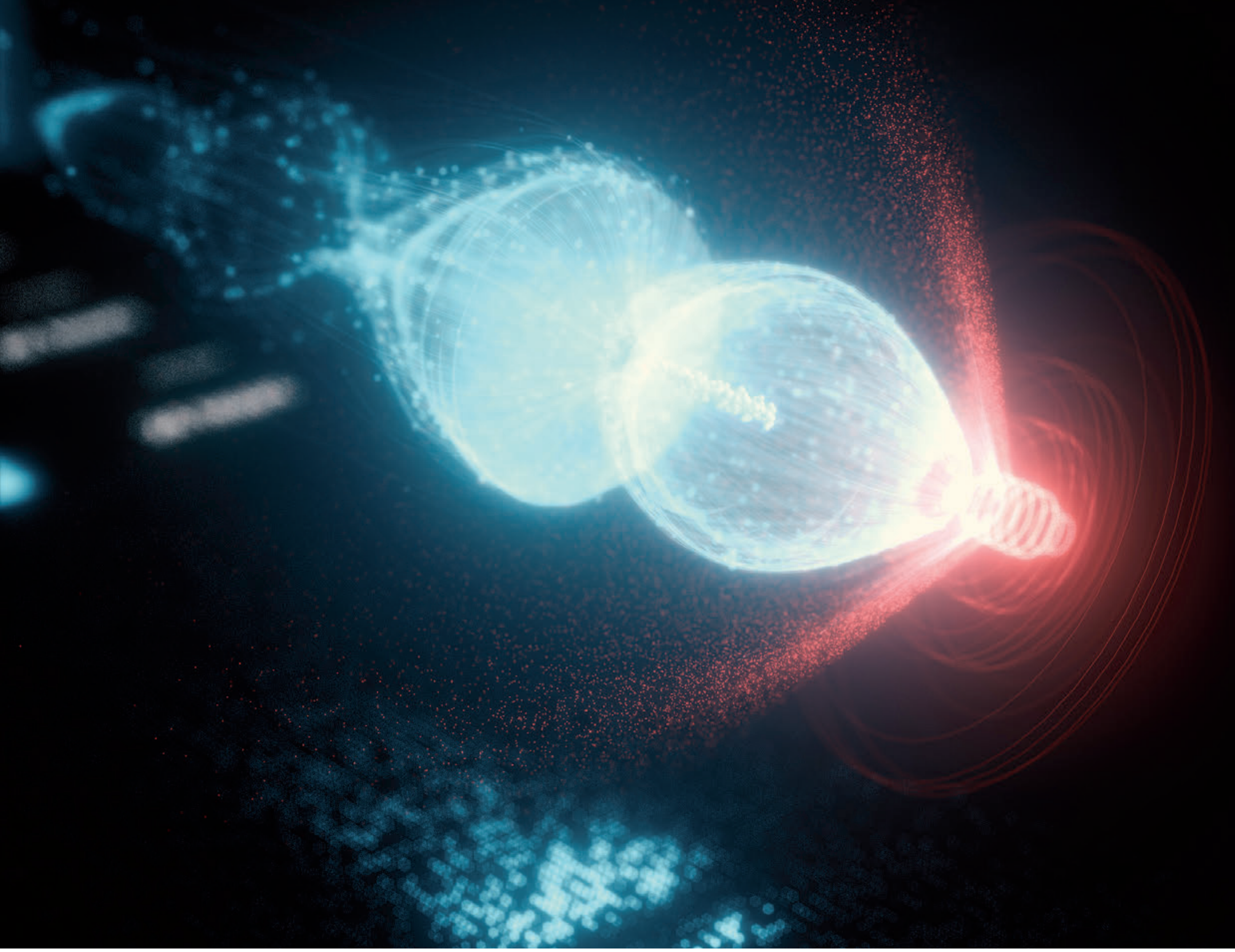


ACCELERATORS 2020.

Highlights and Annual Report

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

Cover

In laser plasma acceleration, a strong laser pulse (red) generates a plasma wave (blue) in hydrogen gas by stripping electrons from gas molecules. The electrons (red) ride the wave like a surfer in the wake of a boat. This pushes them to high energies extremely quickly. The LUX facility at DESY has now continuously delivered more than 100 000 of these particle bunches in around 30 h.

Picture: DESY, Science Communication Lab

ACCELERATORS 2020.

Highlights and Annual Report

Contents

The year 2020 at DESY

Chairman's foreword

Dear Colleagues and
Friends of DESY,

2020 was a truly unusual year for the global society. In March, the coronavirus brought our accustomed everyday life to a standstill and mercilessly exposed the vulnerability of our modern society to such crisis. We will have to put many of our habits, which have finally proven to be unsustainable, to test and find new ways forward. We have already learned a great deal in recent months, most importantly that our society can rely on science and on decision makers who listen to scientists.

We at DESY reacted quickly and very cautiously to the pandemic and moved the research centre into a safe mode that kept the laboratories and our research largely in operation while protecting all staff from infection as efficiently as possible.

These measures were critical with respect to the user operation of our large-scale research facilities PETRA III and FLASH. Especially the unique analysis capabilities at PETRA III have proven to be most important for the fight against the COVID-19 coronavirus. We have to ensure that these technologies will be even more targeted to molecular drug research and even more crisis-proven in the future. To this end, we have drawn up a major proposal for the establishment of a National Analysis Center for Molecular Infection Research, in which new digital and technical concepts, like artificial intelligence, remote control and robotics, are to be incorporated. "Digital DESY" has become a new building block in our DESY strategy, in response to the challenges of the current pandemic and of future crisis

Figure 1

Part of the DESY staff in Hamburg hold up the DESY-60 logo.

Figure 2

Senate reception for the 60th anniversary of DESY in Hamburg: with forward-looking, cutting-edge research into the new decade.

situations. We will also pay even greater attention to sustainable concepts in all our activities and future projects.

DESY is well on its way into this future. The priority project is PETRA IV, which has now entered the technical design phase. We are very pleased that with Riccardo Bartolini, who joined DESY in April 2020, we have been able to attract an internationally renowned accelerator physicist for this future project. In the next few years, the task will be to prepare all the logistical and personnel prerequisites for the upgrade of the synchrotron radiation source PETRA III and to raise the necessary financial resources for this complex project. Nearly all areas of DESY will be involved here in the upcoming decade.

In 2020, we have made good progress in various projects, such as in the development of the Centre for Molecular Water Science (CMWS), the commissioning of the Detector Assembly Facility (DAF) and the construction of the Bahrenfeld Start-Up Labs, as well as in the Centre for X-ray and Nano Science (CXNS), which will open in 2021. An active innovation culture that interlinks basic research and fast transfer of innovative concepts to the market will remain an integral part of DESY's future strategy.

In the coming years, further projects are on the agenda: Major new construction measures include the DESYUM visitor centre, the building for the accelerator division, the TECHNICUM for technical groups, the DESY Innovation Factory and the Wolfgang Pauli Centre (WPC) for theoretical physics.

Important research and upgrade projects, such as the upgrade of the free-electron laser FLASH to FLASH2020+, the KALDERA-ATHENA project for future accelerator technologies, the Any Light Particle Search experiment ALPS II, the telescope in search of dark-matter particles BabyIAXO as well as the Cherenkov Telescope Array (CTA) and its Data Centre, will be implemented.

Promoting our top scientists and our young talents is an essential component of the DESY strategy. The new Helmholtz graduate school DASHH has been well established in 2020. The aim of the school is to educate the future generation of data scientists who can efficiently analyse measured data using e.g. artificial intelligence or machine learning. In 2020, we have implemented the COAST programme, which will assist our postdocs in shaping their individual career pathways. Our HR department has done a remarkable job in this respect. Over the coming months, we must and will develop concepts to offer our top academic performers new career paths within the research centre.

DESY celebrated its 60th anniversary in the Hamburg city hall at the beginning of 2020. Many congratulations came from the global science community and honoured DESY as a world-leading centre in the exploration of matter. We are well prepared for the coming decades to continue the legacy of DESY.

Even in these challenging times, the extraordinary commitment of the DESY staff and all our users and partners, national and international, made research possible at DESY – I would like to thank all those who contributed to the joint efforts!

Helmut Dosch
Chairman of the DESY Board of Directors

Accelerators at DESY

Introduction

Dear colleagues and
Friends of DESY,

In early 2020, prospects looked bright for DESY. In January, we celebrated the 60th anniversary of DESY with a Senate reception in the Hamburg city hall, at which I presented our ambitious plans for the future of our research facilities – including both major upgrades to our existing particle accelerator facilities and new technologies that will enable more compact, efficient and cost-effective accelerators for novel applications. With our facilities successfully powering up after the winter shutdown, all seemed set for another productive year of research and discoveries at DESY.

Then came the COVID-19 pandemic, and with it the realisation that modern society with its ambitions and certainties is far more fragile and vulnerable than we had previously assumed. Quasi overnight, we had to overthrow our plans and adapt to the new situation. To avoid any further spread of the coronavirus, we decided to enter a reduced operating mode on 16 March. Staff were asked to work from home as much as possible to minimise presence on site, the accelerators and other facilities were put in safe mode, and user operation at our X-ray sources PETRA III and FLASH, at our test beam facility and at the European XFEL X-ray laser was suspended until further notice.

Thanks to the extraordinary commitment and dedication of all DESY groups, however, we managed to quickly adjust to the novel situation, with the shift to home office working remarkably well. Just as quickly, we realised that our facilities could make a real difference in fighting the pandemic. DESY set up a fast-track access mode for COVID-19-related research, and PETRA III was powered up for such studies even during the reduced operating mode. Relevant projects included measurements that played a role in the development of the BioNTech/Pfizer vaccine, the screening of potential drugs in contact with crystallised viral proteins and investigations of infected lung tissue to understand the causes of lung failure in patients with severe COVID-19.

The reduced operating mode was maintained until May for PETRA III and August for FLASH, after which user operation resumed with strict measures to minimise the risk of infection. The use of video conferencing tools between the main control room and office locations on and off site enabled effective and safe support by the shift crew. Since users from abroad in particular were often unable to come on site due to travel restrictions, beam time schedules were handled very flexibly and adapted to the availability and travel possibilities of the users. In addition, new beam time concepts were offered: In the “mail-in" procedure, experiments are carried out by DESY staff on site following instructions by the users, while in the “remote-access” procedure, users are allowed to control the experiment remotely from their home institute, with DESY staff installing the samples and setting up the remote control. Thanks to reduced travel of the users, these access modes contribute significantly to increasing the sustainability of our operations. As part of our DIGITAL DESY initiative, we are therefore planning to accelerate the digitalisation of our facilities’ operations using remote systems, artificial intelligence and robotics in order to better ensure resilient research operations with our international user community in the future.

Despite all the restrictions due to the pandemic, we thus managed to successfully run our current facilities and make decisive advances in our key projects for the future:

Our PETRA III synchrotron radiation source and our FLASH soft X-ray free-electron laser (FEL) reached record availabilities of 98.8% and 98.6%, respectively, serving a broad spectrum of user experiments in spite of the pandemic. The European XFEL X-ray laser, the linear accelerator of which is operated by DESY, generated X-ray pulses with a photon energy of 25 keV, i.e. a wavelength of 0.05 nm, setting a new wavelength record for laser light. This was later pushed even further to 30 keV, or 0.04 nm.

The beginning of 2020 marked a major milestone for the PETRA IV project – DESY’s new flagship project to build the world’s brightest hard X-ray ultralow-emittance storage ring – which officially entered the technical design phase. The project successfully underwent evaluation by the Research Infrastructure Commission (FIS) of the Helmholtz Association, and the assessment was concluded with a recommendation from the Commission for inclusion of PETRA IV on the German national roadmap for research infrastructures.

In December 2020, the FLASH2020+ upgrade programme was launched with a virtual kick-off meeting at which the international user community was introduced to the pro-

Outdoor “control room” of the LUX laser plasma accelerator in the pandemic summer 2020 (from left to right: Sören Jalas, Paul Winkler, Wim Leemans, Timo Eichner and Andreas Maier)

gramme’s scientific scope. The upgraded FLASH facility will offer higher electron beam energies combined with new tuneable-gap undulators, which will allow the oxygen K-edge to be reached with polarisation control. A new seeded beamline will provide fully coherent and reproducible pulses up to MHz repetition rates.

Our multifaceted research portfolio also saw great success. The LUX beamline, a laser-driven plasma accelerator jointly developed and operated by DESY and Universität Hamburg, was run for 30 hours while continuously producing electron beams – a world first for laser plasma accelerators and a big step towards stable operation of this innovative accelerator technology. At our FLASHForward beam-driven plasma acceleration facility, a novel technique was developed that allows the shape of the accelerating field to be determined with a resolution of femtoseconds so the acceleration process can be studied in detail, marking another step towards the new era of control and stability that plasma accelerators are entering.

The ARES linear accelerator, an essential component of our new, long-term accelerator R&D facility SINBAD, reached its design energy, marking the transition of the facility from hardware commissioning to beam optimisation and preparation for first experiments. These will aim to test advanced acceleration schemes and develop novel diagnostic devices in ultrafast science. Both ARES and LUX will also play essential roles in our efforts to realise a fully autonomously operated accelerator with the help of artificial intelligence and machine learning approaches.

The development of KALDERA, a laser system with kHz repetition rate and kW average power at the SINBAD facility, with sufficiently high stability and reproducibility to generate high-quality electron bunches from a laser plasma accelerator at a repetition rate of 1 kHz, also made good progress in 2020. The prototype of the seed laser was completed and is being converted into a robust design. Construction work has begun on the KALDERA laser laboratory. KALDERA is a central part of the plasma accelerator structure at DESY to be built around the lighthouse project ATHENA, a new R&D platform on accelerator technology within the Helmholtz Association.

The year 2020 has confronted global society with unprecedented challenges. I am all the more grateful that, thanks to the exceptional dedication of all DESY staff, our advisory committees and our users and partners, we have succeeded in making 2020 another fruitful year for science at DESY. The lessons we learned from the pandemic will help make our research operations more resilient, more sustainable and even more relevant to solving the great challenges of our time.

Wim Leemans
Director of the Accelerator Division

News and events

News and events

A busy year 2020

January

Senate reception to celebrate DESY’s 60th anniversary

On 16 January, about 500 guests attended the Senate reception in celebration of DESY’s 60th anniversary in the Hamburg city hall. On the occasion, Katharina Fegebank, Hamburg’s Second Mayor and Senator for Science, Research and Equality, paid tribute to the achievements of DESY: “As a world-class research centre, DESY has played a major role in shaping Hamburg as a centre of science in the past – and, as a driver of innovation and a fundamental component of the Science City Hamburg Bahrenfeld, it will continue to play an important role in Hamburg’s progress in the future. Like our city, DESY stands for cosmopolitanism, courage and innovative ideas for the world of tomorrow.”

About 500 guests attended the Senate reception in the Hamburg city hall.

Wolf-Dieter Lukas, State Secretary at the German Federal Ministry of Education and Research (BMBF), attributed another far-reaching significance to DESY’s accomplishments: “Basic research is not only the basis for innovation, it is above all an indispensable foundation of a democratic society and of knowledge-based debate in politics. We need research centres like DESY as ‘scientific fact guarantors’ in order to jointly find solutions for urgent challenges of the 21st century, which pose enormous tasks for society and politics, economy and science.”

Katharina Fegebank, Hamburg’s Second Mayor and Senator for Science, Research and Equality, acknowledged the achievements of DESY.

Otmar Wiestler, President of the Helmholtz Association, appreciated DESY’s innovative drive: “DESY has evolved into a centre with enormous international appeal, especially with its new generation of research infrastructures. It thus makes an essential contribution to solving major societal challenges in line with the Helmholtz mission.”

Current and former DESY Directors with State Secretary Wolf-Dieter Lukas (front, centre) and Helmholtz President Otmar Wiestler (middle row, second from right)

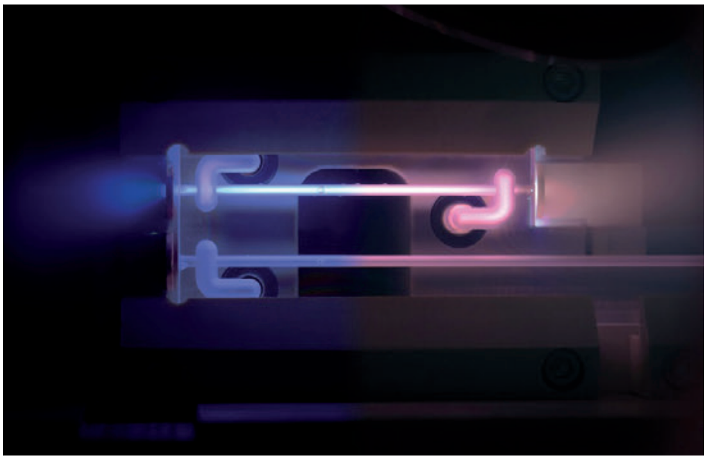
In addition to plans for further improvements to the existing DESY facilities, Wim Leemans, Director of DESY's Accelerator Division, presented his vision of the future for DESY's research on new types of compact accelerators: "We want to make future particle accelerators much smaller, more efficient and more cost-effective using new technologies such as plasma acceleration. This will allow us to use them more flexibly and more widely in environmental technology and medicine, among other areas." If Leemans has his way, then "soon the X-ray device will come to the patient, wherever they are, and not the patient to the X-ray device" – just one example of applied research for the world of tomorrow.

"From the experience of the last 60 years, I am convinced that the centre is well positioned for the future," summarised DESY Director Helmut Dosch. "We are constantly questioning and developing ourselves. But the original mission, to decipher the structure of matter – from the big bang to DNA – this remains."

February

DESY is a finalist in Clusters4Future competition

With its proposal "Tech2Med", which relies on innovative X-ray technologies to accelerate drug development, DESY is one of the finalists of the Clusters4Future initiative to enter the concept phase. The ideas competition was set up by the German Federal Ministry of Education and Research (BMBF) as part of its high-tech strategy to quickly bring groundbreaking developments from basic research into application. The aim is to open up burgeoning fields of innovation and develop suitable solutions for the pressing challenges of our time.

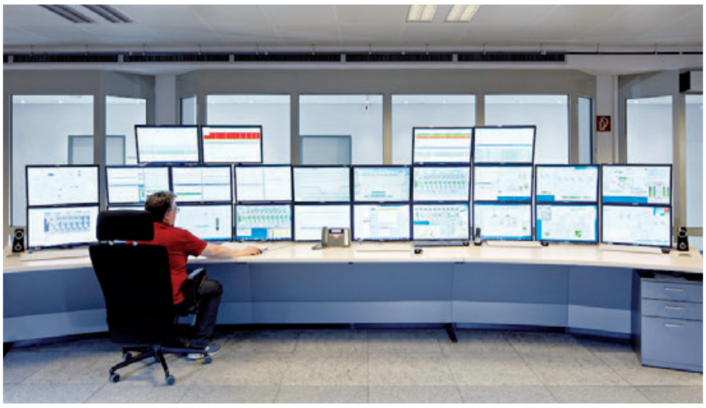


Plasma cells like this one tested at DESY allow the construction of compact particle accelerators.

The cluster proposal "Tech2Med", which was submitted under the coordination of DESY together with Universität Hamburg, aims to support the health sector with new technology developments and, in particular, to accelerate the development of drugs and new active ingredients. To this end, two DESY fields of expertise will be linked: X-ray analysis methods such as protein crystallography, which can provide blueprints for new active ingredients, and the development of compact particle accelerators, which can be used to set up X-ray sources for pharmaceutical research on a lab scale in order to make such X-ray analysis methods more easily and quickly accessible than is possible today. "Tech2Med" enters the concept phase with 15 other cluster initiatives selected among a total of 137 submissions.

March

Corona pandemic: DESY operates in reduced mode


To contain the spread of the SARS-CoV-2 virus, the DESY accelerator control room was operated with reduced staff.

As a measure against the further spread of the SARS-CoV-2 virus, DESY entered a reduced operating mode on 16 March. Although the DESY sites in Hamburg and Zeuthen remained open, staff were asked to work from home as much as possible, so that staff presence on campus was reduced to what was absolutely necessary. Where possible, the particle accelerators and other facilities were put in safe mode, and user operation at the X-ray sources PETRA III and FLASH and at the test beam facility was suspended until further notice. PETRA III was powered up only for SARS-CoV-2-relevant measurements. To help fight the pandemic, DESY set up a fast-track access mode for corresponding research projects. The reduced operating mode was maintained until May for PETRA III and August for FLASH, after which user operation resumed with strict measures to minimise the risk of infection.

Tiny double accelerator recycles energy

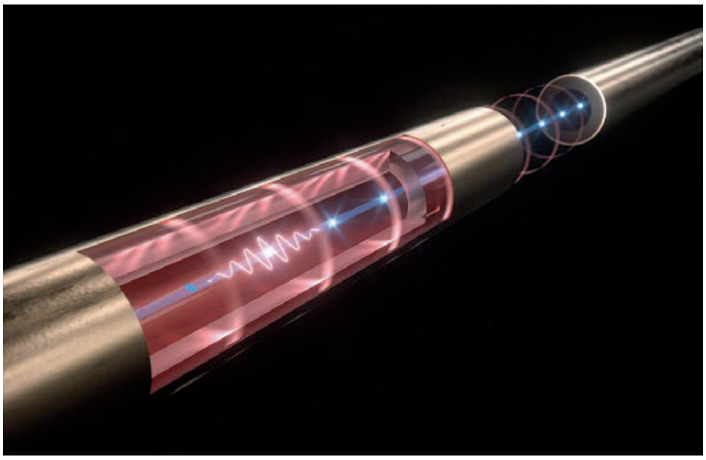
A team of scientists from the Center for Free-Electron laser Science (CFEL) at DESY has built a miniature double particle accelerator that can recycle some of the laser energy fed into the system to boost the energy of the accelerated electrons a second time. The device uses narrowband terahertz (THz) radiation, which lies between infrared and radio frequencies in the electromagnetic spectrum. A single accelerating tube is just 1.5 cm long and 0.79 mm in diameter.

The miniature size of the device is possible thanks to the short wavelength of THz radiation. This makes THz-based accelerators promising candidates for next-generation compact electron sources, which could enable applications where large particle accelerators are just not feasible or necessary. However, the technique is still at an early stage, and the performance of experimental THz accelerators has been limited by the relatively short interaction region between the THz pulse and the electrons.

For the new device, the team used a longer, multicycle pulse comprising many cycles of THz waves, which is fed into a waveguide lined with a dielectric material. Within the waveguide, the pulse's speed is reduced. A bunch of electrons is then shot into the central part of the waveguide just in time to travel along with the pulse. This scheme increases the interaction region between the THz pulse and the electron bunch to the centimetre range – compared to a few millimetres in earlier experiments. Although the device did not yet produce a large acceleration, the team was able to prove the concept by showing that the electrons' energy increased from 55 to about 56.5 keV. A stronger acceleration can be achieved by using a stronger laser to generate the THz pulses.

The setup is mainly designed for the non-relativistic regime, in which the electrons have speeds not too close to the speed of light. Interestingly, this regime enables a recycling of the THz pulse for a second stage of acceleration: Once the THz pulse leaves the waveguide and enters the vacuum, its speed is reset to the speed of light, meaning that the pulse overtakes the slower electron bunch in a couple of centimetres. The team placed a second waveguide at just the right distance that the electrons entered it together with the THz pulse, which was again slowed down by the waveguide. In this way, they generated a second interaction region, boosting the electrons' energies even further.

In the experiment, only a small fraction of the THz pulse could be recycled in this way. But the experiment shows that recycling is possible in principle, and the team is confident that the recycled fraction can be substantially increased. The multistage scheme will greatly reduce the requirements on the laser system needed for electron acceleration in the non-relativistic regime, opening up new possibilities for the design of THz-based accelerators.


The mini-accelerator uses terahertz radiation that can be recycled for a second stage of acceleration.

April

European XFEL reaches world-record photon energies

With a photon energy of 25 keV, corresponding to a wavelength of 0.05 nm, the European XFEL X-ray laser set a new wavelength record for laser light. Furthermore, by changing the setting of the undulator SASE1 – one of the X-ray generation devices of the facility – to 30 keV, DESY's operations team for the European XFEL accelerator was able to push the limit even further, observing clear indications of free-electron laser (FEL) radiation on a scintillating screen.

Karabo address: XFEL.FEL/CAM/BEAMVIEW/output.schema.data.image
DOOCS address: XFEL.FEL/CAM.SA1/SA1_XTD2_IMGFEL/BEAMVIEW

The record European XFEL X-ray flashes on a scintillating screen

The photon energy of 25 keV surpasses the original design photon energy of the European XFEL by a factor of two and marks the far end of the anticipated design envelope. Since high-energy X-rays allow for larger penetration depths, this will enable the investigation of materials in complex, highly absorbing environments. These parameters will be crucial for studying, for example, dynamic processes in materials science and engineering, the structure and dynamics of liquids, melts and solutions, and matter at very high pressure in diamond anvil cells.

After the winter shutdown 2019/2020, the DESY accelerator experts focused on re-establishing the high electron energies that had been reached in 2018. With the help of piezo tuners that mechanically deform each of the 800 superconducting cavities ten times per second to counteract the shape variation inflicted by the electromagnetic forces of the pulsed radio frequency accelerating field, the frequencies of the cavities could be kept constant at so far unreached accuracy. This allowed stable operation at an electron energy of 17.5 GeV for many hours and with the full design number of bunches.

The scientists took advantage of the high electron energies to test the photon energy boundaries of the facility. By setting the SASE1 undulator gaps accordingly, lasing at the world record energy of 25 keV could be observed with an energy measured to be around 100 µJ per X-ray pulse. A first user experiment with the accelerator operating at 16.5 GeV and with a photon energy of 24 keV was planned at the SASE2 undulator for 2020.

May

DESY begins transition to secured normal operation

After the decisions of the German federal and state governments on cautious relaxation of the corona measures, DESY started to adjust the reduced operating mode its research facilities had been in since March, switching step by step to secured normal operation. This included a restart of the facilities and a resumption of a large part of user operation with strict safety measures in place, such as adherence to hygiene and distancing rules and the wearing of protective masks. Through the increased use of "mail-in" and "remote-access" experiments and a flexible adaptation of experiment times to the availability and travel possibilities of the user groups, it was possible to use almost the entire beam time available.

Not least as a lesson learned from the pandemic, DESY will accelerate the digitalisation of the operation of its facilities using remote systems, artificial intelligence and robotics to better ensure resilient research operations with an international user community in the future.

COVID-19 research at DESY

DESY's X-ray source PETRA III had continued to operate even in the reduced mode for essential research on the SARS-CoV-2 virus, such as measurements that played a role in the development of the BioNTech vaccine. Further COVID-19-related studies included the screening of potential drugs in contact with crystallised viral proteins using macromolecular crystallography and investigations of infected lung tissue with coherent X-ray imaging techniques in order to understand why the lungs of many patients with severe COVID-19 stop functioning, causing patients to die despite ventilation. DESY intends to focus more strongly on the analytics of infectious diseases in the future.

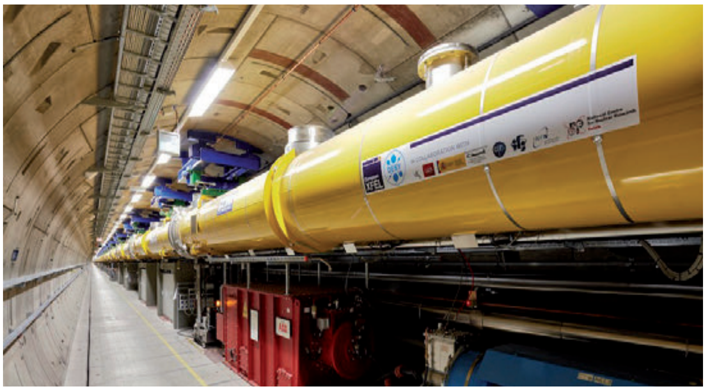
Coronavirus research at DESY's X-ray source PETRA III

June

New Helmholtz International Lab

With their ultrashort pulses that are more than a billion times brighter than those from any other X-ray source, X-ray FELs have opened up a new field of ultrafast X-ray research. However, these facilities are still largely reserved for pioneers with expert knowledge. In the Helmholtz International Laboratory on Reliability, Repetition, Results at the most advanced X-ray Sources (HIR^{3}X), DESY and SLAC in the USA have joined forces to develop methods that will make X-ray laser investigations a routine task even for non-experts. European XFEL is a partner of the cooperation.

The goals of HIR^{3}X include the use of artificial intelligence for the detection and analysis of X-ray signals and the operation of X-ray lasers. Sample exchange robots are to be developed to achieve high sample throughput and thus optimal use of beam time. Joint solutions will enable standardisation of experiments and protocols, fostering collaboration in other areas and promoting reliability and ease of use. The developments will improve the automatisation of many measurements, allowing remote access of experiments and improved operations while maintaining social distancing.



The European XFEL is one of the world’s leading X-ray FELs.

Ultrahigh-speed data connection between Germany and Poland

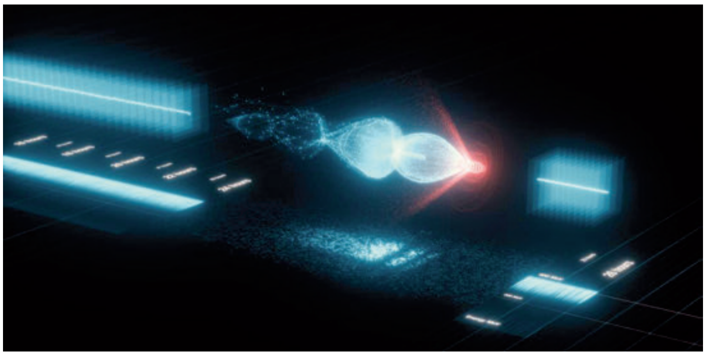
On 12 June, a new, ultrahigh-speed data connection was opened between European XFEL, DESY and National Center for Nuclear Research (NCBJ) in Otwock-Swierk near Warsaw, Poland. It will be used to analyse data from experiments carried out at the European XFEL.

The new connection will enable data to travel at a speed of up to 100 Gbit/s – that’s about 400 times faster than a standard household high-speed internet connection, which can typically manage download speeds of about 250 Mbit/s. On a normal connection, it would take about a month to transfer the huge amount of data generated by an average experiment at the facility. The new connection will reduce this to just a few hours.

August

World record: Plasma accelerator operates around the clock

A team of researchers at DESY has reached an important milestone on the road to the particle accelerators of the future. For the first time, a laser plasma accelerator has run for more than a day while continuously producing electron beams: The LUX beamline, jointly developed and operated by DESY and Universität Hamburg, achieved a run time of 30 hours – a big step closer to stable operation of this innovative particle accelerator technology.



In laser plasma acceleration at the LUX beamline at DESY, a strong laser pulse (red) generates a plasma wave (blue) in hydrogen gas by stripping electrons from gas molecules. The electrons (red) ride the wave like a surfer in the wake of a boat. This pushes them to high energies extremely quickly.

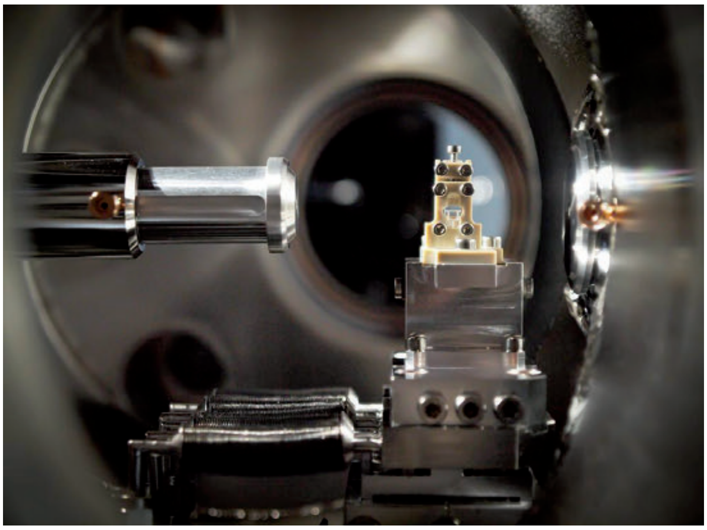
Plasma wakefield acceleration promises to lead to a new generation of powerful and compact particle accelerators that offer unique properties for a wide range of applications, from fundamental research to medicine. In this technique, a laser or energetic particle beam creates a plasma wave inside a fine capillary filled with gas – in the case of LUX, a laser is fired at hydrogen gas. The laser pulses plough their way through the gas in the form of narrow discs, stripping the electrons from the hydrogen molecules and sweeping them aside like a snow plough. Electrons in the wake of the pulse are accelerated by the positively charged plasma wave in front of them, much like a wakeboarder rides the wave behind the stern of a boat.

