun cavities were further consolidated. Substantial efforts went into the production and design of the next generations of cavity prototypes. Photocathodes that are robust to well-established SRF cavity cleaning procedures have attracted increasing attention at DESY. Following the successful completion of the energy upgrade of DESY's FLASH facility in autumn 2022, the resources required to design the SRF photoinjector test stand became available.

SRF gun cavity development

DESY follows an SRF gun cavity design with a cathode plug screwed into a hole on the rear side of the cavity in a cleanroom. After several years of R&D, SRF cavity cleaning procedures now result in typical maximum peak field on axis gradients that exceed the design goal of 40 MV/m by about 40%. In the context of a very good cooperation with KEK in Japan, electropolishing was successfully applied to a cavity prototype (16G4) in 2020. Since then, this cavity has served for further testing, also in 2022. Tests with a lead-coated cathode plug have shown that the coating needs to be made more robust. In fact, it would even be preferable to use bulk metal photocathodes and skip any coating.

The major goal for the next two cavity prototypes (16G09/10) is a cavity frequency staying within the frequency acceptance of the cathode laser. This requires very close production support and monitoring of various parameters, such as frequency trimming of intermediate components and weld shrinkage, as well as methods and tools for tuning the cavities after mechanical production. By the end of 2022, production of the two prototypes was almost complete (Fig. 1).

For the two cavity prototypes after next (16G11/12), we will focus on the beam dynamics aspects of the cavity end group in addition to the existing goals. Coupler kicks, trapped higher-order modes (HOMs), keeping the fields symmetric, a reasonable mechanical fabrication effort and the position of the pick-up antenna were studied in detail. We finalised our design effort with an internal review to start production.

Dry ice (CO_2) cleaning was successfully applied to intermediate SRF gun cavity prototypes (in particular 16G8), getting rid of field emission. This opens up another cleaning option for the cavities.

Photocathodes

The cathodes need to be robust to exposure to air and also to well-established SRF cavity cleaning procedures. Metal cathodes comply with this requirement. As mentioned above, the lead coating applied so far requires further improvement to resist cleaning procedures.

The quantum efficiency (QE) of plain bulk niobium or copper metal photocathodes is insufficient for our needs, but nanostructuring the surface to couple photons and plasmons reduces the reflectivity of incident light and enhances the QE by up to two orders of magnitude. In collaboration with the DESY NanoLab and CFEL, we successfully replicated first proof-of-principle tests in this direction, which were conducted for example at the University of California, Los Angeles. Then we initiated an interdisciplinary R&D effort to use such cathodes for photoinjectors at user facilities.

Solenoid magnet

The electron beam generated through the photoelectric effect at the cathode and accelerated by the RF field in the 1.6-cell SRF cavity needs to be focused by a solenoid field after exiting the SRF cavity. The purchase of a copy of the superconducting solenoid magnet used by HZB in Berlin started at the beginning of 2021. Following the advice of HZB, our magnet comprises some minor modifications. Unfortunately, its delivery in summer 2022 was prevented by leaks discovered by and at the vendor. The windings needed to be redone, and the predelivery inspection and delivery were eventually postponed to 2023.

SRF photoinjector test stand

In order to develop this novel technology, an SRF photoinjector test stand is required to characterise the beam properties provided by an SRF photoinjector [2]. The test stand will also serve for the final qualification of SRF photo-injector cryostat assemblies before they are released for installation in the future European XFEL CW injector. In 2022, we developed an initial concept for the diagnostic beamline, consisting of a straight section and dispersive sections ending in beam dumps.

After successful finalisation of the energy upgrade of the FLASH facility in autumn 2022, resources became available, and we started working on the concepts for the cold integration, namely the SRF photoinjector cryostat requirements and design as well as the concept for the cryogenics supply. Further cold integration topics include the cavity helium vessel, the cavity tuner, the power coupler, the cold beamline and the concept for the assembly process from the cleanroom to the photoinjector test stand.

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The Quadrupole Resonator

When materials science meets SRF cavities

Studying samples helps to identify the surface processes underlying annealing recipes and state-of-the-art coating for superconducting radio frequency (SRF) cavities. So far, however, only cavities allow RF characterisation, which is mandatory to assess recipes and process parameters with regard to accelerator operation. A test cavity called Quadrupole Resonator (QPR) brings together the best of both worlds, allowing full RF characterisation of samples. It enables in-depth studies of how material parameters are influenced by the various surface treatments and how they are linked to RF parameters, boosting our fundamental understanding of SRF and helping to develop robust recipes for project-driven R&D.

A versatile and unique tool for SRF R&D

Figure 1 shows the general design of the QPR. The device uses a compensation technique to directly measure the losses dissipated on the sample surface, which can then be used to determine the surface resistance. Four rods focus the magnetic field on the sample, where Joule heating then occurs on the sample surface. The big advantage is the large parameter space covered by the QPR. Not only can the sample surfaces be measured with RF field strengths up to the operational gradient of the European XFEL, but the sample temperature can also be varied between 1.5 K and 15 K, and multiple frequencies can be applied. These variations are of particular interest, as modern developments in SRF theory include frequency-dependent scattering processes that can be studied on the same surface – which is otherwise impossible for cavities, as the frequency is defined by the cavity geometry.

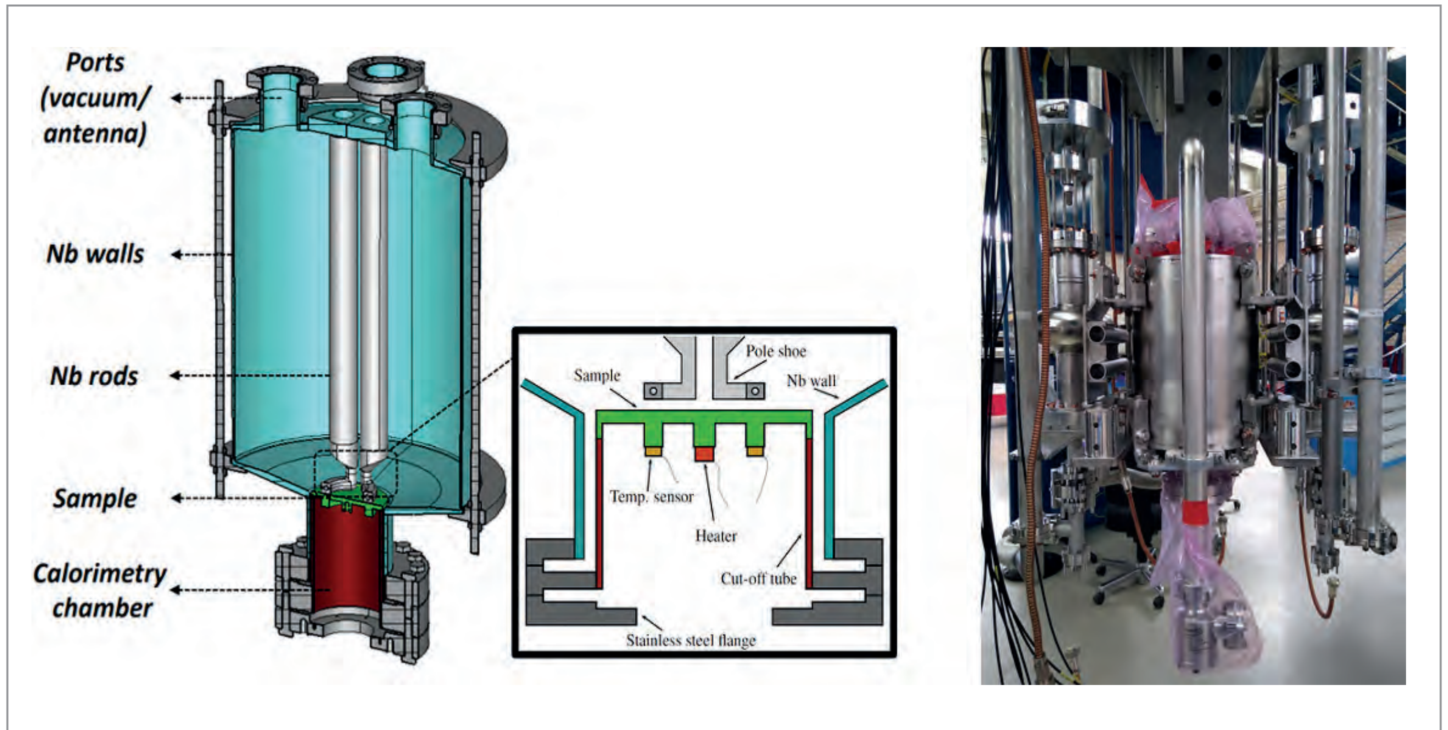

Figure 1

Left: Schematic view of the QPR. The inlet shows a cross section through the sample and the bottom part of the rods [1]. Right: QPR installed and vacuum connections assembled for the first cooldown to 1.5 K at the Accelerator Module Test Facility (AMTF) at DESY.

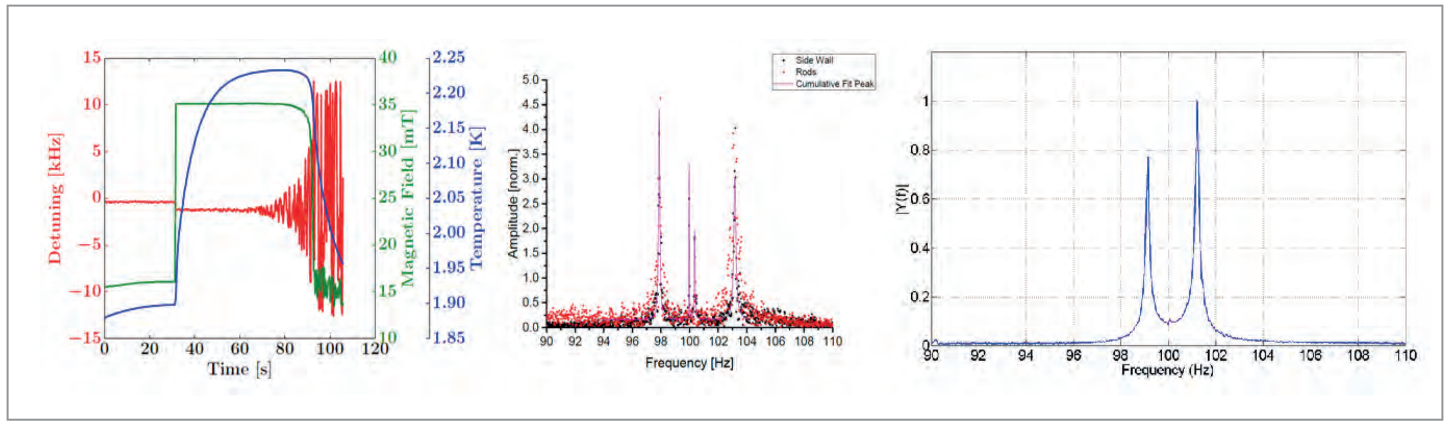

Figure 2

Left: Magnetic field on sample (green) shown as a function of time. An increasing RF detuning can be seen (red), which is a 100 Hz signal, causing the control system to lose the lock on the resonance and the measurement to be interrupted. Middle: The origin is a mechanical resonance of the rods vibrating at 100 Hz [3]. Right: The new design at Universität Hamburg and DESY mitigates the problem by damping the mechanical modes, as shown in the mechanical spectrum [4].

Solving long-standing problems

A common issue for the two QPRs already operating at HZB in Berlin and CERN near Geneva was an unreasonably high surface resistance of the samples tested. The problem occurred only at the third operating frequency Q_3 = 1299 MHz, while the surface resistance at the other frequencies Q_1 = 433 MHz and Q_2 = 866 MHz was in the expected range. A close collaboration set up by Universität Hamburg and DESY, together with HZB and TU Darmstadt, solved this issue [2]. The reason for the high surface resistance was an undamped dipole mode that propagated into the coaxial gap and heated up the bottom part of the sample flange. This additional heat source was then falsely included in the calculation of the surface resistance. The problem was dominant only at the higher operating frequency because the coaxial damping was mitigated in this frequency range. Our joint research solved this long-standing problem common to all existing QPRs and proposed two simple solutions, one of which was already proved to work, enabling the use of the full QPR potential.

Another problem is vibrations of the rods induced by the dynamic Lorentz force of the applied time-varying magnetic field. As shown in Fig. 2, a detuning builds up over time, causing the control system to lose the lock on the operational resonance frequency as the mechanical vibrations grow stronger over time. The underlying issue is a mechanical resonance of the rods close to typical frequencies of RF noise. For the new QPR, we designed the rods to mitigate any vibrations, which was confirmed by a measurement of the mechanical spectrum at room temperature [4]. This relaxes the requirement for the RF control system and allows a faster and more accurate measurement, as the thermal equilibrium needed to measure the dissipated losses can be achieved by continuous RF fields, compared to otherwise pulsed operation.

From commissioning to operation

The first cooldown of the QPR at DESY in December 2022, after a three-year construction and treatment period, was a full success. All planned measurements were successfully carried out, and all measured parameters were in agreement with the values predicted from simulations. The project is at the core of the joint Universität Hamburg and DESY SRF R&D, and the QPR plays a key role in the endeavour to advance beyond niobium and in the further development of our fundamental understanding of SRF.

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First lasing of THz SASE FEL at PITZ

Proof-of-principle experiments on accelerator-based THz source for the European XFEL

DESY's family of free-electron lasers (FELs) has grown: In summer 2022, first lasing of a terahertz self-amplified spontaneous emission (THz SASE) FEL was achieved at the PITZ photoinjector test facility at DESY in Zeuthen. The breakthrough was part of efforts at PITZ to develop a prototype of an accelerator-based tuneable high-power THz source for pump–probe experiments at the European XFEL, with a SASE FEL producing the THz pulses. The narrowband THz SASE FEL pulses with a centre wavelength of 100 µm were generated by high-charge (1–3 nC) electron bunches with a beam energy of ~17 MeV passing through an LCLS I undulator installed in a second PITZ tunnel. The proof-of-principle experiment is an important step in the development of tuneable high-power THz sources supporting the time pulse structure of modern X-ray FELs such as the European XFEL.

PITZ accelerator extension for the THz FEL facility

The THz beamline at PITZ was designed and implemented as an extension of the existing PITZ linear accelerator in the tunnel annex. The existing PITZ beamline was extended by a bunch compressor and a collimator system in the first tunnel and a matching system, an LCLS I undulator and THz diagnostics in the second tunnel annex (second PITZ tunnel) downstream of the existing accelerator (Fig. 1).

A SASE FEL is used to generate the high-power THz pulses. One of the key parameters for high performance of the THz SASE FEL is a high peak beam current of up to 200 A.

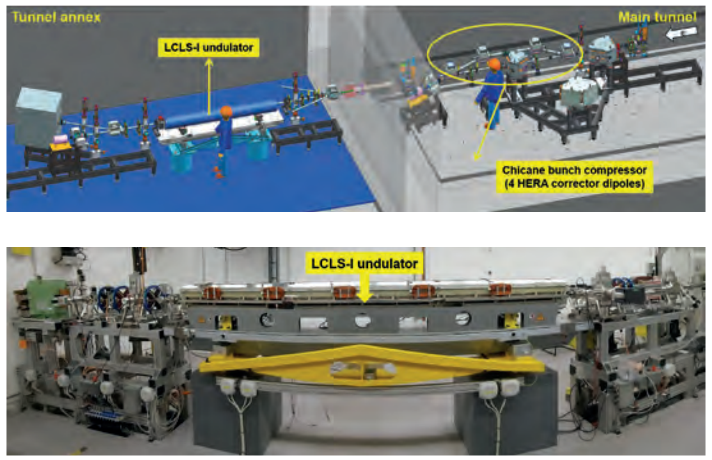

Figure 1

PITZ beamline extension. Top: 3D model.
Bottom: THz beamline in the second PITZ tunnel.

The PITZ radio frequency electron source (RF gun) with a caesium telluride (Cs_2Te) photocathode is capable of generating electron bunches with charges up to 5 nC, making it suitable for proof-of-principle experiments on a high-gain THz SASE FEL.

Space-charge-dominated electron beam matching into the undulator

A planar LCLS I undulator on-loan from SLAC is used to generate the THz radiation. The undulator parameters (period 3 cm, undulator parameter ~3.5) demand an electron beam energy of ~17 MeV for a centre radiation wavelength of ~100 µm. The strong magnetic field with a horizontal gradient requires thorough beam matching. Another challenge is the narrow vacuum chamber (height 5 mm, width 11 mm and length ~3.5 m), which makes matching and transport of the space-charge-dominated electron beams a complicated task.

The horizontal gradient effect is mitigated using a specially designed long coil, which allows lossless transport of the electron beam with moderate energy through the narrow vacuum chamber in the LCLS I undulator. The space-charge-dominated beam transport through the PITZ linear accelerator is realised using two quadrupole triplets. A third quadrupole triplet located in the tunnel annex is used for careful matching of the electron beam into the undulator. The beam matching is achieved by subsequent transverse distribution measurements on YAG screens along the beamline.

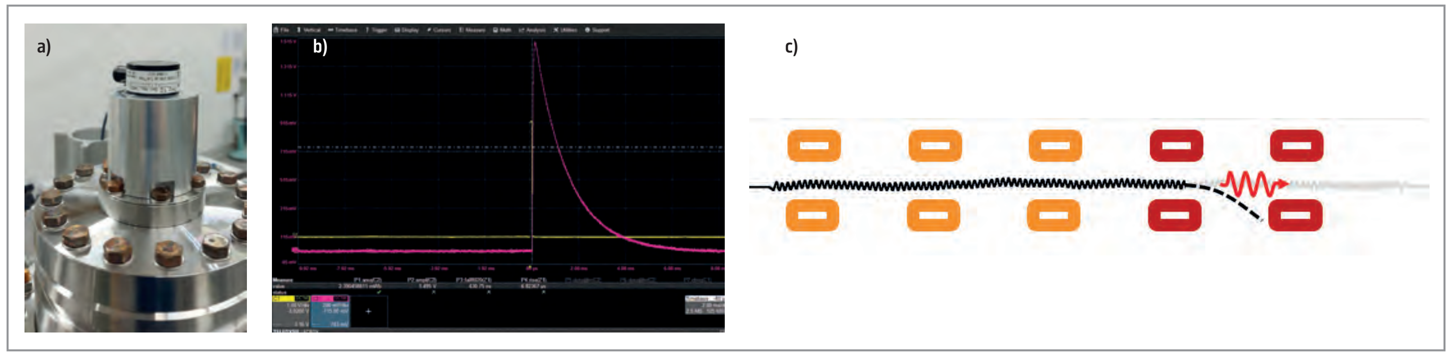

Figure 2

a) Pyroelectric detector on top of the conic adapter. b) Typical scope signal from the pyroelectric detector (pink curve). c) Schematics of the gain curve measurement.

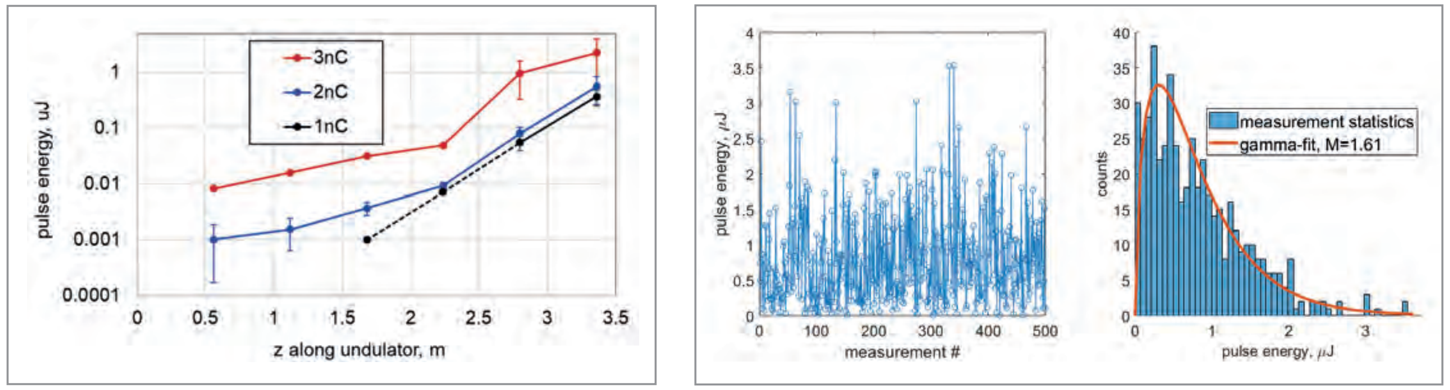

Figure 3

Left: First gain curves for bunch charges of 1 nC, 2 nC and 3 nC. Centre: Shot-to-shot radiation pulse energy measurement using a single electron bunch in a pulse train. Right: Probability distribution of the radiation pulse energy.

THz diagnostics and first SASE FEL lasing

The THz radiation is measured by pyroelectric detectors located on top of dedicated screen stations. Cylindrical adapters with a conic internal surface for radiation collection are mounted on top of a flange with a diamond window (Fig. 2a). The first station is equipped with a movable THz toroidal mirror with a 5 mm diameter hole to allow for electron beam transport further downstream. The second station is a solid mirror without a hole in order to transport the complete THz radiation to the detector. A typical waveform of the pyroelectric detector signal is shown in Fig. 2b.

After optimising the THz radiation signal by averaging many shots and setting the correct electron beam transport, the corresponding gain curve is measured (Fig. 2c). The measurement procedure is based on the application of dedicated short steering coils placed on the side of the undulator, which can be seen in Fig. 1 (bottom). Starting with the last coil, all coils are set one after another to a current of +3 A, which kicks the beam from the lasing trajectory and stops the lasing process at this position.

Figure 3a shows the first measured THz pulse energies (gain curves) using 500-shot statistics along the undulator for three values of the bunch charge. The backward propagation of the exponential range of the gain curves leads to an initial signal at picojoule level, which is in basic agreement with expectations for the shot noise at this wavelength. The estimated FEL gain of ~10^6 indicates a high-gain THz SASE FEL, which is a remarkable result for this radiation wavelength range. Relevant probability distributions for the second-to-last point of the 3 nC gain curve are presented in Fig. 3c. As can be seen, the probability distribution of the radiation pulse energy does indeed follow that of a high-gain SASE FEL in the linear regime. The reduction of the gain curve slope indicates the onset of the saturation regime.

Subsequent multiparametric optimisation of the electron beam that drives the THz SASE FEL resulted in a significant increase of the radiation pulse energy, e.g. >20 µJ for a bunch charge of 2 nC with a clear signature of saturation. Moreover, the first seeding experiments using modulated photocathode laser pulses yielded an increase of the THz FEL pulse energy to >30 µJ and demonstrated characteristic properties of a seeded THz FEL.

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FLASH2020+

Enabling next-generation experiments

Bringing DESY's FLASH free-electron laser (FEL) facility back to life on time after its nine-month shutdown marked the conclusion of the first phase of the FLASH2020+ upgrade project. The period from November 2021 to August 2022 was used for an overhaul of the linear accelerator. Among other measures, the replacement of accelerator modules, the addition of a laser heater and the modification of the bunch compression and diagnostic sections now provide new possibilities for electron beam manipulation and stabilisation at 100 MeV higher energy. First users already benefitted from the resulting extended wavelength range and higher-quality photon beams. Preparations for the renewal of the FLASH1 FEL beamline, which will start in mid-2024, are in full swing, with the aim to realise a beamline tailored for external seeding that will provide fully coherent pulses at MHz repetition rate. With new early-stage science experiments, the course will be set for the best possible exploitation of the future beam parameters for the next generation of user experiments.