This phenomenon allows plasma accelerators to achieve accelerating gradients that are up to a thousand times greater than what could be provided by today’s most powerful facilities. However, a number of technical challenges still need to be overcome before these devices can be put to practical use. Now that the LUX team is able to operate their beamline for extended periods of time, they will be in a better position to tackle these challenges.

During the record non-stop operation, the physicists accelerated more than 100 000 electron bunches, one every second. Thanks to this large data set, the properties of the accelerator, laser and bunches can be correlated and analysed much more precisely than before. Unwanted variations in the electron beam can be traced back to specific points in the laser, for example, so that the scientists now know exactly where they need to start in order to produce an optimised particle beam. This approach lays the foundations for active stabilisation of the beams, as is deployed on every high-performance accelerator in the world.

The key to success was combining know-how from two different fields of expertise at DESY: plasma acceleration and stable accelerator operation. Numerous factors contributed to the accelerator's steady long-term operation, from vacuum technology and laser expertise to a comprehensive and sophisticated control system. In principle, the facility could have kept running for even longer, but the team stopped it after 30 hours.

"This work demonstrates that laser plasma accelerators can generate a reproducible and controllable output. This provides a concrete basis for developing this technology further in order to build future accelerator-based light sources at DESY and elsewhere," summarised Wim Leemans, Director of DESY's Accelerator Division. "The time is ripe to move laser plasma acceleration from the laboratory to practical applications."



The LUX plasma cell (in the centre of the white mounting), where the electrons are accelerated, is just a few millimetres long.

State Secretary Lukas visits DESY

Wolf-Dieter Lukas, State Secretary at the German Federal Ministry of Education and Research (BMBF), paid a one-day visit to DESY to learn about the centre's research and future planning. He was impressed by the interdisciplinary research programme and the state-of-the-art research facilities. In particular, he emphasised the dynamic development of an ecosystem in which basic research, a lively innovation process and efficient technology transfer are expertly intertwined: "DESY offers a unique concept for the future with this state-of-the-art research campus, where international and interdisciplinary expertise come together. This is where cutting-edge research meets the spirit of innovation with the aim of making basic research useful for society as a whole."

Exchanged views on DESY's future planning (from left): Volkmar Dietz, Sabine Carl (BMBF), Robert Feidenhans'l (European XFEL), Arik Willner (DESY), Wolf-Dieter Lukas, Barbara Ohnesorge (BMBF), Helmut Dosch and Christian Schroer (DESY).

DESY presents PETRA IV project to the neighbourhood

On 2 September, DESY presented its planned large-scale PETRA IV project to the citizens in the neighbourhood. The unique 3D X-ray microscope was the main topic of the first Forum Bahrenfeld, which was broadcast live from the Hamburg-Bahrenfeld trotting track on the internet. The new forum serves as a platform for extensive citizen participation in the planning for the Science City Hamburg Bahrenfeld.

The upgraded X-ray source PETRA IV will be the world's best 3D X-ray microscope: It will provide hundreds of times more detailed images of microscopic processes in new materials and future medical active ingredients than its predecessor, DESY's existing high-brilliance X-ray source PETRA III. With PETRA IV, DESY is creating another basic research tool for innovative scientific progress in the fields of health, environment and energy research. To realise the sustainably designed facility, an accelerator using the latest technology will be built into the existing PETRA ring tunnel. A new, largely underground experimental hall is also planned.

September

His Majesty the King's Gold Medal for Carl Lindstrøm

DESY scientist Carl Andreas Lindstrøm was awarded the Gold Medal of His Majesty the Norwegian King Harald V for outstanding young researchers from the University of Oslo. The Norwegian scientist, who works at DESY on future linear accelerators, was honoured for his doctoral thesis on new particle accelerator concepts. Among other things, he improved an innovative plasma lens for focusing particle beams and investigated the acceleration of positrons in a hollow plasma channel.

In active plasma lenses, a strong electric current passes through a plasma, creating a magnetic field vortex that can simultaneously focus the height and the width of a particle beam, making such lenses extremely attractive for use in particle accelerators. However, a key problem had so far prevented the deployment of plasma lenses: An optical flaw in the lens destroys the focus of the particle beam as it passes through the plasma cell. The team in which Lindstrøm was involved managed to eliminate this aberration by using argon gas instead of helium to create the active plasma lens.

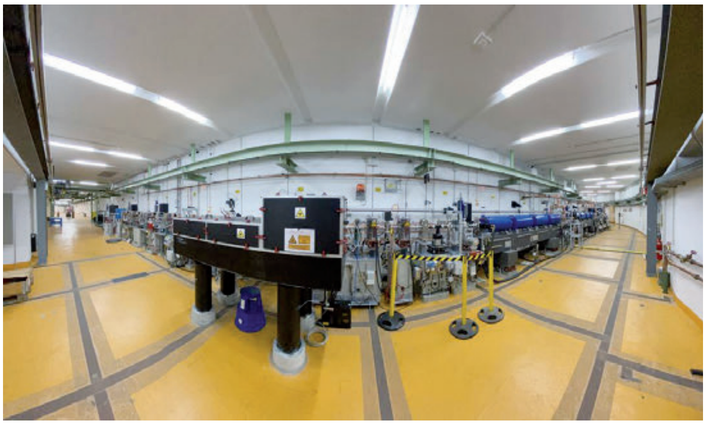
For electrons, plasma wakefield acceleration achieves the properties needed to build the next generation of accelerators: Electrons can be accelerated as a tightly focused particle bunch in the plasma wake, they are accelerated quickly and beam quality is maintained. Positron bunches, in contrast, tend to lose their compact shape and their focus in the plasma environment. At SLAC in the USA, Lindstrøm and his colleagues therefore investigated the options of accelerating positrons in a hollow plasma channel, in which the positrons stayed tightly focused as they flew through.

Carl Andreas Lindstrøm at the award ceremony in Oslo

October

ARES accelerator reaches design energy

One of the latest accelerators at DESY demonstrated its functionality at the end of October, as the ARES team was able to operate the facility for the first time at its design energy of 155 MeV. The linear accelerator ARES (Accelerator Research Experiment at SINBAD) is an essential component of the new, long-term accelerator R&D facility SINBAD (Short Innovative Bunches and Accelerators at DESY), located on the DESY campus in Hamburg within the ring of the former DORIS accelerator. Among other studies, SINBAD will enable accelerator research with ultrashort electron pulses, the development of new acceleration methods and beam manipulation using dielectric structures.



Actually, it's straight: Panoramic view of the ARES linear accelerator in the former DORIS tunnel ("fisheye" representation)

ARES, a conventional S-band electron linear accelerator, will produce and accelerate ultrashort electron bunches to up to 155 MeV. Their arrival time at the end of the accelerator will remain almost constant, varying by less than 10 fs for the individual particle bunches. While the design is optimised for low-charge (picocoulomb), ultrashort (sub-/single femtosecond) bunches, bunch charges of several tens of picocoulombs can also be accelerated at the cost of longer bunch lengths. The achievement of the design energy, at a bunch charge of 1.5 pC, marks the transition of the facility from hardware commissioning to beam characterisation, optimisation and preparation for the first experiments.

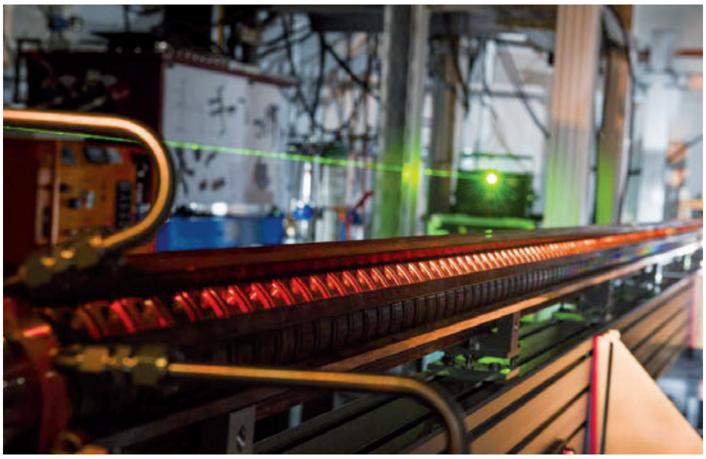
November

Accelerate smarter with artificial intelligence

Particle accelerators are universal tools: They help in production processes in industry, serve for tumour therapy in hospitals and enable unique discoveries and insights in research. However, growing demands on the stability and properties of particle beams make manual operation of these complex facilities increasingly challenging – and call for the highest possible level of automation to support the operators.

A new project of DESY and Karlsruhe Institute of Technology (KIT) is taking first steps towards a fully autonomously operated accelerator. The Autonomous Accelerator collaboration, which is supported by the Helmholtz Association, DESY and KIT within the Helmholtz Artificial Intelligence Cooperation Unit, brings “reinforcement learning” to the operation of two linear accelerators at the two research centres. Reinforcement learning involves measuring state values and adjusting control variables to determine their influence on each other. In this way, a control strategy is learned that also takes into account its effects in the future. In the long term, this will completely replace manual intervention.

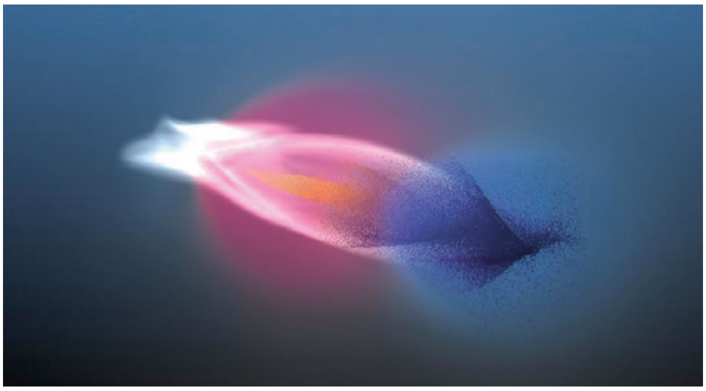
For their experiments, the researchers use the test accelerators ARES at DESY and FLUTE (Far-Infrared Linac and Test Experiment) at KIT. Both facilities are available for accelerator research within the Helmholtz research programme “Matter and Technologies” and offer sufficient test times for developing such algorithms. By using two such similar, compact, but not identical accelerators for the development of their artificial intelligence, the scientists are gaining valuable experience on the transferability of their algorithms to other, larger accelerators. This is important to be able to later implement such algorithms also at complex user facilities such as FLASH and the European XFEL.



The FLUTE accelerator at KIT

Measuring the wave

Plasma wakefield acceleration promises to deliver a new generation of powerful and compact particle accelerators. Prior to applying this new technology, however, various obstacles must be overcome. In particular, precise control of the acceleration process itself must be achieved. Using an innovative technique, researchers at DESY succeeded in measuring the accelerating plasma wave with previously unattained precision. The method allows the shape of the effective accelerating field to be determined with a resolution on the order of femtoseconds so the acceleration process can be studied in detail, paving the way for the controlled and optimised operation of future plasma accelerators.

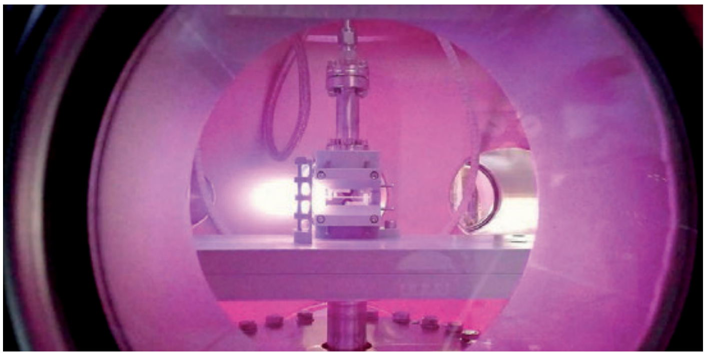


An electron bunch with varying energy (dark blue to orange) drives a plasma wave (white) with strong electric fields (red and blue). Removing thin slices from the tail of the electron bunch in a controlled manner allows the precise measurement of the electric fields.

At DESY’s FLASHForward beam-based plasma acceleration facility, bunches of electrons are fired into a plasma at close to the speed of light, creating a wake of plasma electrons that can be used to accelerate other electron bunches trailing behind them. The acceleration produced by the plasma wake can be up to a thousand times greater than that of today’s strongest conventional facilities. To achieve optimal acceleration, however, the electron bunches and the wake need to be precisely tuned to each other. To this end, the shape of the wake needs to be measured precisely, which is very challenging due to its small dimensions of just a few micrometres.

The FLASHForward team developed a method in which the accelerated electrons themselves are used to reveal the shape of the plasma wake’s accelerating field. To achieve this, the electron bunch is first rotated perpendicularly to the direction of flight by a magnetic chicane. Thin slices can then be removed from the bunch tail by transversely inserting a piece of metal. Finally, the electron bunch is rotated back again. As a result, the energy spectrum of the outgoing electron bunch is altered due to the missing electrons, allowing the strength of the accelerating field at the location where part of the bunch was removed to be deduced. If the bunch is sliced thinly enough, the profile of the effective accelerating field in the plasma wake can be determined with a temporal resolution of femtoseconds. In the experiment, the scientists were able to achieve a resolution of 15 fs – corresponding to a spatial resolution of around 5 μm in the wake. The researchers believe that even higher resolutions are possible.

Using the novel technique, the interaction between the individual experimental components and the acceleration process can now be studied in detail. Other experimental plasma acceleration facilities also stand to benefit from the new technology, which is an important step on the path to a detailed understanding and optimisation of the plasma wake. The experiment thus paves the way for a new era of control and stability that plasma accelerators are entering.

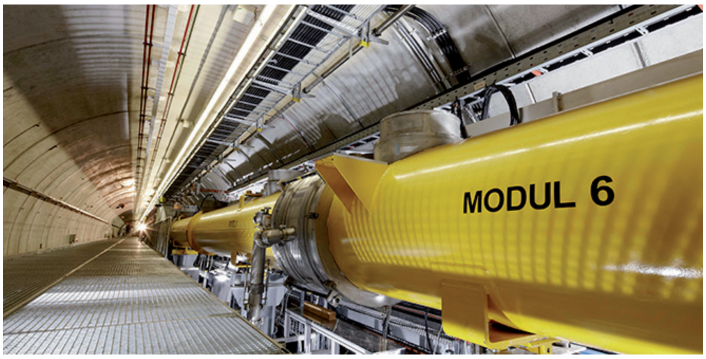


View of the FLASHForward accelerator module. The plasma is generated in the narrow channel in the centre by a high voltage.

December

Kick-off meeting for FLASH2020+ project

The FLASH2020+ upgrade programme of DESY’s FLASH free-electron laser (FEL) facility was launched on 9 December with a virtual kick-off meeting at which the international user community was introduced to the programme’s scientific scope. The FLASH2020+ upgrade involves ambitious developments for the entire FLASH facility, which are planned in several project phases.



The FLASH accelerator tunnel

At the meeting, over 170 participants learned about the new physics and experiments that will be made possible by the improved properties of the upgraded facility and about the scope, structure and timeline of the project. Until 2025, the two FEL lines, FLASH1 and FLASH2, will be equipped with variable-gap undulators and variable polarisation. FLASH1 will be upgraded to offer a unique high-repetition-rate external-seeding setup. The exchange of accelerator modules will extend the tuning range of operation for both FEL lines, and a new, flexible electron beam compression scheme including a laser heater system will improve the FEL properties and reliability.

Plans also include new photon experiments and upgrades to accommodate specially designed monochromators within the existing experimental halls. In addition, the experimental stations will benefit from a new pump–probe laser system, which will provide high-energy, high-repetition-rate synchronised pulses across the whole optical spectrum and beyond.

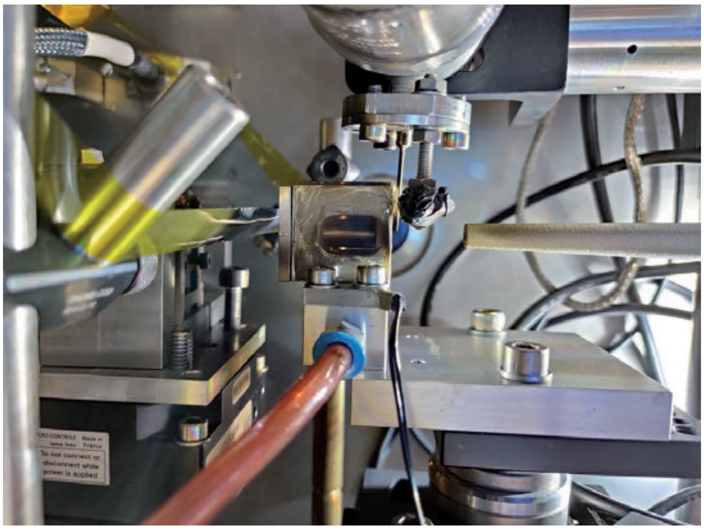
Artificial intelligence improves control of plasma accelerators

An international team of accelerator experts including from DESY successfully demonstrated that an algorithm was able to tune the complex parameters involved in controlling the next generation of plasma accelerators. The algorithm optimised the accelerator much more quickly than a human operator could. The experiments, led by Imperial College London, were conducted at the Central Laser Facility at the STFC Rutherford Appleton Laboratory, UK.

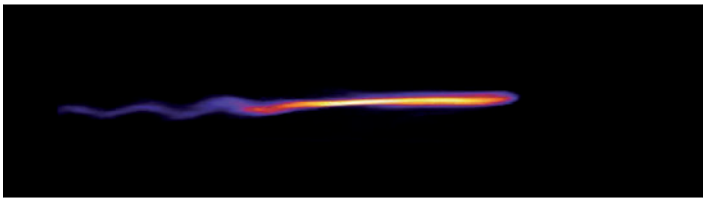
For plasma wakefield accelerators to become prevalent in scientific, industrial or medical applications, they need to move from research projects towards more plug-and-play devices. In particular, precise and reliable control of the acceleration process is mandatory, which is challenging for facilities that operate under such extreme conditions. Artificial intelligence or machine learning is one of the most promising approaches to achieve the required level of control.

The scientists worked with laser plasma accelerators, which combine powerful lasers with a source of plasma to create concentrated beams of electrons and X-rays. Both the laser and plasma have several parameters that can be tweaked to control the interaction, such as the shape and intensity of the laser pulse or the density and length of the plasma. While a human operator can tweak these parameters, it is difficult to know how to optimise so many parameters at once. Instead, the team turned to artificial intelligence, creating a machine learning algorithm to optimise the performance of the accelerator.

The algorithm set up to six parameters controlling the laser and plasma, fired the laser, analysed the data and reset the parameters, performing this loop many times in succession until the optimal parameter configuration was reached. The data gathered during the optimisation process also provided new insights into the dynamics of the laser–plasma interaction inside the accelerator, potentially informing future designs to further improve accelerator performance.



The electrons are accelerated in a plasma cell (centre). A laser beam coming from the right ignites the plasma in the cell.



View of a fluorescence screen with which the energy distribution of the accelerated electrons can be measured

The work resulted in an autonomous plasma accelerator, the first of its kind. As well as allowing the team to efficiently optimise the accelerator, it also simplified its operation and enabled the researchers to spend more of their efforts on exploring the fundamental physics behind these extreme facilities. The computer was able to reliably optimise the plasma accelerator from scratch within minutes, which is difficult to achieve by “human learning” even for experienced operators.

Similar experiments being conducted at the LUX accelerator, a joint project of DESY and Universität Hamburg, support the hypothesis that the application of artificial intelligence to control accelerators is currently being taken to a new level. With artificial intelligence and machine learning deployed on the current and next generation of accelerators at DESY and elsewhere, these facilities are expected to reach unprecedented performance levels.

Accelerator operation and construction

PETRA III

User operation with high availability and good resilience

The year 2020 was a challenging, but also very successful year for DESY's synchrotron radiation source PETRA III. In February 2020, beam operation resumed after a shutdown period that had started on 20 December 2019. During the shutdown, a new undulator was installed for Beamline P62 in the Paul P. Ewald experimental hall. Regular user operation began on 2 March after a short commissioning period of about two weeks. In 2020, 4944 h of beam time had initially been planned for the user run, but due to the COVID-19 pandemic, the plan was revised in favour of a stand-by mode of PETRA III from 20 to 30 March. After the stand-by period, user operation quickly restarted, first for COVID-19-related research and, from May on, in a safe normal operation mode taking into account additional measures related to the pandemic. Eventually, 4797 h of beam time were scheduled for the user run, which were delivered with a record availability of 98.8%.

User operation

During the winter shutdown 2019/20, which ended in February 2020, a new undulator was installed for Beamline P62 in the Paul P. Ewald hall (Fig. 1). Thanks to essential efforts of all the technical groups, all shutdown activities could be finished on schedule. Regular user operation started on 2 March after about two weeks of commissioning. While 4944 h of beam time had originally been scheduled for the user run in 2020, the plan had to be modified in view of the COVID-19 pandemic. After a stand-by period of PETRA III from 20 to 30 March, user operation resumed first for COVID-19-related research. Starting in May, the facility was then operated in a safe normal mode that incorporated additional measures to minimise the risk of infection. The use of video conferencing tools between the main control room and office locations on and off site, for example, enabled an effective and safe support by the shift crew. This and other precautions helped to avoid any further stand-by mode for PETRA III in autumn 2020. In this way, good resilience of PETRA III user operation was achieved under the challenging pandemic conditions.

Finally, 4797 h of beam time were scheduled for the user run, which were delivered with a record availability of 98.8%. In total, including test run time, 5726 h of synchrotron radiation

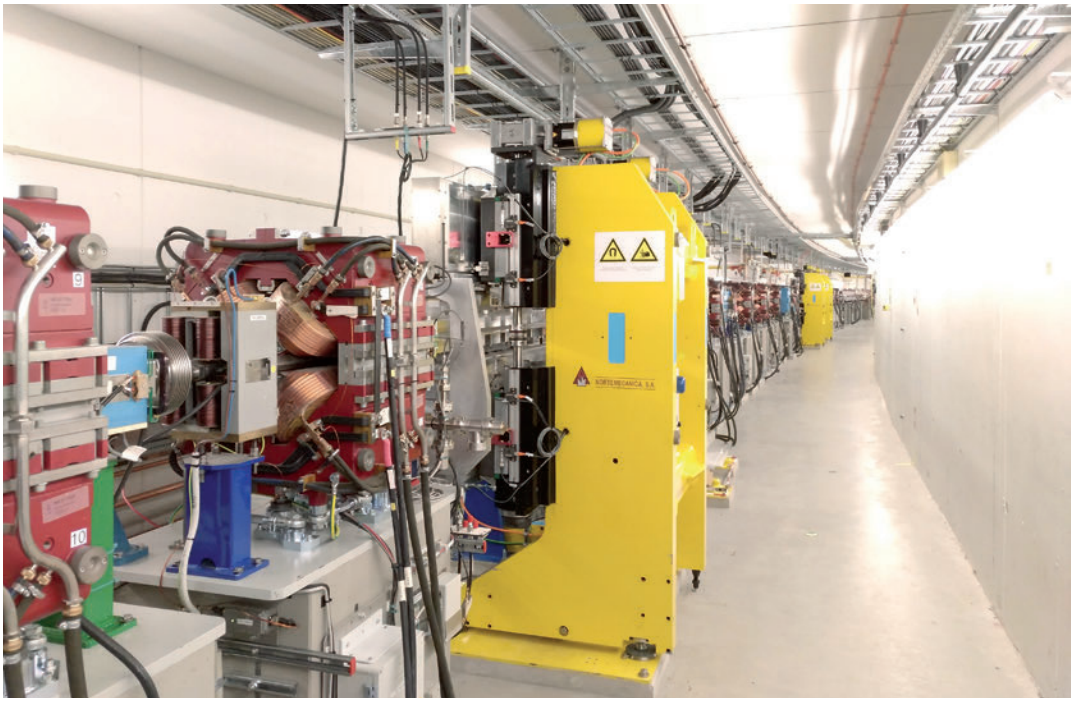


Figure 1

In 2020, a new undulator was installed for Beamline P62 in the Paul P. Ewald experimental hall.

beam time were provided to the users at the beamlines. The necessary maintenance was done in four dedicated service periods distributed over the year and additionally during the three-week long summer shutdown. On Wednesdays, user operation was interrupted by weekly regular maintenance or machine development activities as well as test runs for about 24 h. The distribution of the different machine states in 2020 is shown in Fig. 2.

During user runs, the storage ring was operated in two distinct modes characterised by their bunch spacing. In the "continuous mode", 120 mA were filled in 480 evenly distributed bunches, corresponding to a bunch spacing of 16 ns. The "timing mode" allows users to perform time-resolved experiments and is thus characterised by a considerably larger bunch spacing of 192 ns, corresponding to 40 evenly distributed bunches with a total current of 100 mA. In 2020, 53% of the user beam time was allocated to the 480-bunch mode and 47% to the 40-bunch mode.

Record availability in 2020

High reliability is one of the key requirements for a synchrotron radiation facility. The main performance indicators are availability and mean time between failures (MTBF). In 2020, the weekly availability reached 100% for several weeks of the year. At the end of the user run, the average availability was 98.8%, which is a new record for PETRA III. This availability statics is based on a metrics that is in agreement with internationally used metrics and does not include "warm-up" time after each fault. The long-time development of the availability of PETRA III during the user run is shown in Fig. 3. The average MTBF at the end of 2020 was 75 h, which is a further improvement with respect to the previous years. In 2020, the overall performance of PETRA III thus again reached a level that meets the high international standards for highly available synchrotron light sources.

The number of faults normalised to 1000 h of user operation decreased during the last six years (Fig. 4), indicating that the process to improve the technical reliability of PETRA III made significant progress, assisted by an internal review process to monitor the availability of the facility and guarantee a good root cause analysis of all faults during the user run. Activities to harmonise the quality standards in the technical groups with respect to quality control and process documentation continued in 2020.

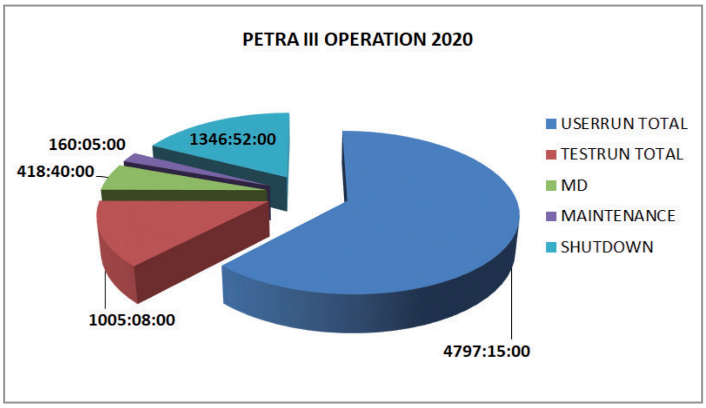


Figure 2

Distribution of the different machine states scheduled during the run period from 2 March to 21 December 2020

Figure 3

Long-time development of the availability of PETRA III during user runs

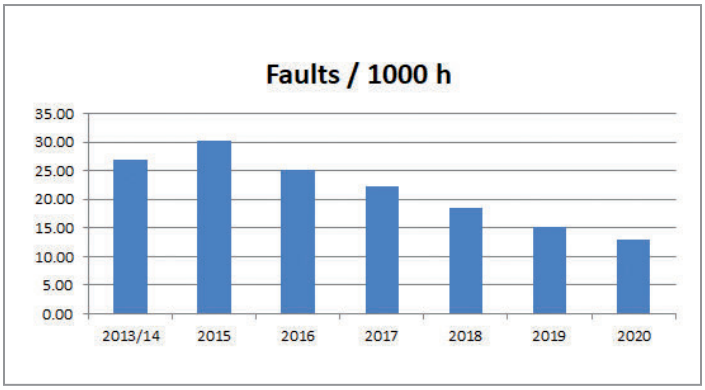


Figure 4

Long-time development of the number of faults per 1000 h of user operation

Plans for the next operation period

During the winter shutdown 2020/21, it is planned to start the installation of front-end components for the dipole beamline P66 in the north-east of the PETRA III ring. One of the quadrupole magnets will have to be replaced with a different type to enable the installation of a new vacuum chamber with an outlet for the synchrotron radiation from a dipole.

Furthermore, maintenance work on the technical subsystems of PETRA III is scheduled in order to maintain the availability of the facility at the high level achieved in the last two years. All these plans can only be realised with a major effort from all the technical groups involved.

Contact: Rainer Wanzenberg, rainer.wanzenberg@desy.de
Michael Bieler, michael.bieler@desy.de

FLASH

Bridging the corona shutdown while maintaining high availability for user experiments

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. In 2020, the FLASH linear accelerator delivered beam for a total of 5101 h for user experiments, FEL studies, preparation of user experiments and accelerator R&D. In spring 2020, the facility had to be shut down because of the COVID-19 crisis, and two user blocks of nine weeks in total had to be cancelled. The FLASH team used this time to continue to explore new favourable ways to run the cryogenic system. User operation resumed in August with a rearranged schedule. Not all users were able to either be on site or conduct their experiments remotely, however. Nonetheless, despite the problems caused by lockdowns, the availability of FLASH has never been higher: 98.8% for FLASH1 and 98.4% for FLASH2.

Operation

The two undulator beamlines FLASH1 and FLASH2 deliver self-amplified spontaneous emission (SASE) radiation in parallel to the experimental halls "Albert Einstein" and "Kai Siegbahn", with beam parameters that can be freely chosen to a certain extend for each beamline. The third electron beamline FLASH3 was set up for the beam- and laser-driven plasma wakefield acceleration experiment FLASHForward.

In 2020, beam time for users at FLASH was again allocated in two user periods, numbered 15 and 16, with three user blocks each and a total allocated beam time of about 4600 h (FLASH linac). Due to the COVID-19 lockdown, however, two user blocks had to be cancelled. About 60 to 70 proposals for user experiments are regularly submitted each year, of which 30 to 40 are approved. Of the 36 experiments scheduled for 2020, 17 unfortunately had to be postponed to 2021. FLASH resumed user operation in August with a rearranged schedule. Due to travel restrictions, however, not all users were able to be on site to perform their experiments. Among those who conducted their experiments remotely with local support were mostly users from German institutions, plus a few Swedish users and an experiment led by French users.

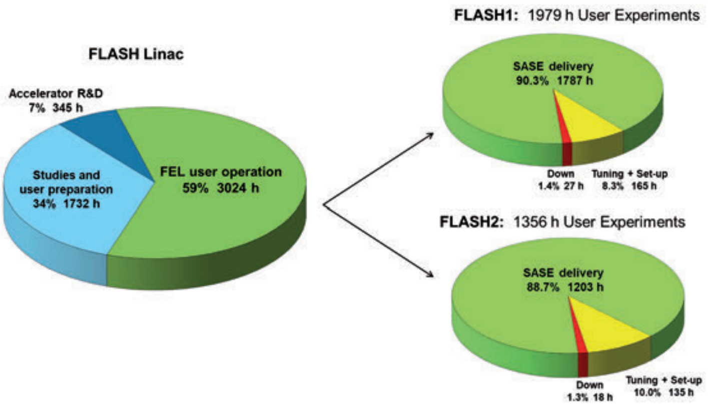


Figure 1

FLASH operation statistics in 2020

Notwithstanding all the corona restrictions, the user feedback from the second half of 2020 was very positive. FLASH ran very reliably, and owing to the new weekly schedule – according to which each experiment was conducted for five or six days in a row – the experiments were able to take data continuously with very little interruptions. Hence, all ended up with good data statistics and very satisfied users and local teams.

Despite the COVID-19 lockdown, the FLASH linear accelerator delivered beam for 5101 h. Of these, 3024 h were devoted to user experiments, partially in parallel operation of FLASH1 and FLASH2. In addition, FLASH provided 1732 h of beam time for FEL-related studies and preparation of user experiments and another 345 h for general accelerator R&D, mostly for FLASHForward (Fig. 1).

The beam time for users includes the time required for setup and tuning of the experiments. Every experiment has its own wish list of photon properties and its own demands regarding high-quality and stable beams. The FLASH team has worked hard to streamline all the related procedures. As a result, the setup and tuning time could be pushed down to a record low of 8 to 10% of the user beam time. The availability of the facility reached a new record high of 98.6% overall, and the downtime for users dropped to a low 1.4% for FLASH1 and 1.3% for FLASH2. Figure 2 shows the development of the availability from 2014 to 2020. For comparison, 21% of the user beam time was required for tuning in 2014.

Cryogenic system low-pressure experiment

The FLASH superconducting acceleration structures are cooled by liquid helium at a temperature of 2 K at a pressure of 30 mbar. During warm-up and cool-down and also during normal operation, the pressure could increase to several bar overpressure, secured by safety valves. The FLASH team used the lockdown time to continue to explore possibilities to run the cryogenic system at lower pressure, a more favourable operation mode. This experiment was possible because it could mostly be performed remotely with only a few persons on site. The experiment successfully showed that full operation not exceeding an overpressure of 0.5 bar is possible – during stable operation, warm-up and cool-down.

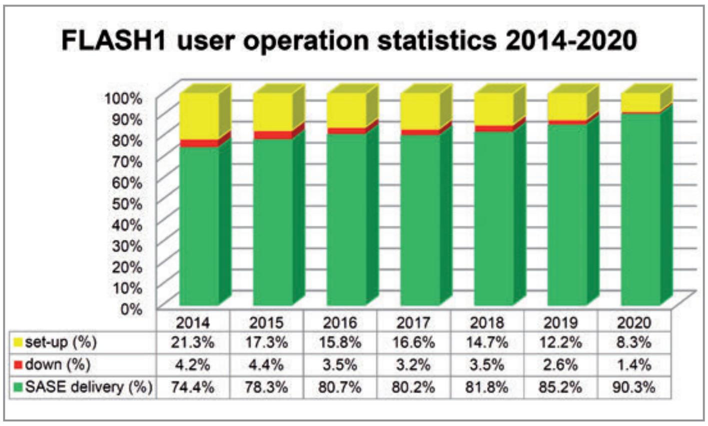
RF gun, photocathode and injector lasers

After 6.5 years of operation at FLASH, the radio frequency (RF) electron source numbered Gun 3.1 was replaced by Gun 4.4 in the winter shutdown 2019/20 due to an unrepairable water leak. The new gun is in steady and stable operation at nominal settings: a field of 50 MV/m on the cathode and a pulse length of 650 μs at a repetition rate of 10 Hz. The caesium telluride (Cs_2Te) cathode (#105.2) has a stable quantum efficiency of 12% after two years of operation.

All three photoinjector lasers are stable and very reliable in operation. During the last 10 years of continued operation, the Lasers 1 and 2 built in cooperation with MBI in Berlin have had a very low downtime of 1 h on average per year. However, because of the unavoidable wear-out of components that are increasingly difficult to replace, a new laser system is being developed in-house. An optical cross correlator similar to the one in operation at Laser 2 has been installed at Laser 1 as well. Since Laser 1 is used more and more for pump–probe experiments, a drift stabilisation of its arrival time with respect to the gun RF below the 50 fs level (RMS) is required, which is now routinely achieved.

PolariX installed in FLASH2

For a couple of years, an S-band transverse deflecting structure called LOLA has been operated in the FLASH1 beamline. It allows the longitudinal phase space of the electron bunches to be measured, albeit with only one streaking direction (vertical).



	2014	2015	2016	2017	2018	2019	2020
🟨 set-up (%)	21.3%	17.3%	15.8%	16.6%	14.7%	12.2%	8.3%
🟥 down (%)	4.2%	4.4%	3.5%	3.2%	3.5%	2.6%	1.4%
🟩 SASE delivery (%)	74.4%	78.3%	80.7%	80.2%	81.8%	85.2%	90.3%

Figure 2

The setup and tuning time required for user experiments at FLASH1 was significantly reduced from 2014 to 2020. In addition, in 2020, the downtime of FLASH1 was at a record low of 1.4%.

The PolariX TDS (Polarizable X-band Transverse Deflection Structure) is an innovative design working in the X-band frequency range. Developed in a collaboration between CERN, PSI and DESY, the new design gives full control of the streaking direction. This allows tomographic-like full characterisation of the longitudinal phase space of the electron bunches by varying the transverse streaking angle. A prototype was installed in the FLASHForward beamline in 2019. In the winter shutdown 2020/21, two additional structures were installed in the FLASH2 beamline (Fig. 3).

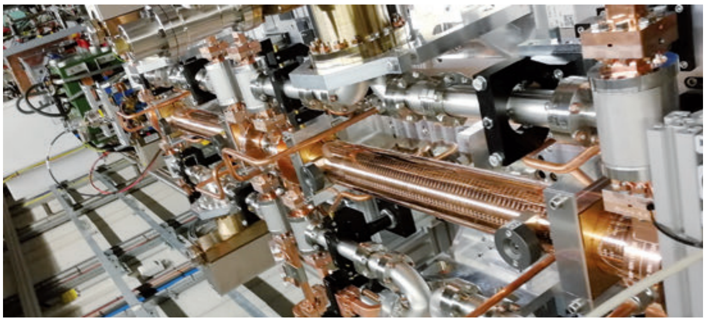


Figure 3

Two new copper PolariX transverse deflecting structures installed in the FLASH2 beamline

At FLASHForward, very promising results have been achieved with the prototype TDS, showing an impressive reconstruction of the longitudinal phase space with femtosecond-scale resolution. The new PolariX structures at FLASH2 will further improve the longitudinal beam properties, with the new possibility to tailor the phase space using the bunch compressor installed at FLASH2 in summer 2019. Moreover, since the PolariX structures are located downstream of the undulators, it will also be possible to measure the longitudinal SASE radiation properties. For example, the SASE process increases the energy spread of the electron beam at the location where the photons pulses are formed.

Xseed

A new chicane has been installed in the former sFLASH section. In preparation for the FLASH2020+ external-seeding project, the new chicane will allow experiments on the generation of seeded FEL radiation using the echo-enabled harmonic generation (EEHG) process. The advantage compared to the previously demonstrated high-gain harmonic generation (HGHG) scheme is the reach towards shorter wavelengths down to 4 nm.

The FLASH team is very grateful to the DESY support staff for making an exceptional machine performance possible.

Contact: Siegfried Schreiber, siegfried.schreiber@desy.de

PITZ

Accelerator R&D and applications

In 2020, research on the development and applications of high-brightness electron sources continued at the PITZ photoinjector test facility at DESY in Zeuthen. Besides fundamental studies on photoinjector optimisation in general, a wide variety of R&D activities was undertaken, and the facility extension towards a proof-of-principle THz self-amplified spontaneous emission (SASE) free-electron laser (FEL) made great progress.

Development of electron sources

Gun development

The L-band long-pulse radio frequency electron source (RF gun) used at DESY's FLASH facility and at the European XFEL X-ray laser was further optimised to increase the RF pulse length from 650 μs to 1 ms in order to deliver more electron bunches per second. An RF field antenna for direct gun field measurement was included in the cavity for the first time for better regulation of the RF field stability. The fabrication of the first prototype, Gun 5.1, was significantly slowed down, however, by the lockdown due to the COVID-19 pandemic and by several unexpected technical problems. The final brazing of all the gun parts was done in mid-December 2020 (Fig. 1). The gun will be tuned in January 2021 and subsequently set up for installation, conditioning and first operational tests at PITZ.

At DESY, injector R&D is ongoing for a future continuous-wave (CW) upgrade of the European XFEL. The main DESY option for a CW gun is a superconducting L-band gun. At PITZ, a 217 MHz single-cell normal-conducting RF gun is being conceptually designed as a backup option. The very-high-frequency (VHF) gun physics design reached a stable solution, featuring a cathode field of 28 MV/m and a gun voltage of 830 kV with an RF power of 100 kW. The gun design was verified with start-to-end simulations, showing compelling beam qualities before the undulator. In August 2020, the conceptual engineering design was started in collaboration with colleagues from LBNL in the USA, who built the first CW VHF gun for the CW X-ray FEL project at SLAC.

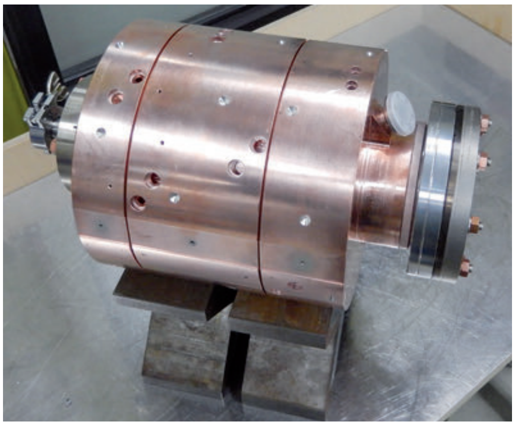


Figure 1

Gun 5.1 after the latest brazing step

Cathode development

Besides the RF gun and photocathode laser pulse shaping, photocathodes have become the main bottleneck for increasing electron source brightness. Therefore, photocathode development and characterisation in high accelerating fields are very important. The PITZ group is collaborating with INFN LASA in Milan, Italy, on developing photocathodes with high quantum efficiency (QE) (>5%) in the green wavelength range (515 nm). A recipe has been established for caesium potassium antimonide (K_2CsSb) cathodes in an R&D chamber, and a production chamber is being assembled in Milan. Testing these "green" cathodes in the high-field PITZ gun was planned for 2020, but the production was significantly delayed by the COVID-19 lockdown in Italy.

Comprehensive cathode characterisation techniques have been established at PITZ, e.g. for measuring QE, thermal emittance, dark current and their spatial and field dependences. These include a photocathode response time measurement technique that uses two short laser pulses with known temporal separation, which was set up at PITZ in 2020. Response times of different caesium telluride (Cs_2Te) cathodes and a gold reference metal cathode were measured with an unprecedented time resolution of tens of femtoseconds (Fig. 2). The results show for the first time the exponential electron emission curve of the semiconductor cathode and its time constant of around 200 fs. This is an important step towards better modelling of both the photocathode physics and the changes in the beam dynamics along the accelerator caused by high-frequency temporal modulations of the laser.

Laser systems

The beam emittance can be optimised by dedicated shaping of the photocathode laser pulses. The laser system for generating 3D ellipsoidal pulses was continuously improved throughout 2020, with the realisation of synchronisation, diagnostics in the infrared (IR) and ultraviolet (UV) range, high conversion efficiency from IR to UV with flexible beam parameters, stable

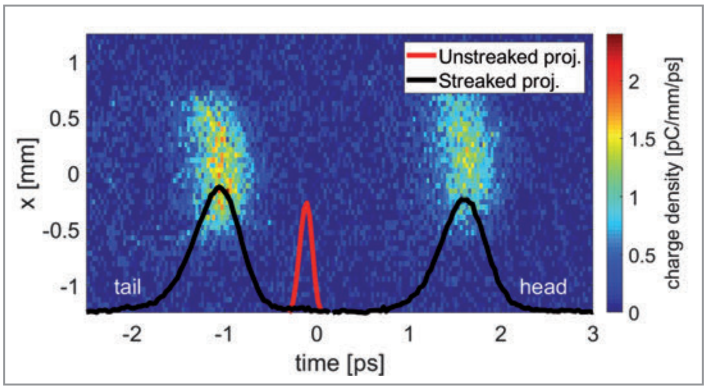


Figure 2

Example of the measured time projection of an electron bunch pair emitted from a Cs_2Te cathode. The red line shows the double bunch without RF streaking, the black line indicates the time-resolved bunches with the characteristic exponential tails.

beam transport to the photocathode and laser controls. The development of 3D laser shaping is still ongoing, but first flexible transverse shaping of electron bunches was successfully demonstrated (Fig. 3). The laser system is now routinely used as a photocathode laser at PITZ complementary to the MBI laser system, thereby greatly increasing the pulse shaping capabilities at PITZ.

Applications of high-brightness electron beams

THz generation studies

The PITZ group is constructing a prototype of an accelerator-based THz source for pump–probe experiments at the European XFEL. For proof-of-principle experiments, an LCLS-I undulator, on loan from SLAC, was delivered and will be installed in the extension of the PITZ tunnel in early 2021. The infrastructure preparations in the future accelerator tunnel were finished in 2020. The interlock system was successfully tested by the TÜV technical inspection association, and the extension of the operation permission is in preparation. The diagnostics components for the extended beamline have been designed to a large extend and are currently being machined. A bunch compressor, to be installed in the current accelerator tunnel, is also being built. It will allow high peak current values to be reached even for lower bunch charges, thus extending the range of possible applications of the PITZ beams. All hardware installations will be carried out during 2021.

Start-to-end simulations of the THz SASE FEL were done based on the measured undulator field and using electron beams with high peak current and bunch charge (e.g. 200 A and 4 nC) from the PITZ accelerator, resulting in a THz radiation energy of ~1 mJ at a centre wavelength of 100 µm. Preparatory experimental electron beam characterisation at high bunch charges and THz generation studies were performed in 2020 and still continue – demonstrating the feasibility of high-charge beam transport and matching towards the undulator.

Simulations and experimental studies of THz FEL seeding by means of intensity modulations of the photocathode laser pulses also continued. Non-linear space charge oscillations of high-charge electron beams are considered for the generation of bunching factors required to stabilise the THz FEL (seeding).

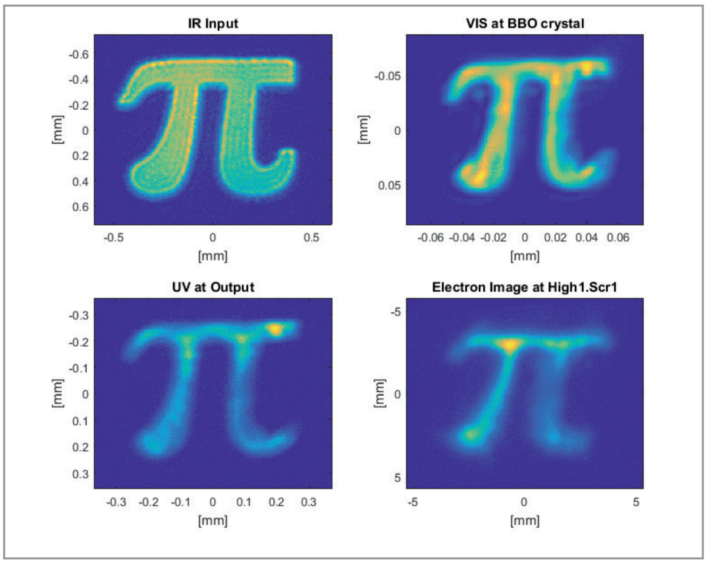


Figure 3

Examples of dedicated shaping of laser pulses: in the IR, after the two-stage conversion via visible (VIS) to UV, and as imaged with the electron beam.

Plasma experiments

To further characterise the self-modulation instability of the electron bunches, plasma experiments with a lithium heat pipe oven were performed. For the first time, a unique setup with a side-coupled ionisation laser was used to conduct a series of measurements over a range of plasma channel lengths in order to characterise the growth of wakefields. In addition, plasma density steps can be introduced with this setup by tailoring the laser intensity. Data were taken, and the evaluation is ongoing.

R&D on radiation biology and *eFLASH* radiotherapy

Recent developments in radiation biology have shown that a major increase of the therapeutic window for cancer treatment – the range in which beneficial effects prevail over detrimental ones – can be obtained by using the so-called FLASH effect radiotherapy, i.e. the application of high dose rates in a short treatment time (referred to as *eFLASH* here to avoid confusion with DESY's FLASH facility). Many aspects of the *eFLASH* effect are still to be understood, however, and treatment has to be optimised for different kinds of tumours.

PITZ can provide a broad range of beam parameters, extending from conventional radiotherapy through state-of-the-art *eFLASH* radiotherapy experiments to as yet unexplored ultra-high dose rates and ultrashort treatment times. Thanks to its ability to generate long bunch trains, PITZ offers unique R&D capabilities for conducting systematic studies on radiation biology and *eFLASH* radiotherapy. This activity has the potential to become a lighthouse far beyond Germany. A corresponding proposal is being prepared together with biologists at TH Wildau and other national and international partners.

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

REGAE

Restart with new momentum

REGAE is DESY's ultrafast electron diffraction (UED) facility. It provides MeV electron pulses with femtosecond duration that are ideally suited for time-resolved experiments. After a few organisational changes, a new science case for REGAE has been developed, with emphasis on quantum materials and structural biology. Several improvements to the facility, the integration of a new collimator and the installation of a Jungfrau 1 M pixelated detector for direct electron detection have significantly improved the achievable signal-to-noise ratio for UED experiments. Foreseen upgrades of the experimental chamber and the implementation of a novel 3 GHz bunch train mode for microelectron diffraction experiments will further extend the experimental capabilities of REGAE in 2021.

After termination of the plasma programme and substantial reorganisation of the managing structure, REGAE will once again concentrate fully on electron diffraction experiments.

Science case for REGAE

In close collaboration with potential on-campus and external user groups, a new scientific programme has been developed for the future operation of REGAE. Compared to diffraction experiments with X-rays, MeV electron diffraction offers a five orders of magnitude stronger elastic scattering interaction with matter, in combination with tremendously reduced radiation damage effects. This makes experiments with MeV electrons the ideal tool for time-resolved diffraction experiments on low-*Z* materials with sub-micrometre sample sizes.

In materials sciences, UED experiments at REGAE will allow the study of phase transformations and transition states in quantum materials after laser excitation of the sample. By matching the sample thickness to the penetration depth of the laser pump light, these experiments can be performed with much higher sensitivity than is currently possible with any other method. The stronger interaction of electrons with matter will further enable these studies to be extended to novel, promising low-*Z* materials, such as twisted bi-layered graphene and fullerenes ("bucky balls"), which currently cannot be studied with X-rays due to their poor scattering cross section.

In structural biology, electron microscopy and diffraction already allow 2D crystals and even single molecules to be investigated and structural details to be resolved at highest resolution. At REGAE, it will be possible to extend these investigations into the time domain with a time resolution down to the femtosecond range and to perform experiments at room temperature. This will enable irreversible transport reactions in 2D protein crystals to be followed and protein dynamics to be observed at a so far unrivalled level of detail. The ability to resolve the positions of hydrogen atoms will also allow a better understanding of enzyme reactions and of the binding of pharmaceutically relevant compounds, where hydrogen bonding and transfer reactions play an essential role for biological function.

Further potential science areas include structural studies of water in collaboration with DESY's new Centre for Molecular Water Science (CMWS) as well as gas diffraction experiments.

Linearisation of the longitudinal phase space

The correlated higher-order energy spread that a sine-like radio frequency (RF) field imposes on the longitudinal phase space of an electron bunch limits both the minimal bunch length that can be reached by compression of the bunch and the minimal energy spread itself. While shortest bunches are required to investigate shortest time scales, the energy spread also becomes important for certain modes of operation, as for example the minimal beam size that can be reached is limited by chromatic effects.

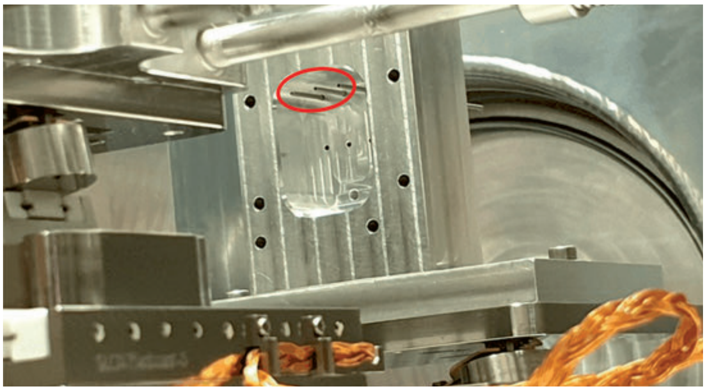


Figure 1

The new collimator tubes (encircled in red) are mounted on a positioning stage that allows precise control of their transverse position and angle.

The compensation of correlated longitudinal emittance contributions is thus of great interest. A new concept has therefore been developed that doesn't require additional hardware. It is based on a special tuning of the electron source (gun) and of the amplitudes and phases of the buncher cavity and involves, in the first stage, a controlled bunch lengthening in the section between the gun and the buncher cavity.

The results achieved in simulations are extremely promising. However, they are also beyond the resolution limits of the diagnostics available at REGAE. With the complete compensation of the second-order non-linearities, this proof of concept has now been demonstrated. The low energy spread achieved with long bunches is one of the key elements for the realisation of the micro-UED experiments foreseen at REGAE.

The second operation mode involving a linearised longitudinal phase space leaves the energy spread high, but compresses the bunches longitudinally down to below 1 fs. Since the resolution of the transverse deflecting structure (TDS) installed at REGAE is about 10 fs, the shortest bunches cannot yet be measured directly. With the implementation of a THz streaking device at the beginning of 2021, higher resolution is in reach. Major progress has been made with preparatory work for this device, which is an experiment in itself. The generation of THz radiation by conversion of infrared laser light in cooled, periodically poled lithium niobate crystals yields the required intensity level at the desired frequency, and the production of a suitable THz structure by means of 3D printing technology has been developed into a mature state. The integration of the complete setup into the REGAE facility and first tests are planned for early 2021.

Improved signal-to-noise ratio

Besides beam parameters such as bunch length, energy spread, transverse emittance etc., the signal-to-noise ratio of the diffraction images is a decisive factor for diffraction experiments. In addition to noise from the detector itself, dark current consisting of electrons released from the cavity walls, especially of the gun cavity due to the high electric field levels, also contributes to the background noise. To inhibit the generation of dark current as much as possible, the cavities are carefully cleaned with a special dry-ice cleaning technique prior to installation so as to reduce the number of emission sites in the cavities. A second measure is to pass the electron beam through a set of collimators, usually metal sheets with a hole for the electron beam, so that dark-current electrons with off-axis trajectories are scraped off. With a set of newly installed dark-current collimators consisting of 3 cm long tubes with an inner diameter of ~0.5 mm (Fig. 1), the dark-current-induced noise has been reduced by another factor of 5, and the background noise is now dominated by the detector noise.

In addition, the detection efficiency and the achievable signal-to-noise ratio have been significantly improved by the installation of a Jungfrau 1 M detector. Whereas, in previous detectors installed at REGAE, electrons first needed to be converted into photons using a scintillator screen before they were imaged onto the chip of a suitable camera, they interact directly with the sensor material in the Jungfrau detector. It thus allows single MeV electrons to be detected while keeping noise levels to a minimum at the same time. Initially designed at PSI in Switzerland to record X-ray diffraction images at X-ray FEL sources, the Jungfrau detector has already shown its performance for MeV electron detection in first experiments at REGAE (Fig. 2). A more detailed characterisation of the detector performance remains to be carried out, but the first results indicate a substantial improvement. In combination with the new collimators, a significantly improved signal-to-noise ratio is now available for diffraction experiments at REGAE.

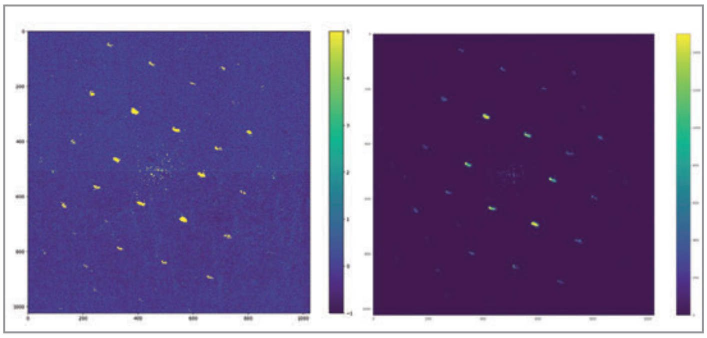


Figure 2

Single-shot diffraction patterns from a single-crystalline gold foil of 50 nm thickness recorded with the Jungfrau 1 M detector at REGAE with 2.7 MeV electrons, demonstrating the improved signal-to-noise ratio now available at REGAE. Left: Diffraction patterns with all intensities truncated at values larger than 5 arbitrary units (a.u.) to highlight the very low achievable background levels. Right: The same diffraction image showing the full dynamic range, spanning more than three orders of magnitude, that is achievable with the detector.

Anticipated upgrades of REGAE

To adapt to the proposed science case for REGAE, we foresee several upgrades in 2021. A new experimental chamber with extended capabilities is being designed, which will provide an on-axis viewing system for improved sample visualisation, a crystallography goniometer for high-precision sample orientation and the possibility of cryogenic sample cooling down to 10 K, as well as a liquid-jet setup for diffraction experiments with liquids. A modular design will allow an easy exchange of components and offer the possibility for future upgrades.

For microelectron diffraction experiments, we plan the implementation of a 3 GHz bunch train mode. One bunch train of 1.5 μs duration will contain a total charge of about 100 fC, which can be focused down to a few micrometres while maintaining a coherence length larger than 10 nm. This new bunch train mode will allow diffraction experiments to be performed with micrometre-sized samples and microsecond time resolution, which are currently not possible at REGAE.

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

European XFEL accelerator

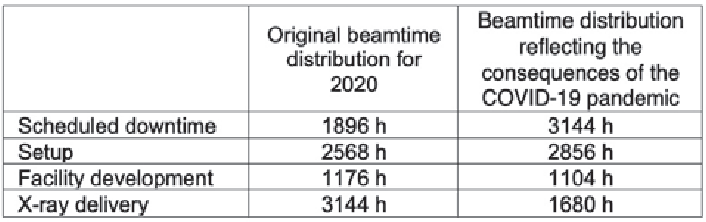
Stable beams for X-ray delivery

In 2020, the operation of the European XFEL accelerator – which is run by DESY – was strongly influenced by measures to prevent the spread of the new coronavirus. This included a forced shutdown of the facility from the end of March until the beginning of May and a very reduced user programme, with only remote access for most of the users from outside Germany. Nevertheless, the accelerator was operated for more than 5600 h with excellent availability. In total, the facility had to be restarted three times after a complete shutdown, which was time-consuming but helped to further develop standard procedures. Possibilities for remote operation and support were extensively exploited. Facility development activities focused on enhancing the free-electron laser (FEL) sources SASE1, SASE2 and SASE3, with excellent results obtained with a new hard X-ray self-seeding setup at SASE2 and a newly installed magnetic delay chicane at SASE3.

Summary of operation

The operation of the European XFEL accelerator is generally divided into the following categories: i) scheduled shutdown, ii) X-ray delivery to experiments, iii) facility development for the accelerator, FEL sources and photon systems, and iv) setup, a category that accounts for the restart of the facility after shutdown, repair accesses outside the scheduled maintenance periods, experiment setup times and the time needed for preparing different machine states.

The following table shows how the time in these different categories was impacted by the schedule changes in 2020, including the enforced shutdown from 20 March to 10 May:



	Original beamtime distribution for 2020	Beamtime distribution reflecting the consequences of the COVID-19 pandemic
Scheduled downtime	1896 h	3144 h
Setup	2568 h	2856 h
Facility development	1176 h	1104 h
X-ray delivery	3144 h	1680 h

In mid-March, the DESY Directorate and the European XFEL Management Board decided to shut down the European XFEL accelerator and take precautions to avoid irreparable damage in case of failure of supporting infrastructure (cryogenic and cooling systems) during lockdown times, when service personnel would not be able to access the facility. This required a special mechanical detuning of the approximately 800 cavities, a procedure that was intended for use only in case of a warm-up of the cold, superconducting accelerator.

As a consequence, of the 6888 h originally scheduled for accelerator operation, 5640 h were actually executed. Within this operation time, 3144 h had been scheduled for X-ray delivery, with 1680 h actually delivered. The remaining operation time was dominated by setup and tuning, which included a total of three facility start-up procedures: after the winter shutdown, after the enforced shutdown and after the regular summer shutdown.

X-ray delivery in the standard self-amplified spontaneous emission (SASE) configuration to all six scientific instruments was highly reliable. All scheduled 12-hour experiment shifts could be served. An automated analysis of the SASE intensity measurements yielded an availability (i.e. SASE intensity above a predefined threshold) of about 95%. Most notably, the performance of the SASE2 undulator could be improved during a dedicated tuning period and is now on the same level as SASE1.

Commissioning and development of the superconducting accelerator take place predominantly during start-up times. A careful calibration of all probe signals at the beginning of the year allowed for a relatively straightforward recovery of the maximum reachable electron energy of 17.5 GeV. While operating at this electron energy, world-record SASE photon energies of 30 keV were demonstrated. Most of the time, however, the accelerator is operated at 14 GeV, which is a good compromise to satisfy the requirements of both the hard and soft X-ray experiments.

Another achievement for the superconducting accelerator was the full commissioning and hand-over to operation of the piezo control that allows for fast tuning of the radio frequency (RF) cavities during an RF pulse and of two different electronic modules that stabilise the electronics against external and internal drifts. These measures yielded an arrival time stability of the electron bunches at the end of the linear accelerator, relative to a reference signal, of below 20 fs RMS. This value can be further reduced to about 6 fs RMS through a beam-based feedback, which is currently in test operation.

Despite the difficult working circumstances, major upgrades to the facility were performed in parallel with standard maintenance during the summer and winter shutdown periods. A magnetic chicane was installed in the SASE3 beamline that will allow the control of the temporal delay between two photon pulses created from the same electron bunch (Fig. 1). Behind the SASE3 undulator, about 30 m of electron beamline were altered to install so-called APPLE-X undulators in order to produce SASE radiation with variable polarisation. Programmable kicker magnets were added in the beam distribution section to improve the compensation of eddy current effects in the beam distribution kicker magnets.

During facility development, important strategic goals were pursued. These included investigations to better understand the undulator system using new diagnostics as well as interdisciplinary studies throughout the entire facility to further improve the photon beam stability. In this context, the transversal electron beam stability was characterised. By means of slow and fast feedback systems, the electron beam position was maintained within 3 µm RMS. This corresponds to the specified value of about 10% of the electron beam size in the undulator (Fig. 2).

Increasingly, facility development now focuses on expanding the experimental possibilities by commissioning special methods for generating X-ray light. These include hard X-ray self-seeding at SASE2, a method to increase the spectral brilliance of the X-ray light, and the operation of SASE3 to deliver photon pulses with two different X-ray energies and adjustable time offset using the newly installed chicane. Both methods will be available to users from 2021. Another set of studies concerned the generation of short photon pulses, either through operation at reduced electron bunch charge, i.e. with shorter bunches of the same electron density, or through non-linear manipulation of the longitudinal phase space, enabling a smaller and shorter fraction of the electron bunch to lase.

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

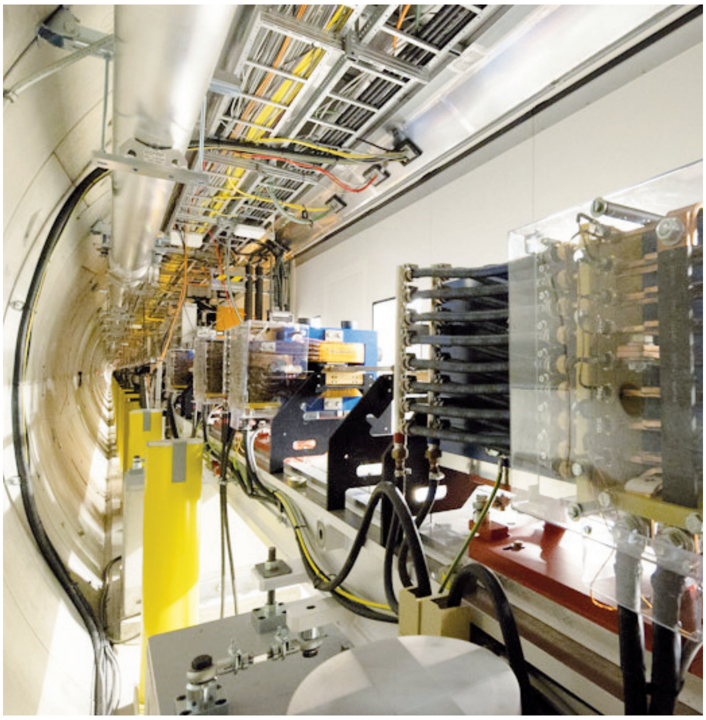


Figure 1

Magnetic chicane as installed in the SASE3 beamline

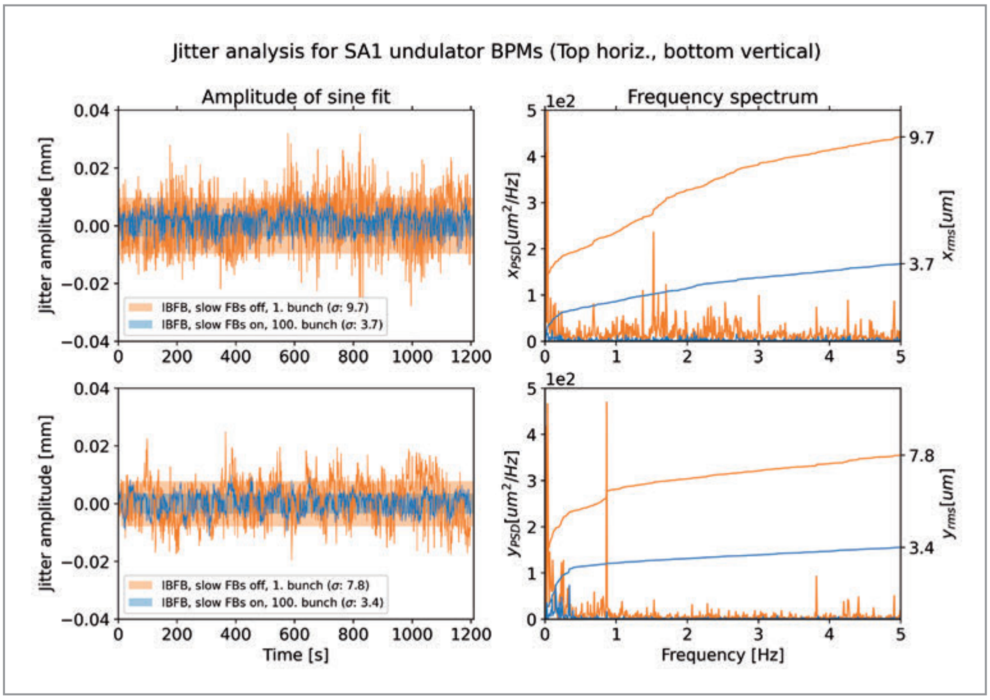


Figure 2

Comparison of the horizontal and vertical electron beam jitter in the SASE1 undulator with (blue) and without (orange) feedback systems in operation

Highlights · New technology · Developments

PETRA IV

The ultimate 3D X-ray microscope

The PETRA IV project is the upgrade of DESY’s synchrotron radiation source PETRA III into a diffraction-limited hard X-ray radiation source. Its highly brilliant and coherent photon flux will be made possible by a new type of magnetic lattice design, the hybrid multibend achromat (HMBA), pioneered at the European Synchrotron Radiation Facility (ESRF) in France for the ESRF-EBS upgrade. However, thanks to its unique ring circumference of around 2.3 km, PETRA IV can be diffraction-limited up to a photon energy of 10 keV. In brightness mode with 200 mA beam current, the planned H7BA lattice will deliver an electron beam with an emittance of $\varepsilon < 20$ pm rad and, in timing mode with 80 mA in 80 bunches, $\varepsilon < 50$ pm rad. Electron beam lifetimes of 3–4 h in brightness mode and 1 h in timing mode can be reached in the presently foreseen design, based on on-axis swap-out injection. With these exceptional characteristics, PETRA IV is envisioned to be the ultimate 3D X ray microscope.