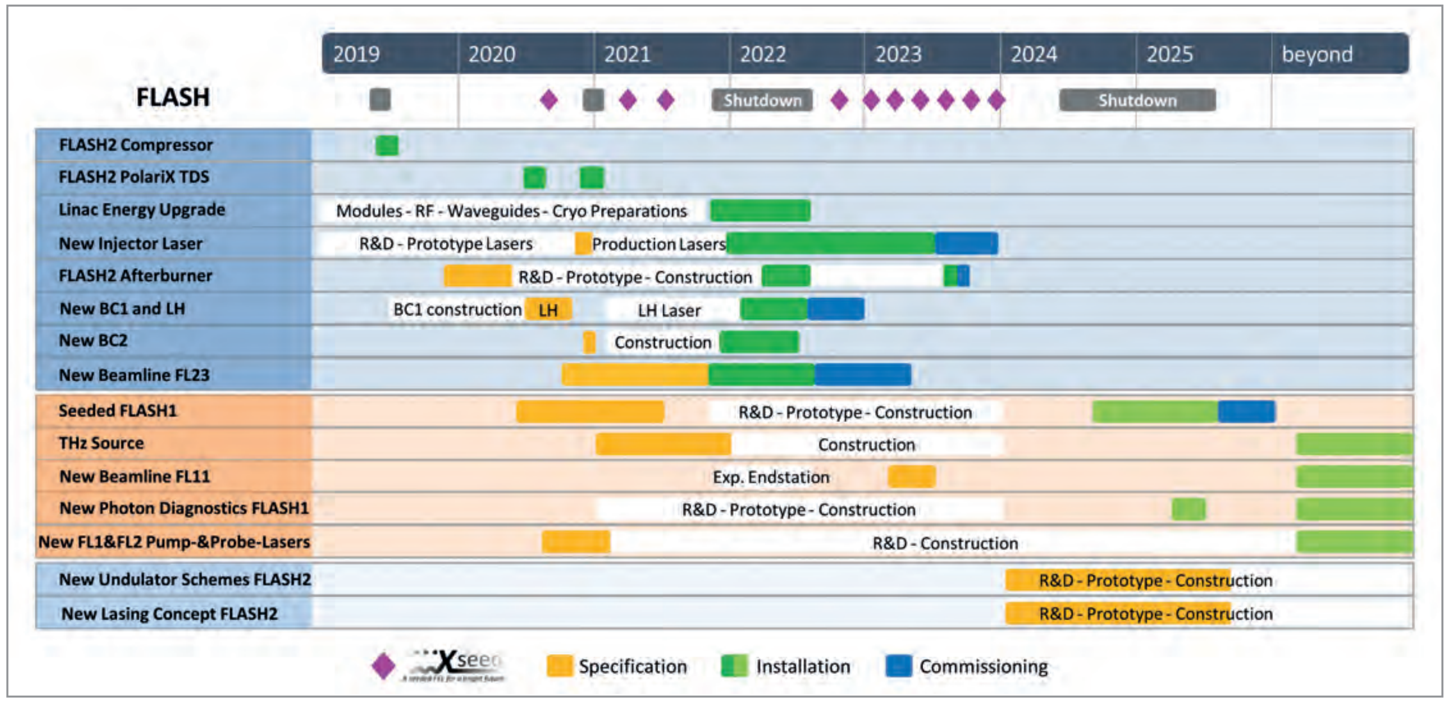

Figure 1

Subprojects of the FLASH2020+ project and their individual timelines

Project progress

In August 2022, FLASH was put back into operation after a nine-month shutdown period. A 60 m long section of the linear accelerator was refurbished and is now equipped with new features designed to further improve the quality and performance of the generated electron beam. This also greatly benefits the FEL radiation delivered to the measuring stations in the experimental halls. The new features are divided into FLASH2020+ subprojects (Fig. 1), several of which have been successfully implemented:

The **FLASH2 Bunch Compressor (BC)** had already been installed and commissioned before the shutdown and proves to be a great addition to the FLASH2 beamline. It enables final compression of the electron beam at its highest energy and thus reduces undesired effects during propagation, improving the overall FEL performance.

The **FLASH2 PolariX Transverse Deflecting Structure (TDS)** had been in operation prior to the shutdown. It allows for high-resolution tomography of the electron beam phase space by streaking in an arbitrary (transverse) direction. Conditioning of the system to full performance is still ongoing. The continuous improvement of the streaking amplitude enables enhanced time resolution, ultimately allowing for sub-5 fs time resolution once the design specifications are achieved.

For the **Linac Energy Upgrade**, the accelerator modules ACC2 and ACC3 were replaced by new modules supporting a higher accelerating gradient. The installation during the shutdown and the subsequent cooldown proceeded as planned. The ramp-up of the modules after the shutdown also went smoothly and enabled an energy gain of 100 MeV compared to before the shutdown. This allows the generation of FEL radiation at shorter wavelengths than ever before. The very first user experiment in early November already made use of the increased energy and delivered promising results on electron dynamics via time-resolved X-ray photoelectron spectroscopy (XPS).

Within the **New BC1 and Laser Heater (LH)** subproject, the first bunch compression (BC) section of FLASH was completely redesigned and a laser heater was installed. Now, a laser-imprinted sinusoidal energy modulation gets smeared out in the following bunch compressor, homogenising the electron beam current distribution. This reduces the microbunching instability gain, generating smoother and more stable beams with better FEL properties. For the future realisation of the externally seeded FLASH1 beamline, these beam properties are a necessity to provide percent-level pulse energy stability of the generated FEL radiation and thus enable experiments that cannot be performed at self-amplified spontaneous emission (SASE) FELs. Currently, the laser heater operation is being successively further improved to make it available for user beamtimes in the near future. Downstream of the bunch compressor, a new diagnostic section allows for measuring and adjusting the transverse beam properties, a process called matching. First results demonstrated sub-micrometre emittance for 400 pC beams, a value that has not been achieved at FLASH for a long time.

In the **New BC2** subproject, the former S-shaped bunch compressor was removed and replaced by a movable C-shaped design that incorporates skew quadrupoles to act on transverse coupling. The diagnostic section downstream of the bunch compressor was also renewed to facilitate beam matching. Both bunch compression sections include new fast orbit correctors that make it possible to act on the trajectory of the electron beams within the MHz burst. During commissioning, it was already demonstrated that reducing the intra-bunch train orbit variations directly translates to a more homogeneous SASE level.

In the FLASH2 experimental hall, the shutdown was used to install the **New Beamline FL23**, which saw first light just before the end of 2022. Once fully commissioned, this open-port, pulse-length-preserving monochromator beamline will make it possible to provide FEL radiation with small bandwidth and pulse length to experiments.

The remaining two installations, the new injector lasers and the FLASH2 afterburner, unfortunately suffered from supply chain problems related to the COVID-19 pandemic and the geopolitical situation and had to be postponed to after the shutdown. For the **New Injector Lasers**, however, great care was taken to already modify the laser incoupling beamline so that commissioning can start when the laser will be available, without requiring additional access to the accelerator environment. For the **FLASH2 Afterburner**, the new 6-mm inner diameter vacuum chamber was installed in the electron beamline. This was an important milestone for the project, as the chamber serves as a proof-of-principle component for the future FLASH1 radiator chain, which is based on the same chamber design. Final installation of the afterburner is foreseen for the beginning of Q4 2023 and will have minimal impact on FLASH1 operations.

After the shutdown is before the shutdown

In parallel to the installations, the planning for the **Seeded FLASH1** subproject to be implemented from mid-2024 on has advanced rapidly. A lot of manpower has been invested in re-optimising and adjusting the existing CAD model to make it compatible with the given financial and temporal constraints. Unfortunately, some other subprojects, namely the THz source, new pump–probe lasers, the new beamline FL11 and advanced photon diagnostics, have therefore had to be postponed until after 2025, subject to budget availability.

In the meantime, most of the components for the Seeded FLASH1 subproject are in the production phase so that, by the end of the upcoming 14-month shutdown in August 2025, FLASH1 will have been transformed into an externally seeded beamline with MHz repetition rate and fully coherent pulses at the Fourier limit. The existing Xseed experiment at FLASH is of great benefit in this respect, as it already enables the exploration of concepts and ideas, such as the world's first parallel operation of external seeding in FLASH1 with SASE in FLASH2.

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Xseed

Paving the way for a seeded FEL user beamline at FLASH

The seeding experiment Xseed, installed in 2009 at DESY's FLASH free-electron laser (FEL) user facility, has been a unique tool to study the interaction of the electron bunch with external laser fields and dispersive beamline components and how these can generate an optimally tailored charge density distribution to imprint real laser-like properties onto FEL radiation. With the extensive FLASH2020+ upgrade project, the focus of Xseed shifted from purely academic studies towards experimental efforts to pave the way for FLASH to become the world's first MHz-repetition-rate FEL user facility. In 2022, due to the long shutdown needed to replace the FLASH accelerator modules ACC2 and ACC3, the focus was on measures to refine the beamline.

Quadrupole magnet movers

Although the FLASH2 beamline has been in operation for years, the buildings are still settling due to the civil construction work for the extension of FLASH into a multi-beamline FEL, which began almost ten years ago. Seeding is very sensitive to the displacement of the electron beam with respect to the magnetic centre of each quadrupole magnet in the beamline. As the issue mentioned above is well known, the installation of remotely controllable electromagnetic movers for the most sensitive quadrupole magnets is planned. This measure consists of two phases: Phase 1, which includes the installation of the quadrupole magnets and their respective vacuum pipes on fixed supports, was finished in 2022. In Phase 2, the quadrupole magnets will be suspended by a special device and the fixed supports replaced by "Easy P2" magnet movers developed in house. This will be done without touching the vacuum and cabling or other time-consuming preparation work.

Stripline beam position monitors

To use the quadrupole magnet movers effectively, the position of the electron beam inside the magnets must be known precisely. Therefore, the quadrupole magnets placed on the movers have been equipped with high-accuracy, high-precision stripline beam position monitors (Fig. 1).

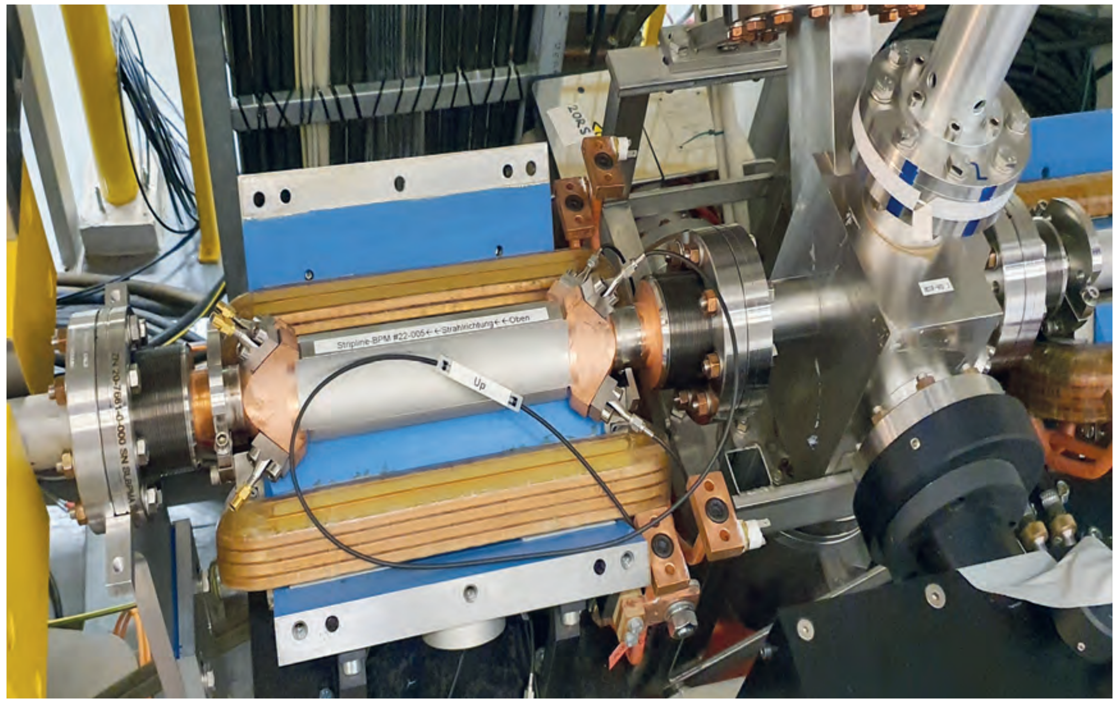

Figure 1
Opened quadrupole magnet. Inside, the special chamber housing the stripline beam position monitor is already installed, and the quadrupole magnet rests on the new supports.

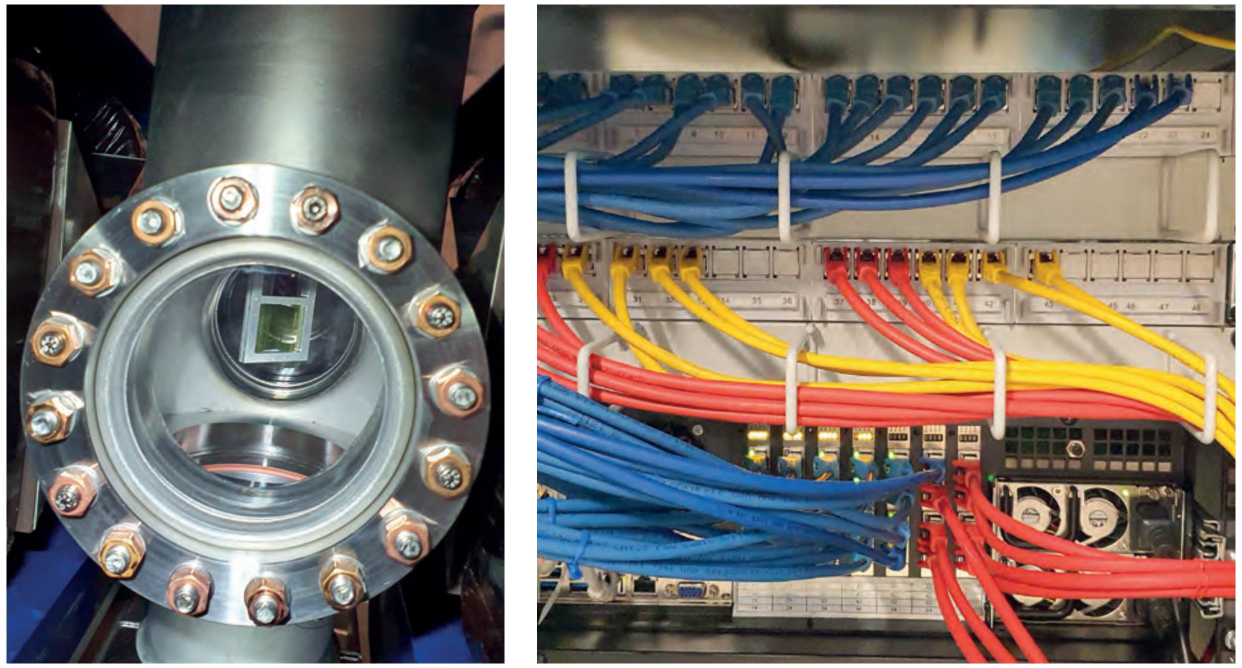

Figure 2
Left: Screens of the new diagnostic station. Right: New camera servers XSEED1 and XSEED2.

Completion of the EEHG chicane

In 2021, the massively dispersive echo-enabled harmonic generation (EEHG) chicane was set up, initially with a placeholder chamber. The central chicane chamber, which features two viewports and an additional ion getter pump, was installed in 2022, making it possible to image the dispersed electron beam or couple out the seed laser beam. A first diagnostic setup was installed (Fig. 2). One of the key features of the chamber is the easy accessibility of the viewport. The other viewport, while unused today, allows for easy installation of further experiments. It is planned to house a mirror in order to prove the concept of resonator-based seeding, an experiment performed by Universität Hamburg.

New laser beam positioners

For historical reasons, the main mirrors to steer the laser beam in the electron beam pipe had been mounted kinematically on *in-vacuo* manipulators called "wobble sticks", operated by stepper motors. These had poor repeatability and stability and posed a risk of moving one axis too far, rendering the device immobile. The mirror chambers now use stick-slip piezo movers with high repeatability and stability. They also allow for the pivot point of the two rotation axes to be on the mirror surface, which is very beneficial for operation.

Virtual modulator

The laser beam profile in the modulator is technically very challenging to measure or image. For this reason, a mover was installed that allows a mirror to be placed into the laser beam path after the last mirror and reflect the laser onto an optical table where the distances to the modulator undulator are simulated. A delay stage makes it possible to freely "move" the position of the virtual screens inside the undulator. In a future upgrade, the mirror will be replaced by a beam splitter that enables conservative measurements of the beam profile and feedback on its position.

New cameras and servers

Since seeding relies heavily on images from the tunnel, the old camera server, although still running well, reached its limits. With the help of the Photon Science division, Xseed was upgraded to a new camera server. This device hosts up to 28 power-over-ethernet cameras, each with its own ethernet port. This allows for very easy setup and commissioning as well as a power cycle of individual cameras. By reducing the ethernet hardware in the tunnel, it has also been possible to drastically increase availability.

Since Xseed also needs information on the spatial profile of the seed laser, cameras sensitive in the ultraviolet range are required. Those specialised cameras are hard to integrate into the control system, have long lead times and are expensive. The Xseed team therefore investigated the option to use standard monochrome cameras with removed protective glass layers in front of the sensor and applied fluorescence coating. These cameras have proved their suitability and are used in the facility.

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A multiscale framework for realistic modelling of seeding

Preparing to augment operation and experiments in high-repetition-rate seeded FLASH

For the high-repetition-rate seeding schemes planned in the FLASH2020+ upgrade project, tracking the electrons in the FLASH accelerator and modelling the free-electron laser (FEL) process, including seeding, using "start-to-end simulations" is essential to understand the detailed physics and limitations of each scheme. A sustainable coupling library for multiscale simulation software and codes is being developed to support current and future external seeding R&D and to provide accessible metadata to everyone in the FLASH environment.

Framework for a realistic model from cathode to photon beamline

External seeding makes it possible to significantly improve the longitudinal coherence of a FEL by initiating the bunching process using coherent light pulses from an external source, such as a laser beam, and prebunching the electron beam before it enters the radiators. For instance, in one of the most challenging cases for FLASH2020+ [1], where the aim is to reach a wavelength of 4 nm, the FEL lases at the 75th harmonic of the original seed lasers. Because of various effects on the electrons from the moment they are created at the photocathode to the point where they generate the FEL radiation, a chain of different simulation tools needs to be used and the interfaces between them must be considered. The goal is to allow systematic studies of effects by tailoring the output, namely the properties of the generated soft X-ray pulse, such as wavelength, intensity, bandwidth and temporal structure.

Most current studies focus on understanding how dynamic beam parameters, particularly chirp and collective effects such as microbunching and coherent synchrotron radiation, influence the FEL output. The effects of the seed lasers on the FEL radiation are also considered. In our model [2], the electron beam is generated by the *Impact-Z* simulation code. This model includes the logitudinal space charge and 1D coherent synchrotron radiation contributions to the density variation along the logitudinal bunch profile as the electron bunch is compressed and accelerated (Fig. 1a–c). The beam is then matched with *elegant* and overlapped with the realistic laser field of laser Seed 1 from *Chi3D* in the first modulator. The modulated electron beam is then de-sliced and handed over to *elegant* for particle tracking (Fig. 2a, b). This process is repeated for laser Seed 2, the second modulator and the second seeding chicane. The prebunched beam is then handed to *Genesis1.3 v4* for the radiator sections. The spectrum and power of the output fields (Fig. 2c, d) from the radiators are among the main parameters used for optimisation.

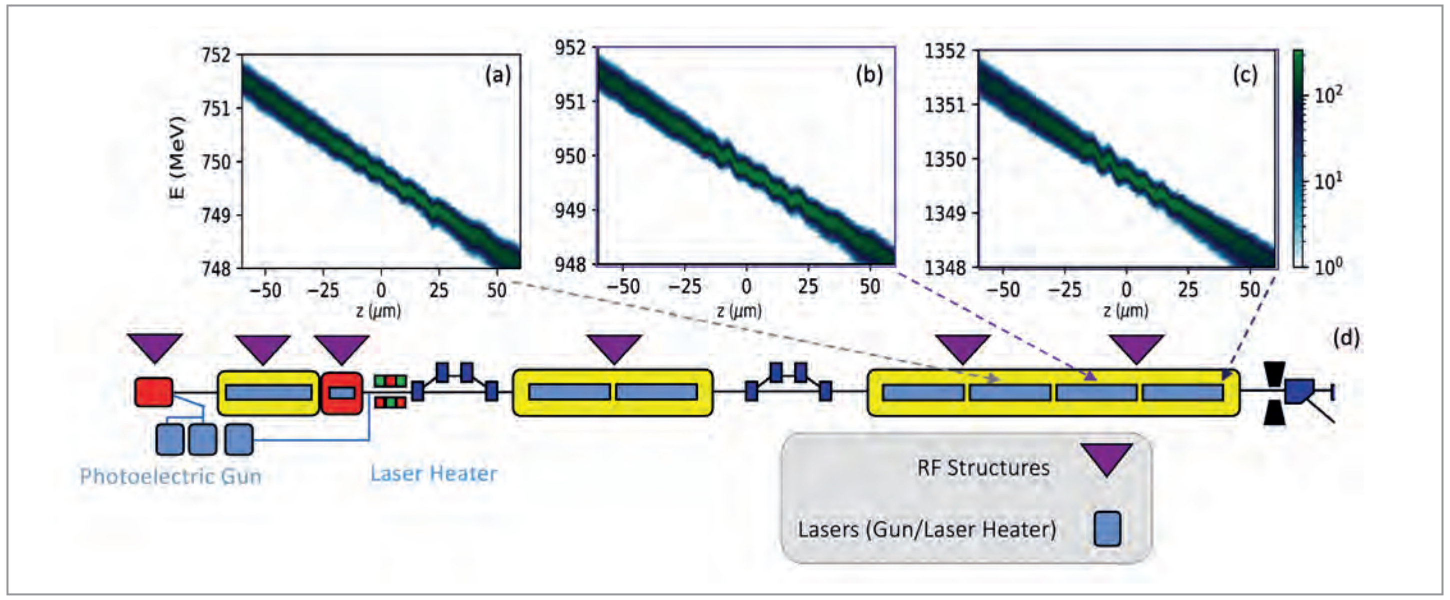

Figure 1

Start-to-end simulations Part I: In the accelerating structures and bunch compressor sections of the beamline, the simulations are performed with *Impact-Z* and *elegant* or *SelaV*. The beams with 400 pC charge used for the three energy working points of (a) 750 MeV, (b) 950 MeV and (c) 1350 MeV are shown along the accelerator layout (d).

Accessible simulation data for virtual diagnostics

One of the primary purposes of the library that is currently being developed is to tether together the open-source set of simulation tools and software prominently used in the accelerator, laser and FEL physics community to study externally seeded FELs. This work is also being adapted to generate simulations for the training of machine learning models and for virtual diagnostics. These machine learning models will be used to extract the pulse duration and properties of the FEL radiation from images of the electron beam phase space generated by simulations, but also to analyse real data from transverse and longitudinal instrumentation, such as transversely deflecting cavities.