Goals of the project

The PETRA IV project aims to develop an ultralow-emittance storage ring for hard X-ray radiation that will provide electron beams of unprecedented brightness, allowing the production of X-rays with exceptional brilliance and coherence. These will yield 3D images of matter at unmatched spatial and temporal resolution. This goal will be achieved by upgrading the existing PETRA III facility with recent pioneering developments in accelerator and undulator technologies.

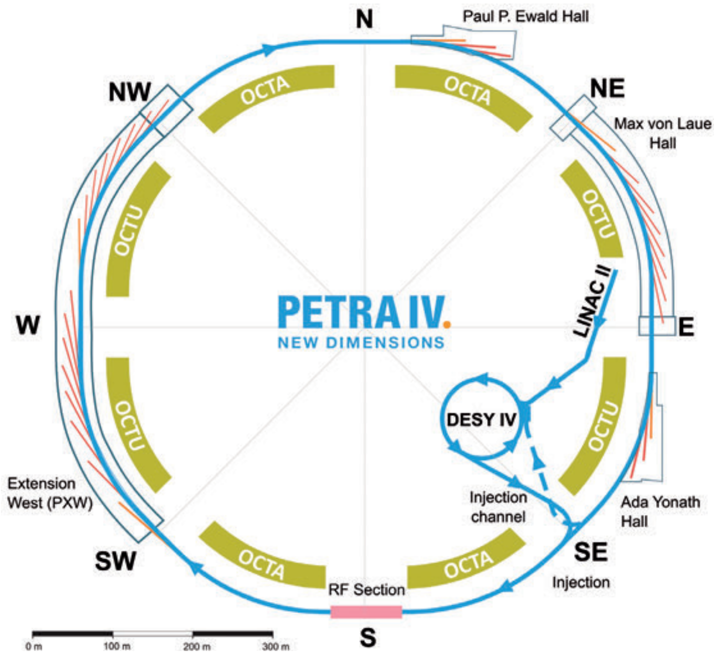


Figure 1

Layout of the PETRA IV storage ring

The gain in brightness, which is the key parameter to characterise the quality of X-ray beams, will be a factor of 100 for hard X-rays at 10 keV and almost 1000 for high-energy photons up to 150 keV. The high spatial coherence provided by the source, particularly at high photon energies, will allow for nearly diffraction-limited focusing capabilities without severe loss of photon flux. This will result in high sensitivity and high spatial and temporal resolution for *operando* and *in-situ* studies of complex systems.

Given the extreme international competition with other light sources in the USA, China and the rest of the world, PETRA IV will be built to restart operation in 2027, keeping Germany and Europe at the forefront of photon science research for the next decades.

The PETRA IV conceptual design report (CDR) was published in November 2019, and the technical design report (TDR) phase started at the beginning of 2020. Dedicated work package groups began tackling specific aspects of machine design and prototyping for key technology systems, such as magnets, vacuum systems, precise support structures, beam diagnostics and feedbacks. A similar R&D effort is ongoing on the design of photon beam delivery and transport systems as well as sample environment systems, labs, technical infrastructure, scientific computing and experiment control, ultra-precision mechanics and detectors.

To support this activity, DESY initiated a strong recruitment campaign. The TDR phase of the project aims to develop the design of the facility so as to be ready to launch the calls for tender by 2023.

Optimising the storage ring lattice

The world-leading performance of PETRA IV relies on an ultralow-emittance lattice based on the HMBA concept pioneered at ESRF-EBS. In the hybrid seven-bend achromat (H7BA) lattice described in the PETRA IV CDR, a total of 64 HMBA cells are distributed in eight octants of the storage ring. Taking advantage of the large circumference of the ring (2.3 km, Fig. 1), the H7BA lattice (Fig. 2) will deliver electron beams with emittances of $\varepsilon < 20$ pm rad in brightness mode (200 mA in multibunch mode) and $\varepsilon < 50$ pm rad in timing mode (80 mA in 80-bunch mode). The design is based on on-axis swap-out injection and foresees a beam lifetime of 3–4 h in brightness mode and in excess of 1 h in timing mode.

The lattice design and optimisation will continue in the TDR phase to improve the ring performance, possibly exploring off-axis injection and increasing the beam lifetime. To this end, two main decisions were taken in 2020. First, the current PETRA III undulator canting schemes are not possible anymore, meaning that all the source points of the ring and all the beamlines on the experimental floor have to be moved. Second, the portions of the ring that won't host insertion devices were significantly modified, resulting in the so-called combi lattice, to allow more freedom in the design and optimisation of the facility.

To deal with the complex non-linear beam dynamics, the optimisation is performed using the most advanced numerical tools, with simulations based on particle tracking, genetic algorithms and artificial-intelligence, neural-network approaches. A common feature of ultralow-emittance lattices is the strong focusing required for the magnetic elements. PETRA IV will need quadrupole gradients in excess of 90 T/m and sextupole gradients above 3000 T/m^2. The design of such magnets requires small apertures (12.5 mm radius) and a careful control of the mechanical precision in manufacturing (less than 20 μm pole profile errors) and in the installation and alignment (less than 30 μm, magnet-to-magnet offset). Following the ESRF-EBS concept, PETRA IV will make extensive use of permanent magnets. This choice is well aligned with DESY's support for developing sustainable accelerators with reduced power consumption. The magnet design is carried out in collaboration with the Efremov Institute in St. Petersburg, Russia, and ESRF.

A consequence of the small-aperture magnets is the need for a reduced cross section of the vacuum chamber and the associated difficulties in creating an average vacuum pressure of 10^{-9} bar along the ring. For these reasons, the design will make extensive use of non-evapourable getter (NEG) pumps, and most of the copper vacuum chamber will be coated. R&D work will be carried out in the TDR phase to define the properties of the coating, the activation procedure and its robustness to repeated activation cycles.

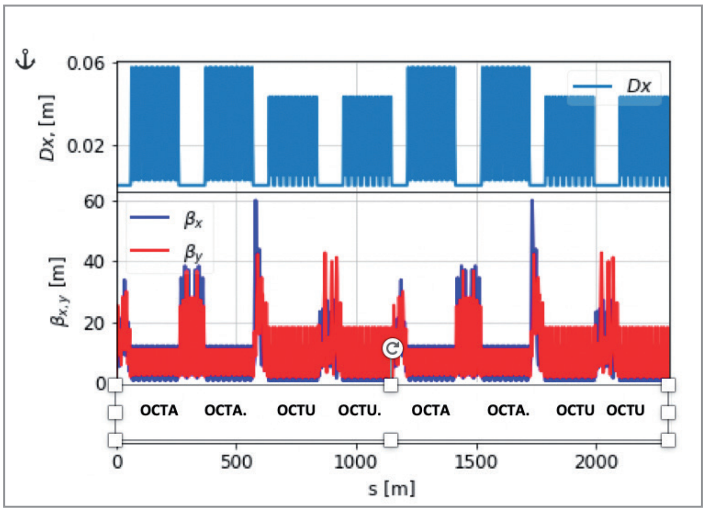


Figure 2

Optical function of the PETRA IV lattice

Crucial for the success of such an ultralow-emittance ring is the availability of highly accurate diagnostic systems that provide comprehensive information on the electron and photon beam behaviour. The electron beam should be measured and stabilised to sub-μm, sub-μrad accuracy over a bandwidth that extends up to 1 kHz, as set by modern detector sampling rates. In this framework, the PETRA IV project team is developing an integrated feedback concept that takes care of the electron and photon beams as one system, modelling and controlling the stability of the photon characteristics at the sample, all the way up to the electron beam at the source point in the ring. This integrated approach requires modelling of the whole process of radiation generation and transport from the insertion device to the sample.

PETRA IV outlook

The PETRA IV project team has completed the first year of the TDR phase. Continuous improvements of the lattice are ongoing to design a diffraction-limited (up to 10 keV) hard X-ray source that will be world-leading. After assessment of the possible lattice types, the final decision and the lattice freeze are due in 2021. In parallel, the design of the pre-accelerator chain has started, including the lattice of the DESY IV booster synchrotron and the transfer line for the bunch injection into the storage ring. In this context, parallel operation of the DESY II Test Beam Facility can be maintained.

In addition, collaboration with DESY groups developing laser plasma wakefield accelerators is planned. In parallel with LINAC II, a 500 MeV laser plasma injector could be installed to bring this new accelerator technology to maturity. As a final step, a 6 GeV laser plasma injector is envisioned for PETRA IV.

Contact: Riccardo Bartolini, riccardo.bartolini@desy.de, Stephan Klumpp, stephan.klumpp@desy.de

FLASH2020+

Preparing the next-generation soft X-ray facility

Recent progress in photon science has sparked a growing interest from the user community in highly coherent pulses in the soft X-ray spectral range at high repetition rates. These needs have driven the studies for the upgrade of DESY's FLASH free-electron laser (FEL) facility, leading to the publication of the FLASH2020+ conceptual design report (CDR) in 2019. In 2020, the FLASH2020+ project was launched with the goal to progressively extend the current capabilities of the FLASH facility. Higher electron beam energies combined with new tuneable-gap undulators will allow the oxygen K-edge to be reached with polarisation control. The new FLASH1 seeded beamline will provide fully coherent and reproducible pulses up to MHz repetition rates. To manage the complex transition while keeping FLASH running for users, a new project structure has been created.

Project goal and timeline

After the approval of the CDR, a new project structure has been created with the goal to continue the work initiated with the FLASH2020+ CDR and to identify all the solutions required to achieve the project target and write the technical design report (TDR). Appropriate funds have been identified and provided to the project management for the next five years to complete the facility upgrade.

Initial upgrades of the FLASH2 FEL beamline have already started with the installation of a dedicated bunch compressor and of two PolariX transverse deflecting cavities for longitudinal electron beam characterisation in 2020. The major upgrades for FLASH2020+ will begin in 2022 (Fig. 1). By replacing two accelerating structures, the maximum electron beam energy delivered by the linear accelerator will be increased to 1.35 GeV, allowing an extension of the tuning range of operation of both FELs, FLASH1 and FLASH2. Furthermore, new flexible electron beam compression schemes, including a laser heater system capable of mitigating microbunching instability, will enable an improvement of the electron beam quality and hence of the FEL properties and reliability.

The second important upgrade phase is planned for 2024. At the FLASH1 beamline, APPLE-III undulators with variable gap and variable polarisation will be combined to realise a unique high-repetition-rate external seeding scheme. At FLASH2, a further upgrade aiming at shorter pulses and variable polarisation is also envisioned.

In parallel to the accelerator and FEL upgrade, the experimental stations will be upgraded to accommodate tight focusing optics and specially designed monochromators. The upgrade will be completed by new pump–probe laser systems providing high-energy, high-repetition-rate synchronised pulses across the whole optical spectrum and beyond.

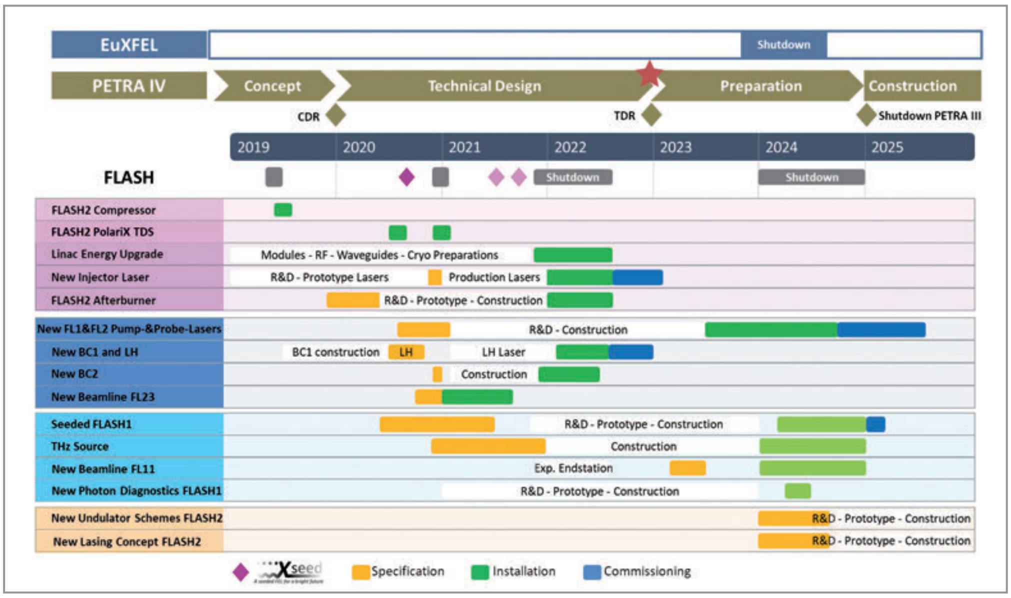


Figure 1

Timeline of the FLASH2020+ project

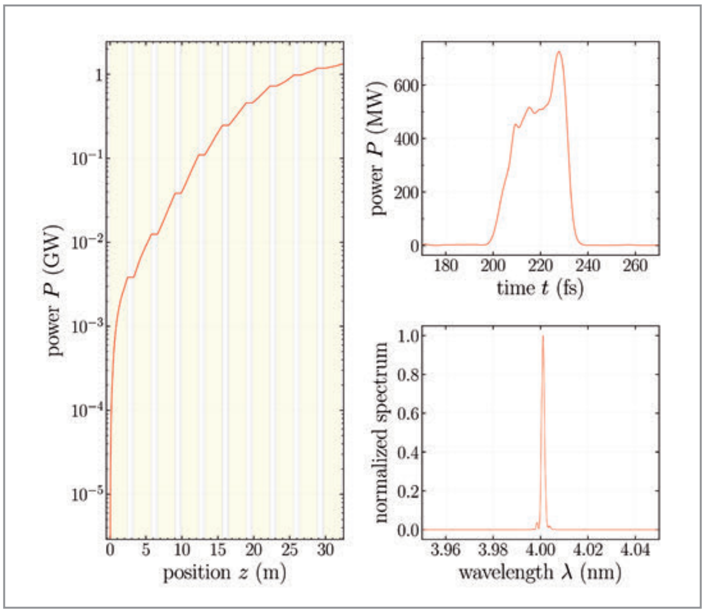


Figure 2

Left: Simulated FEL power growth along the APPLE-III undulators of the seeded FLASH1 beamline in EEHG at 4 nm. Right: Temporal and spectral profiles.

Next-generation photocathode laser

The properties and the quality of the electron beam from the radio frequency photocathode electron source (RF gun) of FLASH can be influenced by ultraviolet (UV) laser pulses from an injector laser. To increase reliability and offer more flexibility in electron bunch generation, a new injector laser platform is being developed for FLASH2020+. The next-generation photocathode laser NEPAL will produce two independent trains of UV pulses contained in a long burst repeated at 10Hz. Each section of the burst will consist of a train with up to 500 tailored UV laser pulses at 1 MHz repetition rate with variable pulse duration, energy and temporal spacing. With these flexible and remotely controllable bursts, a large variety of operation modes and thus more flexibility in the operation of FLASH will be possible.

The future injector laser will be installed in a newly constructed building, connected to the main FLASH hall (Building 28). This building will feature two independent temperature- and humidity-controlled laser labs, which will also include space to accommodate a drive laser for a laser heater system. Both laser systems are scheduled for installation in the second quarter of 2022. First electron gun tests with these new lasers will take place at the end of 2022 after completion of the laser beamline and restart of the facility after the shutdown.

Seeded FLASH1 FEL

With the unique external seeding scheme to be realised at FLASH1 in the second upgrade phase starting in 2024, FLASH2020+ aims at covering the spectral range from 60 nm down to 4 nm with fully coherent pulses at the full repetition rate of the facility. The scheme will rely on echo-enabled harmonic generation (EEHG) for short wavelengths and high-gain harmonic generation (HGHG) for long wavelengths. The development of a new seed laser capable of providing the high quality and intensity required for seeding at the repetition rate of the FLASH linear accelerator is a major part of the project.

In EEHG, the interaction of two seed lasers with the electron beam in undulator magnets called modulators, in combination with two dispersive sections, allows the charge density distribution in the electron beam to be manipulated so as to induce bunching at higher harmonics of the second seed laser pulse. After entering the radiator, the seeded electron beam starts to emit coherent radiation, which is further amplified in APPLE-III undulators, which feature both a variable gap and variable polarisation.

As a result of the seeding, the length of the lasing region in the electron bunch is defined by the length of the manipulated region, which is in turn determined by the duration of the second seed laser pulse. Compared to self-amplified spontaneous emission (SASE), a clear spectrum with a sharp spike is generated (Fig. 2).

Xseed

The hardware currently available at the existing FLASH seeding beamline allowed important experience to be gained with external seeding over the last few years, enabling tests of some of the methods and techniques required to operate the future seeded FEL facility. At the end of the winter 2020/21, an upgrade of the beamline will be completed with the installation of a new chicane that will also enable the implementation of EEHG.

Together with an improved seed laser beamline, the new setup, named Xseed, will offer great flexibility in operation modes, which will be beneficial for the development of advanced seeding schemes. Moreover, in combination with the next upgrades of the FLASH accelerator, the Xseed setup will be a powerful tool for characterising the electron beam quality and help in the commissioning and optimisation of important systems, such as the laser heater and the new bunch compressors.

Innovation, technology transfer and sustainability

In line with DESY's mission, sustainability, innovation and technology transfer are important components of the FLASH2020+ project structure. The operation of research facilities is very energy-intensive. In terms of sustainability, special attention is therefore paid to reducing consumption, increasing efficiency, recovering waste heat and achieving smarter energy management. Ongoing research in the areas of matter, energy and key technologies further supports these developments. The DESY Innovation and Technology Transfer (ITT) group supports the transfer of scientific results into products and processes to make them available to third parties outside the research community.

Contact: Enrico Allaria, enrico.allaria@desy.de
Lucas Schaper, lucas.schaper@desy.de

LLRF CW R&D at DESY and European XFEL

Present status and future research programmes for the European XFEL CW upgrade

The continuous-wave (CW) upgrade of the European XFEL X-ray laser facility planned by European XFEL and DESY offers exciting new research opportunities. The new CW and long-pulse modes of operation will add unprecedented flexibility in terms of the X-ray pulse parameters that can be realised at the European XFEL. The upgrade will require significant changes to the existing accelerator and its control system. To this end, an ongoing R&D programme aims to develop new techniques and methods to control all the superconducting accelerating European XFEL cavities in a safe and reliable way. This article highlights the current status of the R&D programme for the CW low-level radio frequency (LLRF) control system, with results obtained at the European XFEL and using the XM50.1 accelerating module at the CryoModule Test Bench (CMTB) at DESY, and gives an overview of the future development plan for the LLRF resonance control system.

European XFEL CW LLRF challenges

Thanks to recent advances in superconducting RF technology, interest has been growing worldwide in realising CW superconducting X-ray free-electron lasers (FELs). The main advantages of a CW X-ray FEL compared to short-pulse (SP) facilities with duty factors on the order of 1% are an increased bunch repetition rate and more flexibility for light detectors in user experiments. A long-pulse (LP) mode of operation with duty cycles of some 10% also offers a compromise between the high energies realised in SP mode and the repetition rates achieved in CW mode. Therefore, for some years now, a proposal has been under discussion to add a CW mode and an LP mode, alongside the existing SP mode, to the European XFEL.

From the cavity control perspective, the upgrade presents multiple challenges. The quench detection and detuning estimation techniques, which rely on the RF pulse decay, cannot be used in CW mode. Yet catching quenches is essential to avoid excessive power dissipation in the cryogenic bath, resulting in potential machine downtimes. Simultaneously, detuning estimations from the control system are needed to operate the cavities at their maximum efficiency. Therefore, a new online method to estimate cavity parameters independently of the RF pulse shape has been developed.

For the CW upgrade, the accelerating cavities will be operated with loaded quality factors (Q_L) of more than 10^7 to limit the required RF power to a few kilowatts. This modification will result in cavity bandwidths of a few tens of hertz. These narrow bandwidths will make the accelerating gradient more sensitive to mechanical microphonic vibrations and ponderomotive instabilities. New controller algorithms are then required to minimise cavity detuning during operation and avoid incurring gradient drops. Additionally, automated setup strategies are under study to simplify accelerator operation.

Cavity parameter estimation

The accelerating cavities have to be cooled to 2 K to maintain their superconducting state. While operating in CW mode, the typical cavity heat dissipation will be on the order of a few watts. However, when a quench event happens, the heat load

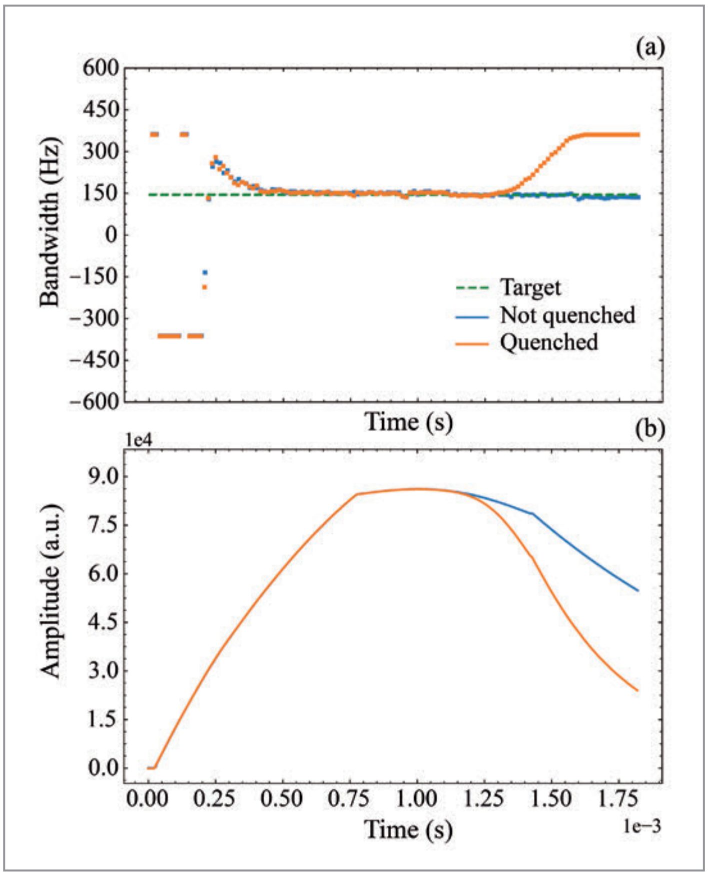


Figure 1

(a) Estimation of cavity bandwidth at the European XFEL and (b) corresponding cavity amplitude, for a nominal (blue) and quenched (orange) RF pulse. An increment of the orange bandwidth trace during the decay phase reveals the presence of a quench.

can increase by orders of magnitude. It is therefore of utmost importance to stop the cavity drive as soon as a quench is detected. Moreover, the detection system has to discriminate between quenches, beam loading and detuning events to avoid stopping the beam acceleration unnecessarily.

For this reason, a new quench detection component was developed in the field-programmable gate array (FPGA) logic of the LLRF system. This component uses an inverse cavity model to compute cavity bandwidths at a sample rate of 72 kHz with a delay of 170 µs, making it more than three orders of magnitude faster than the current quench detection system. Particular care was taken to allow the realisation of up to 16 cavity channels for the LLRF system in order to make it compatible with the vector sum control scheme used at the European XFEL. As an additional benefit, the component is able to compute the cavity detuning, which makes it valuable as input stage for resonance control algorithms.

Tests performed at the European XFEL and at CMTB at DESY show that the component is able to catch quenches and estimate detuning with an error of just a few hertz (Fig. 1). Additional tests conducted in collaboration with HZDR in Dresden-Rossendorf at their ELBE accelerator demonstrate that the component can compute detuning in the presence of beam loading of several hundred microamperes without increase in the estimation error.

Resonance control

With bandwidths of a few tens of hertz, cavities will be susceptible to mechanical deformations. These deformations can be due either to external sources, such as environmental noise or pressure changes in the cryogenic bath, or to the radiation pressure that the electromagnetic field inside the cavity exerts on the cavity walls. For this last disturbance source, a positive feedback loop between the cavity's mechanical and electromagnetic dynamics can lead to strong detuning oscillations or gradient drops.

For this reason, a new resonance controller is being developed to prevent these effects. Piezoelectric tuners will be used as actuators to modify cavity detuning. The new resonance controller will rely on different control strategies depending on the detuning disturbance to be regulated. A detuning integrator will compensate for slow mechanical drifts with a spectrum below 5 Hz. A recent analysis has also shown how this controller policy can prevent ponderomotive gradient jumps or monotonic instabilities (Fig. 2).

Future studies will explore the possibilities to improve the integrator with a linear parameter-varying control policy to address non-linearities in the cavity resonance plot generated by Lorentz force detuning. A narrow-bandwidth active noise control (NBANC) policy will regulate periodic microphonic noise, mostly produced by rotary machines (e.g. fans, pumps). Measurements at CMTB show that, with NBANC, it is possible to reduce the detuning to 0.5 Hz RMS. Compared to the previous implementation, the new NBANC will automatically find the actuator phase delay, thus simplifying setup procedures. Possible improvements include automatic tracking of the disturbance centre frequency.

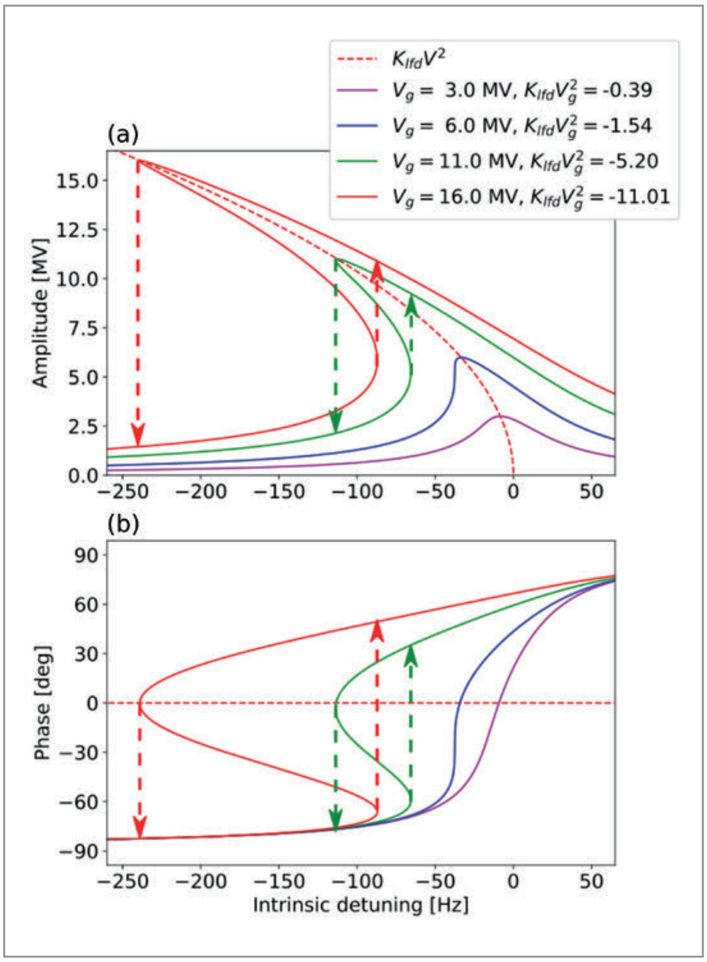


Figure 2

Ponderomotive effects on the cavity resonance curve at different gradients: (a) field amplitude and (b) phase. At higher gradients, an instability zone is generated. This in turn results in potential gradient and phase jumps (arrows).

Finally, the FeedBack ANC (FBANC) will address the problem of regulating wide-bandwidth microphonics and ponderomotive oscillations. To perform this task, the FBANC will use the least mean square algorithm to find its control parameters in an automated way. The new controller will be deployed in 2021 and tested at CMTB.

Contact: Andrea Bellandi, andrea.bellandi@desy.de
Julien Branlard, julien.branlard@desy.de

European XFEL high-power RF system

Optimisation results and a new challenge

In the past years, a sophisticated monitoring system was developed to monitor the high-power radio frequency (RF) systems of the European XFEL X-ray laser. This made it possible to identify the causes of failures in the first three years of operation and to precisely quantify their effects on the operation of the facility. Based on these findings, a bundle of measures was implemented to optimise availability. This article discusses the effectiveness of these measures especially in the case of failures caused by a loss of communication within the control system of the high-voltage modulators.

Optimisation of availability

In 2019, the causes of failures that had accounted for the longest downtime during the first three years of operation of the European XFEL were addressed:

- The RF stations were made resistant to power outages and power surges.
- The flow monitors of the waveguide cooling system were made insensitive to pressure fluctuations of the cooling water.
- A remote power cycle for a modulator measurement system (YAU41) was implemented in the tunnel.
- In the winter 2018/19, water hoses burst in three klystrons during operation. The water hoses, which had been designed too weakly by the manufacturer, were replaced by more robust types in all klystrons of this kind.

These measures, which were implemented in 2019, were 100% effective. The faults no longer occurred and did not cause any tunnel access or other downtime in 2020.

One remaining task was the design and construction of a klystron transport vehicle together with the DESY installation group, in cooperation with industry (Fig. 1). The transport vehicle used so far had been designed to install modules and other heavy components during the installation phase of the European XFEL. It is oversized for pure klystron transport. Due to its size, three days are required to get it into and out of the tunnel. With the new, much smaller vehicle, which will be available from 2021 on, this can be done in less than a day.

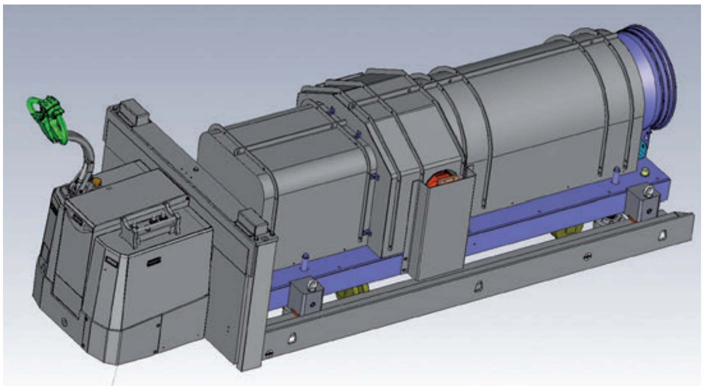


Figure 1

New transport vehicle for the European XFEL tunnel, loaded with a klystron

Fortunately, only two klystrons had to be replaced so far because of the water hose problem mentioned above. The water hoses were repaired outside the tunnel. After four years of operation, none of the klystrons was permanently broken, which might be attributed to the very thorough incoming tests of the klystrons prior to their installation in the European XFEL tunnel.

A new challenge

In 2020, more than half of the downtime of the high-power RF system was caused by a fault in the control system of the high-voltage modulators. The first appearance of this type of failure dated back to the commissioning phase in 2016/17. During the first years, it appeared very rarely, with only a slight increase in the failure rate: In 2016 and 2017, it occurred seven times, yielding a mean time between failure (MTBF) of 104 days. In the following two years, 2018 and 2019, it occurred 40 times, and the MTBF rose to 18 days. This meant that it was still a small problem compared to other failure causes, and solving other problems had priority. In 2020, however, there was an unexpected, sharp increase in the frequency of errors. The fault occurred approximately every two days and thus dominated.