Outlook: Prediction and control from simulations and experimental data

In addition, reduced model simulations are benchmarked with the start-to-end simulations around the main FLASH1 working point. For instance, the *SelaV* code developed in house (see p. 72) accelerates the studies in the accelerator region. When coupled effectively with insight gained from full simulations using other codes, the reduced model-based simulations combined with new developments in machine learning, such as neural network methods, are promising for managing complex and coupled systems in real time. The overarching goal is to develop sustainable methodologies that exploit the benefit of data (simulated and experimental) and learning structures to have better predictive models and, finally, better control.

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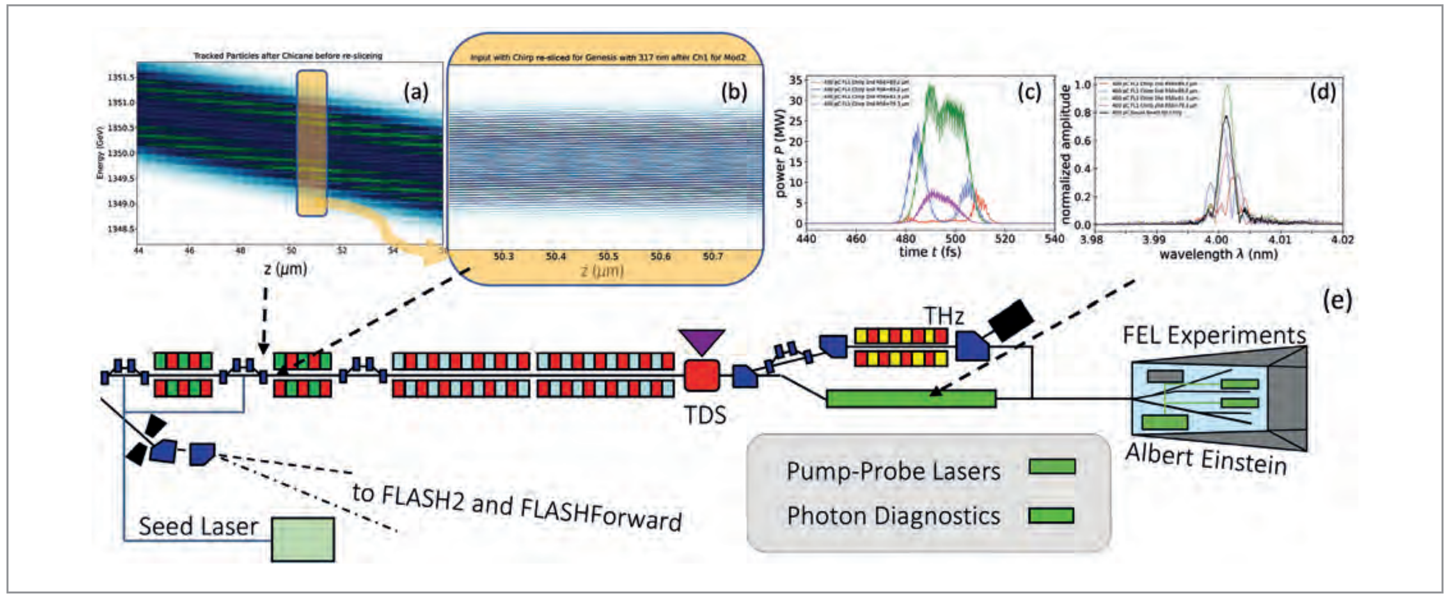

Figure 2

Start-to-end simulations Part II: Phase space distribution of the electron beam (a) after modulation and tracking and (b) after re-slicing. Tracking codes use weighted beams, while FEL codes use sliced beams, hence the need for this handover and the different visual representation. (c) Resulting radiation power along the bunch. (d) Spectrum. (e) Continuation of the layout from Fig. 1d.

Laser heater at FLASH

First successful beam heating and improving SASE just after startup

As part of the FLASH2020+ injector upgrade, a laser heater has been installed to mitigate unwanted electron beam instabilities that potentially degrade the free-electron laser (FEL) output performance of DESY's FLASH FEL facility. Laser pulses of a dedicated laser system are superimposed on the electron bunches in a short undulator. In a resonant process, an energy–position correlation is induced in the electron bunches that is then smeared out in the subsequent bunch compression chicane, resulting in an increase of the uncorrelated energy spread, i.e. heating of the electron beam. The right amount of heating is now important: It can be used to blur and mitigate the unwanted beam instabilities; however, too much heating will in turn negatively affect the FEL amplification process and thereby reduce the FEL performance.

Electron beam heating with a laser

For the operation of the high-gain, single-pass FELs at FLASH, ultrashort electron bunches with high brightness are required, which are longitudinally compressed in several stages by off-crest acceleration in combination with bunch compression (BC) chicanes. Random longitudinal charge density modulations, which occur already at the electron gun and are unavoidable, can be transformed into energy modulations by coherent collective effects. These energy modulations are then transformed again into density modulations in the bunch compression chicanes. This amplification of initial charge modulations is referred to as microbunching instability (MBI). MBI can degrade the FEL output performance and is particularly detrimental to FEL operation based on external seeding schemes.

A laser heater (LH), which was already proposed for FLASH 20 years ago [1, 2], has been installed upstream of the first bunch compression chicane (Fig. 1). A dedicated laser system that generates laser pulses at a wavelength of 532 nm is coupled into the accelerator beamline and deflected by an *in-vacuo* mirror onto the electron beam axis. The short LH chicane is used to guide the electron beam around the *in-vacuo* mirror. Two screen stations equipped with scintillation screens enable simultaneous measurement of the laser and electron beam to achieve spatial overlap of both beams in a short movable-gap undulator with 11 magnet periods and a period length of 43 mm. Once the undulator gap is tuned to the matching resonance condition, the laser will imprint a sinusoidal energy modulation on the electron bunch. The wavelength of this modulation is short enough to be strongly over-folded in the downstream bunch compression chicane, causing the modulation to generate a controlled amount of uncorrelated energy spread, i.e. beam heating. The amount of beam heating can be controlled by the laser power and optimised such that the initial modulations driving the MBI are "smeared out". The LH therefore supplies a means to mitigate the otherwise unavoidable MBI.

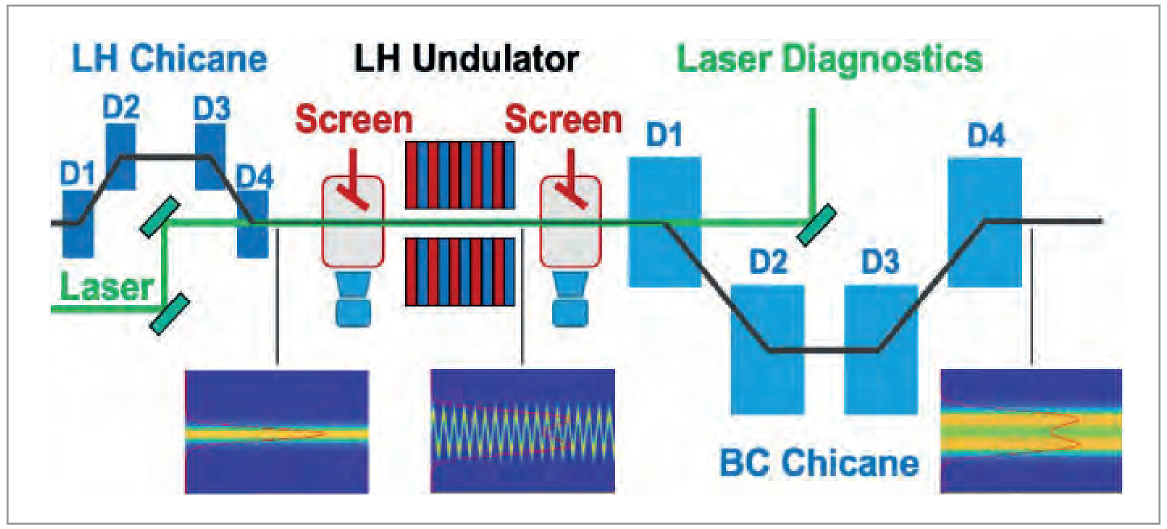

Figure 1
Schematic layout of the laser heater. The small images illustrate the longitudinal phase space of an electron bunch and the beam heating, i.e. the increase in energy spread caused by the sinusoidal energy modulation due to the laser and the "smearing out" in the BC chicane.

Suppression of microbunching instability

MBI can be made visible with the help of transverse deflecting structures that can transfer the longitudinal bunch distribution, i.e. the time axis, to a transverse plane for imaging the electron bunch with a camera on a view screen. Figure 2 shows examples of electron bunches for which the compression was optimised for seeding studies. In the top part, with the LH switched off, a filamentation of the electron bunch into stripes due to MBI is clearly visible. Note that the typical distance of each stripe is on the order of about 10 µm, whereas the typical wavelength of the FEL radiation is about a factor of 1000 shorter. When the LH laser is operated at the correct power, MBI is suppressed and the electron bunch exhibits a smooth charge density distribution (Fig. 2, middle). With the LH laser operated at high power, the energy spread is drastically increased and a non-Gaussian heating into two energy regions becomes obvious (Fig. 2, bottom).

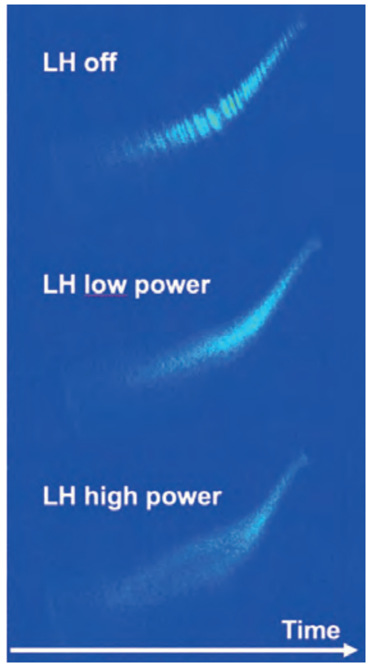

Figure 2
Beam images of electron bunches optimised for seeding studies. Top: LH switched off, MBI clearly visible. Middle: LH laser at the right power, MBI washed out. Bottom: LH laser at high power, strong increase in the energy spread.

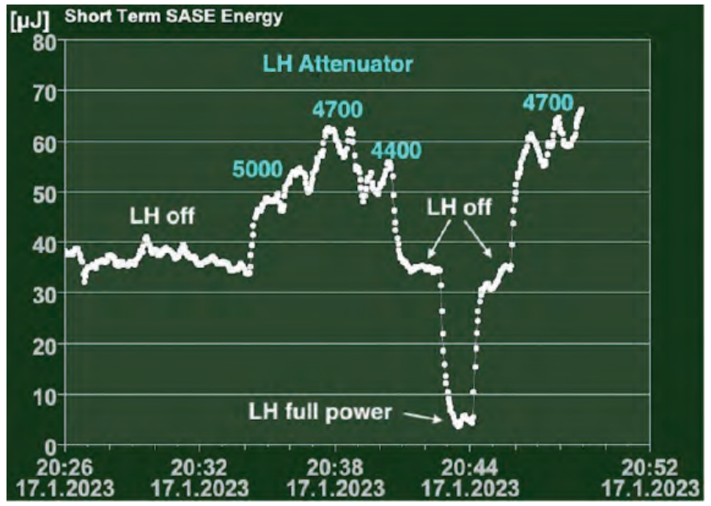

Figure 3
Correlation between the FEL output energy and the LH laser power. The FEL output energy was optimised with an LH attenuator as indicated (in arbitrary units).

Laser heater in FEL operation

In case MBI has a negative effect on the FEL performance, an increase in the FEL output energy may be achieved with the LH set to the correct laser power to suppress the MBI. On the other hand, if the LH laser power is increased further, the additional energy spread induced by the LH leads to a reduced FEL amplification and a decrease in the FEL output energy. This is demonstrated in Fig. 3, where the FEL output energy is plotted for various LH laser power settings. At the beginning, with the LH switched off, the FEL output energy is around 40 µJ. The LH is then switched on and optimised for maximum FEL output energy by varying the LH laser attenuator, as indicated in Fig. 2. With the LH laser at full power, though, i.e. without the LH attenuator, the FEL output vanishes almost completely. When the LH laser power is reduced to an attenuator setting of 4700, the FEL output energy reaches its maximum of about 60 µJ again.

Outlook

During the next FLASH shutdown, scheduled from mid-2024 to mid-2025, a complete refurbishment of the FLASH1 beamline is foreseen to enable FEL operation with external seeding. Until then, it is envisaged to gain as much experience as possible with the operation of the LH itself as well as with the effect of the LH on FEL operation and during seeding studies within the Xseed campaign.

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Beam optics for the FLASH injector

Significantly enhancing the electron beam quality

DESY's FLASH free-electron laser (FEL) facility is currently in the middle of a substantial upgrade and refurbishment project, FLASH2020+. The goal is to deliver electron beams of enhanced quality to the FEL beamlines FLASH1 and FLASH2 to enable the production of highest-quality FEL beams for the experiments. The project includes two main upgrade shutdowns, the first of which was successfully completed in mid-August 2022. In this first shutdown, the common part of the FLASH facility – the injector and the linear accelerator – was upgraded. This article discusses aspects of the electron beam focusing structure – the electron beam optics.

Transverse beam optics and FEL process

A FEL employs electron bunches and the coupling of their electrons' charges to photons in magnetic devices, called undulators, to amplify an initial photon field coherently and with exponential gain. The result is a highly brilliant photon beam – in the case of FLASH in the extreme-ultraviolet and soft X-ray wavelength range. The process requires high longitudinal and transverse charge density in the lasing part of the bunch. Therefore, among other things, good control of the transverse beam properties along the complete FEL is mandatory for efficient lasing and high coherence of the photon beams at the exit of the undulator.

Figure 1 shows a characteristic beam envelope along the common part of FLASH and up to the end of the undulator section in the FLASH1 beamline. The required longitudinal charge density is too high to be stable at low energy, especially at the source. Thus, the bunches have to be generated with moderate longitudinal density and then "compressed" in successive bunch compression chicanes at successively increased beam energy before they are ready to be injected into the FEL undulator beamlines. The FLASH injector was modified during the 2021/22 shutdown to, among other things, improve control of the transverse beam optics in the common part of FLASH.

The FLASH injector starts with the electron source (gun), which delivers bunches with a momentum of 5.6 MeV/c, followed by a superconducting accelerator module and a third-harmonic longitudinal lineariser to shape the longitudinal phase space. Then, at a beam energy of 143 MeV, the first magnetic bunch compression chicane starts to compress the electron bunches. The second compression chicane is operated at a beam energy of 550 MeV provided by two new high-gradient accelerator modules installed between the two chicanes. Each bunch compressor is followed by a section designed to allow the transverse beam optics to be measured and matched to the nominal optics by imaging the beam profile on screens and iteratively correcting the optics using a dedicated set of quadrupole magnets.

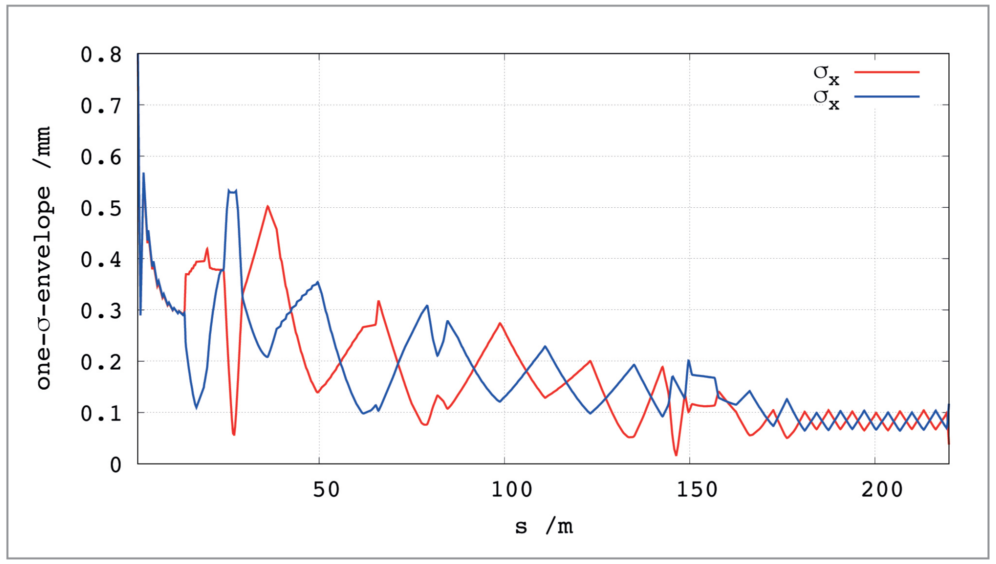

Figure 1

Characteristic beam envelope along the common part of FLASH and the FLASH1 beamline from electron gun to the end of the FEL undulators. The beam is accelerated up to an energy of 1350 MeV, and the FLASH2020+ optics is used. The overall decay of the envelope (increase in charge density) is caused by the well-known effect of adiabatic phase space shrinking.

A laser heater (see p. 64) was installed just before the first bunch compressor in order to ameliorate processes that degrade the longitudinal bunch homogeneity (see p. 72). The space required was realised by shifting the bunch compression chicane downstream. This necessitated a modification of the matching concept in this section.

The second bunch compression chicane was completely rebuilt to create the space to accommodate the second matching section downstream of the chicane. Figures 2 and 3 show examples of raw and evaluated transverse charge densities. Optical transition radiation screens measure the transverse profile of the electron beams with a resolution of 10 µm.

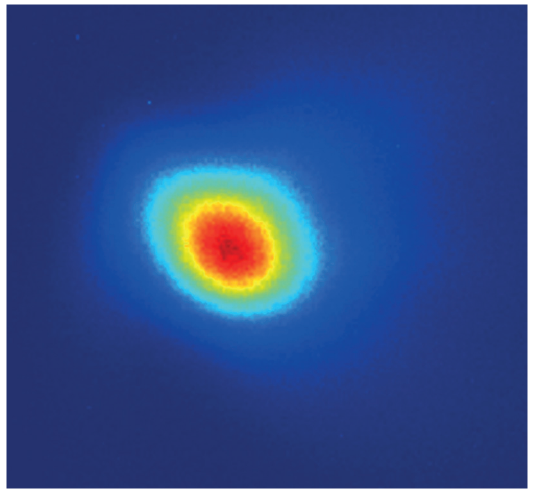

Figure 2

Transverse two-dimensional charge density (false-colour image) from a beam screen using optical transition radiation for maximum linearity

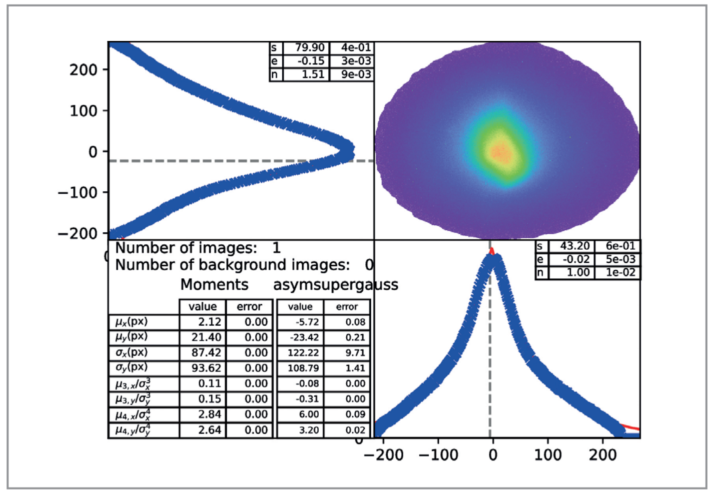

Figure 3

Example of a non-Gaussian fit to the projected horizontal and vertical one-dimensional charge densities to extract transverse beam parameters for rematching

Optics rematch downstream of the first compression chicane

The section around the first compression chicane has to perform multiple tasks: It must accommodate the laser heater and transport the beam at a relatively low energy of 143 MeV without strong disruption due to the space charge effect. It also has to accommodate the chicane and supply a special optics inside the chicane to ameliorate collective effects that would perturb the bunch.

Downstream of the compression section, transverse beam sizes are measured at several screen stations to characterise and correct the beam optics in the horizontal and vertical planes. The installation of the laser heater required a reduction of the number of operational degrees of freedom for matching. Hence, a new concept for measuring and matching the optics was implemented. Two distinct optics for unperturbed beam transport and for measuring the optics parameters were developed. As a fall-back solution, an option was established to increase the number of matching degrees of freedom at the cost of returning to the design optics further downstream in the beamline.

Optics rematch downstream of the second compression chicane

In order to improve the optics control over an extended range along the injector, the section of the second bunch compression chicane was modified as well. In the past, the section did not contain the necessary degrees of freedom to measure and correct the optics with a second rematch. Space required to increase the degrees of freedom was created by completely redesigning the chicane itself. The old chicane was a lengthy six-dipole S-shaped chicane, while the new one is a four-dipole C-shaped chicane and therefore much more compact. It now has round vacuum chambers to accommodate corrector quadrupoles to empirically compensate correlations between the two transverse phase planes and the longitudinal position inside the bunch. This significantly improves certain key properties of the transverse phase space essential for the FEL process, especially for external seeding. The inner two dipoles are movable on rails to preserve the possibility to vary the compression parameters.

The new second matching section now contains enough degrees of freedom for matching. The improvement of the beam parameters is clearly visible in the increase in stability of the photon beam delivered to experiments during standard operation.

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Femtosecond reference for FLASH

New radio frequency main oscillator with world-class performance

Modern linear accelerators can produce electron bunches with femtosecond pulse durations. To achieve stable bunch profiles and arrival time conditions for these ultrashort bunches, a synchronisation system that provides radio frequency (RF) and optical signals to the accelerator subsystems with femtosecond time resolution is required. The heart of the synchronisation system for generating very stable signals is, in addition to numerous subsystems, the reference or "main oscillator". After 15 years of successful operation, the main oscillator of DESY's FLASH free-electron laser (FEL) facility was completely redesigned as part of the FLASH2020+ upgrade. Its time jitter in the relevant frequency offset range was improved from 38 fs to extraordinary 3 fs at a high RF power level of +47 dBm, allowing the optical links to follow with greater accuracy, which benefits the entire accelerator. The main oscillator also sets standards from the technical point of view. The reference is significantly improved in terms of RF signal parameters, module compactness, reliability and serviceability. As a technology transfer, the main oscillator is licensed to industry and available as a high-performance and high-power RF source for the accelerator community and the microwave market in general.

Reference for FLASH based on DRO technology

After 15 years of successful operation of the main oscillator driving the FLASH facility, spontaneous signal phase jumps were observed, which were most probably caused by altering effects in oscillators based on quartz technology. It also turned out that slower accelerator subsystems could not perfectly follow fast phase fluctuations of the reference, so that the reference itself had to be further improved. Within the FLASH2020+ upgrade, the main oscillator was completely redesigned, as shown in the simplified block diagram of Fig. 1.

Usually, a reference signal is generated from a series of phase-locked oscillators to minimise the overall phase fluctuations. A 100 MHz signal is locked with a phase lock loop (PLL) to a standard long-term stable 10 MHz GPS signal. After multiplication, an ultralow-phase-noise dielectric-resonator oscillator (DRO) is locked to 1300 MHz, amplified to a high RF power level of +47 dBm and finally distributed in the accelerator.

Figure 2 shows the main oscillator module located in the FLASH injector racks, which are temperature-controlled. For high availability, two oscillator modules operate redundantly with uninterruptable power supplies. The module is realised in the 19" industry packaging form factor and offers excellent diagnostic features for system health monitoring. All relevant parameters, such as power levels, lock status, fan control, temperatures, humidity etc., can be fully remotely controlled and monitored using the integrated 19" DESY management system connected via ethernet.

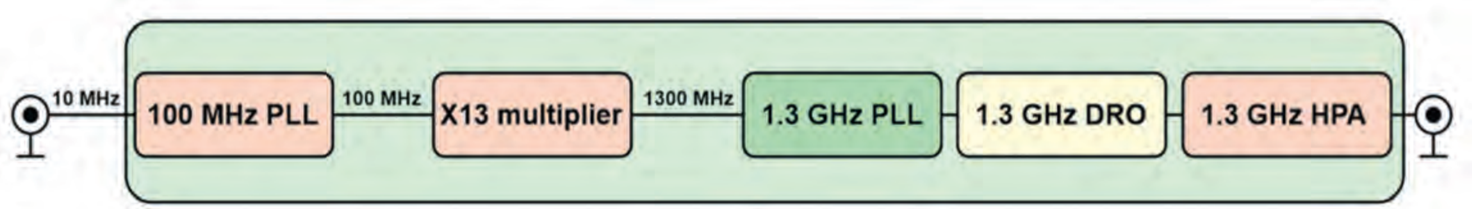

Figure 1

Simplified block diagram of the new main oscillator at FLASH

Figure 2

FLASH's new main oscillator module, located in the injector area, provides RF signals at a power level of +47 dBm to many accelerator subsystems. The module is significantly improved in terms of performance, compactness and serviceability, with excellent diagnostic features for system health monitoring.

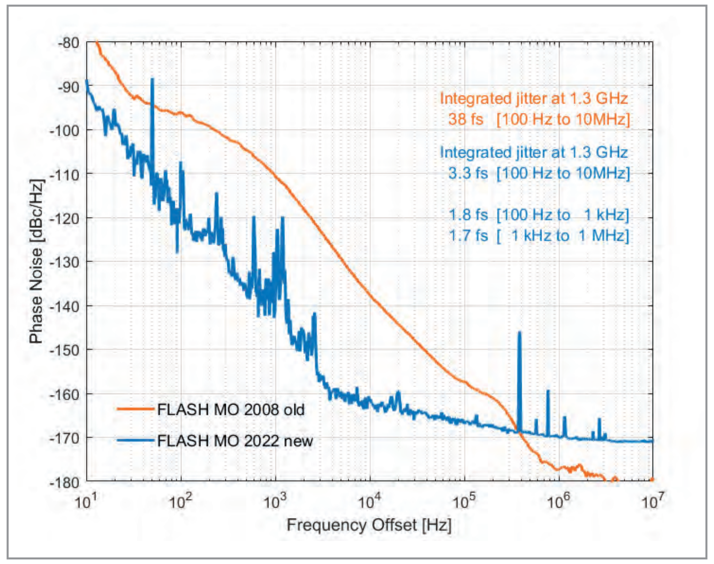

Figure 3

Phase noise and time jitter performance of the new FLASH main oscillator at 1.3 GHz (blue curve) compared to the old one (orange curve). The integrated time jitter within 100 Hz to 10 MHz is improved from 38 fs to 3 fs and within 1 kHz to 1 MHz from more than 15 fs to 1.7 fs. The reduction of this 1/*f* noise regime allows slower accelerator subsystems to follow much more precisely.

As a technology transfer, the main oscillator is licensed to industry [1] and available as a high-performance and high-power RF source for the accelerator community and the microwave market in general.

Performance on the sub-1 fs level

One relevant quality factor of a reference driving an accelerator is the purity of the phase of its output signal, given by the phase noise spectrum. Because different subsystems in the accelerator can follow these phase deviations slower or faster, the subsystems are more precisely synchronised for lower phase noise.

Figure 3 shows the phase noise and time jitter performance of the new FLASH main oscillator [2]. The integrated time jitter from 1 kHz to 1 MHz above the locking bandwidth of optical systems is improved by a factor of about 10 to 1.7 fs, which is dominated by vibrational excitations of the DRO near 1 kHz. Preliminary measurements of femtosecond laser systems locked to the reference show for the first time a significant improvement by one decade, which allows the systems to follow with greater accuracy, benefitting the entire accelerator.

In the near future, bunch arrival time measurements at the accelerator will be performed to verify further stability improvements. As the advances at FLASH demonstrate, modern accelerators will still benefit from the worldwide progress in ultralow-phase-noise oscillator devices.

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[2] M. Urbanski *et al.*, "An Upgrade of RF Reference Generation and Distribution Modules for FLASH2020+", IEEE Trans. (2023)

On the path to demonstrating an XUV FEL oscillator at FLASH

First simulation results and ongoing modifications at FLASH

Externally seeded high-gain free-electron lasers (FELs) can provide fully coherent radiation with high shot-to-shot stability and wavelengths down to the soft X-ray range. However, at short wavelengths, such setups are limited by the repetition rates of suitable seed laser sources. Cavity-based FELs can be used to overcome these limitations, combining short wavelengths and high repetition rates while preserving the full coherence. DESY's FLASH FEL can provide electron bunches at repetition rates of 1 MHz and above, making it the perfect facility for demonstrating such a cavity-based scheme. The FLASH team plans to set up such a system operating at a fixed wavelength of 13.5 nm and at a repetition rate of 3 MHz.

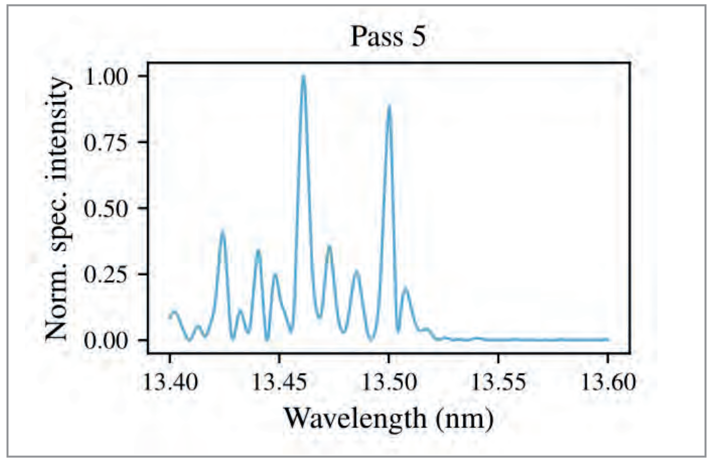

Figure 3a
Spectrum at Pass 5 (buildup)

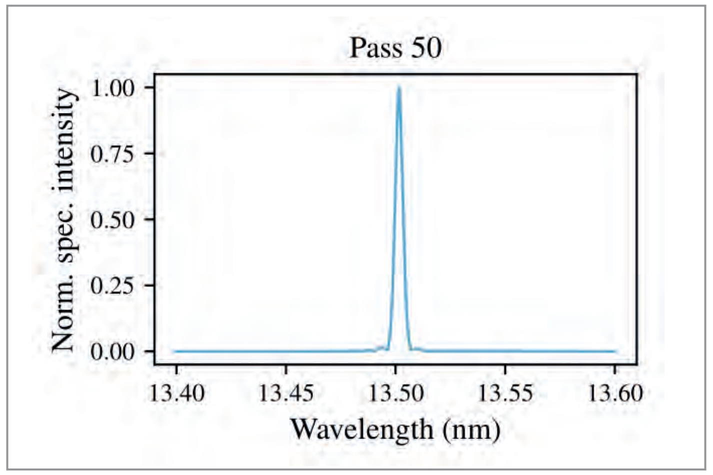

Figure 3b
Spectrum at Pass 50 (steady state)

Motivation

FELs operating in self-amplified spontaneous emission (SASE) mode can be used to generate high-power FEL pulses with wavelengths down to hard X-rays, at the repetition rate of the accelerator. The SASE output has a low degree of temporal coherence, however, and is subject to shot-to-shot fluctuations. This is improved in externally seeded FELs, which rely on a seed laser and provide fully coherent radiation with high shot-to-shot stability at the wavelength of the seed laser or its harmonics (harmonic conversion). The limitation of externally seeded schemes aimed at the generation of short-wavelength radiation lies in the availability of seed laser sources that fulfil specific requirements.

For instance, while superconducting accelerators, such as FLASH, can provide electron bunches at several MHz repetition rates, seeded schemes at such accelerators are still limited to the lower repetition rates of the available seed laser systems (typically tens of Hz). With the FLASH2020+ upgrade, which will introduce a new laser system, seeding at 1 MHz repetition rate is planned and harmonic conversion schemes will be used to achieve wavelengths down to the X-ray range. Cavity-based FELs have been considered as a basis for going further up in the repetition rate and lower in the wavelength [1].

High-gain FEL oscillator setup

A high-gain FEL oscillator setup is planned to be implemented at FLASH in the framework of XRAY (XUV generation by Resonator-Aided seeding with ultra-high repetition rate and Yield), a collaborative research project between Universität Hamburg and DESY funded by the German research ministry (BMBF). The oscillator setup is depicted in Fig. 1. The undulator currently used for seeding experiments at FLASH within the Xseed project will be employed for that purpose. It will be enclosed in a cavity formed by molybdenum–silicon (Mo/Si) multilayer mirrors. The FEL pulse generated in the first pass will be stored in the cavity and used as a seed for the subsequent electron bunches.

If the losses in the cavity are overcompensated by the FEL gain in the undulator, the power stored in the cavity rises from pass to pass. So, no seed laser is required and the power is built up from shot noise. After a certain number of passes, the oscillator naturally reaches a steady state at a certain power level, in which the losses are exactly compensated by the FEL gain. Figure 2 shows the simulated power as a function of the number of passes. A control mechanism will be developed to tune the steady-state power level and keep it below the mirror damage threshold.

It is worth emphasising that the FEL is operating in high-gain mode, so that the power rises exponentially within a single pass through the undulator. This makes it possible to tolerate the significant losses on the mirrors as well as other potential losses and outcoupling. This is particularly important as high-reflectivity mirrors are not available for the wavelength of interest.

Spectral filtering in the cavity can be achieved with the use of a monochromator. Simulations show that, in the first passes, the power is low and the output radiation is essentially SASE, as seen in the spectrum in Fig. 3a. After several passes, however, temporal coherence is established and preserved. The simulated output spectrum in the steady state is shown in Fig. 3b. The width of the line corresponds to a single peak in the SASE spectrum, representing a longitudinal mode.

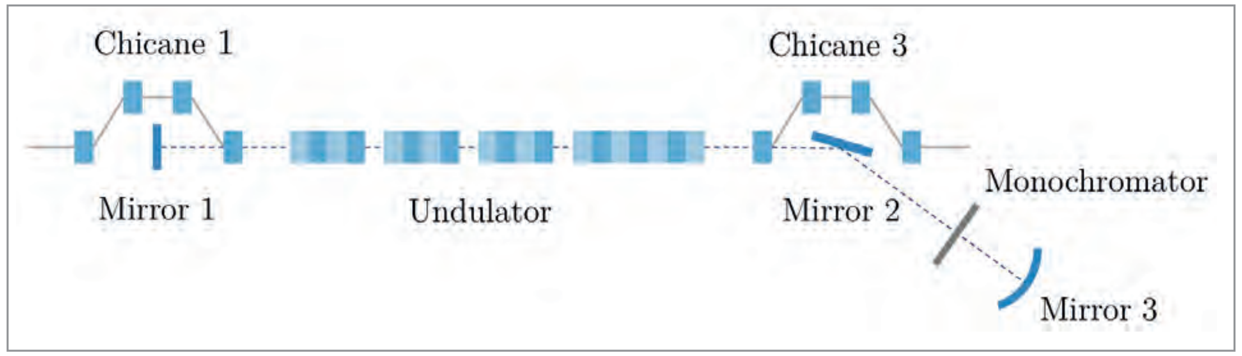

Figure 1
Schematic depiction of the oscillator

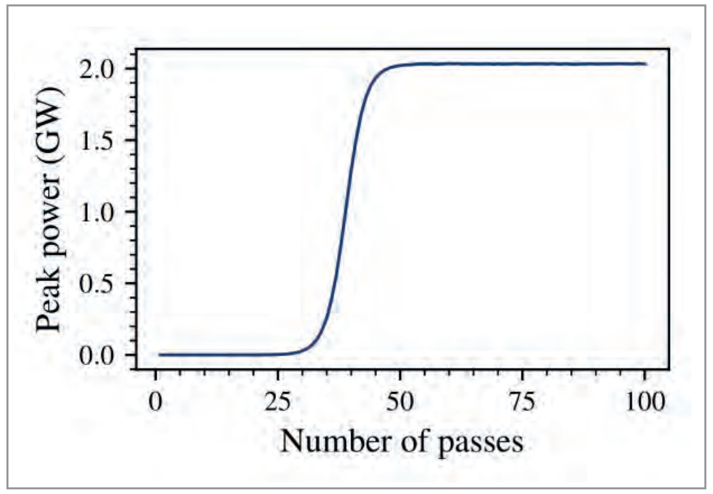

Figure 2
Power as a function of the number of passes

Ongoing work

Preparations are under way for the installation of the end mirror in Chicane 1. The setup in Laboratory 28h is being redesigned to meet the requirements for future installation of appropriate diagnostics and the curved end mirror (Mirror 3 in Fig. 1) while ensuring a cavity length of 50 m, corresponding to the chosen repetition rate of 3 MHz. In the first setup of the cavity, no monochromator will be introduced. Further simulations are being established to investigate the working parameters of the oscillator and the stability criteria.

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Reference:

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Understanding microbunching at FLASH

Evaluation of working points for external seeding at FLASH2020+ using Vlasov simulations

External seeding is the key feature of the new FLASH1 beamline within the FLASH2020+ upgrade project. It is a delicate process, which requires electron bunches with a sufficiently long, smooth, homogeneous and at most linearly chirped central part, with sufficiently high charge density and sufficiently low local energy spread to drive the free-electron laser (FEL) amplification at all required harmonics. One of the most severe instabilities counteracting this goal is the microbunching instability, which can potentially amplify small initial density inhomogeneities or energy modulations over successive bunch compression stages to amplitudes unacceptable for stable external seeding. This article describes the use of our semi-Lagrangian tree code *SelaV1D* [1] to simulate the Vlasov systems [2] representing FLASH in order to compute and evaluate the microbunching gain for selected working points, leading to parameter sets suitable for seeding.

Bunch compression and microbunching

The charge densities necessary to establish FEL gain, i.e. the amplification of an initial photon field, are typically too high to be stable at low energy in the electron source of the FEL. Since the strengths of the coherent instabilities decrease with energy, the charge density at the source can only be moderate and must be increased successively with increasing energy. Longitudinally, this is achieved by successive bunch compression stages. Unfortunately, these necessary compression stages are exactly the amplification stages of the detrimental microbunching process.

Nevertheless, the relation between compression and microbunching gain is strongly non-linear so that it is possible to find working points with suitable compression and low microbunching gain. In addition, a laser heater (see p. 64) can be used to increase the initial local energy spread of the bunch in a controlled way: high enough to attenuate the microbunching gain and small enough to preserve the required amount of FEL gain. Figure 1 shows the microbunching gain for two compression working points and with three laser heater strengths each for the final compressed wavelength. It is obvious that more laser-heater-induced energy spread attenuates the gain and that the working point WP2 supports less gain for all initial energy spread settings than WP1. Details are discussed in the next section.

Simulations

The two working points WP1 and WP2 are compared here as an example. WP1 was originally proposed with an initial bunch peak current of 31 A and both compression stages set up to linearly compress the bunch by a factor of 4 each (so a factor of 16 in total). WP2, which uses an initial peak current of 20 A, with both compression stages set at a factor of 5 (25 in total), was devised after the simulations were performed with WP1.

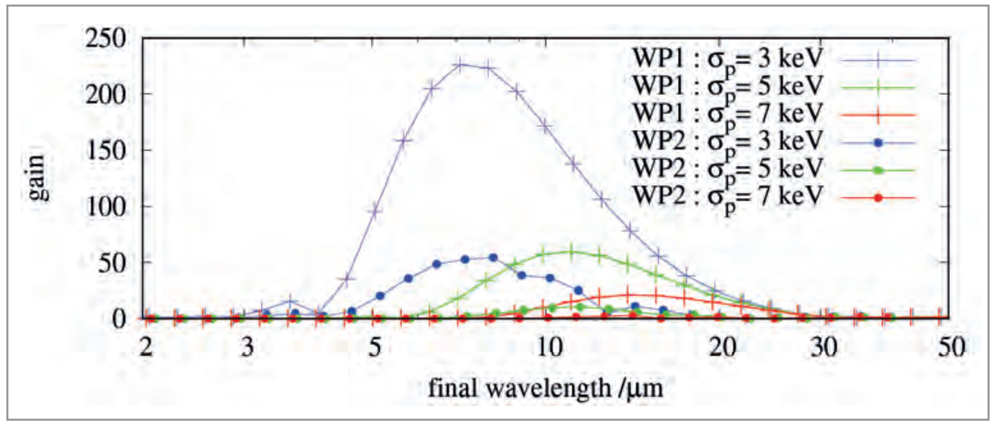

Figure 1
Microbunching gain as a function of the final compressed wavelength for working points WP1 (plus signs) and WP2 (solid circles) and for a laser-heater-induced local "slice" energy spread of 3 keV (blue), 5 keV (green) and 7 keV (red)

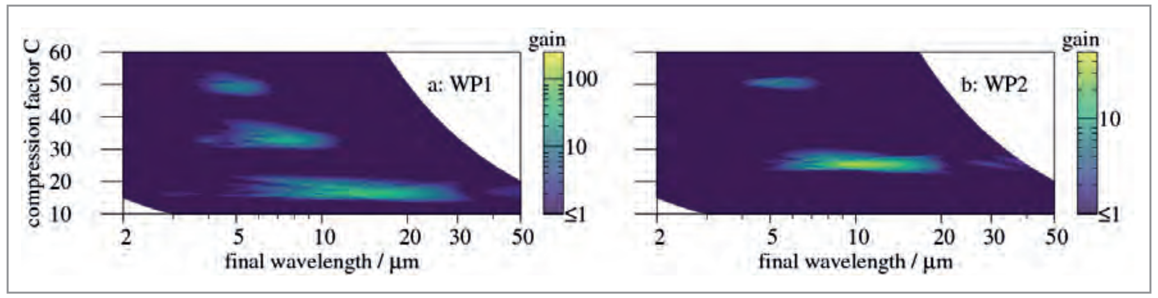

Figure 2
Two-dimensional, non-linear gain curve for a) WP1, showing the generation of the second and third harmonic, and b) WP2 with reduced gain in the fundamental and the second harmonic

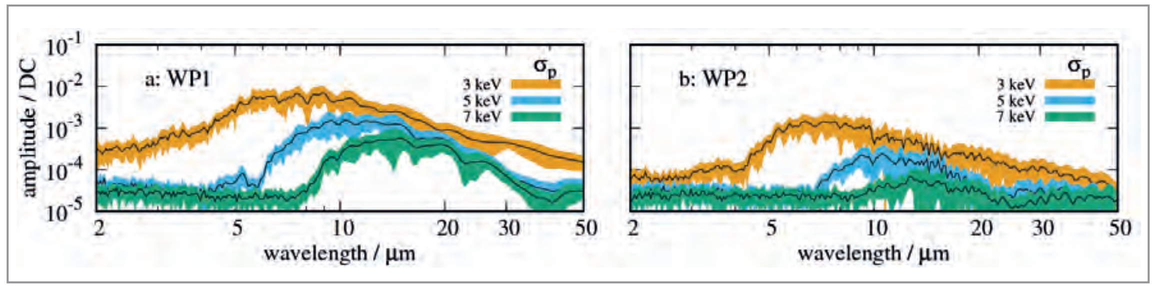

Figure 3
Final spectra of shot-noise-driven microbunching with realistic noise amplitudes for 16 seeds of a 400 pC bunch for a) WP1 and b) WP2

The tree code *SelaV1D* [1] simulates the longitudinal dynamics on a virtual rectangular grid in phase space, which only becomes real in regions with non-vanishing phase space density [2]. Simple one-dimensional gain curves are computed by modulating a homogeneous density with a small monochromatic sinusoidal oscillation of fixed wavelength, tracking the modulated density through FLASH and computing the Fourier spectrum of the final density. The gain is the Fourier amplitude of the tracked density at the compressed wavelength normalised by the Fourier amplitude of the initial modulation. Figure 1 plots this gain for WP1 and WP2 and for various laser heater settings as a function of the final compressed wavelength.

These simple gain curves can be computed in linear perturbation theory and are, in principle, not new. However, the fully non-linear theory and simulation describe effects of higher-harmonic generation, frequency mixing, etc. Figures 2a and 2b show two-dimensional gain functions. Each "row" shows the full Fourier spectrum of a monochromatically seeded and then tracked bunch. The horizontal axis is, again, the final wavelength, and the rows are indexed by the hypothetical "compression factor" C needed to compress the initial wavelength to the final one. This representation makes it easier to identify and differentiate between various higher harmonics. The colour encodes the gain. For WP1, Fig. 2a shows three distinct bands around C = 16, 32 and 48, corresponding to the fundamental and the second and third harmonic. Figure 2b for WP2 has a different colour scale: Yellow corresponds to a gain of 50, not 200 as in Fig. 2a. Of course, the harmonics have moved due to the higher compression: The fundamental is around C = 25, and the second harmonic is at C = 50 and already hardly visible.

Approximate treatment of shot noise in an intrinsically smooth simulation

The smooth phase space density of semi-Lagrangian simulations represents the probability of finding an arbitrary particle in an infinitesimal volume around every point in phase space. It is not the particle distribution of a real finite ensemble in a concrete bunch. However, means exist to "roughen up" the *initial* density on each grid point according to the fluctuations reflecting the finite number of real (not macro!) particles in some domain around that grid point. Figures 3a and b show the final oscillation spectrum of tracking simulations seeded by this model of shot noise for bunches of 400 pC charge (corresponding to 2.5 billion real particles) for WP1 and WP2, respectively, all averaged over 16 shot noise seeds.

To summarise, we employed our analytical and computational Vlasov framework to identify an improved, suitable working point (WP2), promising successful external seeding in the FLASH1 beamline.

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Preserving the beam quality

FLASHForward demonstrates first preservation of emittance in a plasma accelerator

High beam quality is key to the performance of many accelerator applications, such as free-electron lasers (FELs) and linear colliders. Parameters to be optimised include emittance, energy spread and bunch charge. Going from radio frequency (RF) accelerators to plasma accelerators, which promises to drastically reduce the size and cost of accelerator facilities, the question arises: Can plasma accelerators maintain a high beam quality? While possible in theory, this is very challenging in practice, demanding extreme precision and control. Recent experiments at DESY's FLASHForward plasma accelerator facility demonstrated, for the first time, simultaneous preservation of emittance, energy spread and charge while accelerating bunches in electric fields beyond 1 GV/m – a major leap towards application-ready plasma accelerators.