Consequently, the focus was then placed on the “red spider” problem – called like this because a red spider appears on the display when a communication error occurs in the modulator electronics (Fig. 2). As soon as this error occurs, communication is stopped completely and, as a result, the modulator fails. It can be restarted only by means of a power cycle of the entire control system. This fault was difficult to find because it occurred randomly in about two-thirds of the 26 modulators, with no discernable pattern. The related

Figure 2

The display in the modulator control system that gave the communication error its name

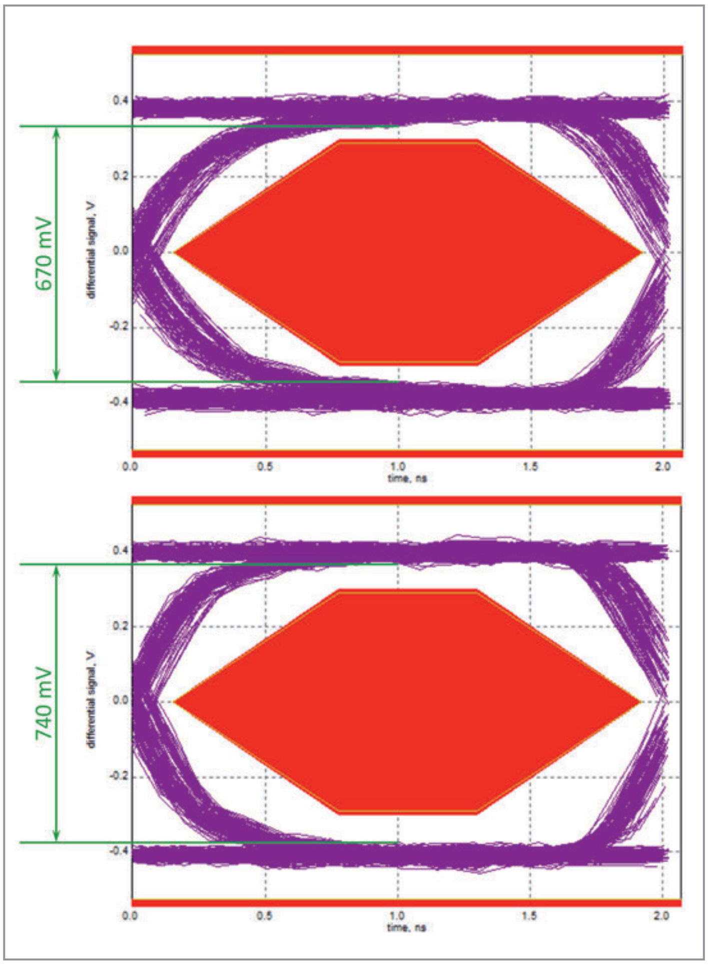


Figure 3

Top: Eye diagram with the USB cable previously used in the modulator control system.

Bottom: Eye opened wider due to the much lower attenuation of the new USB cable.

electronic components were replaced several times without lasting success.

The modulator control system consists of two electronic boards and a server, which communicate with each other by USB cable. Since it was suspected that the problem occurred on this communication path, a USB analyser was procured that could record the data exchange, and analysis of the communication between the server and one of the boards that was particularly sensitive to the error began. The communication then ran via the USB analyser, and the hope was to find out what happened on the data line in the event of an error. But the setup, which showed the error several times a day without the analyser, worked perfectly. The test setup seemed to solve the problem; the question was why.

On closer inspection, it became clear that the USB analyser was not only recording what was being transmitted on the line, but was also reading out the signals, passing them on to the output in a processor and generating new electrical USB signals there for transmission. The working hypothesis was then formed that the USB analyser improved the signal quality and that therefore no more bit errors occurred in the modulator electronics.

This hypothesis needed to be tested. For this purpose, a complex measurement setup consisting of an oscilloscope with a bandwidth of several GHz, a special board for the signal taps and the appropriate software was required. With the help of this measurement setup, eye diagrams of the USB signals could be recorded, which were used to assess the signal quality (Fig. 3). Such an eye diagram consists of a superimposition of several hundred to several thousand bits. Basically, one can say that the wider the eye is open, the better the signal quality. Theoretically, the eye opening of a USB 2.0 signal should be 800 mV. In practice, however, the vertical eye opening is reduced due to amplitude noise, and the attenuation of a connected USB cable decreases the opening even further.

We compared different USB devices and noticed two things. First, the eye diagram of the modulator server and the boards was 5 to 9% less wide open vertically than for other typical USB devices. Second, the cable used at that time reduced the eye opening by a further 8 to 11%. As a general rule, reducing the eye opening leads to an increase in the bit error rate. For a typical USB application, the resulting bit error rate would probably not be a problem, as such applications do not have to run error-free for a long time. In this case, however, the increased bit error rate led to a communication error every one to two months, which caused the failure of a modulator and thus of the entire RF station. With 26 RF stations in the European XFEL, this resulted in an MTBF of two days. During the reconstruction of the signal, the USB analyser opened the eye so much that no more bit errors occurred. The same effect can be achieved by reducing the cable attenuation.

So the problem was understood, and we started looking for a USB cable with lower attenuation. This was not easy, but we finally found a cable with a barely measurable insertion loss.

Figure 3 shows a USB signal at the end of the transmission with the originally used cable (top) and the new cable (bottom). With the new cable, the eye is about 10% more open vertically. All modulators have now been equipped with these cables, which significantly improved the signal quality. Since then, the “red spider” problem has not reappeared.

Contact: Michael Bousonville, michael.bousonville@desy.de
Stefan Choroba, stefan.choroba@desy.de

Beam position monitor performance

BPM system for the European XFEL provided by DESY, CEA and PSI

The European XFEL X-ray laser includes a beam position monitor (BPM) system provided by DESY, CEA in Saclay, France, and PSI in Villigen, Switzerland. One main requirement the system has to meet is the specified resolution, i.e. the signal-to-noise ratio in units of length. This value represents the smallest change of position that the system can measure. The BPM system fulfils the European XFEL resolution requirement and offers a range of additional features, such as single-bunch measurement, self-trigger mode, multibunch signal processing, fast data transfer for feedbacks and connection to the machine protection and dosimeter systems.

The European XFEL BPM system

At the European XEL, electron bunches are generated and accelerated to produce high-brightness free-electron laser (FEL) light in three undulators through the self-amplified spontaneous emission (SASE) process. To transfer the bunches from the bunch generation section through the accelerator to the undulators and on to the beam dump, the position of the beam in the vacuum system needs to be measured with high precision. A resolution below 1 µm in the undulators is required to be able to overlap the electron bunches with the emitted FEL light in order to enable a reliable SASE process. For the whole facility, a dedicated BPM system was developed, which has been in operation from the first day.

The European XFEL BPM system consists of various monitors and corresponding electronics. The different monitor types are button and cavity BPMs provided by DESY. In addition, each of the installed 96 cryogenic accelerator modules is also equipped with a BPM, with 24 of them being re-entrant cavity BPMs from CEA Saclay. All in all, about 500 BPMs are installed along the vacuum system. All BPMs measure the individual position and charge of up to 2700 bunches in one bunch train separated by a minimum spacing of 222 ns, with a train repetition rate of 10 Hz.

Each BPM is connected to a modular BPM unit (MBU), supplied by PSI, which is responsible for processing the signals from the monitor so as to provide the beam position and charge. The MBU consists of front-end electronics for down-converting the signals and field-programmable gate arrays (FPGAs) for data processing, including recalculating the values in physical units (the front-ends for the re-entrant cavities were supplied by CEA Saclay). All the front-end electronics are designed to minimise the signal-to-noise ratio of the specially developed monitors by using low-noise amplifiers and active temperature regulation. The internal analogue-to-digital converters (ADCs) operate in their optimum range thanks to the application of attenuators with automatic gain control. Altogether, this results in the good measured resolution shown in Fig. 1. The data are transferred by fibre links to the MicroTCA system and visualised using the DESY-internal control system DOOCS.

The MBUs are structured in a modular setup to be able to include all different kinds of BPMs. Beside the front-end electronics, they are equipped with a timing system and a digital input–output card, which offer additional features, as described below. A second data connection via network is available for maintenance support because the electronics are installed in the tunnel and not accessible during facility operation.

Achievable resolution

The different BPM types provide different resolutions, as can be seen in Fig. 1. The button BPMs (red) are more numerous, as they are more cost-efficient than the re-entrant (green) and cavity (blue) BPMs. The cavity BPMs are more expensive due to their more extensive design, but give a better resolution. They are installed at positions where a better resolution is required.

The higher (i.e. worse) resolution values at the end of the beamline in Fig. 1 are caused by sweeper magnets, which change the beam position so that different parts of the beam dump are hit, thus distributing the deposited beam energy over a larger area. This worsens the resolution in the present analysis scheme.

Except for these BPMs at the dump, all resolution values at the bunch charge of 250 pC shown in the figure meet the European XFEL requirement. All in all, the resolution was demonstrated to fulfil the specified requirement in a charge range from a few pC up to 1 nC.

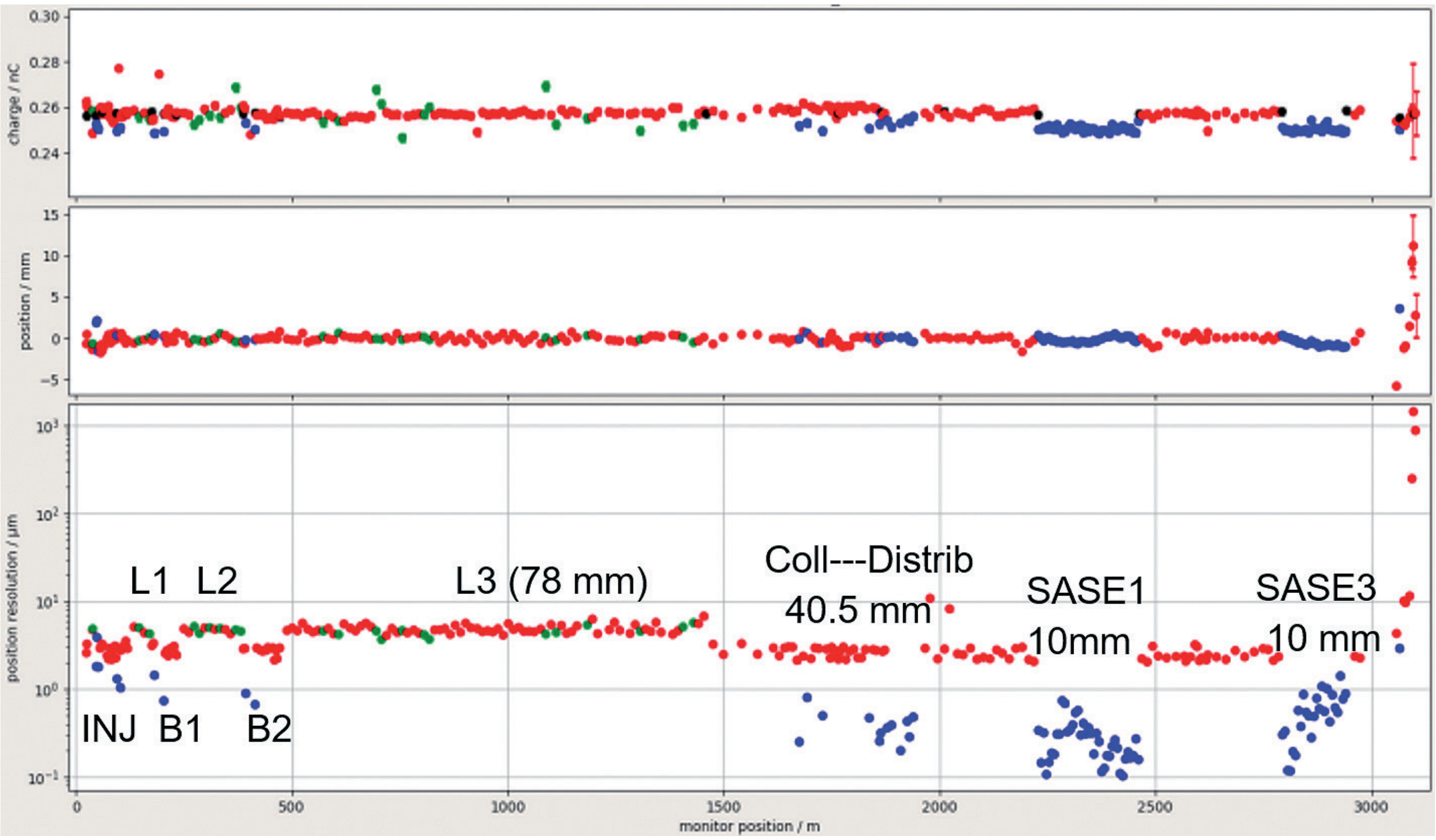


Figure 1

Diagram of the bunch charge measurement, beam position measurement and position resolution of each BPM from the injector (INJ) over the accelerator section L1, the bunch compressor B1, the accelerator section L2, the bunch compressor B2, the accelerator section L3, the collimator section (Coll), the distribution section (Distrib) and the SASE sections 1 and 3 on to the beam dump. Red: button BPMs, green: re-entrant BPMs, blue: cavity BPMs. The values in mm in the lower panel indicate the inner diameter of the beam pipe. The upper panel shows the measured bunch charge (in nC), the middle panel the measured beam position (in mm), and the lower panel the position resolution (in µm) of each BPM along the European XFEL.

Additional features

The MBUs offer additional features beside the measurement of the beam position and charge values. One important feature is the self-trigger mode, which starts the data processing when the signal exceeds a threshold. This provides the capability to measure the bunch position and charge during beamline commissioning without any external trigger, which was very helpful on the first day of operation. In this mode, the resolution is reduced but acceptable because, during commissioning, the goal is the transmission of the beam and not the precise measurement of each bunch.

Another feature is the measurement of a single generated bunch without a bunch train or repetition rate. Here, measuring the beam properties by applying the automatic gain control is difficult because the ADC would go into saturation. The single-bunch measurement feature switches the automatic gain control off, so that the last settings with beam of the attenuators are fixed and a single bunch with similar properties will generate a signal that does not exceed the ADC limit. This mode ensures that the restart of the accelerator after a short break can be controlled with a single bunch, reduces the radiation load and therefore protects the components in the tunnel.

For fast feedback, the MBUs are equipped with special fast data processing and fast connections to be able to react depending on the beam properties within one bunch train. This is used in the intra-beam feedback system, where the bunch position is successfully corrected by fast kicker magnets to minimise the beam jitter within the train. This fast link is also used for the low-level radio frequency system for beam loading compensation.

Each MBU can be connected to the machine protection system so that, if the beam exceeds certain thresholds, operation can be stopped automatically for safety. This connection is already in operation at the hard X-ray self-seeding (HXRSS) experiment at the European XFEL, where the inserted crystal needs to be protected when the beam is close to it. Each MBU includes an online dosimeter system, which can measure the radiation dose during operation.

In addition to a good resolution, the BPM system thus offers many more features to support the successful operation of the European XFEL.

Contact: Dirk Lipka, dirk.lipka@desy.de
Kay Wittenburg, kay.wittenburg@desy.de

FEL science highlights at the European XFEL

Record self-seeding power and two-colour X-ray pulse delivery for user operation

In 2020, the free-electron laser (FEL) R&D group at DESY achieved a variety of scientific advancements. Most prominent was the maturing of the hard X-ray self-seeding technique from demonstration to being ready for pulse delivery for user experiments, establishing new intensity records on the way. A second, equally significant achievement was the first delivery of two-colour X-ray pulses with a scannable delay for user operation at the European XFEL X-ray laser, including the important zero-delay crossing. Furthermore, proof-of-principle experiments on frequency mixing and harmonic lasing paved the way for a future extension of the European XFEL X-ray wavelength range in both directions.

Hard X-ray self-seeding

Hard X-ray self-seeding is an active-filtering technique allowing for nearly Fourier-limited X-ray FEL pulses [1]. It offers increased longitudinal coherence, higher spectral flux and a spectral brightness that is much higher compared to self-amplified spontaneous emission (SASE), the usual standard operation mode (Fig. 1). Furthermore, it allows operation at higher repetition rate when monochromatisation in the experimental hutches is required. In fact, in this case, monochromator operation is limited by the heat load, which is reduced in self-seeded mode. By providing a rapid train of extremely short, yet very bright X-ray pulses, this technique opens the door for various new scientific advancements.

The working principle of self-seeding is to generate and amplify an initially weak seed photon pulse, thereby enhancing longitudinal coherence and narrowing the spectra. The seed photon pulse is created from a standard SASE pulse in a first undulator part by spectral filtering with a single-crystal diamond and subsequent temporal windowing. This last operation is achieved through the interaction of the X-ray pulse and the electrons in the subsequent undulator line.

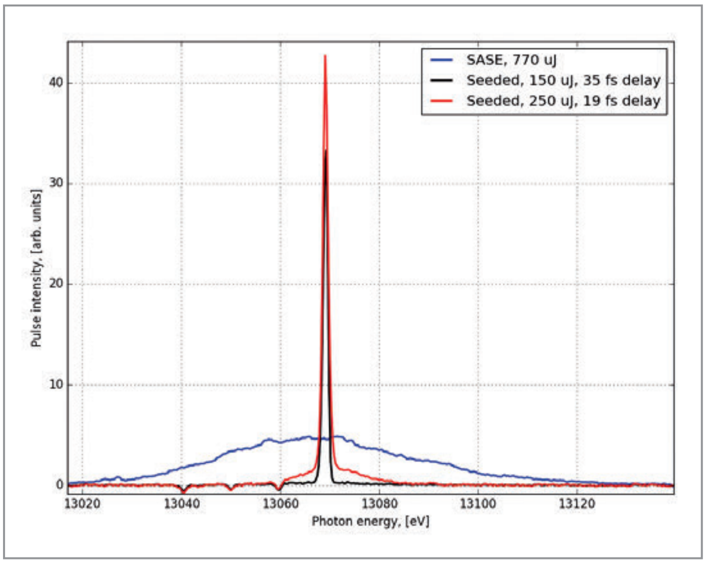


Figure 1

Average self-seeding spectra at 13 keV for two different optimisation cases. Blue: nominal SASE operation. Black: setup optimised for spectral purity. Red: setup maximising the spectral flux.

Two cascading setups (Fig. 2 shows one of these) are installed within one of the European XFEL undulator lines, allowing for an increased signal-to-noise ratio, which could lead to potentially cleaner spectra and mitigation of heat load effects in case of high average photon flux on the filtering crystals.

First self-seeding was observed in September 2019. Today, the technique allows the generation of seeded X-ray beams with an average pulse intensity of more than 800 μJ within 0.7 eV FWHM at a photon energy of 9 keV (1.3 mJ including wide-bandwidth background). Furthermore, high-repetition-rate capabilities have been demonstrated by running at 4000 pulses per second with minimal effects on the pulse intensity and the spectral properties compared to lower pulse rates. Therefore, self-seeding is now ready for X-ray delivery to users in the upcoming run, and there are many users interested in this operation mode.

Further exploring the potential of self-seeding, a proof-of-principle experiment showed that second-harmonic radiation with improved longitudinal coherence could also be generated, reaching a photon energy of 18 keV. In addition, multiple self-seeded colours within the FEL bandwidth could be created

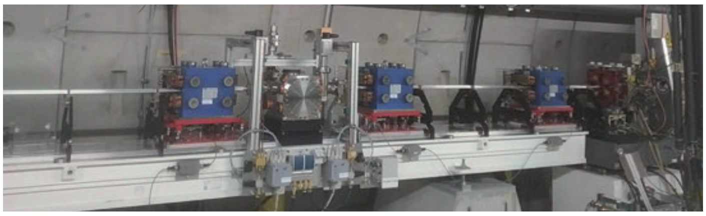


Figure 2

Hard X-ray self-seeding setup installed at the European XFEL simultaneously in the non-linear regime, indicating the generation of attosecond pulse trains [2]. These results demonstrate the power of the technique and suggest that we are still very much at the beginning of this journey through all that self-seeding has to offer.

Two colours

Splitting the undulator into two parts allows the generation of two distinct X-ray pulses with different colours. This two-colour operation mode is particularly useful for pump–probe experiments. Adding a scannable delay between the two pulses enables molecular movies to be created with both pump and probe pulses being high-intensity X-rays.

The two X-ray pulses are generated from the same electron bunch, which emits the first colour in the first undulator part (U1) and the second colour in the second undulator part (U2). To control the delay between the pulses, a chicane between the two undulator parts is used to adjust the arrival time of the electrons at U2 relative to the arrival time of the photons that were emitted in U1.

One of the major challenges is the zero-delay crossing, since the chicane can only delay electrons but not photons. This issue was overcome by selectively suppressing the lasing process in parts of the electron beam, so that the electrons from the rear of the bunch emit the first colour and the electrons from the front of the bunch the second colour. In this way, the pulse from the second undulator part will be in front of the pulse generated in the first undulator part, unless the electrons are delayed by the chicane (Fig. 3). In other words, initially there is a “negative” delay [3].

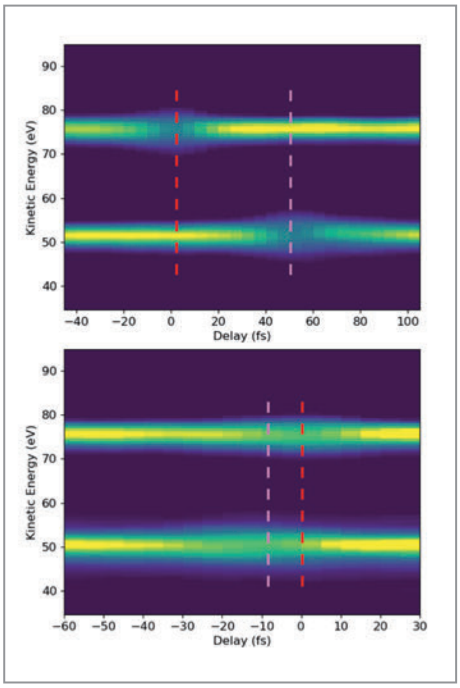


Figure 3
Zero-delay crossing of two X-ray pulses demonstrated through different delays of the electron chicane. The red line corresponds to the photons produced in the first undulator part, the purple line to the photons produced in the second undulator part. The relative optical delay was measured using photoelectron energy sidebands.

Harmonic lasing and frequency mixing

To extend the photon wavelength range of the European XFEL, techniques of harmonic lasing and frequency mixing have been investigated. The facility features a single linear accelerator serving multiple undulator lines. Therefore, parallel operation requires compromises in the choice of the electron energy, which translate into constraints on the wavelength that can be simultaneously offered to the users. These advanced techniques can be used to relax these constraints. Furthermore, while the tuneable-gap undulators allow for a wide tuning range of the photon energy at a given electron energy, even their reach is limited.

One approach to increase the photon energy is to use two colours that are harmonics of one another. The first undulator part, tuned to the fundamental wavelength, will create a bunching at both fundamental and higher-harmonic frequencies. The second part, tuned at one of these higher harmonics, will then only amplify the already existing higher X-ray photon energy while ignoring the fundamental. This allows an extension of the wavelength reach with only a few additional undulator segments suited to such high photon energies. For this purpose, four superconducting undulators are planned to be installed in one of the European XFEL undulator lines.

Proof-of-principle experiments at shorter wavelengths showed that the European XFEL has the required beam quality to achieve third-harmonic lasing at 1.5 keV. Relevant photon energies above 25 keV will require further R&D to quantitatively measure and cleanly transport the photon beam to the experimental hutches.

One way to decrease the photon energy, or increase the wavelength, is frequency mixing. The idea behind this technique is to alternate the undulator setting between two resonance frequencies. Non-linearities create a signal at the difference (and sum) in photon energies between the colours. An undulator used as an afterburner will then be able to further amplify this signal. Like harmonic lasing, this allows the photon wavelength range to be extended with only minimal hardware investment.

Several proof-of-principle experiments were conducted between 500 eV and 1100 eV, as first demonstrations of this technique in a SASE X-ray FEL

Contact: Marc Guetg, marc.guetg@desy.de
Shan Liu, shan.liu@desy.de
Gianluca Geloni, gianluca.geloni@xfel.eu

References:

[1] G. Geloni et al., J. Mod. Opt. 58:16, 1391–1403 (2011), doi: 10.1080/09500340.2011.586473
[2] S. Serkez et al., “Generating Trains of Attosecond Pulses with a Free-Electron Laser”, in Proc. FEL2019, Hamburg, Germany, 692–694 (2019), doi: 10.18429/JACoW-FEL2019-THP051
[3] M. W. Guetg et al., Phys. Rev. Lett. 120, 264802 (2018), doi: 10.1103/PhysRevLett.120.264802

Oscillator-amplifier seeded FEL

New option for a multi-MHz repetition rate externally seeded FEL

Free-electron lasers (FELs) can deliver fully coherent radiation with enhanced control thanks to external seeding techniques. One main aspect of these techniques is that they are heavily based on the characteristics of the external seed laser, which initiates the process and determines the characteristics of the final FEL radiation. While this means that coherence, stability and pulse characteristics are under control, the repetition rate and the wavelength cannot be tuned arbitrarily. To overcome this limitation, the combination of a seed laser with an optical cavity that facilitates recirculating the light pulses is being investigated at DESY. This relaxes the demands on the seed laser systems and enables considerably higher repetition rates in the multi-MHz range.

From SASE to seeding

FELs such as FLASH and the European XFEL provide tuneable X-ray radiation with wavelengths down to fractions of a nanometre for user experiments. The radiation is generated by self-amplified spontaneous emission (SASE), which is initiated by the random stochastic fluctuations of the electron distribution in the beam. The electrons follow a sinusoidal path in an undulator and individually emit radiation that is summed incoherently. After some distance, they self-organise in the longitudinal space (Fig. 1), so that the individual microbunches start to emit radiation coherently. The result is that the final FEL radiation has a high degree of transverse, but not longitudinal coherence. This is reflected in the resulting broad spectrum with various spikes (Fig. 2). One of the most promising methods to significantly improve the longitudinal coherence is the use of the seeding technique.

With seeding, the electron bunch is pre-shaped before entering the undulator in order to emit coherent radiation immediately. To do so, an intense laser pulse is overlapped with the electrons, and they travel together in a short undulator called a modulator (Fig. 3). As a result of the mutual interaction, the electron beam energy becomes periodically modulated. A chicane downstream of the modulator converts the energy modulation into a density modulation of the electron bunch. Finally, the bunch enters the undulator, which in this scheme is called an amplifier, and emits coherent radiation directly, as the microbunches formed in this process emit radiation in a correlated manner. The high degree of coherence exhibited by lasers can thus be transferred to the final FEL radiation, resulting in a single-spiked narrow spectrum that has more than 100 times the intensity of a single SASE spike (Fig. 2).

Repetition rate of the FEL radiation

While longitudinal coherence is an important figure of merit of the FEL radiation for many user experiments, the number of photon pulses generated per second can be crucial too. Each

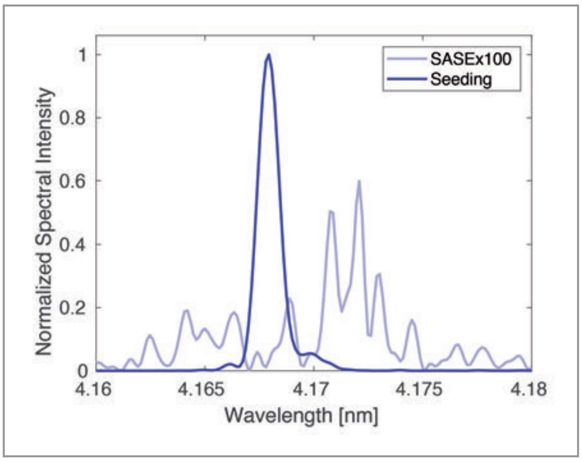


Figure 2

Comparison of the FEL radiation spectrum generated by SASE and seeding. The seeded FEL radiation consists of an intense single spike. In contrast, the SASE spectrum features several individual spikes that are more than two orders of magnitude less intense compared to seeding.

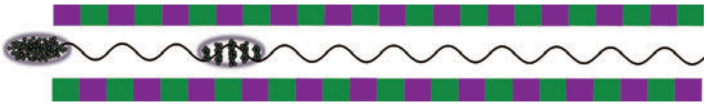


Figure 1

In the SASE process, an electron beam with randomly distributed electrons enters an undulator and follows a sinusoidal path. After a while, the electrons form periodic microstructures in the longitudinal space and can emit partially coherent radiation.

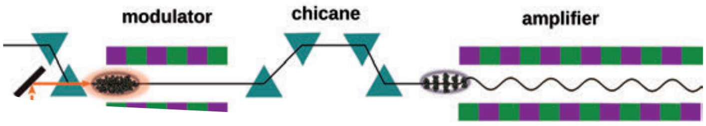


Figure 3

In seeding, the electrons interact with a seed laser in the modulator, allowing the chicane downstream to form microbunches. The bunched electron beam can then emit fully coherent radiation in the amplifier at the repetition rate of the seed laser.

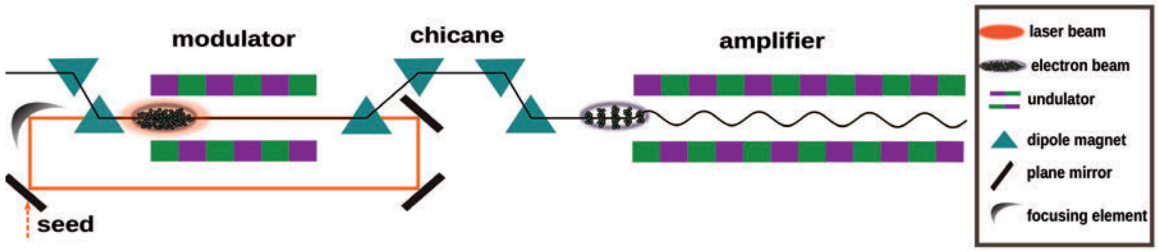


Figure 4

In a seeded oscillator amplifier, laser pulses are recirculating in a laser cavity. The advantage is that, using a low-repetition-rate laser compatible with existing technology as a source, laser pulses circulate in the oscillator with a high repetition rate that is not possible with the standard seeding shown in Fig. 3. This makes an externally seeded FEL with multi-MHz repetition rate possible.

electron bunch generates one photon pulse; therefore, it is important to ensure that:

- Each photon pulse is fully coherent.
- As many photon pulses per second as possible are generated.

The first aspect is fulfilled with seeding, while the second refers to the repetition rate. Currently, accelerators can deliver thousands of electron bunches per second at MHz repetition rates. For instance, FLASH currently provides up to 5000 SASE photon pulses per second to user experiments (up to 1 MHz bursts with a length of up to 0.8 ms at 10 Hz, serving two beamlines simultaneously).

For seeded operation, the maximum repetition rate is determined by the repetition rate delivered by the current seed laser technology. As an example, the currently installed laser of the Xseed setup at FLASH operates at 10 Hz and, therefore, only 10 electron bunches per second can be used for seeded operation. With the upcoming upgrade of FLASH within the FLASH2020+ project, it is planned to exploit a seed laser of 100 kHz in the first stage, with a final goal of 1 MHz. This repetition rate of the seed laser sets the ultimate upper limit for external seeding, and it drives the state of the art of seed laser sources.

Seeded oscillator amplifier: an option for high-repetition-rate seeding

In order to overcome the limitations induced by the seed laser repetition rate, the seeding technique can be combined with an optical cavity to recirculate the seeding light pulse (Fig. 4). In our case, an external seed laser pulse is first injected into the cavity where it is overlapped with an electron bunch. Now two processes occur: i) The electron bunch gets energy-modulated by the laser pulse, and ii) the laser pulse gets amplified thanks to the interaction with the wiggling electron bunch. While the modulated electron bunch can then be extracted from the cavity, the amplified laser pulse is recirculated to the entrance of the modulator. The following electron bunches are then overlapped with the recirculated light pulse and, when steady-state conditions are satisfied, they maintain the light pulse intensity constant over the bunch train while they get seeded. Downstream of the in-cavity modulator, the process for the electrons is the same as in the standard seeding shown in Fig. 3. Their energy modulation is converted into a density modulation in the chicane, and coherent emission is possible in the amplifier.

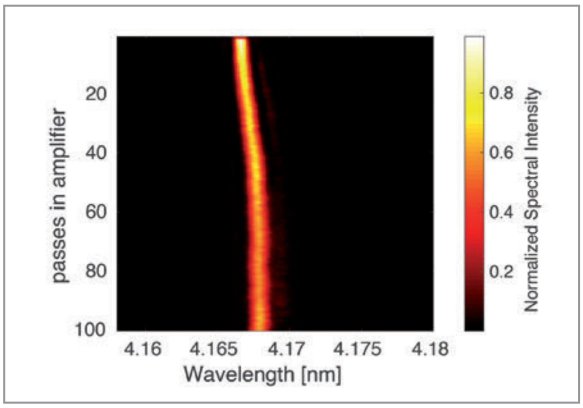


Figure 5

Spectra of 100 consecutive light pulses generated in a seeded oscillator amplifier. All successive electron bunches are seeded and generate spectra that consist of a single bright spike.