Beam quality: essential for applications

Particle physicists and photon scientists alike are asking for ever-brighter beams with ever-higher energies. However, without ever-increasing budgets, accelerator physicists have to get creative. This is the premise behind plasma acceleration: use the ultrastrong fields that can be sustained in a plasma to shrink the size of accelerators. In experiments, gradients 1000 times [1] those in RF accelerators are now commonplace.

However, new solutions bring new problems: Plasma accelerators have microscopic accelerating structures (plasma wakes) with strong internal focusing. This makes it challenging to accelerate particle beams without degrading beam quality. Parameters to be optimised include *emittance*, which quantifies how tightly beams can be focused, *energy spread*, which quantifies the spread of particle energies within a bunch, and the total *charge*. To deliver high performance, applications such as FELs and

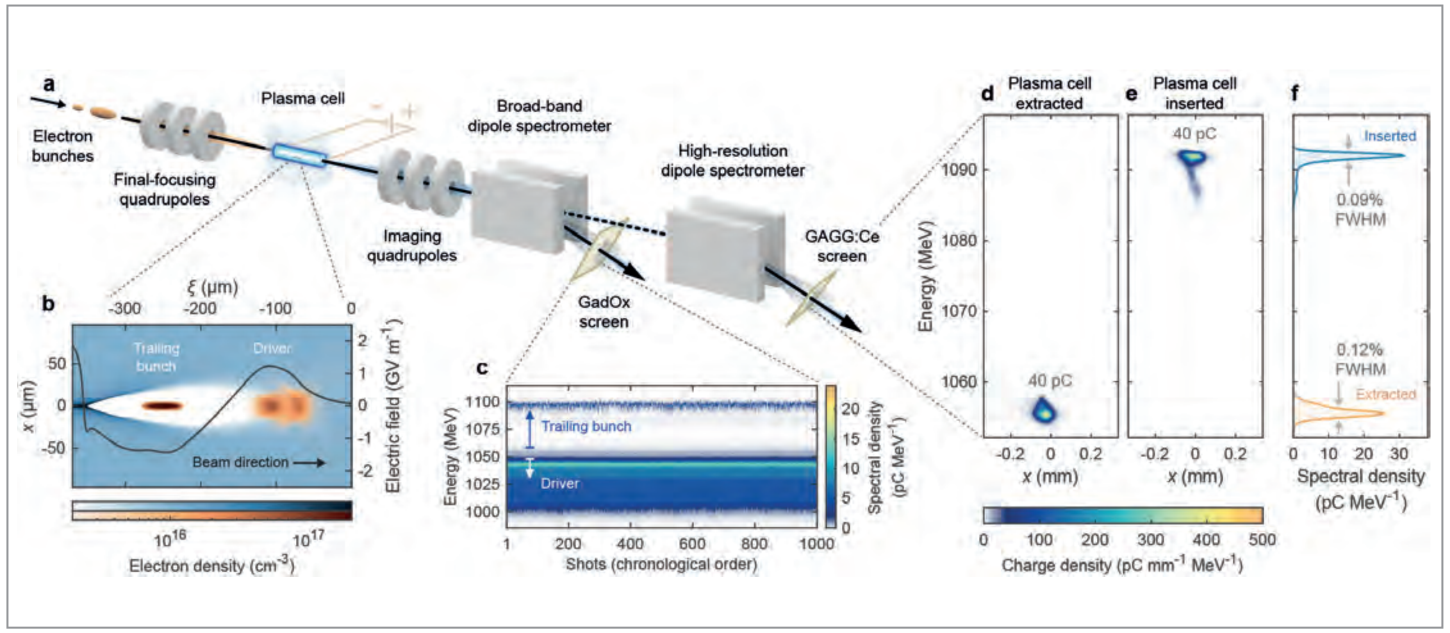

Figure 1

a) Experimental setup at FLASHForward. b) Insets showing the simulated, beam-driven plasma wake. c) Measured, highly stable energy spectrum of the accelerated beam. d) Spectrometer images demonstrating both charge and energy spread preservation. From [3].

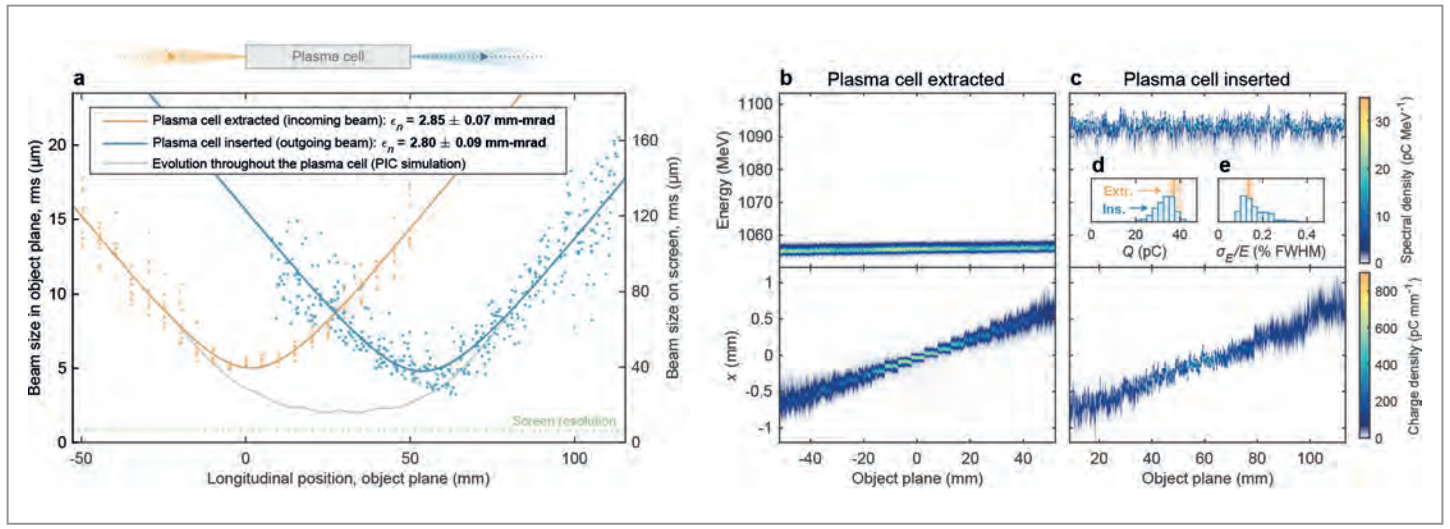

Figure 2

a) A multi-quadrupole scan measured the evolution of the (virtual) beam size around the plasma accelerator, b)–c) showing a 50 mm shift in focal location but also a preserved emittance. Throughout the scan, both d) the charge and e) the energy spread were preserved. From [3].

linear colliders demand low emittance (< 1 mm·mrad), low energy spread (< 1%) and high charge (> 100 pC).

Can plasma accelerators preserve beam quality?

Preserving beam quality in a plasma accelerator is possible, but very challenging in practice. Charge can be preserved by injecting all the particles into the (microscopic) plasma wake. Energy spread can be preserved by strong beam loading – that is, by using sufficient beam current to create a new, destructively interfering plasma wakefield so that a uniform accelerating field is formed inside the wake. This was demonstrated at FLASHForward in 2020 [2].

Preserving emittance, however, requires a large number of parameters to be very finely tuned. Among these are the exact beta function (i.e. the "Rayleigh length" of the beam), which must be matched to a very small value on the millimetre scale, and the transverse alignment of the accelerated bunch with respect to the beam driver, typically on the scale of a few micrometres in position and 0.1 mrad in angle. Moreover, beam gas scattering and beam plasma instabilities (including the hose instability) must be suppressed.

Demonstration of emittance preservation

The X-2 experiment at FLASHForward (Fig. 1) aimed to overcome all these challenges. The high-quality and high-stability beams from the FLASH accelerator promised to enable the long-awaited preservation of beam quality for the first time. After several years of work, it was finally achieved in July 2021.

After several days of setup and precision tuning of the facility (e.g. at the 0.1% level for some quadrupoles), the bunch was focused and aligned to the required size (5 x 5 µm RMS) – roughly the size of a red blood cell! Figure 2 shows the measured simultaneous preservation of normalised emittance (2.8 mm·mrad), energy spread (0.1% FWHM) and charge (40 pC) while accelerating the bunch by about 40 MeV in fields as high as 1.4 GV/m.

While the energy gain is certainly modest, this result, recently submitted for publication [3], marks a significant step forward in the field of plasma acceleration and forms the basis of beam quality preservation also in longer plasma accelerators. Combining this with previous demonstrations of large energy gain [1] and the potential for high repetition rate [4], plasma accelerators may indeed soon deliver on their (now 40 year old) promise.

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KALDERA

Starting laser development in the new KALDERA Laser Lab

KALDERA, the Kilowatt Average Power Laser at DESY for Revolutionary Accelerators, will demonstrate a new high-repetition-rate laser plasma accelerator with application-ready electron beams. It will be driven by a novel, high-average-power laser developed in house. The KALDERA laser system will be located in a dedicated lab, which was built with the support of 23 DESY infrastructure and technical groups and completed in autumn 2022. With up to 400 m^2 of ISO5 and ISO6 cleanroom space, the KALDERA Laser Lab provides ideal conditions for the challenging developments of a kW-class laser. Since its completion in October 2022, the laser lab has become the centre of the KALDERA project.

KALDERA Laser Lab

For the development of the KALDERA laser, a new laser lab room was built inside the former DORIS hall (now SINBAD) close to the location of the former ARGUS detector. The laser lab was completed in October 2022 with the contribution of many tireless individuals from the DESY infrastructure and technical groups. It features four levels: 1) the basement, with a rack gallery for power supplies, IT equipment, electronics and any unwanted sources of heat, 2) the 400 m^2 cleanroom with 0.1°C temperature stability and 3% humidity stability, 3) the plenum with 133 filter fan units to create a laminar air flow in the cleanroom and 4) the roof with air conditioning hardware.

The cleanroom with a total of four laser labs is built on a single concrete slab, which is vibrationally isolated from the SINBAD hall by a layer of Sylomer. Personnel enters the lab through a sluice and an additional air shower. Laser parts undergo a four-step cleaning process in two different adjacent cleanrooms before entering the main KALDERA Laser Lab – the largest of the four cleanrooms with 200 m^2 (Fig. 1). Strict rules are followed to keep particle counts equivalent to ISO5 above the laser tables and ISO6 everywhere else. On one side of the lab, a rolling door can be opened to allow visitors a view through a large window into the laser lab without interfering with the cleanroom environment.

The cleanroom is divided into eight dimmable light zones, allowing individual sections of the KALDERA system to be independently controlled. Below the optical tables are distributors for water, gas, electricity, IT and laser interlock, which are fed via media supply channels leading directly to the rack gallery in the basement. Monitors

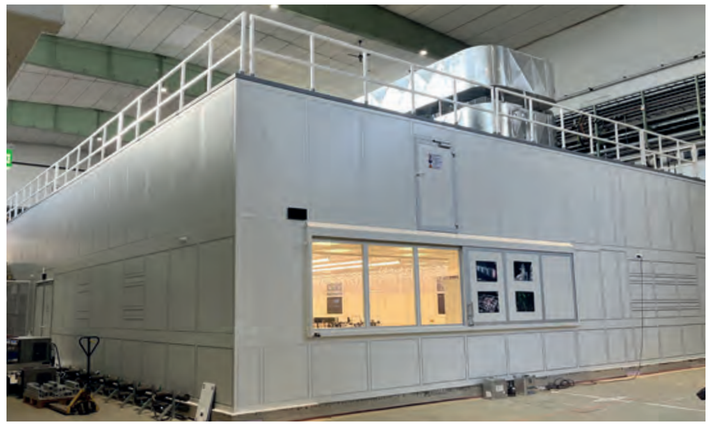

Figure 1

Left: Completed KALDERA Laser Lab, which is part of the ATHENA complex in the former DORIS hall. Right: First laser tables installed in the KALDERA cleanroom.

Figure 2

Detail view of the KALDERA seed laser

presenting a thousand and one laser performance parameters are directly integrated into the walls. The KALDERA Laser Lab is located directly next to the former DORIS accelerator tunnel. In the future, the KALDERA laser pulses will be sent through the 70 m long straight section of the tunnel to power several plasma accelerators.

Laser development

The laser design is based on the experience and many lessons learned from DESY's leading plasma accelerators. Over the past few years, we have identified several mechanisms that influence the stability and reproducibility of a laser-plasma-generated electron beam. Many of them can be directly linked to properties of the drive laser pulse and eventually to the design of the laser. As we are developing a new system from scratch, we can tailor the laser to our needs. One important feature will be the significantly increased, kHz-level repetition rate, which will enable us to use active stabilisation and feedback techniques, similar to those DESY has been successfully deploying in all of its large-scale accelerators. The combination of ultrashort, femtosecond laser pulses with TW-class peak power and kHz-level repetition rate is well beyond the current state of the art and requires the development of new custom laser and amplifier concepts. Some subsystems and components are also being developed with industry partners and research institutes.

Commissioning of the KALDERA front-end has already started. Seed laser pulses are generated by a twin system of the MALCOLM laser installed and tested for long-term operation at the ANGUS laser (Fig. 2). Currently, several amplifier stages are being developed based on titan-doped sapphire as the gain medium.

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Stable laser plasma accelerators

New technique enables permille energy spread and energy jitter

Laser plasma accelerators (LPAs) are able to provide accelerating gradients that are orders of magnitude higher than conventional radio frequency technology. However, their performance is typically affected by fluctuations in key beam parameters, such as the energy, as well as by a large energy spread, preventing LPAs from achieving a competitive beam quality for demanding applications. To address this issue, a new technique has been developed at DESY that allows the energy spread and energy stability to be simultaneously improved after acceleration using a combination of bunch decompression and active plasma dechirping. Start-to-end simulations including realistic fluctuations demonstrate the potential of this technique for reducing a state-of-the-art energy spread and jitter of 1–2% to ≲ 0.1%, thus closing the beam quality gap to conventional acceleration schemes.

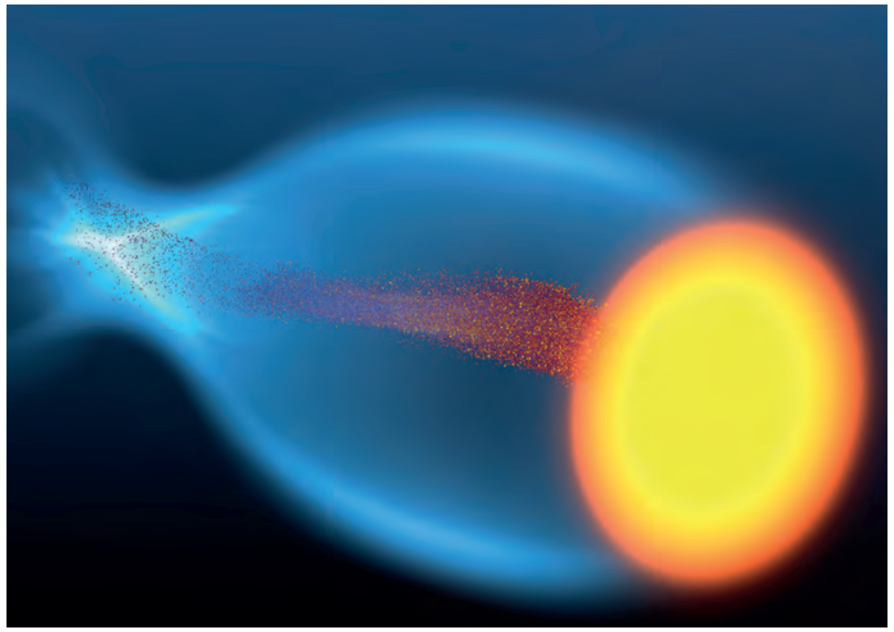

Figure 3

Visualisation of the laser (orange), plasma wake (blue) and electron beam (red) in the APD, as obtained from an *FBPIC* simulation. Render made with *VisualPIC* [7].

Beam quality in laser plasma accelerators

The extreme electromagnetic fields sustained by LPAs allow the acceleration of charged particles to high energies in tiny, centimetre-scale structures. Compared to the kilometre size of conventional facilities, LPAs could lead to a new generation of compact and cost-effective accelerators. One of the main challenges on the road towards this goal is realising LPAs with competitive beam quality, in terms of both of single-shot performance and reproducibility. In particular, achieving a sufficiently small energy spread and high energy stability is of key importance to fulfil the requirements of demanding applications. This is a challenge due to the complex laser–plasma and beam–plasma interaction within the LPA, which requires careful optimisation [1, 2] and is highly sensitive to fluctuations in the laser system [3], among others. As a result, state-of-the-art LPAs are currently limited to an energy spread and jitter that is typically in the few-percent range, an order of magnitude higher than required for most applications.

Plasma-based energy compression

To address this issue, a new technique for realising a plasma-based energy compression system has been developed at DESY [4]. As shown in Fig. 1, the concept makes use of a magnetic chicane to longitudinally stretch the LPA beam and convert the initial energy spread into a linear energy–time correlation that can later be compensated for in a so-called active plasma dechirper (APD). The APD consists of a short, millimetre-long plasma stage that is driven by a fraction of the main LPA laser driver. Owing to the linear longitudinal electric fields generated in the APD and the intrinsic synchronisation between the LPA and APD drivers, the device is able to simultaneously compensate for the energy spread and the shot-to-shot energy variations of the beam.

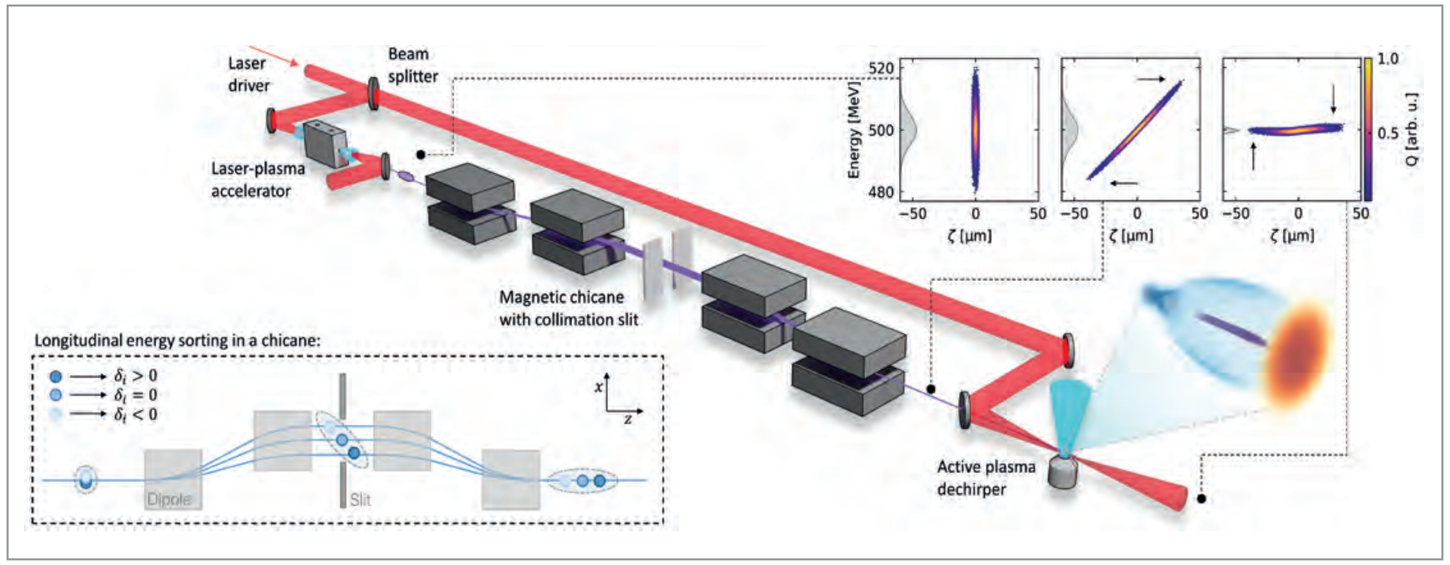

Figure 1

General overview of the energy compression concept showing the main components and beam manipulations. Adapted from [4].

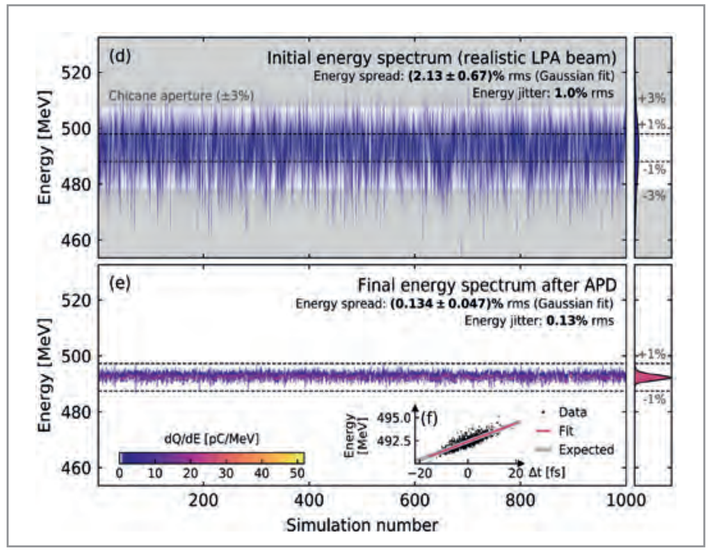

Figure 2

Shot-to-shot energy spectrum of the LPA beam before (top) and after (bottom) the energy compression beamline. Adapted from [4].

Demonstration with start-to-end simulations

The working principle of this technique and its performance were demonstrated with a full start-to-end simulation study of a realistic LPA setup. Thanks to the cost-effective simulation code *FBPIC* [5], hundreds of simulations could be performed to account for the shot-to-shot fluctuations that are experimentally observed in laser systems. The results of the study, as seen in Fig. 2, indicate that the proposed method allows for a drastic reduction of the energy spread (from ~2% to ~0.1%) and the energy variations (from ~1% to ~0.1%).

This level of performance would allow LPAs to be a competitive option for compact free-electron lasers or injectors for storage rings. In this regard, the energy compression concept is already being explored at DESY for realising a compact injector for the upgraded synchrotron radiation facility PETRA IV, where the APD is replaced by an X-band cavity [6].

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Plasma source R&D

For the PETRA IV plasma injector

PETRA IV is a planned new hard X-ray source designed to push the limits of X-ray imaging. As part of this state-of-the-art upgrade of DESY's PETRA III synchrotron radiation source, a new injector based on plasma technology has been proposed. This injector will use a laser-driven plasma accelerator to generate a 6 GeV beam in an accelerator module less than 30 cm long, significantly lowering the power consumption and spatial footprint of the complex. A major component of this cutting-edge accelerator is the plasma source in which the electrons are injected and accelerated to high energies. The 3D structure of this plasma source will be tailored to provide a high degree of control over the laser propagation and electron acceleration process.

Laser plasma accelerators

Laser plasma accelerators combine high-intensity lasers and plasmas to create compact sources of electrons with energies in the MeV to multi-GeV range [1]. The required high intensities can be generated by focusing an ultra-short (30 fs), high-energy (several joules) laser pulse down to a spot on the order of tens of micrometres. When focused into a plasma, the laser pushes the plasma electrons out of its way, leaving the ions behind due to their increased mass. The ions pull the electrons back on axis, generating an electron density wave or "wake" that trails the laser (Fig. 1). The strong electric fields generated in this wake due to the separation of electrons and ions can be as high as hundreds of GV/m, more than three orders of magnitude larger than what is available in conventional radio frequency accelerators. Thus, an electron beam injected into this structure can be accelerated to GeV energies on centimetre scales.

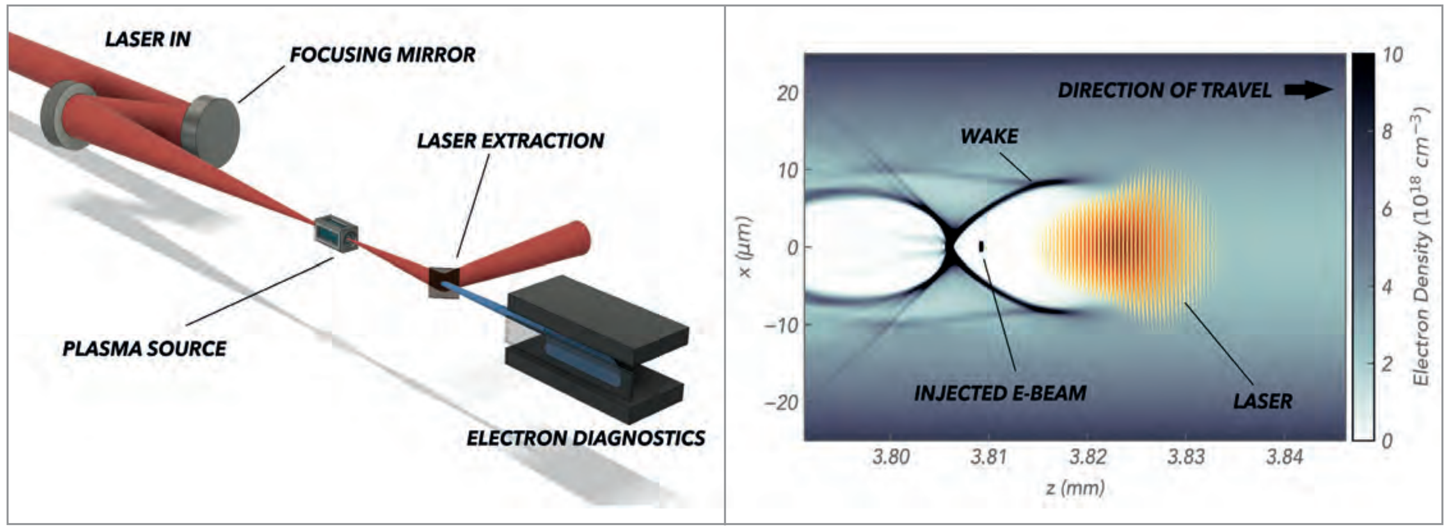

Figure 1

Left: Schematic of a typical laser plasma accelerator. A high-energy femtosecond laser pulse is focused into a plasma source using a focusing mirror. In the plasma source, electrons are injected and accelerated to high energies. After this, the laser and electron beams are separated. Right: Simulation showing a snapshot of the acceleration process. The laser, travelling from left to right, sweeps the plasma electrons aside as it passes, leaving a cavity of ions behind the pulse. The electrons then get pulled back in towards this ion cavity and overshoot, generating a wake structure. The simulation also shows an electron bunch that has been injected into this structure and is being accelerated forwards.

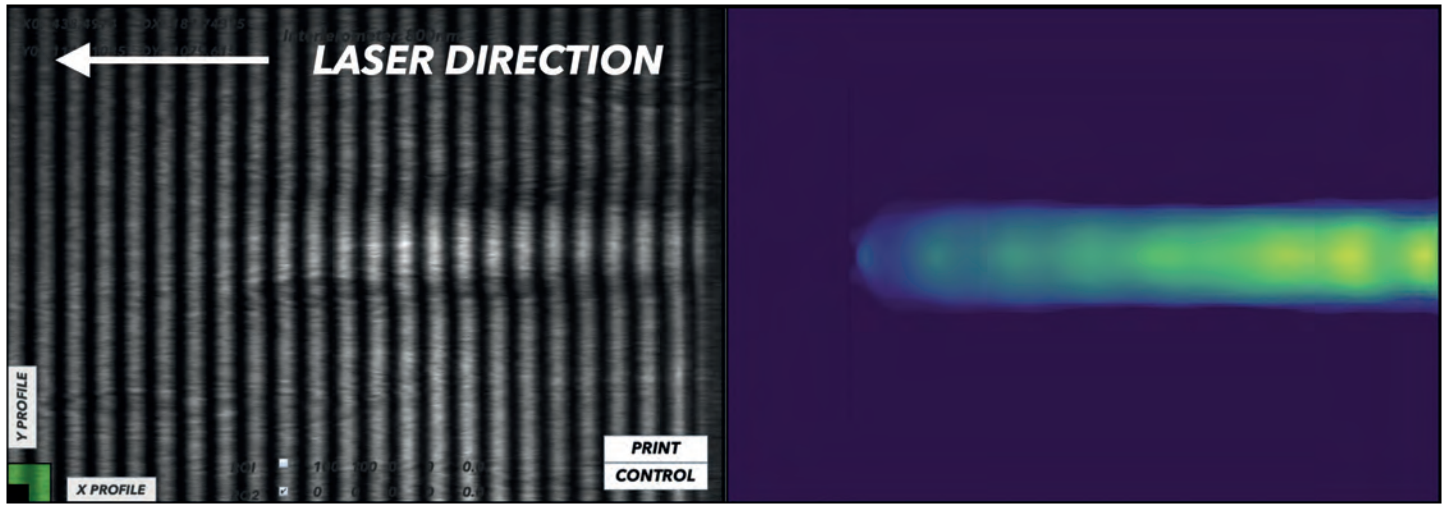

Figure 2

Preliminary data showing "first plasma" measurements in the new experimental setup for plasma source R&D. A plasma ionised by an optical field is created using few-millijoule pulses and then probed with transverse interferometry. The plasma induces a phase shift on the probe beam, causing the fringes in the interferogram to bend (left). These images can then be analysed to extract the phase shift induced on the probe beam (right), which can be used to determine the spatially resolved electron density.

Tailoring the 3D plasma density profile

In addition to tuning the laser parameters, the acceleration process may be controlled by tailoring the 3D structure of the plasma source. The plasma in a plasma accelerator is typically created by the leading edge of the main laser pulse itself, by an electrical discharge or by an auxiliary laser pulse. Tailoring the plasma density longitudinally, along the direction of laser propagation, can be achieved by shaping the neutral gas prior to ionisation, a technique that is frequently used to localise the injection of electrons into the acceleration structure [2]. This is essential for generating high-quality electron beams.

Tailoring the plasma transversely can be achieved by heating the plasma electrons (via laser or discharge) and allowing them to expand hydrodynamically. Transversely structured plasmas can be used to guide a high-intensity laser pulse over long distances, keeping it tightly focused so it remains intense enough to maintain the acceleration into the multi-GeV regime [3, 4]. The plasma source for the PETRA IV plasma injector will require both longitudinal and transverse tailoring to create a plasma structure suitable for the injection and acceleration of a high-quality 6 GeV beam.

Plasma source prototyping

An experimental setup for plasma source R&D is currently under construction at DESY and will be used to develop a source suitable for the PETRA IV plasma injector. It will utilise an existing multi-TW laser system together with a new experimental arrangement to test prototypes of the plasma source. The lab provides the capacity to study both discharge-generated and laser-generated plasma sources. Additionally, there is the possibility to perform electron acceleration experiments. Several diagnostics, such as interferometry and optical spectroscopy, will be used to investigate the plasma properties, while an existing suite of laser and electron beam diagnostics will facilitate studies on the performance of the source in the context of the overall laser plasma acceleration process.

The setup is currently in the commissioning phase, with first plasma recently observed (Fig. 2). Over the coming months, the plasma source dynamics will be studied in detail and compared with hydrodynamic simulations. Following this, detailed studies on the performance of a variety of plasma source prototypes will be pursued.

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Cryogenic lasers for accelerators

Advances in output pulse energy and average power

Secondary laser-driven sources and novel acceleration techniques, such as THz acceleration and laser wakefield acceleration, require revolutionary approaches to realise the necessary high-energy and high-average-power lasers. What is needed are kilowatt-class lasers that provide output energies reaching the joule level and beyond. Cryogenic laser technology can deliver such power and energy levels. Over the past decade, 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 advanced cryogenic lasers that provide femtosecond, picosecond and nanosecond pulses close to the desired energy and power levels.

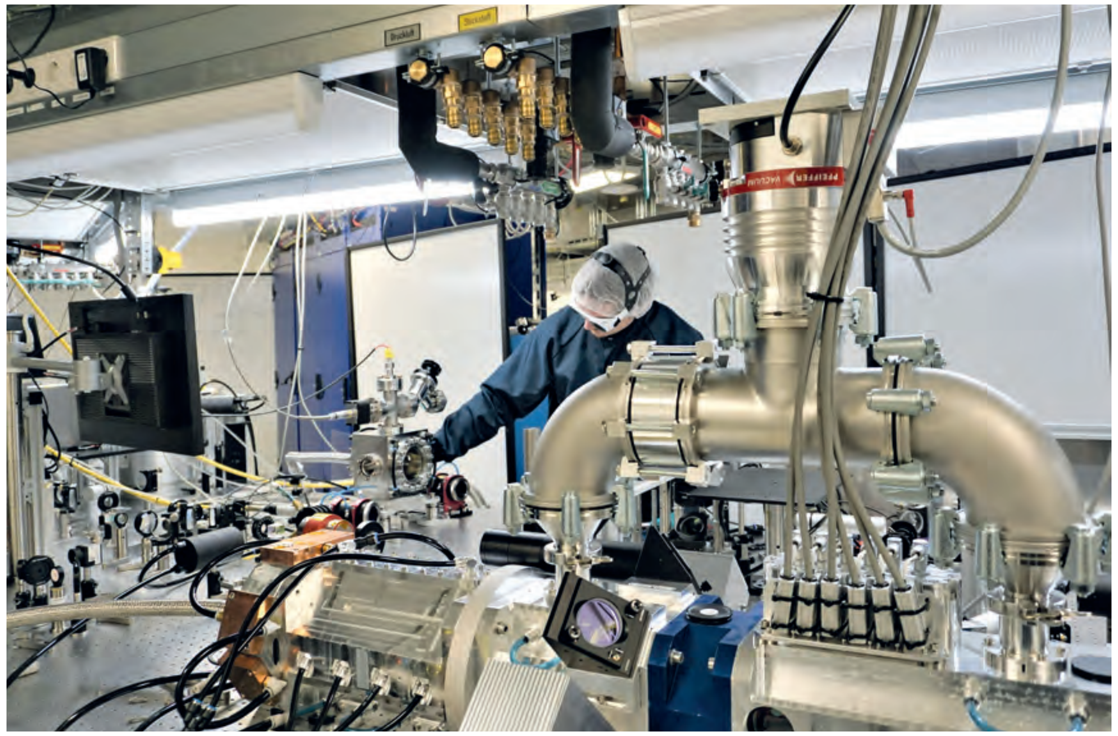

Figure 2
Laser engineer installing a 2 J composite Yb:YAG thin-disk booster amplifier in the AXSIS laser laboratory at DESY. In the foreground is a 16-pass composite Yb:YAG thin-disc amplifier.

Cryogenic laser basics

Since the emergence of pulsed solid-state lasers as enabling sources for non-linear processes in the 1970s and 1980s, laser scientists have faced the dilemma of simultaneously increasing the energy and repetition rate of laser systems. Increasing the output pulse energy requires increasing the optical aperture of the gain elements to avoid laser-induced damage, which leads to an increase in gain volume, preventing effective heat dissipation from the gain element. The engineering response to the decrease of the gain-medium-cooling surface–volume ratio is the use of Yb^{3+} as active laser ion, due to its low quantum defects, and the development of high-brilliance industrial-grade pump laser diodes.

Classical ytterbium laser technologies, such as thin-disk amplifiers or coherent fibre combining, are close to the limit of their ability to further increase the pulse energy. We are following the breakthrough approach of using laser amplification materials at cryogenic liquid-nitrogen boiling temperatures (78 K). The changing properties of ytterbium-doped gain material at cryogenic temperatures offer exciting prospects for high-energy and high-average-power lasers.

Current status of development

The CFEL UFOX group has been pursuing the development of cryogenically cooled lasers with Yb:YLF and Yb:YAG since 2012 (Fig. 1). Yb:YAG is well known as the "bread-and-butter" amplification medium for cryogenic lasers because it has a fivefold higher laser emission peak and a fivefold higher thermal conductivity at cryogenic temperature compared to room temperature. This creates an ideal laser material for extracting high-energy pulses in simple laser geometries.

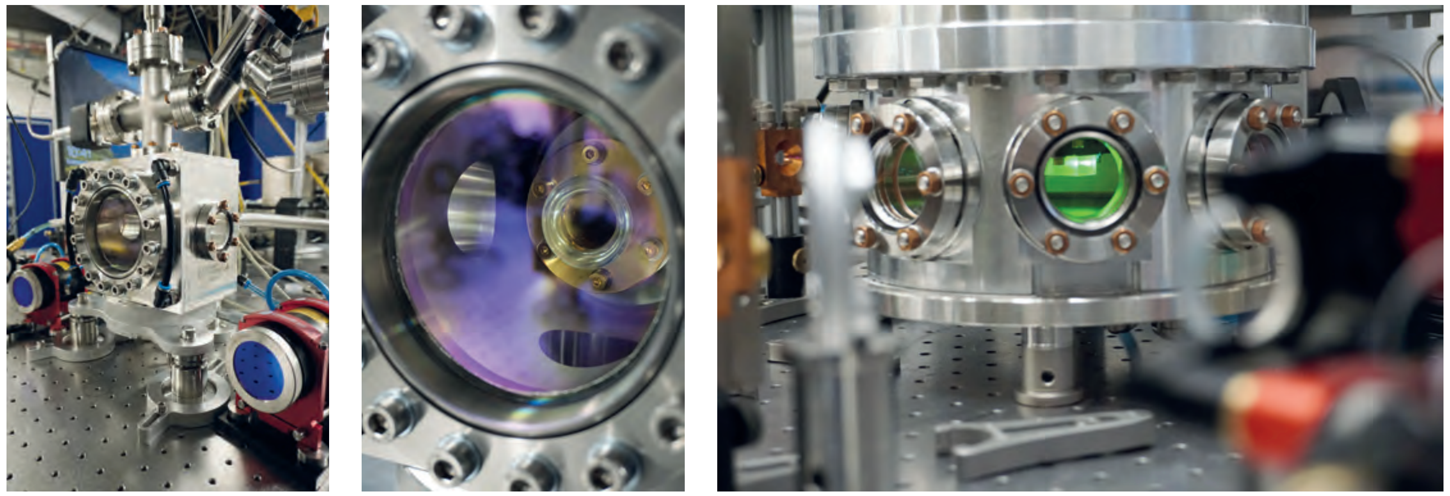

Figure 1
Examples of UFOX cryogenic laser developments. From left to right: booster amplifier, composite Yb:YAG thin disk and Yb:YLF cryogenic amplifier.

We have created a complete development cycle for lasers, starting with mode-locked oscillators and fibre amplifiers, then cryogenic regenerative amplifiers and high-energy multipass amplifiers. Currently, we can deliver pulses with 1 J energy and 5 ps pulse duration at repetition rates up to 500 Hz from a 16-pass cryogenic composite Yb:YAG thin-disk amplifier [1]. This makes an excellent pump source for inverse Compton scattering applications and high-energy THz pulse generation.

To reach femtosecond pulses, Yb:YLF can be used as gain material. Yb:YLF has outstanding advantages, such as broad band gain (10 nm) and negative thermo-optic coefficients at cryogenic temperatures. This allows us to extract hundreds of watts of average power from a single gain crystal with the ability to compress pulses to a duration of only 300 fs [2]. We have developed a Yb:YLF cryogenic laser system that provides 100 mJ, 980 fs pulses at a repetition rate of 1 kHz [3]. The system is used as a pump source for high-harmonic generation and laser spectral broadening followed by pulse compression. The system will be further scaled to higher energies for high-energy multicycle THz generation in the near future.

Further advances for higher-energy and higher-average-power lasers

In 2023, we will install a new booster composite Yb:YAG thin-disk amplifier to reach 2 J output pulse energies and 4.5 ps duration at 500 Hz repetition rate (Fig. 2). The system can be applied to produce single-cycle, extremely intense THz pulses for generating relativistic electrons from a THz-driven electron gun. This source could also be used as pumping source for high-energy titanium-sapphire lasers for the plasma wakefield acceleration of electrons.

The installation of a newly developed broadband fibre front-end will provide enough spectral bandwidth to achieve 350 fs output pulses from the Yb:YLF system. The subsequent installation of an already designed Yb:YLF cascade slab amplifier as an extension of the 100 mJ Yb:YLF system will generate 450 mJ output pulses, pumping highly efficient multicycle THz generation stages to accelerate electrons to relativistic energies.

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The SINBAD-ARES linear accelerator

A precision tool for accelerator science, technology and application developments

In 2022, the linear accelerator of the Accelerator Research Experiment at SINBAD (ARES) delivered more than 200 days of beamtime for DESY-internal and external accelerator R&D and medical applications. Two new experimental stations were built at the end of the accelerator to offer full flexibility to users. Outstanding electron beam parameters (energy spread and bunch length) were demonstrated and measured down to the resolution limit. The novel beam instrumentation, consisting of two PolariX X-band transverse deflecting structures (TDS), is currently in the commissioning phase, after which it will allow for a remarkable resolution of a few hundred attoseconds. First medical experiments with living cells irradiated with a 155 MeV electron beam were performed within a collaboration between the ARES team and the University of Manchester, UK.

New experimental areas and first external users

In February 2022, two new experimental areas were set up at the ARES linear accelerator (Fig. 1). A dedicated experimental chamber for detector tests was installed in collaboration with the DESY Particle Physics division in the dispersive section of the spectrometer. This chamber is separated from the machine vacuum by a titanium foil, enabling detector tests in air, at low pressure or in special gases. At the end of the beamline, two new quadrupole magnets and an exit window made of a 50 µm thick titanium foil were installed, followed by an experimental area in air. The station is equipped with an additional intensity measurement (integrating current transformer), an in-air screen station and a set of linear stages. This area offers full flexibility to users.

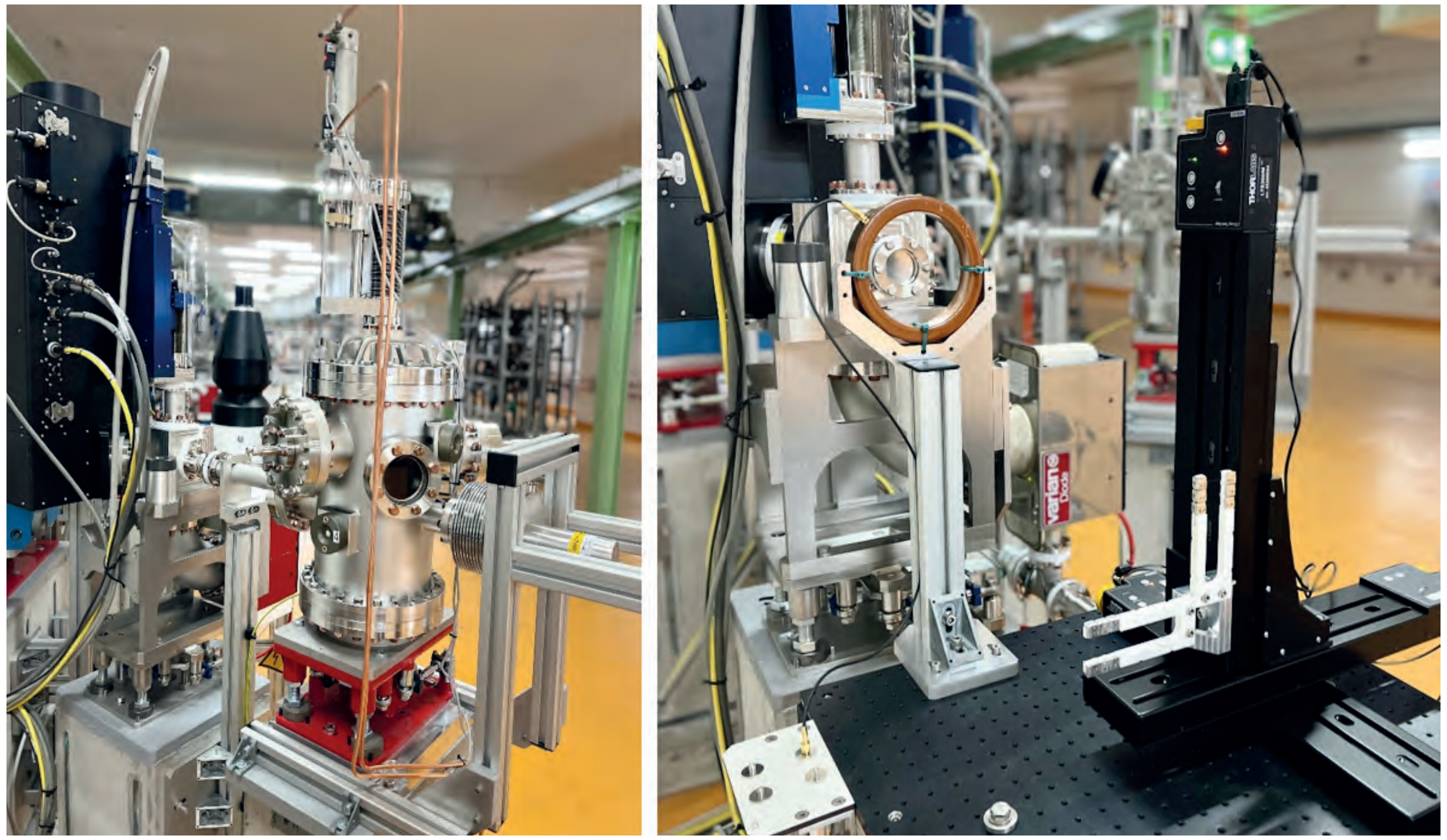

Figure 1
New experimental areas. Left: Vacuum chamber for detector tests. Right: In-air experimental station.

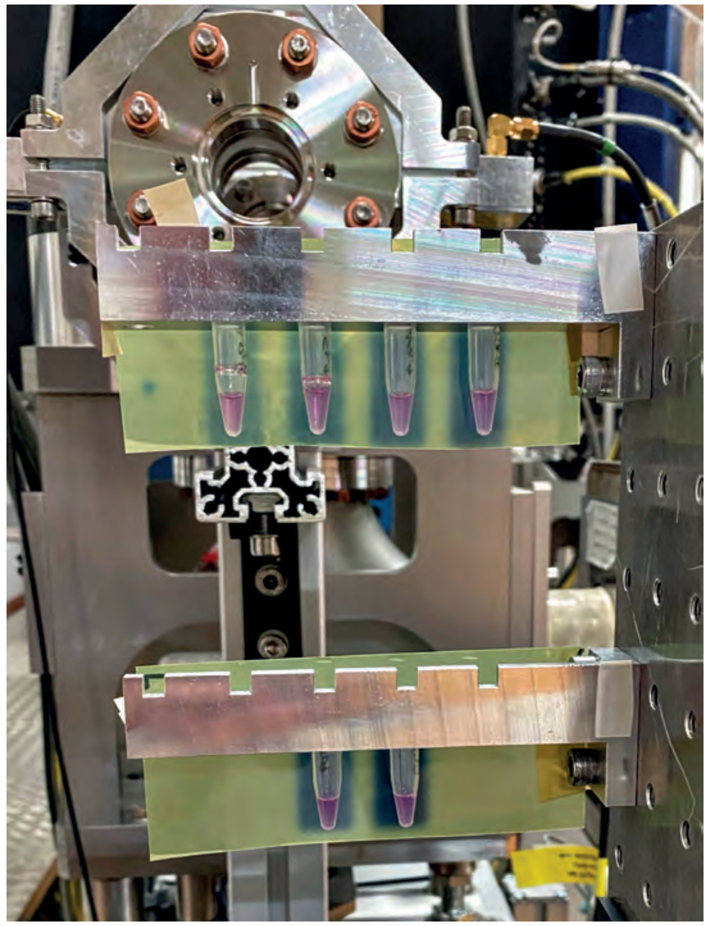

Figure 2
Detail of the holder system for UKE tubes filled with cancer cells (pink liquid). The cells were irradiated with different doses between 1 Gy and 6 Gy at an electron beam energy of 155 MeV. These first cell survival studies were performed in collaboration with the University of Manchester.