Simulation of high-repetition-rate seeded FEL pulses

Numerical simulations were implemented to verify the feasibility of this proposed high-gain harmonic generation (HGHG) seeding scheme. In this scheme, the seeded FEL radiation can be varied between 4.167 nm and 60 nm. The seeding process was evaluated for 100 consecutive electron bunches seeded by the light stored in the optical cavity. The final spectrum is bright with a narrow single spike as a result of the improved longitudinal coherence compared to SASE (Fig. 2). Figure 5 shows the evolution of the spectral intensity for all the 100 simulated passes. The spectrum is reasonably stable in wavelength and intensity, since all successive electron bunches are seeded.

The simulation results suggest that the seeded oscillator amplifier can generate fully coherent and high-repetition-rate seeded FEL radiation with a seed laser that is compatible with already existing technology. In this scheme, the repetition rate can be increased to match the electron bunch repetition rate without limitations, by simply adjusting the cavity length to achieve synchronism between the recirculated radiation pulse and the arriving electron bunches. This would allow FELs to offer seeded radiation even beyond the 1 MHz repetition rate of FLASH2020+. User experiments would greatly benefit from the high flux of fully coherent radiation in a wide range of experiments.

Contact: Georgia Paraskaki, georgia.paraskaki@desy.de
Lucas Schaper, lucas.schaper@desy.de
Enrico Allaria, enrico.allaria@desy.de

Two-colour operation of FLASH2

Preparing two-colour lasing for user operation

The FLASH2 undulator beamline at DESY's FLASH soft X-ray free-electron laser (FEL) facility comprises variable-gap undulators, which allow the application of advanced lasing concepts. Two-colour lasing is a popular operation mode of self-amplified spontaneous emission (SASE) X-ray FEL user facilities. At FLASH2, in 2020, a two-colour operation mode was tested and successfully used for a pilot experiment. The scheme, which is based on alternating tunes of the undulator segments, has several advantages compared to a more standard one based on the successive generation of two colours in two consecutive sections of the undulator line. First, the source positions of the two FEL beams are close to each other, making it easier to handle them. Second, the amplification is more efficient in this configuration since the segments with respectively "wrong" wavelength still act as bunchers. In addition, new methods for online intensity measurements of the two colours were developed at FLASH, and the simultaneous measurement of the spectral and temporal properties of two pulses with different wavelengths became possible.

Principle of two-colour lasing with alternating undulator gap tunes

The FLASH2 undulator beamline consists of twelve 2.5 m long tuneable-gap undulator segments. The lasing wavelength (colour) of a SASE FEL is defined by the undulator parameter *K*, which depends on the electron beam energy and can be controlled at FLASH2 by the undulator gap width. This tuneability allows the application of different lasing schemes and increases the parameter space. Some photon experiments require two different soft X-ray wavelengths. In the lasing scheme tested at FLASH2, in order to generate two colours, some undulator segments are tuned to one wavelength and the rest to the other one.

Compared to the frequency doubler scheme [1], which was also demonstrated at FLASH2, this scheme has the advantage that the two wavelengths can be chosen more independently from one another, which is important for many photon experiments. The two-colour lasing can be set up in different configurations, but a scheme based on alternating tunes, where all odd undulator segments are tuned to the wavelength λ_1 and all even segments to λ_2, was found to be beneficial. Figure 1 shows a schematic of this undulator configuration [2].

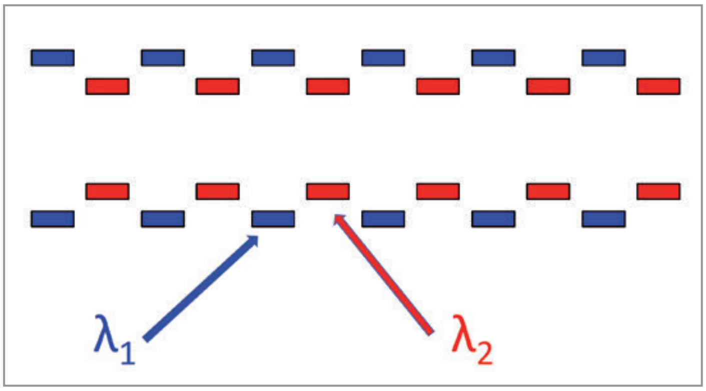


Figure 1

Tuning of the gaps of the undulator segments in the two-colour lasing scheme with alternating undulator tunes

With respect to the amplification of the electromagnetic wave with the wavelength λ_1, the FEL process is disrupted as soon as the electron beam leaves an λ_1 segment and enters a "wrong" segment tuned to the wavelength λ_2. However, energy modulations in the electron bunch, accumulated due to its interaction with the electromagnetic field in the λ_1 segment, continue to get converted into density modulations, which are the basis of the lasing process. Due to its longitudinal dispersion, the additional bunching in the λ_2 segment quickly radiates a stronger field than the one coming from the previous λ_1 segment, which is diffracted in addition, and the FEL process continues with higher amplitudes.

For FLASH2, this means that alternating the undulator tunes generates a higher pulse energy for both colours than tuning all segments at the beginning of the undulator to λ_1 and the last ones to λ_2. A further advantage of this scheme is that the source positions of the two colours are close to each other, which is important for the experiments using the two colours.

Operation of the two-colour scheme

The operation of the two-colour scheme requires a special control of the undulators, phase shifters and quadrupoles. The undulator control was modified for two-colour operation so as to assign to each undulator segment the wavelength λ_1

or λ_2. Thus, it was possible to adapt the corresponding undulator optics and correct the focusing effect of the undulator using the corresponding quadrupole magnets. An important feature of two-colour operation for many experiments is that both colours can be aligned independently on the same optical path. This alignment was successfully tested, and a setup procedure was established.

At an electron beam energy of 750 MeV, two-colour operation was performed for various wavelength combinations between 15 nm and 34 nm. Figure 2 shows a spectral measurement for one of the combinations (24.3 nm and 25.8 nm) using a grid spectrometer.

In addition, the photon diagnostics needed to be adapted to this special operation mode. The photon pulse energy is measured using different gases in X-ray gas monitor detectors (XGMDs) with known cross sections for λ_1 and λ_2. For an exact measurement using this system, it is important to identify the transmission value from the XGMD located in the accelerator tunnel to the one in the experimental hall independently for both colours. The determination of the transmission is a touchy process since the bunching effect needs to be preserved while detuning one wavelength.

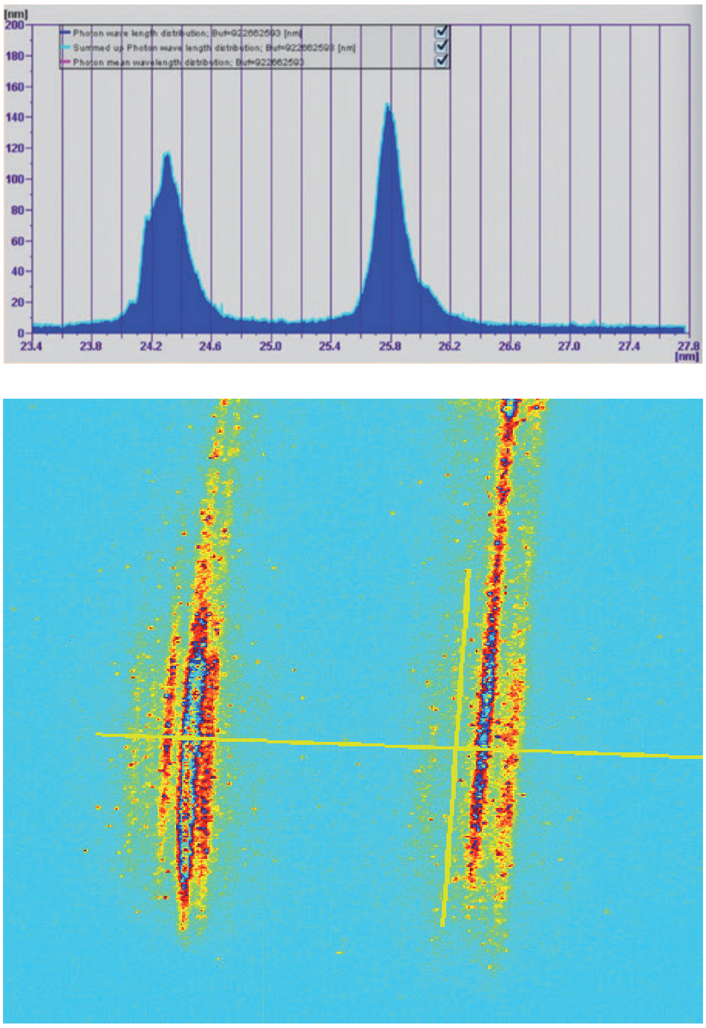


Figure 2

Spectral measurement of two-colour lasing using a grid spectrometer: spectral distribution (top) derived from the camera image of the spectrometer (bottom)

The implementation of the two-colour mode in the FLASH XGMD software was successfully commissioned and tested, as was the ability to scan wavelengths. The online photoionisation spectrometer's (OPIS) two-colour tool performed extremely well, but it is very specific and has to be adapted after parameter changes. A separate adjustment of the photon beam intensity was implemented, and an online measurement tool of the SASE pulse energy of both colours was developed, in which XGMDs and OPIS are linked.

Pilot user experiment

In September 2020, a pilot photon experiment, which analysed the L2-edge of a silicone membrane using the two colours generated with the scheme based on alternating tunes, was successful performed. The photon energies of about 126 eV (corresponding to a wavelength of about 10 nm) and 96 eV (about 13 nm) were produced using electron bunches with a beam energy of about 1100 MeV. The 10 nm pulses were used to excite the sample, while the 13 nm pulses served as probes.

The saturation length for 10 nm is longer than for 13 nm. To achieve a reasonably equal photon pulse energy for both wavelengths, seven undulator segments were tuned to 10 nm and five segments to 13 nm. Although the photon wavelength of the pump pulse was optimised for 13 nm, it could be scanned from 9.9 nm to 13.75 nm. Both colours were focused onto the experimental interaction region. A pulse duration shorter than 50 fs for both colours was required for successful performance. The pulse duration was determined to be (40 ± 10) fs for both colours using the THz streaking technique. To achieve such short pulses, electron bunch charges below 100 pC were used.

Contact: Juliane Rönsch-Schulenburg,
juliane.roensch@desy.de
Evgeny Schneidmiller, evgeny.schneidmiller@desy.de

References:

[1] M. Kuhlmann, E. A. Schneidmiller, M. V. Yurkov, "Frequency doubler and two-color mode of operation at free electron laser FLASH2", Proceedings of IPAC2017, Copenhagen, Denmark (2017)
[2] E. A. Schneidmiller, M. Braune, B. Faatz, F. Jastrow, M. Kuhlmann, A. Sorokin, K. Tiedtke, M. V. Yurkov, "Two-color operation of FLASH2 undulator", Proceedings of FEL2019, Hamburg, Germany (2019)

FLASH2020+ injector upgrade

First upgrades to the FLASH accelerator for brighter electron beams

The FLASH2020+ project to upgrade DESY's FLASH free-electron laser (FEL) facility consists of several stages, of which the injector upgrade will be realised first. The aim of this stage is to enhance the capability of the injector to reproducibly provide electron bunches of highest brilliance at an increased energy of about 550 MeV. In addition, the injector must be capable of simultaneously enabling high-gain harmonic generation (HGHG) and echo-enabled harmonic generation (EEHG) seeding at the FLASH1 beamline as well as self-amplified spontaneous emission (SASE) at the FLASH2 beamline. The three key ingredients to achieve this goal are installing a laser heater, replacing the two oldest accelerator modules by state-of-the-art European XFEL-type modules and rebuilding the second bunch compression section.

Low-energy injector part with laser heater

The present injector lasers will be replaced by a new, versatile and up-to-date laser system that will be better maintainable. The radio frequency photocathode electron source (RF gun), the initial superconducting 1.3 GHz accelerator module, the third-harmonic compression lineariser and the adjacent normal-conducting feedback cavity will stay in their present configuration. The new laser heater section (Fig. 1) will start directly downstream of the feedback cavity.

An efficient high-gain FEL process requires electron bunches of both high transverse and high longitudinal charge density. Such bunches cannot be maintained at low energy starting from the cathode. Instead, the bunches are created with moderate longitudinal charge density at the gun and compressed later in successive stages during acceleration. The compression mechanism employed at FLASH facilitates longitudinal dispersion, which is generated in magnetic bunch compression chicanes.

However, in each compression stage, this mechanism supports an unwanted effect. Coherent collective forces potentially generate energy modulations inside the bunch, driven by small initial density modulations. These energy modulations in turn drive density modulations via the dispersion of the chicane. The initial modulation at certain wavelengths can thus be amplified, a process that is referred to as microbunching. Unfortunately, microbunching typically occurs at early stages in the accelerator and at unwanted wavelengths, thus potentially degrading the FEL performance. The degradation is particularly harmful for the delicate beams needed for seeded FEL operation.

A laser heater, located upstream of the first compression chicane, generates a controllable energy modulation at a wavelength that is short enough to be strongly overfolded in the downstream chicane. It thereby produces a controlled amount of uncorrelated energy spread. This energy spread can be optimised so as to blur the energy modulation caused

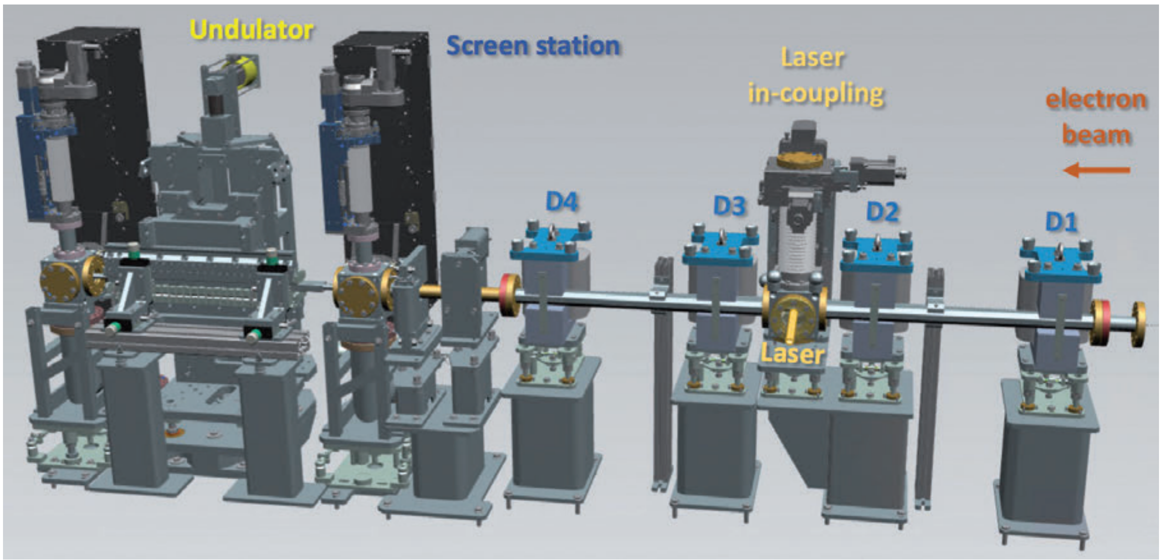


Figure 1

Layout of the new laser heater section for the suppression of microbunching effects

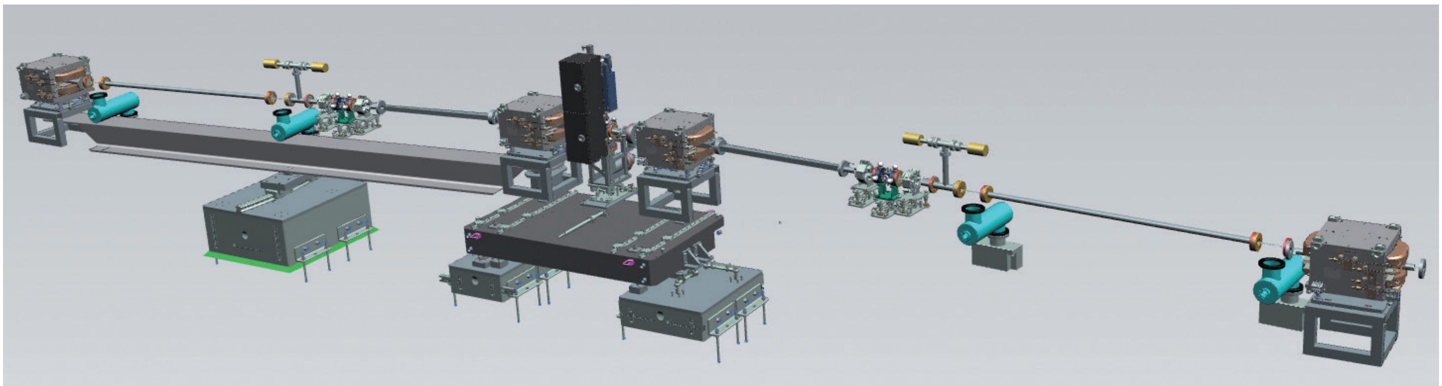


Figure 2

CAD drawing of the new second bunch compression chicane with movable chicane legs and quadrupole / beam position monitor / skew quadrupole units for correcting longitudinal–transverse correlations in the centre of each leg

by the coherent interaction that drives the microbunching. The laser heater thus supplies a means of mitigating the otherwise unavoidable microbunching gain.

The layout of the laser heater section (Fig. 1) follows the original proposal, first published almost 20 years ago, and differs in some aspects from the common layout implemented at many other FEL facilities. For instance, a dedicated laser system will be used to generate laser pulses at a comparatively short wavelength of 532 nm, which allows efficient suppression of the microbunching gain. The laser will be coupled into the accelerator beamline and deflected by 90° onto the nominal electron beam axis using an in-vacuum mirror. A short four-dipole chicane (denoted D1–D4 in Fig. 1) will be used to guide the electron beam around the in-vacuum mirror. Two screen stations equipped with Chromox scintillation screens will enable the simultaneous measurement of the laser and electron beam to achieve a spatial overlap of both beams in a short tuneable-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 an energy modulation on the electron bunch, which will develop the desired energy spread for suppression of the microbunching gain in the subsequent compression chicane. The amount of induced energy spread can be controlled by the laser power.

The control of the electron beam optics is crucial for best FEL performance. The installation of the laser heater requires a shortening of the beam diagnostic section downstream of the first chicane. In order to maintain the capability to match the space-charge-dominated beam from the RF gun into the optics of the downstream beamline, the magnetic lattice supports two different optics: one for transporting the beam through the linear accelerator in normal FEL operation and a measurement optics for matching. In matching mode, a five-screen beam optics reconstruction with 150° phase coverage is possible, as are (multi-)quadrupole scans.

The two oldest accelerator modules (Number 2 and 3) will be replaced by refurbished, modern modules initially designed as prototypes for the European XFEL. Together with an optimised waveguide distribution system, the new modules will provide an energy upgrade from 1.25 GeV to 1.35 GeV.

Medium-energy injector part with modified second compression chicane

The current beamline with the second bunch compression chicane does not allow a rematching of the optics before feeding the electron bunches into the main linear accelerator and the subsequent FEL beamlines. In order to enable rematching, the new design reserves space to build up the betatron phase advance required for measuring the beam parameters using a multiquadrupole scan. To achieve this, the new second chicane (Fig. 2) was designed to be 3.5 m shorter than the old one. It will be equipped with quadrupoles and skew quadrupoles in the legs on each side of the chicane. These magnets can be used to compensate linear correlations between the longitudinal and transverse degrees of freedom by employing the transverse dispersion inside the chicane and the energy chirp of the bunch. Quadrupoles, on the other hand, have a circular bore and do not work well with the usually flat vacuum chambers in chicanes. In order not to compromise the flexibility of the compression parameters, round, movable vacuum chambers and movable dipoles on rails will be installed.

Most of the electron diagnostics installed at FLASH have already been upgraded in recent years. For the injector upgrade, the screen stations will be replaced with a modern type, compatible with the ones installed at the European XFEL and at the FLASH2 beamline. The stations are based on optical transition radiation screens and achieve a resolution of 10 μm for most electron beams.

Contact: Mathias Vogt, mathias.vogt@desy.de

Arrival time stabilisation at FLASH

Using a normal-conducting bunch arrival corrector cavity (BACCA)

For seeding and pump–probe experiments at free-electron lasers (FELs), femtosecond-precise arrival time stability of the electron bunches is mandatory. At DESY's FLASH FEL facility, a longitudinal intra bunch train feedback (L-IBFB) regulates the arrival time, measured by a bunch arrival time monitor (BAM), with femtosecond resolution. To compensate fast arrival time fluctuations within a bunch train, the electron energy is modulated by the accelerator's superconducting radio frequency (SRF) cavities ahead of a bunch compression chicane. In 2020, a novel broadband normal-conducting RF cavity was installed in front of the first bunch compression chicane, which is used as a fast energy corrector cavity. First measurements show arrival time stabilities of the electron bunches down to 5 fs (RMS) at the exit of the linear accelerator if the normal-conducting cavity acts together with the SRF cavities in the L-IBFB system.

Introduction

Femtosecond synchronisation between external lasers and FEL pulses is required e.g. for pump–probe experiments. To stabilise the arrival of the FEL photon pulses, an L-IBFB system adjusts the electron bunch energies in front of a magnetic bunch compression chicane, which introduces an energy-dependent path length. The relative arrival times of the electron bunches, with a bunch-to-bunch spacing of up to 1 MHz, are measured by BAMs against a femtosecond-stable optical reference system that is also used to precisely synchronise the external lasers.

A low-level radio frequency (LLRF) controller regulates the 1.3 GHz RF field of the SRF cavities in amplitude and phase. The LLRF controller provides different control strategies, e.g. a second-order multiple-input multiple-output (MIMO) feedback controller to react within a bunch train and a learning feedforward controller to minimise the repetitive control error from one bunch train to another bunch train. A combination of beam-based measurements, e.g. the arrival time, and field information is included in the LLRF control strategy and used by the L-IBFB to stabilise the arrival time. Since SRF cavities typically have only a few 100 Hz bandwidth, a short normal-conducting bunch arrival corrector cavity (BACCA) was installed to allow for small but fast energy corrections in order to push the arrival time stability down to 5 fs (RMS).

Longitudinal intra bunch train feedback at FLASH

The schematic in Fig. 1 shows the FLASH facility with the SRF accelerator modules, diagnostic units and the laser-based reference synchronisation system. BACCA is located in front of the first bunch compression chicane (BC1). The beam-based feedback strategy at FLASH includes three feedback loops (denoted "FB" in the green boxes in Fig. 1). The arrival time measurement of the BAM after BC1 (BAM.1) is used to stabilise the arrival times. The RF field of the SRF module ACC1 is modulated for slow corrections (< 40 kHz), the RF field of BACCA for fast corrections (40 kHz to 250 kHz). In addition, a second beam-based feedback loop regulates the RF field of the SRF modules ACC2 and ACC3 to stabilise the arrival times after the second bunch compression chicane (BC2) using a third BAM (BAM.2) as sensor.

The arrival time measurement of the very first BAM (BAM.0) shows the incoming arrival time jitter from the injector, but is not influenced by the L-IBFB. Accelerator modules after the second bunch compression chicane increase the beam

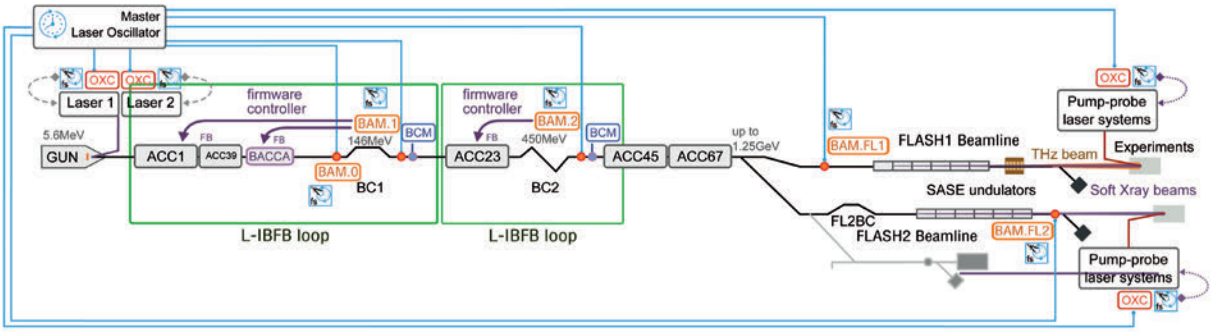


Figure 1

Scheme of FLASH with the different L-IBFB locations, the superconducting modules (ACC), the normal-conducting BACCA cavity, the diagnostic units and the distribution of the optical synchronisation system

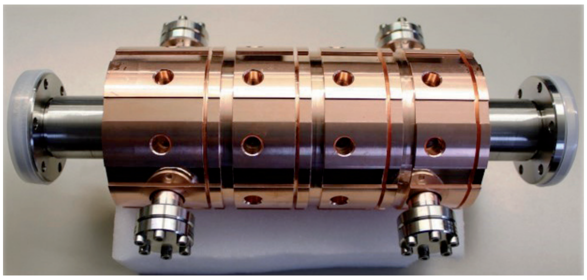


Figure 2
The bunch arrival corrector cavity (BACCA)

energy, but have no influence on the arrival times for the FLASH1 beamline. The readout electronics of the LLRF control system and the BAMs are based on the MicroTCA.4 electronics standard. Real-time data processing of the L-IBFB is carried out on field-programmable gate arrays (FPGAs) of both the diagnostic unit and the controller unit. The measured arrival time is transmitted via an optical low-latency link to provide the data from the diagnostic unit to the controller with low latency.

BACCA is a four-cell normal-conducting cavity. Fig. 2 shows a picture of the cavity, which is installed after the third-harmonic accelerator module (ACC39). To keep the length of the cavity short, due to the limited beamline space, the cavity operates at 2.9972 GHz. The main design requirements are a maximum feedback loop latency of 700 ns, an energy correction of about ±50 keV and a cavity half bandwidth of 500 kHz. The cavity is driven by a 1 kW solid-state RF amplifier. To drive the input, a MIMO controller with proportional integral (PI) properties is used.

The BAMs provide the arrival time bunch by bunch with low latency. The main elements of a BAM are an RF pickup, an electro-optical modulator and a data acquisition unit. Four pickups are used to capture the electromagnetic field induced by an electron bunch. Timing-stabilised laser pulses are provided by the optical synchronisation reference system for the electro-optical unit. The RF signal from the pickup modulates the reference laser pulses so that the strength of the modulation is proportional to the arrival time variations of the electron bunches. The reference laser pulses also drive the clocks for the data acquisition system. The optimisations and developments of the past years for the BAMs and for the laser-based synchronisation system have led to a resolution in the sub-10 fs range.

Measurement results

The measurement data were taken with 400 bunches per bunch train, a bunch repetition rate of 1 MHz and a charge of 0.4 nC. The repetition rate of the bunch trains was 10 Hz. All measurement results are related to the FLASH1 beamline. The L-IBFB was activated for the SRF module ACC1 together with BACCA and the SRF module ACC23.

Figure 3 shows the mean free arrival time measured by BAM.2 after the second chicane. The grey lines are the measured arrival times of 600 subsequent bunch trains. The arrival times of two highlighted bunch trains, #100 and #550, are shown as examples. The green dashed lines represent the standard deviation of the 600 bunch trains for every bunch. Due to time delays and limited closed-loop controller bandwidth, the first bunches cannot be controlled, so the arrival time jitter at the beginning of the bunch train is comparable only to the RF accelerator field control. These values can be used as reference and give an impression of how the L-IBFB significantly reduces the peak-to-peak value of the arrival time from bunch to bunch (grey lines) and thus minimises the arrival time jitter (green dashed lines).

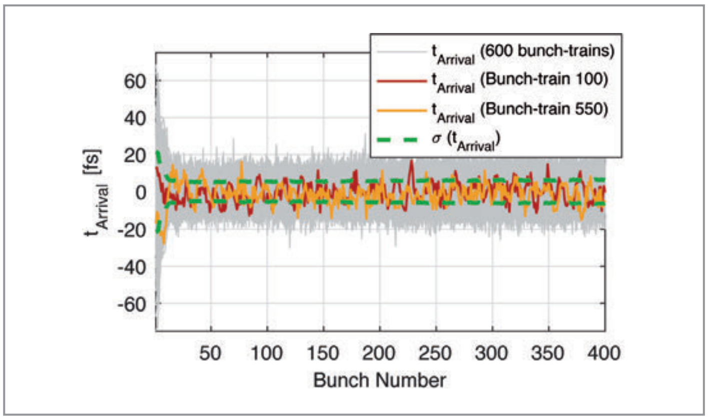


Figure 3
Mean free arrival time after the second bunch compression chicane (measured by BAM.2) and standard deviation of the arrival time of 600 bunch trains

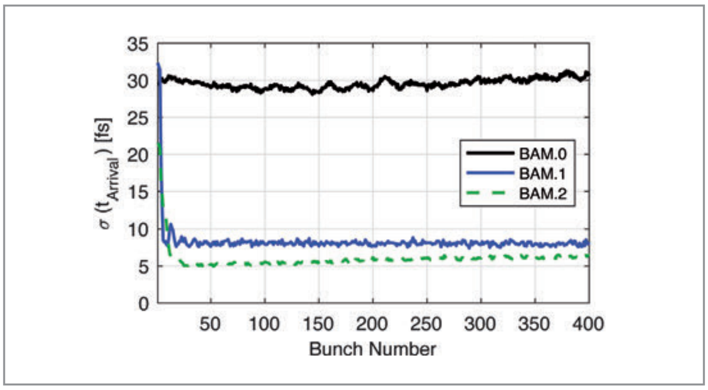


Figure 4
Standard deviations of the arrival time of 600 bunch trains (BAM.0, BAM.1 and BAM.2)

Figure 4 shows the changes in the arrival time jitter along the accelerator. BAM.0 (black solid line) indicates an incoming arrival time jitter of around 30 fs (RMS). After the first bunch compression chicane, the arrival time jitter is pushed down to around 8 fs (RMS) by the L-IBFB at ACC1 together with BACCA (BAM.1, blue solid line). BAM.2 (green dashed line) shows the results if the three feedback loops operate together. The arrival time stability increases significantly from 22 fs (RMS) down to 5 fs (RMS) at the beginning of the bunch train, with a slight increase along the bunch train. This results in a mean arrival time stability of the entire bunch train of around 6 fs (RMS), which corresponds to an increase in stability by a factor of 3.5 compared to the first bunches.

Contact: Björn Lautenschlager,
bjoern.lautenschlager@desy.de

PolariX TDS at FLASH

Commissioning with beam at FLASHForward and new structures for FLASH2

In 2019, a prototype of a PolariX transverse deflecting structure (TDS) was installed in the beamline of the FLASHForward plasma wakefield acceleration experiment at DESY's FLASH facility. Using this device, a direct measurement of both the longitudinal phase space density and the longitudinal current profile of an electron bunch in any transverse plane is possible. In addition, it also enables advanced measurements such as the 3D charge density of the bunch. Since the installation of this novel cavity, a lot of effort has been put into commissioning the structure in various measurement campaigns. The FLASHForward TDS is now routinely used in the setup of plasma wakefield experiments. Additionally, two new structures for the FLASH2 beamline were constructed and arrived at DESY in late 2020. They were installed downstream of the FLASH2 undulators in early 2021 to enable online measurements of the photon pulse duration at FLASH2.

The PolariX TDS

The PolariX TDS (Polarizable X-band Transverse Deflection Structure) project is a collaboration between CERN, PSI and DESY [1]. Within the scope of this project, a novel design for a TDS was developed and a prototype was built, which was installed in the FLASHForward beamline in 2019 [2].

TDSs are used in accelerators to impose a transverse streak on the electron bunch. This streak is correlated to the longitudinal position of the individual electrons within the bunches, such that a direct measurement of their longitudinal coordinate is possible. While standard TDS cavities are confined to a streak in a predefined direction through the introduction of a controlled defect into the cavity design, the PolariX TDS offers the possibility to streak the bunch in arbitrary transverse directions by removing this defect and controlling the polarisation with a phase shifter.

This is a desirable feature, as one cannot assume axial symmetry after bunch compression in FLASH due to coherent synchrotron radiation (CSR) influencing predominantly the horizontal plane. Such an assumption would quickly run into trouble given the interaction of the bunch with the kT/m focusing fields produced in plasma at FLASHForward, which would rapidly amplify any asymmetries in the beam. To study all these influences, it is therefore of the utmost importance to be able to measure more than just the longitudinal coordinate with respect to a single transverse plane.