As part of the Accelerator Research and Innovation for European Science and Society (ARIES) transnational access programme, ARES welcomed the first external users. The first group from PSI in Switzerland performed tests with a micro-wirescanner consisting of 1 µm thick gold wires, which resulted in an outstanding beam profile reconstruction precision. The second group from EPFL in Switzerland studied the damage induced by electrons impacting on single-crystalline diamonds. For this experiment, ARES successfully sent electron bunches continuously over four days onto a 100 µm-sized diamond.

Accelerator R&D and medical applications at ARES

In 2022, ARES was frequently used for various internal and external accelerator R&D projects, such as the development of beam position monitors, intensity measurement devices and beam loss monitors. For the first time, novel miniaturised beam screens were successfully tested as part of the Accelerator on a CHip Program (ACHIP). The DESY Beam Controls group regularly used ARES to perform studies on the Helmholtz Autonomous Accelerator project, including shared beamtimes with the collaboration partners from KIT in Karlsruhe. The ARES team is also involved in the development of novel compact bunch length diagnostic methods within a European EIC Pathfinder Project called Terahertz Wave Accelerating Cavity (TWAC) (see p. 86). Together with the DESY Test Beam team, silicon strip sensors for the ATLAS experiment at CERN were tested in the new experimental chamber, showing their potential to be used not only for single-particle detection but also in the accelerator environment.

Medical applications at ARES ramped up remarkably in 2022 with regular beamtimes for Universitätsklinikum Hamburg-Eppendorf (UKE) and the DESY Radiation Protection team for dosimetry studies. This is an absolutely essential step towards novel cancer treatments with electron beams. Together with the University of Manchester, UK, living cancer cells were irradiated with the 155 MeV electron beams and the cell survival rate was studied. The experimental setup is shown in Fig. 2.

Outlook and new challenges

The main milestones for ARES in 2023 will be the completion of the PolariX X-band TDS installation and the next steps towards the generation and characterisation of ultrashort electron bunches. In terms of R&D projects, ARES will be used by several DESY groups, e.g. for waveguide window studies, which form the basis for all DESY X-band systems (PETRA IV plasma injector, FLASH and FLASHForward). In addition, extraction kicker magnet tests for PETRA IV are scheduled, and autonomous-accelerator studies and beam arrival time monitor R&D will be performed. The ACHIP experiments will continue with attosecond bunch trains.

ARES will further ramp up the experiments in life sciences and cancer treatment with cell culture and animal phantom studies in collaborations with UKE, the University of Manchester and CANDLE in Armenia.

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The European project TWAC

Applying ARES electron bunches to cutting-edge R&D on duration diagnostics

The European Terahertz Wave Accelerating Cavity (TWAC) project aims to build a prototype that paves the way towards a compact low-energy and high-peak-current electron accelerator, which is highly sought after for applications in research, medical and industrial environments. The TWAC project is funded by the EIC Pathfinder Open 2021 scheme of the Horizon Europe programme for a duration of four years and started in April 2022. It relies on a synergy between several European research institutes and companies, with expertise in accelerator physics, electron beam diagnostics and laser physics. The role of DESY within the project is to develop compact electron bunch duration diagnostics with a resolution at the femtosecond level and benchmark them on the ARES accelerator.

Figure 2
Members of the TWAC consortium

Demonstrating a compact hybrid accelerator for applications

The TWAC project aims to build a prototype that opens the way towards a compact (metre-scale), low-energy (≈ 10 MeV) and high-peak-current (≈ 1 kA) industrial electron accelerator, with an electron bunch duration on the femtosecond scale [1]. This type of accelerator would democratise access to femtosecond-scale high-peak-current electron bunches, which are currently only available at large-scale research facilities (Fig. 1). It is therefore highly sought after in various fields, e.g. in research into ultrafast phenomena, in medical applications (radiotherapy) and in industrial applications (material inspection and characterisation).

The TWAC vision is to achieve femtosecond-scale electron bunches, with well-characterised properties and excellent repeatability, by injecting them into a centimetre-long and millimetre-wide structure – called ZITA – driven by a THz pulse. The ZITA structure will accelerate the bunches and compress them in time, so that the target energy and peak current can be achieved within a distance compatible with a metre-scale layout.

A synergetic European project

The TWAC project, coordinated by CNRS in France, relies on a strong synergy between several European research institutes and companies (Fig. 2) with expertise in the various fields that must be combined to achieve its ambitious goal: high-power lasers, non-linear optics, accelerator physics and electron beam diagnostics.

The prototype accelerator will be hosted at IJCLab in France, which is leading the development of the ZITA accelerating structure and the commissioning of the prototype. The THz source to drive the ZITA is being developed by the University of Pécs in Hungary. DESY and PhLAM in France are leading the development of diagnostics for the electron bunch duration and for the THz source, respectively. The industrial partners ITEOX in France and RadiaBeam Europe in Switzerland will conduct investigations on the industrialisation potential of the prototype accelerator developed within TWAC.

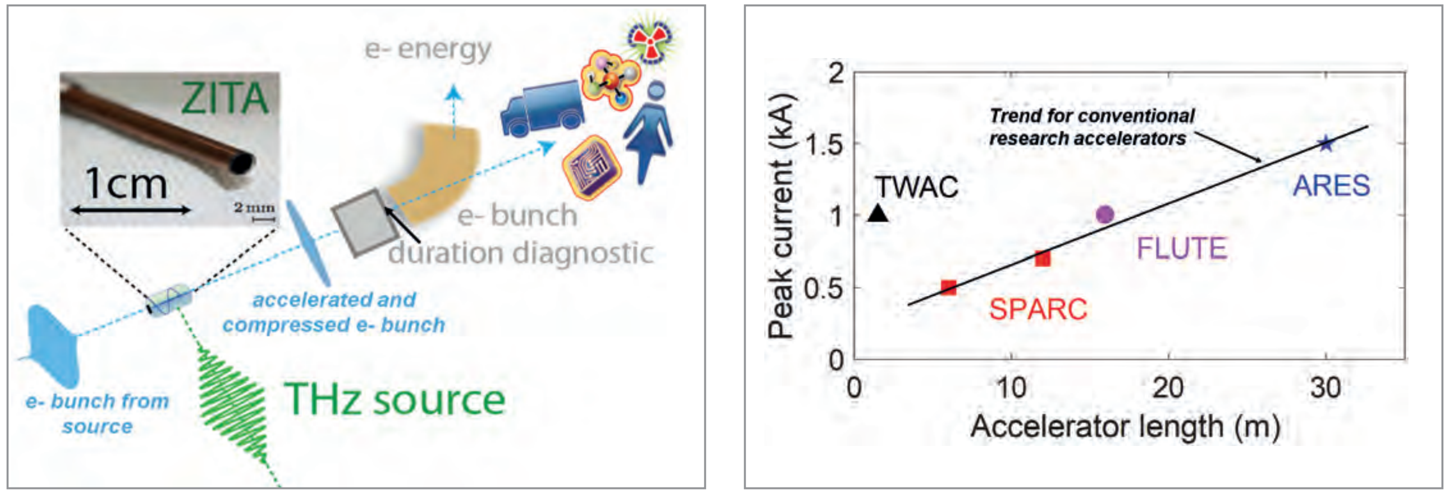

Figure 1
Left: Vision of the TWAC project. Right: TWAC in the peak current versus accelerator length plane (SPARC [2], FLUTE [3], ARES [4]).

ARES as cutting-edge benchmark platform for advanced bunch duration diagnostics

The main role of DESY within the TWAC project is to develop electron bunch duration diagnostics that are compatible with the properties expected at the prototype accelerator. This objective is a challenge on its own, as it requires a combination of single-digit femtosecond resolution, compactness and minimal complexity of the technical environment to fit the diagnostics into an overall metre-scale layout. This development work is performed within the DESY Accelerator R&D group.

The ARES facility at DESY (see p. 84) provides a unique and ideal benchmark platform for the duration diagnostics to be developed within TWAC. On the one hand, it can provide electron bunches with versatile properties, especially durations expected down to the sub-femtosecond level, thus matching and even exceeding the properties anticipated in the TWAC project. The electron bunches delivered by ARES also present excellent stability in terms of momentum spectrum and arrival time. On the other hand, ARES is being equipped with cutting-edge conventional duration diagnostics consisting of X-band transverse deflecting structures of the PolariX type [5]. These are expected to achieve sub-femtosecond resolution [6] and are therefore highly suited to benchmark the compact diagnostics developed within the TWAC project.

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The TWAC project has received funding from the European Union's Horizon Europe research and innovation programme (EIC Pathfinder scheme) under grant agreement Nr. 101046504. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or EISMEA. Neither the European Union nor the granting authority can be held responsible for them.

AXSIS

THz accelerator laboratory at DESY

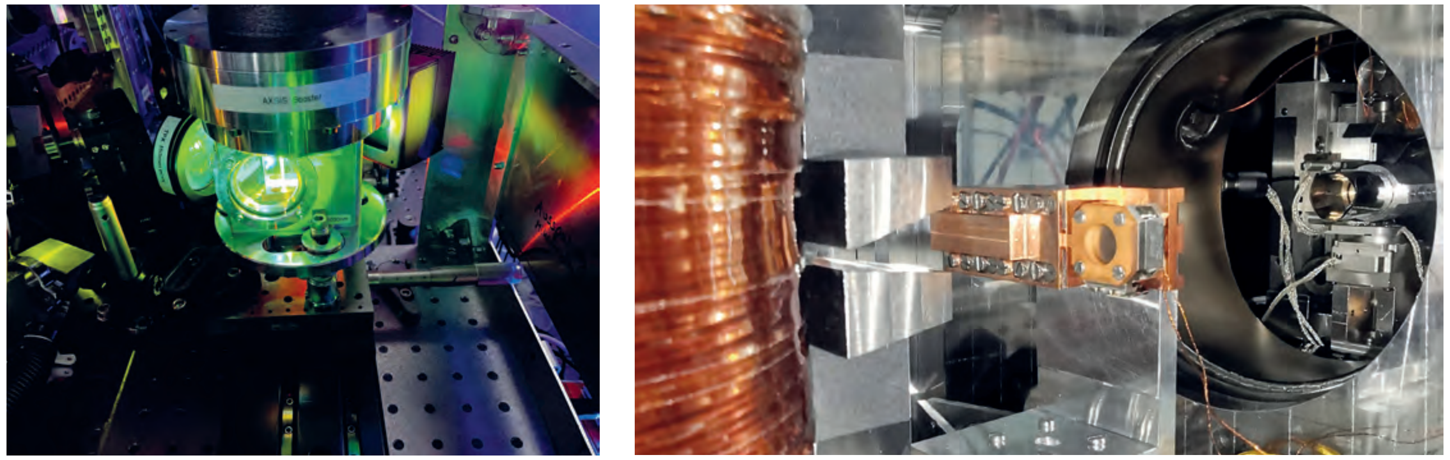

Figure 2
Left: THz generation module under excitation by the 200 mJ laser system. Right: THz accelerator module installed in the chamber.

In 2014, the European Research Council (ERC) awarded a Synergy Grant for the project "Attosecond X-ray Science – Imaging and Spectroscopy" (AXSIS) to four DESY principal investigators for pioneering THz-driven accelerator technology and its use to develop a novel, compact X-ray light source capable of resolving atomic and electronic structure on sub-femtosecond time scales [1]. This visionary and audacious project has led to the construction of a unique, world-class facility at DESY that combines high-power lasers and record-setting THz sources with novel, compact electron sources. Located in DESY's SINBAD R&D complex, the facility – with its cleanroom-rated laser laboratory, shielded accelerator tunnel and X-ray beamline hutch as well as control room and dedicated sample preparation rooms – is a state-of-the-art resource that enables the development of the multiple layers of technology required to achieve the ambitious goals of the AXSIS project.

The AXSIS facility

The primary resources of the AXSIS facility are a temperature-controlled, cleanroom-grade laser laboratory, a shielded accelerator tunnel, an X-ray hutch and a set of sample preparation rooms (Fig. 1). The laser lab houses on separate tables the three primary laser systems for driving the accelerator and light source: a 200 mJ, 400 fs, 50 Hz commercial system for generating mJ-scale single-cycle THz pulses to drive the electron gun; a 2 J, 500 ps, 10 Hz commercial system together with a 256 pulse, 300 GHz burst mode system with 40 mJ, sub-ps pulses for generating mJ-scale multicycle THz pulses to drive the THz linear accelerator; and a 1 J, 5 ps, 300 Hz cryogenic composite-disk laser system developed in house to drive the optical undulator / inverse Compton scattering process for X-ray generation.

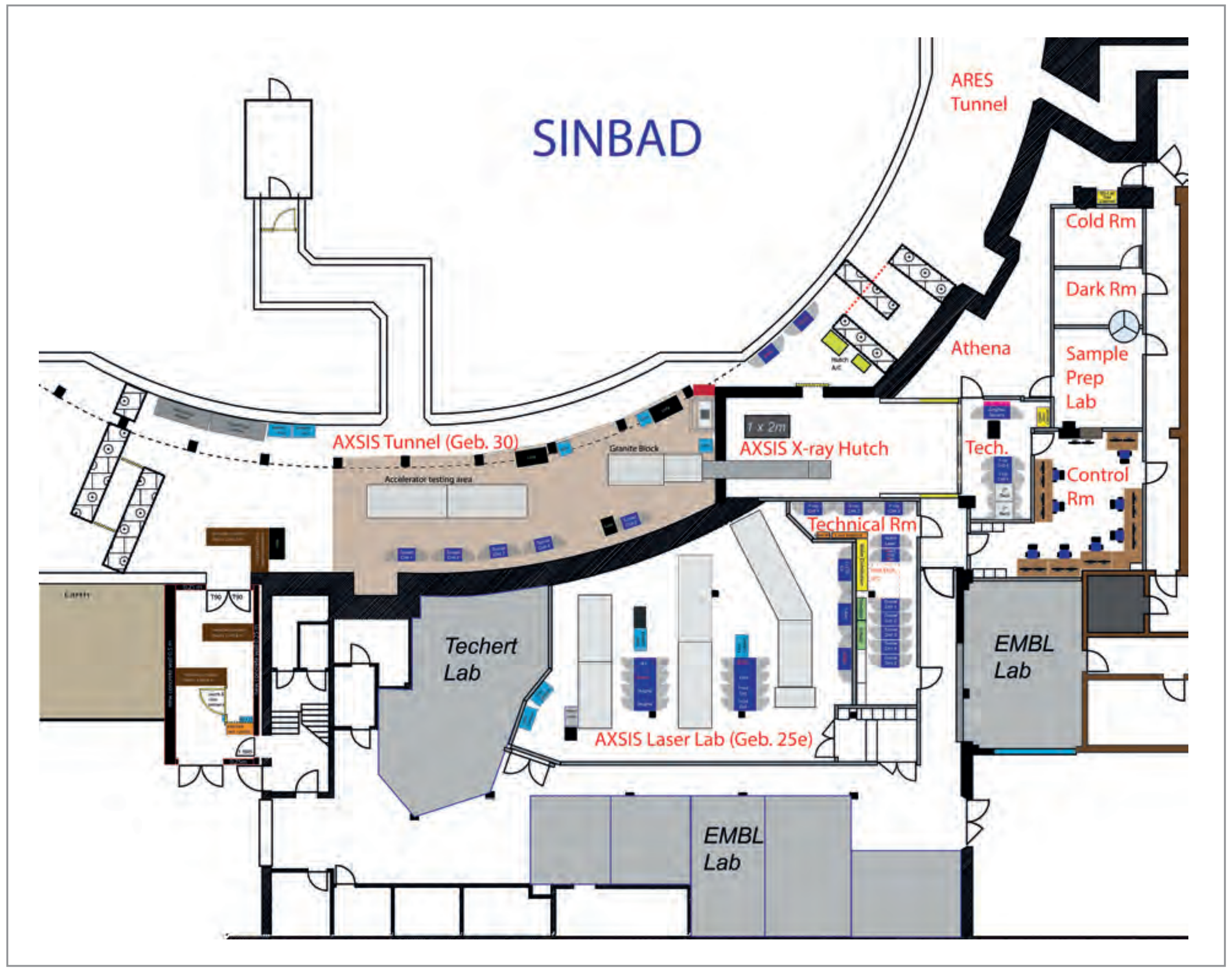

Figure 1
Layout of the AXSIS facility

Besides housing the lasers, the laser lab provides an environment for experimentation and prototyping of THz generation and THz-driven electron manipulation concepts. The accelerator tunnel is a 50 m long section of the old DORIS synchrotron, which was renovated and repurposed for THz-driven accelerator development. Surrounded by 1 m thick shielding and equipped with a (nearly completed) radiation interlock system, this laboratory is ideal for testing novel electron acceleration concepts. A 10 m long solid granite block, half of which resides in the tunnel and the other half in the X-ray hutch, provides an ultrastable platform for the development of the combined accelerator prototype and X-ray beamline. A second large optical table serves as a space for testing and prototyping of new concepts and is already equipped with a flexible-energy diagnostic station.

A unique feature of this laboratory is the integration of optical breadboards into the accelerator support, which reflects the all-optical character of the facility. The large X-ray hutch, which required modification of the tunnel shielding wall, provides ample space for setting up a state-of-the-art X-ray beamline planned with X-ray serial crystallography as well as X-ray absorption and X-ray emission spectroscopy (XAS/XES). An optical parametric amplifier (OPA)-based laser system adjacent to the beamline provides a versatile capability for performing time-resolved pump–probe experiments. The sample preparation labs, including a dark room and a cold room, are conveniently located to allow rapid transfer of delicate crystal samples to the X-ray interaction point on demand and eliminate the necessity of transportation.

Status of the facility

The facility is currently fully functional, with the exception of the radiation interlock, the design of which is undergoing final review. The lasers in the cleanroom are fully commissioned and are used on a daily basis to support the experimental programme, currently focused on the development of high-energy THz sources, THz-powered electron accelerators and future high-power laser systems. The THz-driven accelerator prototype, which is being assembled and tested on the granite table, represents an experimental effort encompassing multiple projects. These include the development of compact, THz-driven and RF-driven electron photoguns, THz-driven electron boosters and linear accelerators as well as conventional permanent-magnet-, electromagnetic- and electrostatic-based components for beam transport and diagnostics. Simultaneously, the critical components for the X-ray beamline, including a "road-runner" high-speed sample-rastering system for femtosecond serial crystallography, an X-ray spectrometer for XAS/XES and a robotic detector-positioning system, have been developed and tested using synchrotron and X-ray free-electron facilities around the world.

The AXSIS facility is thus a unique and functioning resource for performing the state-of-the-art R&D required to develop a pioneering THz-driven electron and light source technology.

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Compact RF gun for ultrafast electron diffraction

Enabling structural dynamics with ultrabright electron bunches from a tabletop machine

Ultrafast electron diffraction (UED) is an attractive and relatively low-cost alternative to time-resolved X-ray techniques in the field of structural dynamics. To capture the fastest structural rearrangements on the Ångstrom scale, a temporal resolution on the order of 10 fs is required, implying the generation of electron pulses of similar duration with sufficient brightness. While large klystron-driven radio frequency (RF) structures can reach these parameters in the relativistic (MeV) regime, as demonstrated in the REGAE facility (see p. 32), DC electron guns used in sub-relativistic UED have an inherently lower brightness due to limitations on the achievable extraction field strength at the photocathode. Starting in 2018, a sub-relativistic RF gun has been designed, constructed and tested in a cross-divisional collaboration at DESY. The 180 keV RF gun employs field enhancement at a pin-shaped cathode to produce an extraction field strength of 100 MV/m using a solid-state amplifier with only 10 kW peak power. This article describes the progress in the construction and characterisation of this elegant little RF photogun system and provides an outlook for exciting prospects in structural dynamics experiments.

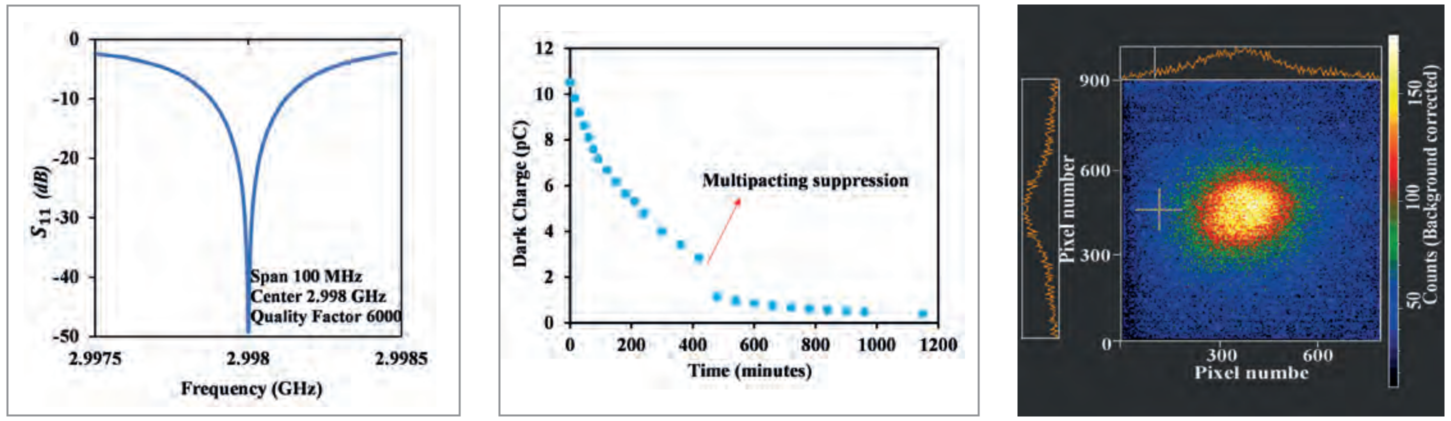

Figure 2

Left: Frequency response of the RF cavity, showing the necessary loaded quality factor of 6000. Centre: Reduction of dark charge and multipacting during conditioning. Right: Dark-charge beam measured using a YAG scintillator.

Design, simulations and testing of the RF cavity

The RF cavity, designed particularly with UED applications in mind, is based on a half-cell pill-box incorporating a pin-shaped photocathode with a flat 1 mm diameter tip that results in strong field enhancement and large fields even at modest driving power (Fig. 1). A solenoid lens is placed directly in front of the anode for beam collimation. Simulations predict that high-brightness electron bunches with a duration of 10 fs (RMS), a radius of 500 µm and a spatial emittance of 0.1 mm·mrad are possible for a bunch charge of 10 fC.

An initial challenge during operation was multipacting, which was further exacerbated by the solenoid magnetic field. Through a better understanding of this phenomenon using simulations and the development of a careful conditioning protocol, multipacting was nearly eliminated (Fig. 2).

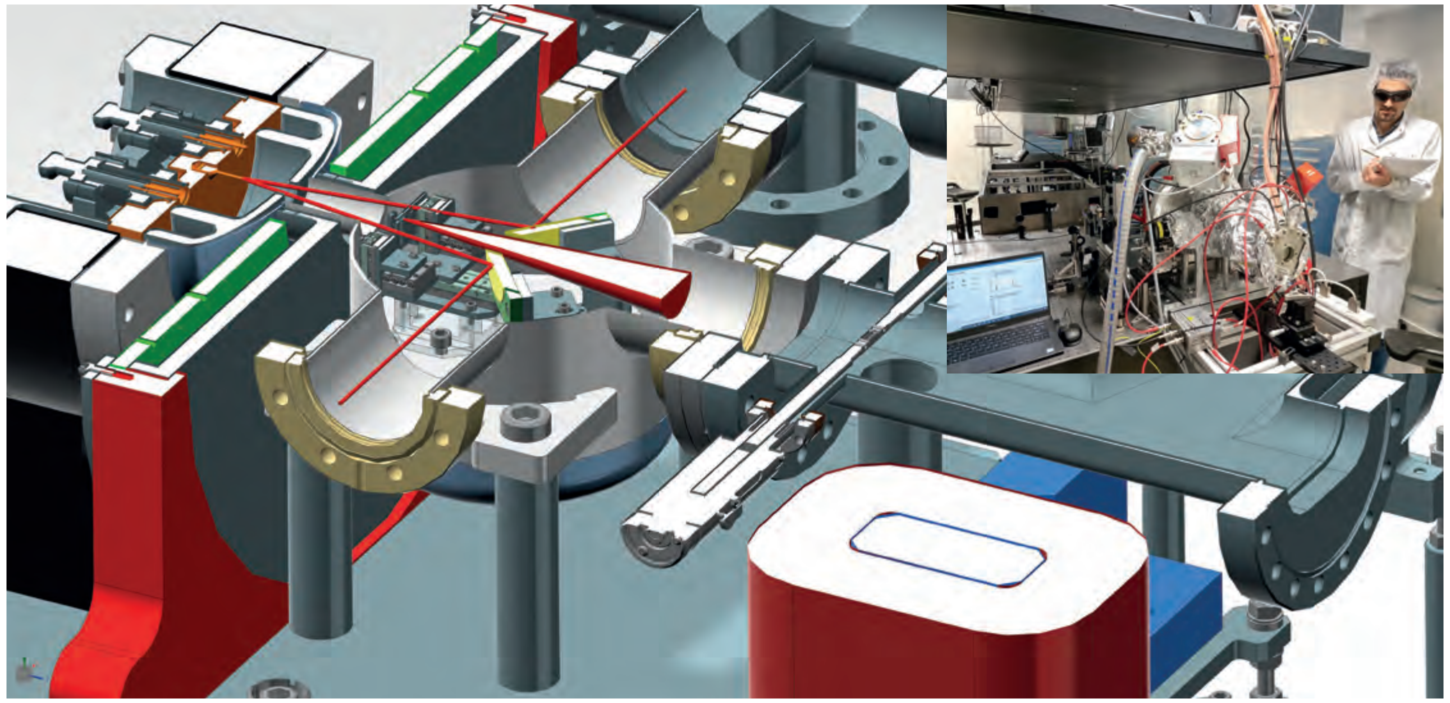

Figure 1

CAD rendering of the RF gun test setup, showing electron gun, specimen and streak camera assemblies, in-vacuum mirrors with ultraviolet beam path (red lines) and electron path (cone). The inserted photo shows the setup, as it is currently installed in the CFEL building.

Setup for photoelectron bunch generation and characterisation

For the next step of achieving and characterising photoelectron bunches, the RF gun setup was installed on an optical table in the building of the Center for Free-Electron Laser Science (CFEL) in the summer of 2022. The laser beamline is headed by a Coherent Legend Elite Duo amplifier operating at 800 nm centre wavelength and delivering 5 mJ pulses with a pulse duration of 35 fs. For photoemission from the copper pin cathode, the 800 nm fundamental is tripled to 267 nm, followed by spatial and temporal shaping. The former is accomplished by imaging an illuminated pinhole onto the photocathode, and we have demonstrated a 1σ truncated Gaussian beam profile of 30 µm diameter, approximating the ideal "half-circle" radial profile desired for linear space charge expansion dynamics. Temporal shaping to the required picosecond time scale for effective RF cavity compression is accomplished by a four-prism stretcher.

Beam characterisation features of the setup include a microchannel plate imaging detector, a Faraday cup for charge measurement and a streak camera featuring a gallium arsenide photoconductive semiconductor switch (GaAs PCSS) for sub-100 fs resolution electron bunch profiling and arrival time jitter measurement. The latter was developed in collaboration with the Max Planck Institute for the Structure and Dynamics of Matter (MPSD). In addition, a magnetic energy spectrum analyser currently in fabrication will be installed in the future.

Challenges and outlook

A major milestone will be the achievement of photoemitted electron bunches compressible to 30 fs in duration with 20 fs stable synchronisation to the photoinjector laser in order to fully benefit from the ultrashort compressed pulse duration. We believe that the GaAs PCSS streak camera technology is adequate for measuring and verifying this synchronisation level while in addition being very compact and of low complexity. The synchronisation scheme relies on the proven µTCA technology provided by DESY and a low-noise RF signal generator combined with a Balanced Optical Microwave Phase Detector (BOMPD) from Cycle GmbH.

Subject to achievement of high-brightness electron bunches, we plan to conduct UED studies of phonon dynamics in lithium niobate to improve THz generation for the AXSIS project (see p. 88), and eventually use a copy of this electron gun as a photoinjector for the AXSIS source.

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Cable-shielding metrology laboratory for industry

Joint laboratory for quality assurance and development of high-quality cables

Modern synchrotron radiation sources and free-electron lasers rely on demanding accelerators that must offer high beamtime availability for user operation. As accelerators consist of thousands of cables and interconnections, the proper choice of cables and connectors as well as high-quality cable assembly during installation are important factors. In particular, the shield properties of high-frequency cables in conjunction with connectors are critical. Non-compliance with high-quality standards leads to irregular malfunctions in signal transmission, entailing complicated error detection. To prevent such failures, DESY and the cable specialist elspec group offer a new laboratory for cable-shielding metrology as a service, where the frequency-dependent screening attenuation of specific cable assemblies can be determined. As an example, this article shows how the screening of widely used semi-ridged cables degrades with their number of bends. From experience, interconnection malfunctions often appear, even after years of operation, as a result of wrong installation methods. To avoid this, elspec group invented a new installation technique, called "semi-installation method".

New laboratory for cable-shielding metrology

The shield of a high-frequency cable carries the return current of the signal and also defines the signal transmission quality, which is often neglected. Figure 1 (left) shows a typical structure of a high-frequency cable with two layers of shields. To test, improve and verify the quality of various cable shields and its relation to the assembled connector, DESY's Innovation & Technology Transfer (ITT) department, the Machine Beam Control group and the cable specialist el-spec GmbH / elspec group have built up a new cable-shielding metrology laboratory located in the Innovation Village at DESY. The setup is available for the accelerator and research community and industry in general.

Figure 1 (right) shows a block diagram of the setup for measuring the transfer impedance of a cable for lower frequencies and the screening attenuation for higher frequencies. The cable under test is driven by a source generator of up to 8 GHz and terminated. The radio frequency (RF) energy radiated from the cable shield is collected and measured using a vector network analyser. The screening attenuation is defined as the ratio of radiated to input RF power for a certain cable length. With this, the quality of the shield, the specific connector assembly, or unwanted leakages during production and installation can be characterised and monitored. Figure 2 shows the cable shield setup in the new laboratory.

As an example, Fig. 3 (left) shows the measured screening attenuation of a conformable cable, which is widely used in laboratories, as a function of its number of mechanical bends. From the measurement floor of about 125 dB/m, the screening attenuation degrades by 15 dB for 10 bends and 50 dB for 100 bends, respectively. As shown in Fig. 3 (right, marked in red), this is caused by microscopic cracks of the soldered shield braid.

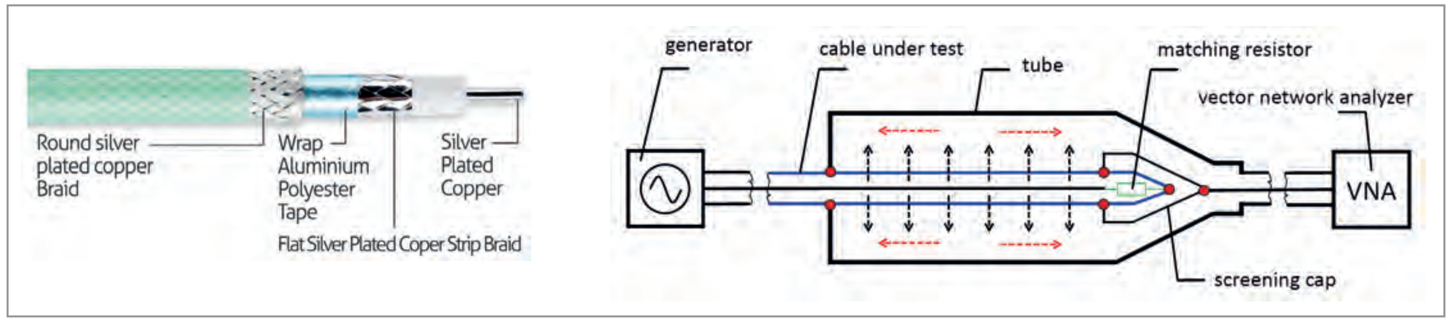

Figure 1

Left: Layer structure of a high-frequency cable with two layers of shields. Right: Simplified block diagram of the setup for measuring the radiation passing the shield of a high-frequency cable.

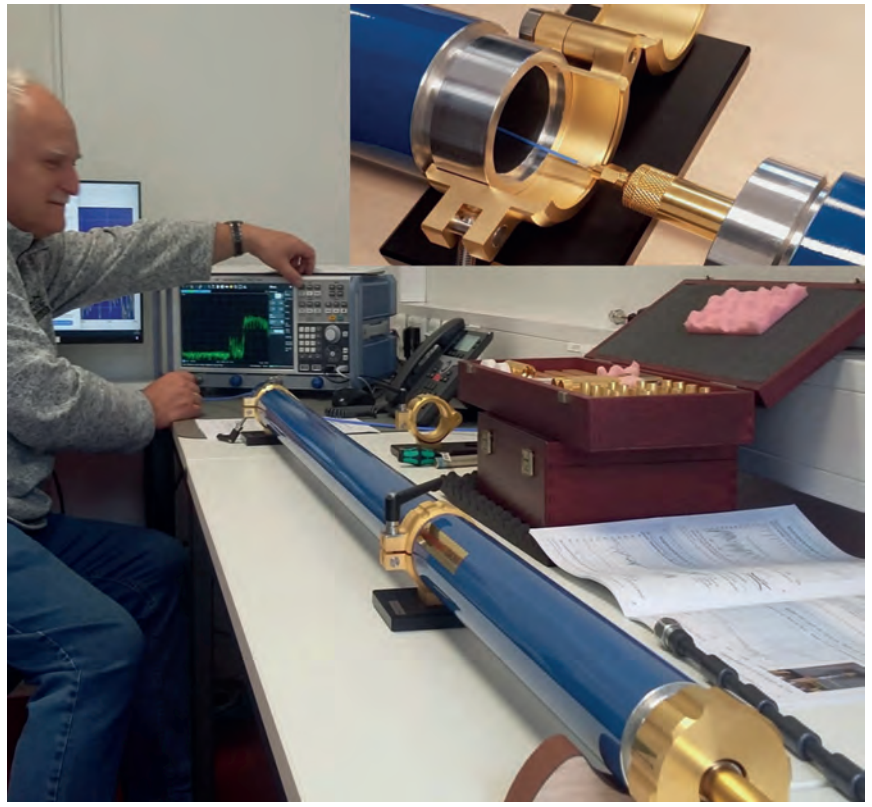

Figure 2

Setup for measuring the screening attenuation of an RF cable

Semi-installation method

After installation and operation of RF cables in the accelerator interconnection, malfunctions can appear. Detecting such semi-faulty connections is extremely time-consuming and can jeopardise reliable facility operation. During installation, a pre-assembled and connected RF cable is placed and bent into its final location. This leads to mechanical stresses in the cable, so that the inner signal conductor pins can move by several millimetres, resulting in faulty signal connections (Fig. 4). To avoid this, elspec group has invented a new installation technique, called "semi-installation" method, in which the cable is installed but only connected on one side. After a relaxation phase of several days, the cable is finally fully connected. This method promises a much more reliable operation.

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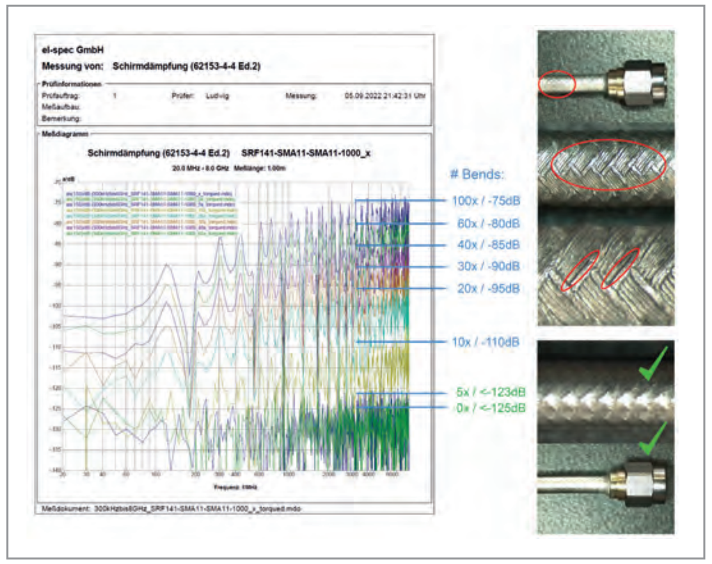
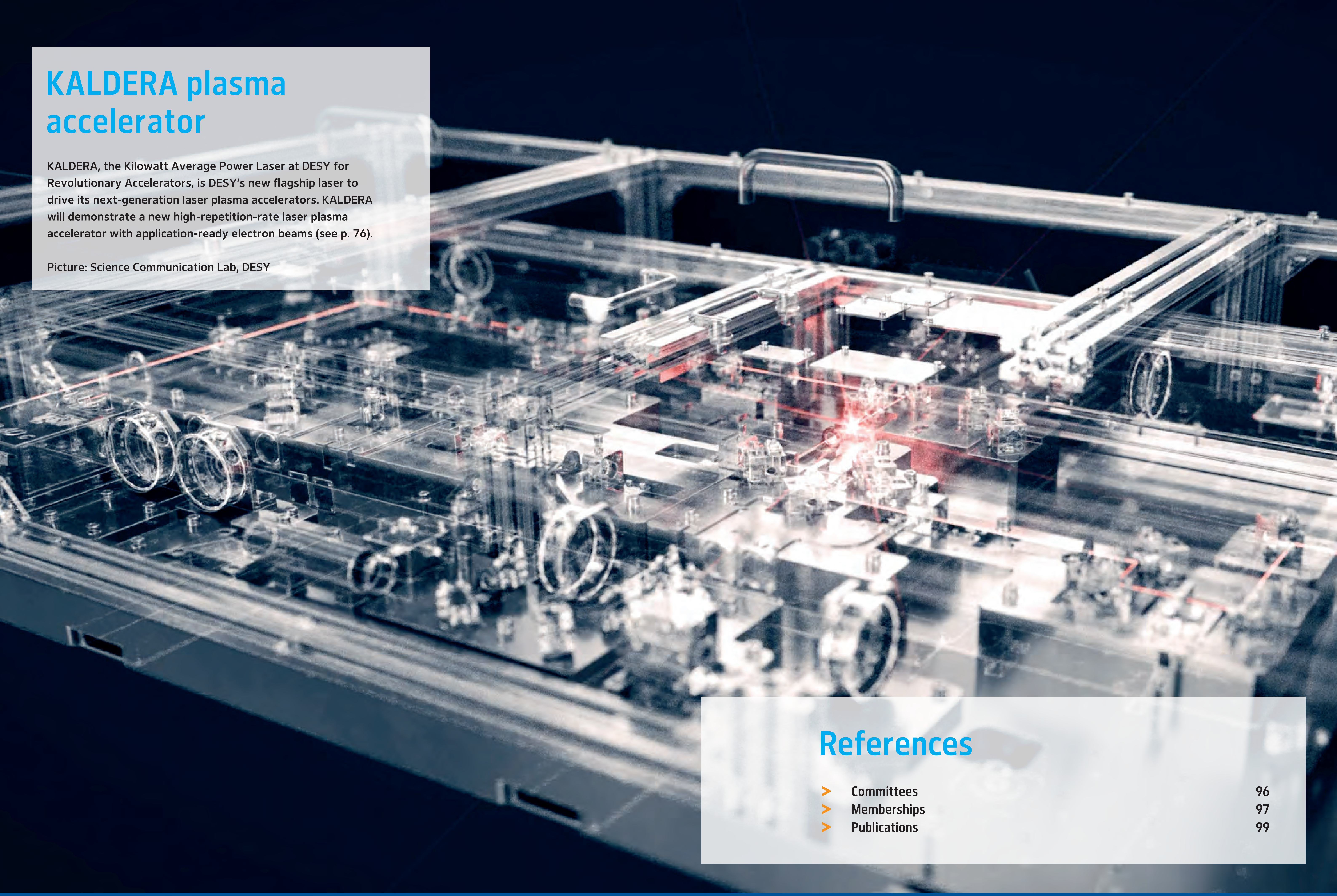


Figure 3

Screening attenuation of a conformable RF cable for different numbers of mechanical bends. The attenuation degrades after some bends due to microscopic cracks of the soldered shield braid.

Figure 4

Movement of inner connector pins due to stress



KALDERA plasma accelerator

KALDERA, the Kilowatt Average Power Laser at DESY for Revolutionary Accelerators, is DESY's new flagship laser to drive its next-generation laser plasma accelerators. KALDERA will demonstrate a new high-repetition-rate laser plasma accelerator with application-ready electron beams (see p. 76).

Picture: Science Communication Lab, DESY

References

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UK/ESS High Beta Cavity Project Board
Detlef Reschke

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Winfried Decking

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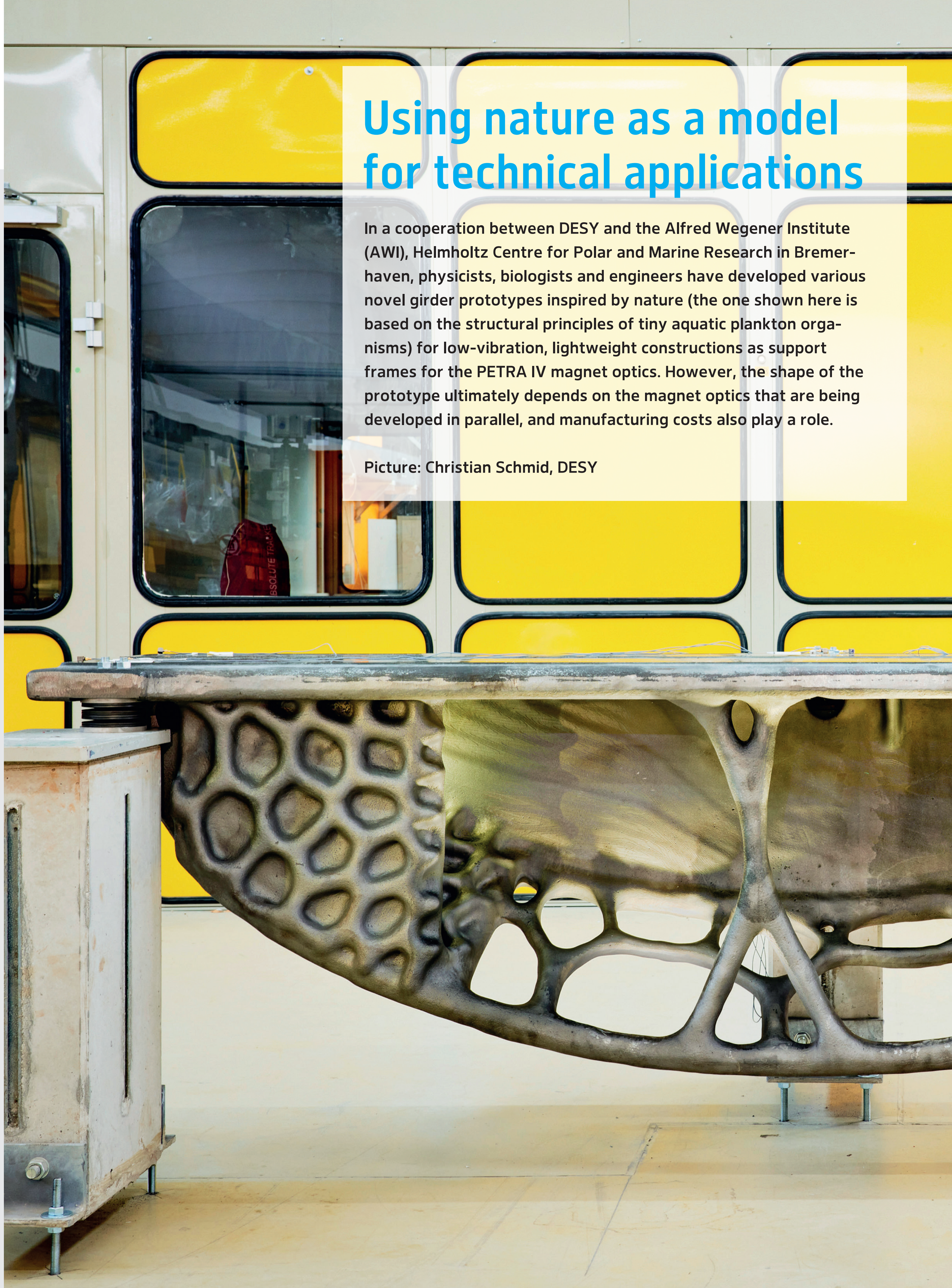

Using nature as a model for technical applications

In a cooperation between DESY and the Alfred Wegener Institute (AWI), Helmholtz Centre for Polar and Marine Research in Bremerhaven, physicists, biologists and engineers have developed various novel girder prototypes inspired by nature (the one shown here is based on the structural principles of tiny aquatic plankton organisms) for low-vibration, lightweight constructions as support frames for the PETRA IV magnet optics. However, the shape of the prototype ultimately depends on the magnet optics that are being developed in parallel, and manufacturing costs also play a role.

Picture: Christian Schmid, DESY

Helium refrigeration plants

DESY's cryogenic plants provide liquid helium for cooling the European XFEL and FLASH accelerators, for the ALPS II particle physics experiment and for various test facilities that use superconducting components operating at low temperatures close to absolute zero. Procuring helium at an affordable price has become a real challenge in 2022.

Picture: Dirk Nölle, DESY

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