Since the successful radio frequency (RF) conditioning of the PolariX TDS at FLASHForward, many measurement campaigns have been conducted to test all the features of the system and enable operation during regular FLASHForward shifts [3]. In 2020, the cavity was routinely used to reliably set up the beam for plasma wakefield experiments [4].

Two additional structures were produced for installation at FLASH2 and arrived at DESY in December 2020, ready to be installed in the winter shutdown 2020/21.

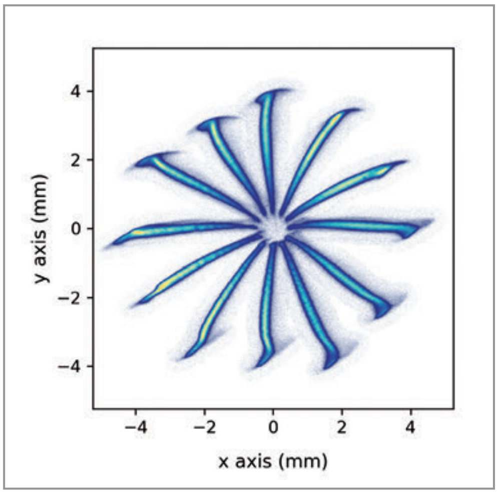


Figure 1
Image of electron bunches streaked at 12 different angles using the PolariX TDS at FLASHForward

Variable streaking direction

The key feature of the PolariX TDS is, as previously mentioned, the possibility to streak the bunch in arbitrary transverse directions. This enables the observation of *x*–*z* as well as *y*–*z* space. With this functionality, it is possible to measure the slice emittance in both planes using just a single cavity. Additionally, a tomographic reconstruction of the 3D charge density is possible.

Figure 1 shows the screen images of consecutive electron bunches streaked in 12 different directions, with the tail of the bunch in each case artificially located close to the origin of the coordinate system. In principle, it is possible to produce nearly continuous streaking, only limited by the RF stability and the step motor moving the RF components.

Longitudinal phase space density

To image the longitudinal phase space density (LPSD), the streak produced by the PolariX TDS is combined with a dipole that deflects the bunch perpendicular to the streaking direction. Figure 2 shows an example LPSD. In this case, the electron bunch was bisected into a bunch pair using a scraper system located in a dispersive section of the FLASHForward beamline. By previously introducing an energy chirp to the beam, the transverse coordinate in the dispersive section relates to the longitudinal one. A wedge is then moved in to block the electrons in the central part of the bunch, resulting in the shown LPSD. Such a bunch pair can then be used for plasma wakefield experiments, with the first bunch acting as a wakefield driver and the second as a witness to the driven plasma wakefields. This shows how crucial such a device is to the reliable setup of plasma wakefield experiments requiring micrometre-level precision. With a direct measurement of the LPSD, it becomes possible to precisely shape the bunch pair, paving the way for exciting, new science.

3D tomography

The novel feature of variable polarisation opens up new opportunities for measurements. By streaking bunches at different angles (Fig. 1) and combining them with tomographic reconstruction, it is possible to reconstruct the 3D charge distribution of the beam [5].

During the commissioning of the FLASHForward TDS in 2020, a lot of effort was dedicated to data taking at different working points for 3D tomography. Figure 3 shows the result of a tomographic reconstruction. As can be seen, in the vertical plane the bunch is rather straight. In the horizontal plane, however, the aforementioned influence of CSR is clearly visible: The bunch has acquired a banana-like shape and the head of the bunch has increased in size. These observations helped to deepen our understanding of the underlying beam dynamics in the FLASH accelerator.

PolariX structures for FLASH2

The next stage of the project was to equip FLASH2 with two PolariX cavities to directly measure the bunch length and indirectly measure the photon pulse duration [6]. The resolution of the measurement using a TDS is mainly influenced by two parameters: the beam optics and the total deflecting voltage. At FLASH2, it is necessary to measure the longitudinal coordinate with a resolution better than 5 fs. Due to the constraints of a pre-existing beamline, there are limited possibilities to change the beam optics in the undulator area. Therefore, to maximise the deflecting voltage, it was decided to use two PolariX TDSs to reach this goal. Additionally, a barrel-open cavity (BOC)-type pulse compressor was integrated into the RF system to further boost the resolution. This BOC will enable the compression of the RF pulses, increasing the input power (resolution) by a factor of 4 (2).

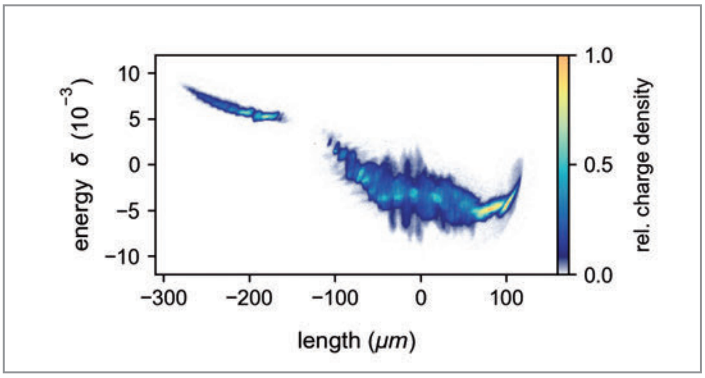


Figure 2

Longitudinal phase space density of an electron bunch. The bunch is scraped in the central part to be used for plasma wakefield experiments.

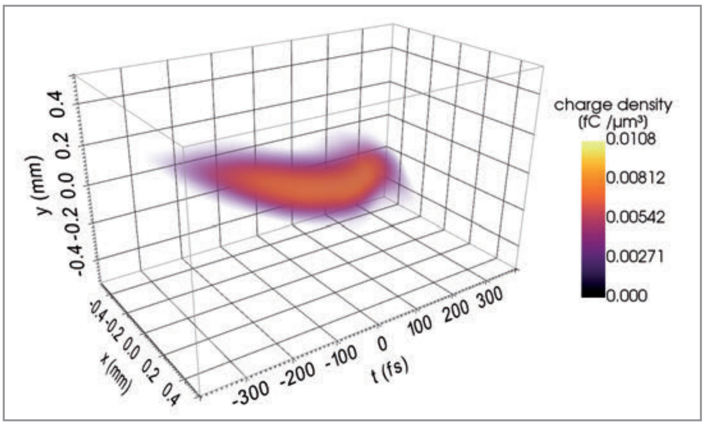


Figure 3

3D tomographic reconstruction of the charge distribution of an electron bunch, using the images in Fig. 1

In preparation for this installation, the FLASH2 beamline downstream of the undulator section underwent a significant design change in summer 2020. This redesign included the integration of new magnets, a beam kicker and a new screen station, as well as the clearing of space for the new structures. Both structures arrived at DESY in late 2020 (Fig. 4) and were installed in the FLASH2 beamline in the winter shutdown 2020/21. Commissioning has started with first promising results. The goal is to have both structures operational for experiments in summer 2021.

Contact: Florian Christie, florian.christie@desy.de
Pau González Caminal, pau.gonzalez@desy.de
Richard D'Arcy, richard.darcy@desy.de

References:

[1] P. Craievich et al., Phys. Rev. Accel. Beams 23, 112001 (2020)
[2] R. D'Arcy et al., Philos. Trans. R. Soc. A 377, 20180392 (2019)
[3] B. Marchetti et al., Sci. Rep. 11, 3560 (2021)
[4] C.A. Lindstrøm et al., Phys. Rev. Lett. 126, 014801 (2021)
[5] D. Marx et al., Sci. Rep. 9, 19912 (2019)
[6] F. Christie et al., Proc. FEL2019, WEP006 (2019)

Measuring the wake

FLASHForward enters state of precision operation

Plasma wakefield acceleration schemes have received much interest over the last decades due to their inherently large accelerating gradients on the GV/m level. Important milestones within the research field are the optimisation of the transfer of energy during acceleration as well as the preservation of high beam quality, which both depend on the exact nature of these GV/m electric fields. A wakefield measurement technique is therefore needed that is suitable to support the process of acceleration optimisation through precise field tailoring. At the FLASHForward plasma wakefield acceleration experiment at DESY's FLASH facility, such a method has been developed, which is particularly powerful due to its operational simplicity and femtosecond resolution. The unique insights this technique reveals herald a new era of beam-driven plasma wakefield acceleration: precision operation.

Plasma wakes and their shapes

Beam-driven plasma wakefield acceleration is a promising avenue of exploration for future particle accelerators, holding the potential to reduce their size by orders of magnitude and by that also the associated costs. The fundamental capability to accelerate particles with high efficiency as well as high average power while maintaining exquisite beam quality makes this technology particularly interesting for future high-energy accelerator facilities. Following the demonstration of the basic concept, the research focus is rightly shifting towards beam quality control.

The resulting energy spectrum and the efficiency of the acceleration process strongly depend on the shape of the wakefield. As a result, and similarly to conventional accelerator structures, the control and optimisation of the acceleration are fundamentally linked to the ability to fine-tune the wakefield structure. A prerequisite for this is the ability to measure the wake. The challenge is that, unlike with conventional accelerators, the small size of the plasma cavity requires diagnostic tools with femtosecond resolution.

How to sample the wake

During the interaction with the plasma, a characteristic energy distribution is imparted on the original longitudinal phase space of the incident electron bunch (Fig. 1). In principle, the plasma-accelerated bunch contains complete information about the wakefield with which it has interacted: The head of the bunch transfers its energy to the wake; the rear extracts the energy from the wake. Measuring the energy spectrum of an electron beam is a simple task; the challenge to overcome is to extract the timing information. For this purpose, the newly developed technology [1] uses the ultrarelativistic property of the electron beam: Removing the tail of the bunch does not alter the wakefield in front of the cut. The wakefield measurement principle then becomes: Remove the bunch tail gradually and observe the corresponding change in the energy spectrum of the outgoing bunch.

The achievable time resolution now depends on the ability to precisely remove the bunch tail. This can be realised by using a linearly chirped bunch, in which the longitudinal positions of the particles within the bunch are linearly correlated to their

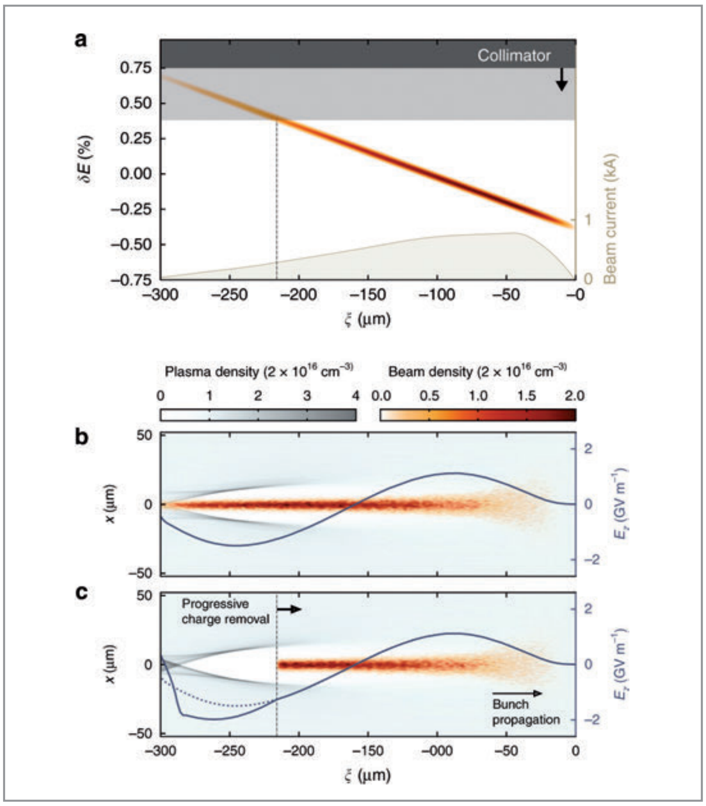


Figure 1

Wakefield sampling method. (a) The energy collimation of a linearly chirped bunch enables effective bunch tail cutting. (b) The beam–plasma interaction imprints an energy spectrum onto the phase space of the incident bunch that is characteristic for the wakefield shape. (c) By causality, the wakefield experienced by the bunch remains unaltered by removing the bunch tail. The removed charges experienced the original wakefield. [1]

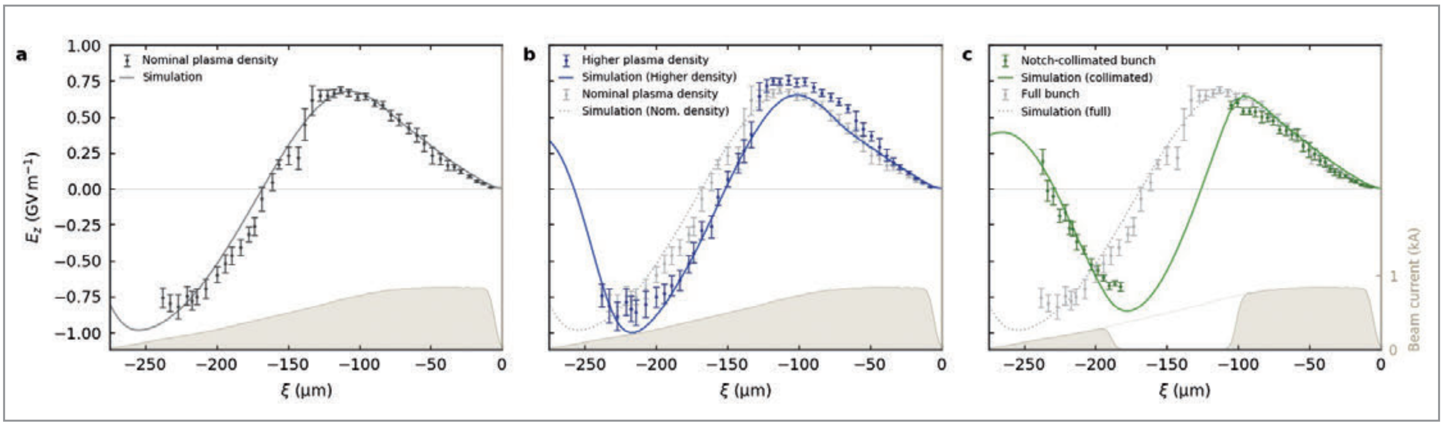


Figure 2

Experimental results. (a) The wakefield of the nominal beam and plasma is sampled with a 6 µm granularity. Error bars represent the shot-to-shot standard deviation. The solid line shows the corresponding particle-in-cell (PIC)-simulated wakefield. (b) The measurement is repeated with the same beam current profile and an 80% higher plasma density, producing a shorter-wavelength wakefield. (c) At the nominal density (same as in (a)), the beam current is notch-collimated into a double-bunch profile, producing a wakefield that is identical at the head, but strongly altered at the tail of the bunch. [1]

energy. In a transversely dispersive section, i.e. a magnetic chicane, the energy and thus also the effective longitudinal position within the bunch are translated to an offset in the transverse plane of the beamline.

At FLASHForward, an advanced collimator device has been developed and installed in such a dispersive section for sophisticated beam current manipulation [2], which also allows for effective bunch cutting from the tail (Fig. 1a). The temporal measurement of the wakefield is now reduced to a high-resolution calibration of the collimator position to an effective longitudinal intra-bunch position, which must be carried out only once and prior to the wakefield optimisation campaign. The advantage of this technology is evident: The generally challenging femtosecond-resolution measurement is completely decoupled from the relatively simple measurement of the energy spectrum. Furthermore, the time measurement is outsourced to a calibration procedure of the collimator that can be performed with the non-interacting electron bunch.

FLASHForward gets precise

To measure the plasma wakefield in its entirety, a bunch was used that fills all phases of the plasma cavity. Plasma wakefields with GV/m-level amplitudes were measured whilst achieving a resolution of 15 fs (Fig. 2a). Thanks to the robustness of the developed measurement technique, the change in the wakefield shape – which depends on the plasma and beam parameters – could be investigated for the first time.

The increase in plasma density leads to the expected decrease in size of the plasma cavity (Fig. 2b). The reduction in charge load after the peak decelerating phase drastically changes the wakefield shape and, in particular, reduces the size of the plasma cavity too. This is the first direct observation of the underlying effect of beam loading in plasma wakefields. Simulations performed for this broad constellation of beam and plasma parameters demonstrate strong agreement with the data, which is only possible through precise modelling of the experimental environment.

Simulations become reality

Confirming precision measurements with simulations requires careful modelling of the experimental environment. Consequently, an unparalleled effort was made to determine both the beam properties and the plasma properties at the time and location of the interaction. The plasma density profile along the acceleration path was accurately examined in a test stand [3]; the full 6D phase space of the electron bunch at the entrance of the plasma channel was inferred using a combination of different diagnostic tools, one of which was recently developed and prototyped at FLASHForward [4]. This new understanding of the experimental setup resulted in a huge advance in agreement between experiment and simulation, with the method becoming the blueprint for the precision modelling of the beam–plasma interaction at FLASHForward in the future.

This newly developed wakefield measurement technique is now routinely used at FLASHForward for a simple and quick feedback on the qualitative status of the acceleration process, it accompanies the common optimisation of the acceleration process and is ultimately used for the quantitative precision measurement of the plasma wakefield. The path towards the ultimate stage of a high-gradient, highly efficient and quality-preserving beam-driven plasma wakefield accelerator is paved!

Contact: Sarah Schröder, sarah.schroeder@desy.de

References:

[1] S. Schröder et al., Nat. Commun. 11, 5984 (2020)
[2] S. Schröder et al., J. Phys. Conf. Ser. 1596, 012002 (2020)
[3] J. Garland et al., preprint, arXiv:2010.02567 [physics.plasm-ph] (2020)
[4] C. A. Lindstrøm et al., Phys. Rev. Accel. Beams 23, 052802 (2020)

PLASMED X

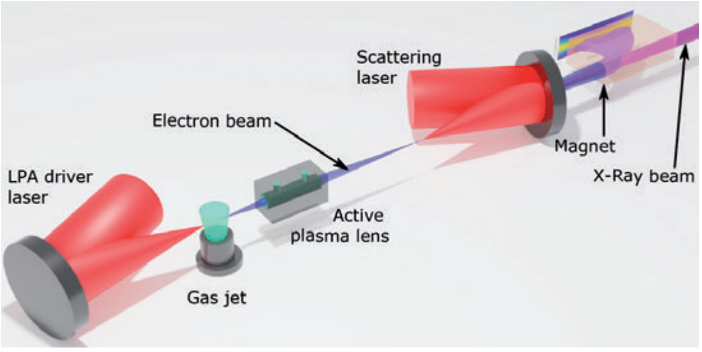
Compact plasma-based X-ray source for novel imaging applications

PLASMED X is a demonstration setup at DESY of a compact, all-optical source of bright and hard X-ray beams suitable for X-ray fluorescence imaging (XFI). A laser plasma accelerator is used as an electron beam source, with a fraction of the 25 TW drive laser energy used to Thomson scatter off the generated electron beam to produce X-rays. The use of active plasma lenses allows for limiting the bandwidth of the generated X-ray beam. The setup has been commissioned, and many milestones, such as the demonstration of long-term robust operation of the laser plasma accelerator, the demonstration of narrowing of the width of the energy spectrum of the X-ray beams and the measurement of the fluorescence signal, have been completed, setting the stage for the demonstration of XFI with the PLASMED X source.

The PLASMED X project

X-ray imaging is a standard diagnostic tool nowadays, with billions of examinations performed every year. However, as every single scan involves exposing the patient to ionising radiation, there is a constant drive to reduce the dose delivered to the patient while extracting as much diagnostic information as possible. The promising technique of XFI, which allows for a reduced dose deposited in the patient while boasting high spatial and temporal resolution, has recently been studied in more detail with the participation of DESY scientists [1].

XFI involves imaging the distribution of functionalised nanoparticles inside the patient by exciting the nanoparticle material with X-ray radiation around its K-edge (81 keV for gold, 50 keV for gadolinium) and then measuring the fluorescence signal. The X-ray absorption coefficient is lower at such high X-ray energies, which can result in a smaller dose deposition. By scanning the pump beam across the patient, a 3D image of the distribution of the nanoparticles can be constructed. A narrow-bandwidth X-ray beam is required to ensure the unique detection of the fluorescence signal. A hard X-ray source with tens of keV energy, low divergence and narrow bandwidth is thus needed for XFI [1]. While all these requirements are fulfilled by third- and fourth-generation light sources, a compact and affordable X-ray source would be needed to allow a widespread adoption of this imaging modality.



Laser plasma accelerators can accelerate electron beams to 100 MeV-scale energies in mere millimetres, as the accelerating field supported by the plasma is on the order of 100 GV/m. Thomson scattering allows the generation of X-rays with energies of tens of keV by scattering optical photons off electrons of such energies. In Thomson scattering, incident laser photons of energy E_0 are upshifted to an energy given by $E_x \simeq 4\gamma^2 E_0$, where γ is the relativistic factor of the electrons. These two mechanisms provide the foundation for constructing an all-optical X-ray source.

The PLASMED X project will demonstrate a compact, fully laser-driven hard X-ray source with narrow bandwidth using an all-optical setup where a fraction of the drive laser generates the electron beam and the remaining laser energy is used for scattering. Recent theoretical work led by DESY [2] has shown that the bandwidth of the scattered X-rays can be controlled by using an active plasma lens [3] to tailor the effective energy spread and divergence of the electron beam. This reduces the stringent requirements on the electron beam spectrum and allows the use of simpler, more robust injection methods, while the ultrahigh focusing strengths of active plasma lenses make it possible to maintain the compact footprint of the source.

Figure 1

Schematic layout of the PLASMED X experiment. A laser plasma accelerator (LPA) is driven by a laser pulse, generating an electron beam in a gas jet plasma source. The electron beam is refocused using an active plasma lens, and a second laser pulse is scattered off the electrons at the focus of the lens. A dipole magnet deflects the electron beam, leaving a low-divergence X-ray beam.

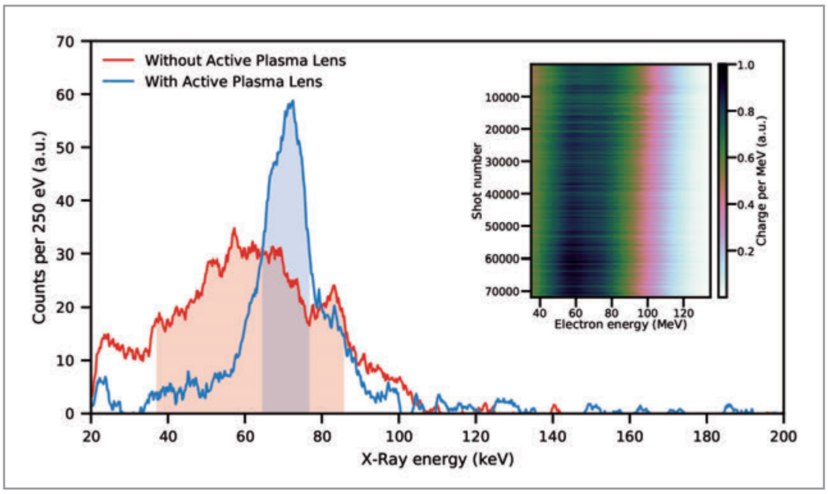


Figure 2

Experimentally measured X-ray spectrum with and without active plasma lens. Using an active plasma lens results in the FWHM bandwidth being reduced by nearly a factor of 5. The inset shows a waterfall plot of electron spectra, demonstrating reliable injection and stable generation of electron beams over a duration of 8 h.

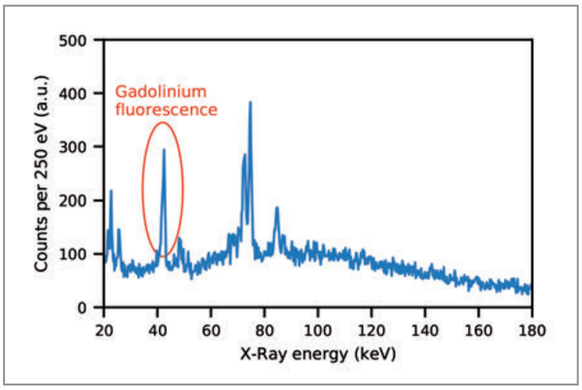


Figure 3

Measured fluorescence signal from a vial filled with a solution of gadolinium nanoparticles, irradiated with X-rays from the PLASMED X source

A schematic layout of the PLASMED X experiment is shown in Fig. 1, highlighting the key elements of the source, which were carefully commissioned in 2020.

Narrow-bandwidth X-ray beams

The first milestone in developing the X-ray source was obviously the demonstration of stable electron beams. The inset in Fig. 2 shows a waterfall plot of more than 70 000 laser shots, taken in sequence at a repetition rate of 2.5 Hz. Corresponding to a run time of more than 8 h, the electron beam delivered by the source is seen to be stable, with a charge of 14.5 ± 3.8 pC injected using the robust ionisation injection technique.

After commissioning of the electron source, the Thomson scattering beam was installed and overlapped with the electron beam right after its exit from the plasma, without using a plasma lens. The size of the electron beam at the scattering plane was about 10 μm, with the scattering laser focus being of similar size. In addition to the obvious difficulties of overlapping an electron beam and a laser pulse in space to micrometre-level precision, the femtosecond pulse duration of both beams requires similar accuracy overlap also in the temporal domain. This onerous task was completed by developing novel diagnostics. The measured X-ray spectrum generated by scattering the laser off electrons right after their exit from the plasma is plotted as the red line in Fig. 2. The full-width-at-half-maximum (FWHM) width of the spectrum is denoted by the red shaded area, corresponding to a relative bandwidth of about 80%.

To control the energy bandwidth of the X-ray beam, an active plasma lens was then integrated into the setup, as schematically shown in Fig. 1. The focused electron beam was again overlapped with the scattering laser pulse in both space and time, with more diagnostics commissioned to make this possible. The X-ray spectrum measured with the active plasma lens is shown in Fig. 2 as the blue line. A clear narrowing of the energy spectrum is observed, with the relative FWHM bandwidth highlighted by the blue shaded area now being 17%, a nearly fivefold reduction. The successful commissioning of the active plasma lens was the last step in demonstrating the use of the setup as a hard and narrow-band X-ray source.

Upcoming first imaging experiments

The demonstrated X-ray beams were then used to perform a proof-of-principle measurement of the fluorescence signal from gadolinium nanoparticles. The X-ray spectrum measured with a detector placed perpendicular to the beam propagation direction is shown in Fig. 3. A clear signature of gadolinium fluorescence can be seen, highlighted by the red ellipse, demonstrating that the PLASMED X source is indeed suitable for exciting fluorescence in nanoparticles commonly used for medical purposes.

The next milestone is to use the PLASMED X source to image an industry standard imaging target, a mouse phantom that can be filled with different nanoparticle solutions. The setup will undergo some further optimisation to increase the photon yield, after which the unique PLASMED X source will be used to take an XFI image of the mouse phantom.

Contact: Kristjan Põder, kristjan.poder@desy.de

References:

[1] F. Grüner et al., Sci. Rep. 8, 16561 (2018)
[2] T. Brümmer et al., Phys. Rev. Accel. Beams 23, 031601 (2020)
[3] C. A. Lindstrøm et al., Phys. Rev. Lett. 121, 194801 (2018)

The SINBAD-ARES linear accelerator

New tool for accelerator R&D reaches design energy

The ARES (Accelerator Research Experiment at SINBAD) linear accelerator is a major part of the new, long-term dedicated accelerator research facility SINBAD (Short Innovative Bunches and Accelerators at DESY), hosted in the premises of the former DORIS accelerator at the centre of the DESY campus in Hamburg. ARES aims to produce and accelerate ultrashort electron bunches with an energy of up to 155 MeV and an arrival time jitter below 10 fs (RMS). While the design is optimised for low-charge (pC-level), ultrashort (sub-/single-fs) bunches, bunch charges with several tens of picocoulombs can also be accelerated. The few-femtosecond-long electron bunches are an R&D topic in itself, but ARES will also offer the possibility to test accelerator components and advanced acceleration schemes and develop novel diagnostic devices in ultrafast science.

Beam operation at ARES

Starting in 2015, DESY's old DORIS accelerator and its outdated infrastructure were removed, and the newly designed SINBAD facility for dedicated accelerator R&D has been implemented in the refurbished space. One part of SINBAD is occupied by the ARES linear accelerator (linac), which will produce and accelerate electron bunches up to 155 MeV while compressing them to few-femtosecond bunch length. This is the first of multiple experiments in the SINBAD area.

At the end of 2019, a team of young DESY scientists detected the first electrons from the ARES photoinjector. These electron bunches with a momentum of 3.5 MeV/c were characterised in the diagnostic section of the electron source (gun) before being sent to the next stage – a linac consisting of two S-band travelling-wave accelerating structures, able to accelerate the bunches up to their design energy. This goal was reached and exceeded on 29 October 2020, with an energy of 155 MeV, a repetition rate of 10 Hz and a bunch charge of 1.5 pC at the spectrometer magnet located at the end of the linac. The experimental area and a new electron gun were also installed in 2020 (Fig. 1).

In the following weeks, the beam was further characterised, and the bunch charge was increased to 20 pC. In 2020, all the accelerator components were put into operation, tested and

Figure 1

Panoramic view ("fisheye" representation) of the ARES linear accelerator installed in the former DORIS tunnel (installation status at the end of 2020). The gun area is to the right, the experimental area in the middle, and the beam dump to the left.

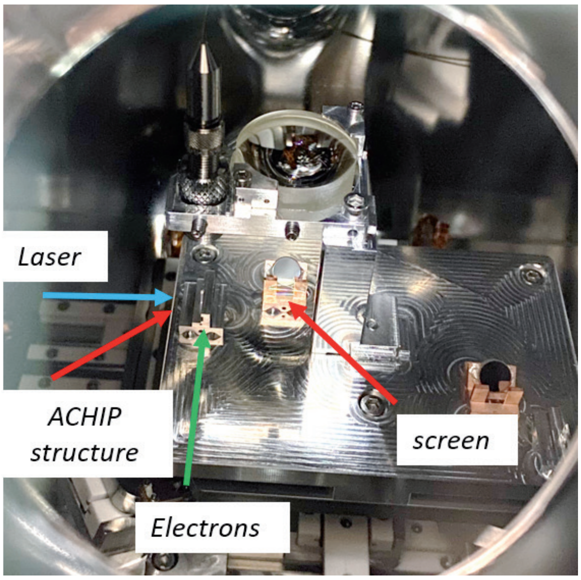


Figure 2

ACHIP setup in the experimental chamber

optimised. The relative momentum stability was measured to be 2.8 x 10^{-4} over 62 h of beam operation at 156 MeV/c, which is already excellent compared to other S-band linacs.

In the coming years, the ARES accelerator will be used to produce and optimise high-brightness ultrashort electron beams. The longitudinal beam parameters will be measured with single-femtosecond resolution by two novel polarisable X-band transverse deflecting structures, which will be installed in early 2021. These PolariX TDS devices were conceived, developed and procured in collaboration with CERN and PSI in Switzerland. Their novel polarisation feature will allow the streaking of the bunch characteristics with femtosecond resolution in 3D, instead of 1D with a conventional TDS.

Thanks to their tuneable characteristics, their stability and their reproducibility, the high-brightness ultrashort electron bunches from ARES will be ideally suited to test accelerator components as well as novel accelerating schemes, e.g. using laser-driven dielectric structures, or to develop new diagnostic devices for ultrafast science.

First user experiment at ARES

The first experiment at ARES, involving dielectric laser acceleration (DLA), will be performed in the context of the Accelerator on a CHip International Program (ACHIP). Its main goal is to demonstrate for the first time an energy spectrum shift of about 1 MeV for relativistic electron bunches externally injected into a DLA structure (Fig. 2).

Despite 12 weeks of COVID-19-related downtime, five dedicated shifts for ACHIP-related experiments were granted for the first time at the end of 2020. During these five shifts, essential equipment was commissioned (final focus quadrupole triplet, screen at the interaction point, 6D positioning system, motorised parts in the drive laser beamline, etc.). The team also tried to show first electron transmission through the 2.3 µm aperture of one of the installed DLA structures. Although no clear electron transmission was recorded, experimental procedures could be tested and optimised on both the electron and laser side, making these shifts nonetheless a success. A second week dedicated to ACHIP was scheduled for the beginning of 2021.

In 2021, the ARES linac will be further upgraded with a magnetic bunch compressor and the two PolariX X-band TDSs to produce and characterise the ultrashort pulses, respectively (Fig. 3). Also, a set of seven beam position monitors will be installed to improve the beam handling. An additional gun solenoid will be set up to allow the production and guidance of high-charge bunches above 100 pC.

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

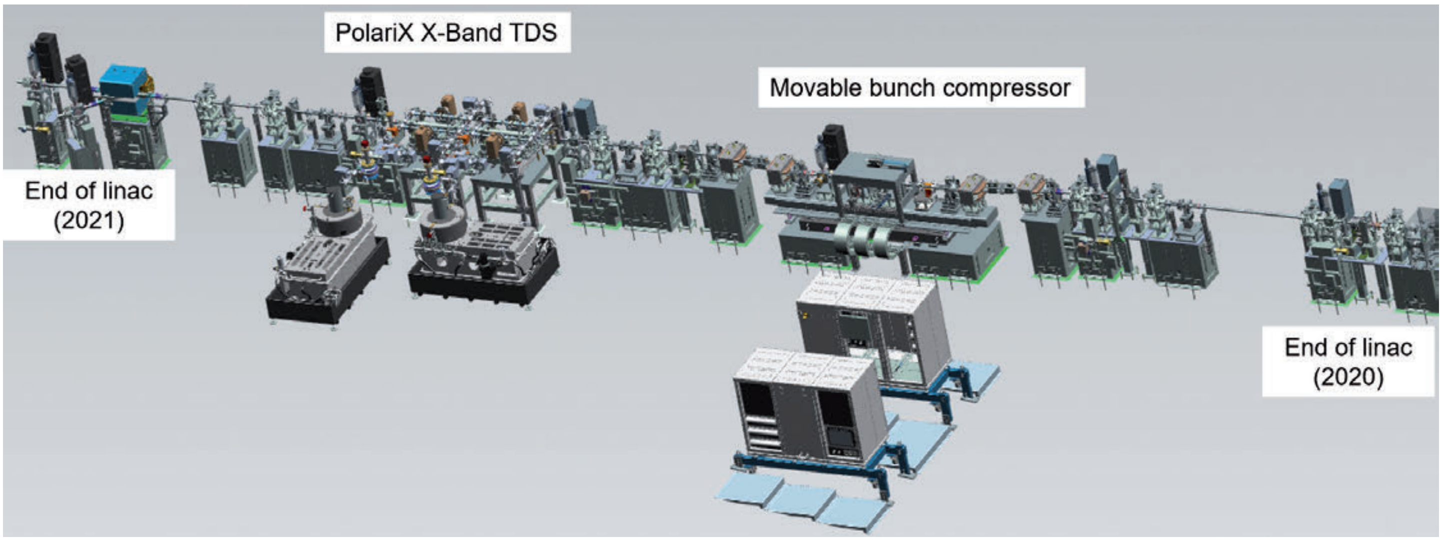


Figure 3

CAD model of the ARES linear accelerator with bunch compressor and two X-band TDSs

LUX

A laser plasma accelerator

The Laser-Plasma Driven Undulator X-Ray Source (LUX) is a laser plasma accelerator that combines the state of the art in novel plasma acceleration with DESY's modern accelerator technology and diagnostics. As such, LUX is a test bed aiming to turn the promising concepts of plasma acceleration into a technology ready to drive real-world applications. In 2020, the LUX team reported the first 24-hour operation of a laser plasma accelerator. Based on an extensive data set, the main contributors to energy variability in the plasma electron beam could be identified and linked to variations in the drive laser. These insights open the path to implementing active feedback in order to stabilise the accelerator performance at a level suitable for applications.

The LUX beamline is being developed and operated within a close collaboration of DESY and the accelerator physics group at Universität Hamburg. Its mission is to advance the state of the art of the field and push the limits of laser-plasma-accelerated electron beams towards the reliable and reproducible generation of high-quality beams.

In LUX, electron beams are generated by the interaction of ultrashort (few 10 fs) pulses of the 200 TW ANGUS laser system with a small volume of hydrogen gas (Fig. 1). The laser drives a plasma wave, which traps electrons from the plasma background (Fig. 2) and, in typical operation, accelerates them to an energy of 300 MeV within only a few millimetres. After generation, the beams are captured by a transport optic and carefully diagnosed.

The whole facility, including the drive laser and the plasma accelerator, is integrated in the DESY accelerator control system to record data and the facility status in real time.

In 2020, the LUX team was able to publish a study reporting the first continuous 24-hour operation of a laser plasma accelerator [1]. The experimental campaign resulted in a large data set that provided detailed insights into the sources of electron energy variability, which could mainly be attributed to fluctuations in the drive laser parameters (Fig. 3). Correlating laser and electron measurements, a parameterisation could be derived that predicted the plasma electron beam properties from the measured drive laser parameters. This predictive modelling is a first step

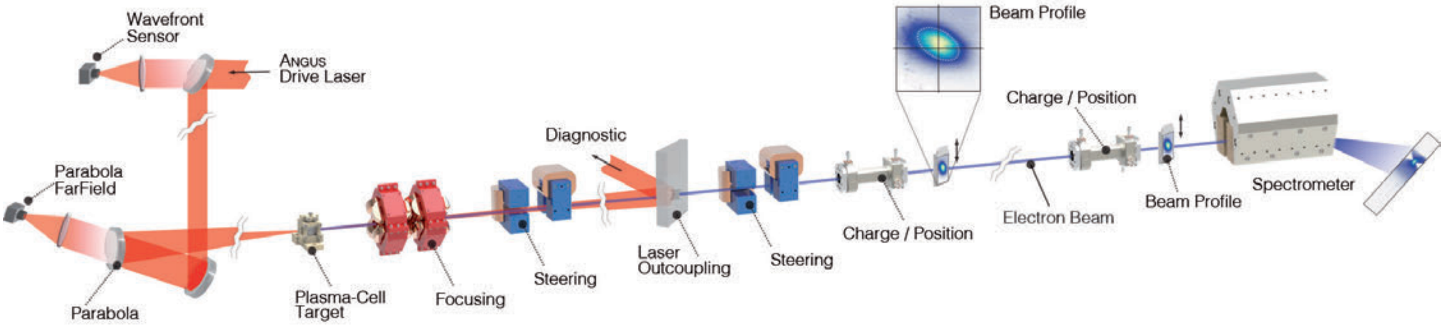


Figure 1

Schematic of the LUX laser plasma accelerator. The drive laser (red) is focused into a plasma cell target, where it ionises hydrogen gas to form a plasma. A trailing plasma wave traps and then accelerates electrons from the plasma to an energy of several hundred MeV over a distance of only a few millimetres. After the target, the laser is extracted from the beam axis for diagnosis. The electron beam is captured and transported using quadrupole magnets and corrector dipoles. Retractable scintillating screens and cavity-type beam position monitors are used to diagnose the beam. For clarity, only a few of the many laser diagnostics are shown.

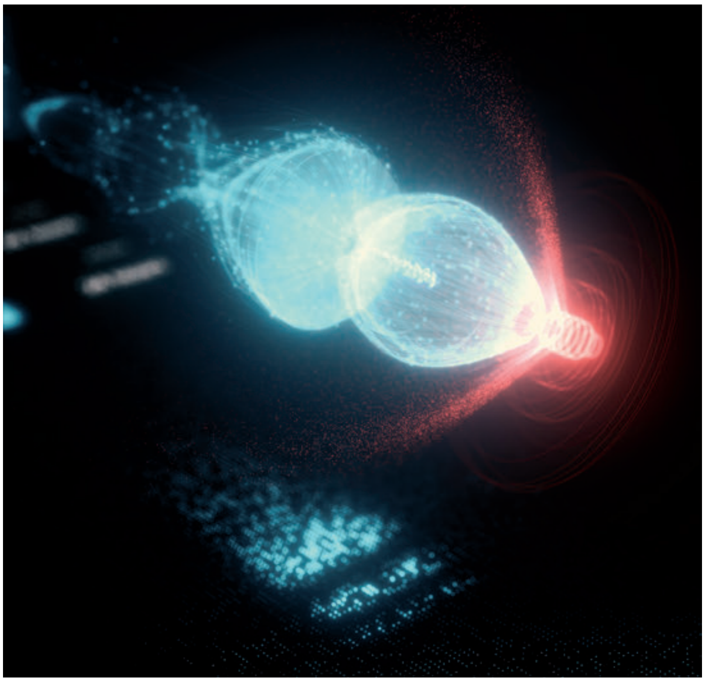


Figure 2

Artistic representation of the plasma wave in the LUX accelerator

towards implementing active stabilisation and feedback, as is deployed in any modern accelerator worldwide.

In addition, the capability to operate the facility steadily for an extended period of time forms the very basis for using more complex and advanced plasma target designs, which promise dramatically improved electron beam properties. An example for such a more advanced target design separates the injection, i.e. formation, of the electron beam from the subsequent acceleration. Although this concept requires a tightly integrated plasma target design, it promises kilo-ampere-level peak currents and beams with sub-percent energy spread, which would already be suitable to drive first applications. The LUX team has started an experimental campaign to test such novel designs at the facility.

In parallel, the LUX beamline was upgraded to demonstrate first free-electron laser gain from a plasma-driven undulator. For this upgrade, which was almost completed by the end of 2020, many more quadrupoles and diagnostics were added to the beamline. In the future, the LUX electron beam will be first captured and then slightly decompressed, i.e. stretched, to reduce the local beam energy spread at the cost of a moderate decrease in peak current. Afterwards, the beam will be matched to a new cryogenic undulator. The emitted soft X-ray undulator radiation will interact with the electron beam and thereby amplify the emitted radiation. This effect will be very difficult to verify, however. The steady and continuous operation of the LUX beamline, which the team could demonstrated in 2020, will be a crucial foundation for this and other increasingly complex experiments to come.

Contact: Andreas Maier, andreas.maier@desy.de
lux.desy.de

Reference:

[1] A. R. Maier et al., Phys. Rev. X 10, 031039 (2020)

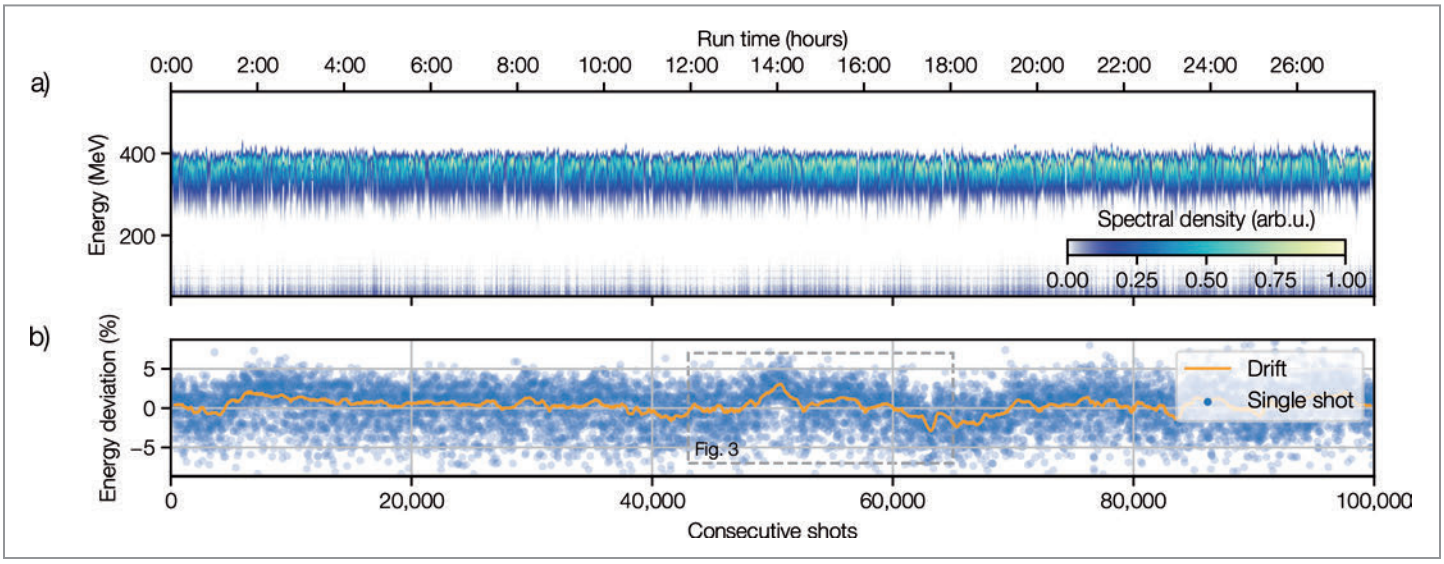


Figure 3

a) 100 000 consecutive electron spectra recorded at 1 Hz repetition rate. b) The variations of the electron peak energy (dots) can be attributed to variations in the drive laser properties. Correlations of the drive laser and electron parameters enable a parameterisation of the electron beam properties using the measured laser data. They form the basis for future active stabilisation of the plasma accelerator performance.

KALDERA

High-average-power laser plasma acceleration

Laser plasma acceleration has seen rapid progress over the past few years. The next big step for the field will be the implementation of active feedback loops and stabilisation to improve the reproducibility of the generated plasma electron beams to a level where they can readily drive first applications. With the KALDERA project, DESY is building a novel high-repetition-rate laser to drive subsequent plasma accelerator stages at unprecedented average power. Delivering up to 1000 pulses per second, KALDERA will enable active stabilisation techniques and thus high-quality plasma electron beams.

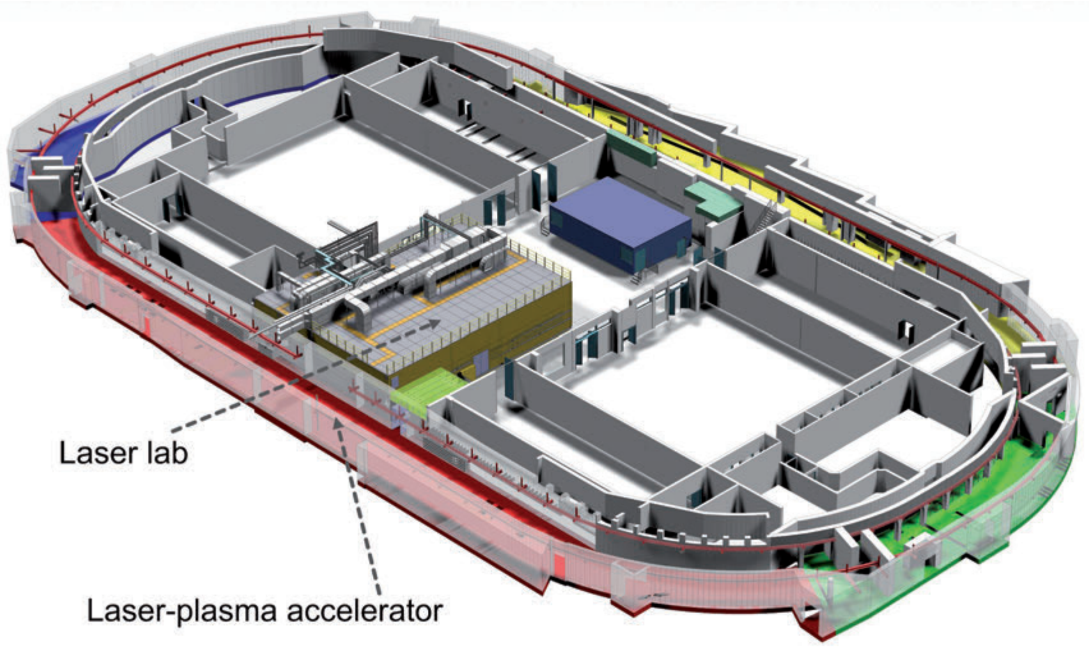


Figure 1

KALDERA will be part of the SINBAD accelerator R&D facility within the former DORIS accelerator complex. The laser lab, a fully air-conditioned 400 m^2 ISO6 cleanroom, will be located next to an accelerator tunnel (red area) that will house a laser plasma test accelerator. The high-quality, kHz-level repetition rate KALDERA drive laser will enable active feedback and stabilisation mechanisms to improve the quality of laser plasma electron beams to a level suitable to drive first applications.

Laser plasma acceleration has made great progress in recent years. Not least through intensive research at DESY, valuable insights have been gained into how exactly the drive laser pulse and the plasma interact to generate high-energy electron bunches. However, for any form of application, reliable and reproducible beam properties are essential. Although plasma accelerators have already impressively demonstrated their ability to generate high beam energies over extremely short distances of only a few millimetres, improvements in stability and reproducibility are still needed before the technology is ready for use in concrete applications.

Recently, the influence of shot-to-shot fluctuations of the drive laser on the generated electrons has been studied in detail at DESY. This has made it possible to uncover important mechanisms that are responsible for the reliability of the generated plasma electron beams. A fundamental finding of these investigations is that laser plasma accelerators will have to be operated at significantly higher repetition rates in the future.

It is common practice at modern accelerators, such as the European XFEL or DESY's synchrotron PETRA III, to counteract fluctuations in the beam parameters by active control. Certain quantities, such as the path of the electron beam, are measured many times per second. In the event of any deviations of the electron path from the nominal value, it is then corrected immediately. However, this can only compensate for fluctuations that vary more slowly than the frequency with which the deviations are measured. It is therefore important to have electron beams with the highest possible repetition rate in order to correct deviations precisely. At the European XFEL, which can deliver up to 27 000 electron bunches per second, this requirement is usually met.

In today's laser plasma accelerators, only one electron bunch is usually generated per second due to the design of the drive laser. This makes it very difficult to stabilise the laser system and thus the generated electron beams: Disturbances and fluctuations of beam properties are caused, among other

Figure 2

Status of the construction of the new KALDERA laser laboratory at the end of 2020

things, by vibrations and oscillations in the laser setup, which occur at a few 10 to 100 Hz.

To bring the field of laser plasma acceleration a major step closer to application-ready plasma electron beams, DESY has therefore launched the KALDERA project on the initiative of Wim Leemans. KALDERA comprises the construction of a new laser laboratory, the development of a drive laser with a kilohertz repetition rate and the construction of a laser plasma test accelerator (Fig. 1). The very high repetition rate will make it possible for the first time to transfer the concepts of active stabilisation, which are being used very successfully at DESY's modern accelerator facilities, to laser plasma acceleration.

KALDERA is being implemented under the leadership of the newly established DESY MLS group and with the involvement of a large number of technical groups at DESY, as well as national and international partners. Construction of the new laser laboratory (Fig. 2), a nearly 400 m^2 cleanroom in which the KALDERA laser will be developed once the lab is completed, began in 2020. The laboratory is part of the SINBAD accelerator R&D facility at DESY and will be built in the hall of the former DORIS synchrotron, which has been extensively renovated and equipped with renewed infrastructure for this purpose.

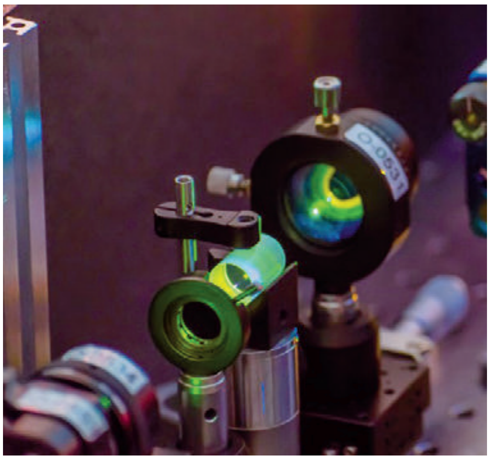


Figure 3

Development of the KALDERA laser has already started. The picture shows a close-up of the new seed laser, generating the initial high-quality pulses that will be amplified to full energy in a series of subsequent laser amplifiers.

The development of the laser is scheduled for five years and has already begun (Fig. 3). Once completed, the laser will operate at a repetition rate of up to 1000 pulses per second. This will make it possible to stabilise the main sources of fluctuations of the electron beam properties. The laser beams will then power the LUX2 test accelerator, which will be built in a part of the former DORIS accelerator tunnel directly adjacent to the laser laboratory. The ultimate goal is to demonstrate electron beams of sufficient quality to drive a plasma-based free-electron laser in the vacuum ultraviolet wavelength range.

Much of the knowledge that informs the construction and development of KALDERA comes from experiments at the LUX plasma accelerator, which is currently in operation. Two recently published articles [1, 2] have shown a way to improve the electron beams through machine learning and active stabilisation. Until completion of KALDERA, LUX will therefore be operated in parallel to continue research at the forefront of the field and to test technologies and concepts for use in KALDERA at a very early stage.

Contact: Wim Leemans, wim.leemans@desy.de
Andreas Maier, andreas.maier@desy.de

References:

[1] S. Jalas et al., Phys. Rev. Lett. 126, 104801 (2021)
[2] M. Kirchen et al., Phys. Rev. Lett. 126, 174801 (2021)

References

Committees

DESY Board of Directors

H. Dosch
(Chairman of the DESY Board of Directors)

W. Leemans
(Accelerator Division)

J. Mnich
(Particle Physics Division)

E. Weckert
(Photon Science Division)

C. Stegmann
(Astroparticle Physics Division)

C. Harringa
(Administrative Division)

A. Willner
(Chief Technology Officer)

Machine Advisory Committee (MAC)

Ilan Ben-Zvi (BNL, USA) till November 2020
Oliver Brüning (CERN, CH, Chair)
Joël Chavanne (ESRF, F) since November 2020
Franz-Josef Decker (SLAC, USA)
Ángeles Faus-Golfe (IFIC, Valencia, E)
Edda Gschwendtner (CERN, CH)
Michiko Minty (BNL, USA)
Peter Ratoff (Univ. Lancaster, UK)
Fernando Sannibale (LBNL, USA) since November 2020
Christoph Steier (LBNL, USA) till May 2020
Andrzej Wolski (Univ. Liverpool, UK)

DESY Scientific Board

M. Ackermann (DESY)
R. Aßmann (DESY)
B. Atlay (HU Berlin)
N. Baboi (DESY)
S. Bari (DESY)
R. Bartolini (DESY)
T. Behnke (DESY)
D. Berge (DESY)
M. Bieler (DESY)
I. Bloch (DESY)
K. Borras (DESY)
R. Brinkmann (DESY)
A. Burkhardt (DESY)
K. Büßer (DESY)
F. Calegari (DESY)
H. Chapman (DESY)
M. Diehl (DESY)
R. Döhrmann (DESY)
H.-J. Eckoldt (DESY)
F. Ellinghaus (KET)
S. Fiedler (EMBL)
E. Gallo (DESY)
H. Graafsma (DESY)
I.M. Gregor (DESY)
C. Grojean (DESY)
G. Grübel (DESY)
V. Gülzow (DESY)
C. Gutt (KfS)
J. Haller (U Hamburg)
S. Heim (DESY)
B. Heinemann (DESY)
K. Honkavaara (DESY)
Ç. İşsever (DESY)
H. Jansen (DESY)
R. Kammering (DESY)
F. Kärtner (DESY)
M. Kasemann (DESY)
J. Knapp (DESY)
M. Kowalski (DESY)
G. Kube (DESY)
J. Küpper (DESY)
T. Laarmann (DESY)
L. Lilje (DESY)
D. Lott (HZG)
I. Mahns (DESY)
I. Melzer-Pellmann (DESY)
S. Molodtsov (European XFEL)
K. Mönig (DESY)
N. Müller (DESY)
A. Mußgiller (DESY)
C. Niebuhr (DESY)
S. Ohm (DESY)
K. Peters (DESY)
E. Plönjes-Palm (DESY)
M. Pohl (DESY)
C. Porthun (DESY)
R. Porto (DESY)
A. Ringwald (DESY)
R. Röhlsberger (DESY)
N. Rohringer (DESY)
K. Rossnagel (DESY)
R. Santra (DESY)
M. Schmitz (DESY)
M. Schnell (DESY)
V. Schomerus (DESY)
T. Schörner-Sadenius (DESY)
S. Schreiber (DESY)
C. Schroer (DESY)
H. Schulte-Schrepping (DESY)
C. Schwanenberger (DESY)
O. Seeck (DESY)
K. Sengstock (U Hamburg)
G. Servant (DESY)
H. Sondermann (DESY)
A. Stierle (DESY)
K. Tackmann (DESY)
S. Techert (DESY)
M. Tischer (DESY)
R. Treusch (DESY)
P. van der Reest (DESY)
K. Valerius (KAT)
N. Walker (DESY)
G. Weiglein (DESY)
H. Weise (DESY)
W. Winter (DESY)
H. Yan (DESY)

Memberships

Accelerator Advisory Committee (AAC) Fermilab
Hans Weise

ACHIP Consortium Advisory Board
Reinhard Brinkmann

ACHIP Executive Board
Ralph Aßmann

Advanced Accelerator Concepts Workshop, Core Committee
Wim Leemans

ALBA Scientific Advisory Committee
Reinhard Brinkmann

ALS-U Machine Advisory Committee
Winfried Decking

APS DPB Executive Committee
Wim Leemans

Apollon/CILEX Technical Advisory Committee
Ralph Aßmann

AREAL Project, Armenia, International Technical Advisory Committee
Klaus Flöttmann

ARIES European Coordination of Accelerator R&D
Ralph Aßmann (Deputy Coordinator)

ARIES Sub-Work Package Leader WP8.5.
Kay Wittenburg

ARIES Workshop on Materials and Engineering Technologies for Particle Accelerator Beam Diagnostic Instruments, Scientific Programme Committee 2020–21
Kay Wittenburg, Gero Kube

BerlinPro Machine Advisory Committee
Holger Schlarb, Siegfried Schreiber

BESSY Machine Advisory Committee
Winfried Decking

BNL Collider Department, Machine Advisory Committee
Ralph Aßmann

CAS Advisory Committee
Kay Wittenburg

CAS Advanced Level (2021) Programme Committee
Kay Wittenburg

CEA (CSTD)
Lutz Lilje

CERN Scientific Policy Committee
Reinhard Brinkmann

CHILFEL CAS–Helmholtz International Laboratory on FEL Science and Technology
Hans Weise (DESY Co-Spokesperson)

Cockcroft Institute, Scientific Advisory Committee
Wim Leemans

DPG-Nachwuchspreis für Beschleunigerphysik, Committee
Reinhard Brinkmann

ELI Beamlines, International Scientific Advisory Committee
Wim Leemans

ESRF Machine Advisory Committee
Hans Weise

ESS Project Advisory Committee
Reinhard Brinkmann

EuPRAXIA Collaboration Board
Ralph Aßmann, Wim Leemans

EuPRAXIA International Consortium Coordinator
Ralph Aßmann

EuPRAXIA@SPARC_LAB CDR Review Committee
Siegfried Schreiber

European Network for Novel Accelerators (EuroNNAc)
Ralph Aßmann (Chair)

European Physical Society Accelerator Group (EPS-AG)
Ralph Aßmann (Chair)

FACET-II Programme Advisory Committee
Andreas Maier

FAIR Machine Advisory Committee
Kay Wittenburg

FEL 2022 Scientific Programme Committee
Frank Stephan, Mathias Vogt

Helmholtz Think Tank
Hans Weise

HKIAS HEP 2021 International Organising Committee
Ralph Aßmann

IBIC 2020 International Programme Committee
Kay Wittenburg

ICALEPCS International Scientific Advisory Committee
Reinhard Bacher

ICFA Beam Dynamics Panel
Rainer Wanzenberg

IFAST Work Package Technology Infrastructures
Hans Weise

INFN/LNF Scientific Committee
Ralph Aßmann

Innovationszentrum Forschungscampus Hamburg-Bahrenfeld GmbH, Beirat
Hans Weise

IPAC 2021 International Organising Committee
Ralph Aßmann

IPAC 2022 International Organising Committee
Ralph Aßmann

IIVEC 2021 Technical Programme Committee
Stefan Choroba

John Adams Institute, Advisory Board
Reinhard Brinkmann (Chair)

LCLS-II DOE/SC Review
Dirk Nölle

LCLS-II Status Review
Dirk Nölle

LCLS-II Re-Baseline Review
Dirk Nölle

LCLS-II Directors Review
Lutz Lilje, Winfried Decking

LCLS-II HE Facility, Advisory Committee
Lutz Lilje

LCLS-II Vacuum System Review
Lutz Lilje

LINAC 2022 International Organising Committee
Hans Weise

LINAC 2022 Scientific Programme Committee
Stefan Choroba, Hans Weise

NRC-ACOT Advisory Committee on TRIUMF
Hans Weise

PCaPAC Programme Committee
Philip Duval, Reinhard Bacher

PIP-II Machine Advisory Committee Fermilab
Hans Weise

PITZ Collaboration Board
Frank Stephan (Spokesperson)

POHANG Accelerator Laboratory, International Advisory Committee
Winfried Decking

PSI Photon Science Advisory Committee
Reinhard Brinkmann

PSI SLS-2.0 Machine Advisory Committee
Reinhard Brinkmann

SNOWMASS 2021 Co-Convener AF06 Group
Ralph Aßmann

SNOWMASS 2021 Accelerator Frontier Topical Group Accelerator Technology R&D
Hans Weise

SPIRAL-2 Commissioning Review
Hans Weise

SRF 2019 International Programme Committee
Detlef Reschke

SuperKEKB Machine Advisory Committee
Ralph Aßmann

TESLA Technology Collaboration (TTC)
Hans Weise (Chair)

TESLA Technology Collaboration (TTC) Technical Board
Detlef Reschke (Co-Chair)

ThomX Machine Advisory Committee
Siegfried Schreiber

TIARA Governing Council
Ralph Aßmann, Wim Leemans

UK/ESS High Beta Cavity Project Board
Detlef Reschke

Workshop on Transition Radiation Detectors TRD 2020/2021 Scientific Committee
Gero Kube

VHEE 2020 Scientific Advisory Committee
Frank Stephan

Publications

Publications

S. Ackermann et al.
Novel Method for the Generation of Stable Radiation from Free-Electron Lasers at High Repetition Rates.
Physical review accelerators and beams, 23(7):071302, and PUBDB-2020-02865.
doi: 10.1103/PhysRevAccelBeams.23.071302.

R. W. Assmann et al.
EuPRAXIA Conceptual Design Report.
European physical journal special topics, 229(24):3675, and PUBDB-2020-03112.
doi: 10.1140/epjst/e2020-000127-8.

S. K. Barber et al.
A Compact, High Resolution Energy, and Emittance Diagnostic for Electron Beams Using Active Plasma Lenses.
Applied physics letters, 116(23):234108 (1, and PUBDB-2020-04748.
doi: 10.1063/5.0005114.

A. Bellandi et al.
Results on FPGA-Based High-Power Tube Amplifier Linearization at DESY.
IEEE transactions on nuclear science, 67(5):762, and PUBDB-2020-04936.
doi: 10.1109/TNS.2020.2980929.

C. Benedetti et al.
Corrigendum: An Accurate and Efficient Laser-Envelope Solver for the Modeling of Laser-Plasma Accelerators.
Plasma physics and controlled fusion, 62(8):089501, and PUBDB-2020-04744.
doi: 10.1088/1361-6587/ab9a63.

C. Benedetti et al.
High-Quality Positron Acceleration in Beam-Driven Plasma Accelerators.
Physical review accelerators and beams, 23(12):121301 (1, and PUBDB-2020-05003.
doi: 10.1103/PhysRevAccelBeams.23.121301.

T. Brümmer et al.
Design study for a compact laser-driven source for medical x-ray fluorescence imaging.
Physical review accelerators and beams, 23(3):031601 (1, and PUBDB-2020-05317.
doi: 10.1103/PhysRevAccelBeams.23.031601.

Y. Chen, I. Zagorodnov and M. Dohlus.
Beam Dynamics of Realistic Bunches at the Injector Section of the European X-Ray Free-Electron Laser.
Physical review accelerators and beams, 23(4):044201, and PUBDB-2020-04828.
doi: 10.1103/PhysRevAccelBeams.23.044201.

Y. L. Chen et al.
Budgeting the Emittance of Photoemitted Electron Beams in a Space-Charge affected Emission Regime for Free-Electron Laser Applications.
AIP Advances, 10(3):035017, and PUBDB-2020-01066.
doi: 10.1063/1.5129532.

Y. Chen et al.
Frequency-Detuning Dependent Transient Coaxial RF Coupler Kick in an L -Band Long-Pulse High-Gradient RF Photogun.
Physical review accelerators and beams, 23(1):010101, and PUBDB-2020-00656.
doi: 10.1103/PhysRevAccelBeams.23.010101.

F. Christie et al.
Temporal X-ray Reconstruction using Temporal and Spectral Measurements at LCLS.
Scientific reports, 10(1):9799, and PUBDB-2020-02173, arXiv:1911.06090. DESY-19-198.
doi: 10.1038/s41598-020-66220-5.

W. Cichalewski et al.
Continuous Wave Operation of Superconducting Accelerating Cavities With High Loaded Quality Factor.
IEEE transactions on nuclear science, 67(9):2119, and PUBDB-2021-00509.
doi: 10.1109/TNS.2020.2993539.

J. Corno et al.
Uncertainty Modeling and Analysis of the European X-Ray Free Electron Laser Cavities Manufacturing Process.
Nuclear instruments & methods in physics research / A, 971:1, and PUBDB-2020-04056, 164135. arXiv:1906.09151.
doi: 10.1016/j.nima.2020.164135.

P. Craievich et al.
Novel X-band transverse deflection structure with variable polarization.
Physical review accelerators and beams, 23(11):112001 (1, and PUBDB-2020-04482.
doi: 10.1103/PhysRevAccelBeams.23.112001.

G. Darivianakis, A. Eichler and J. Lygeros.
Distributed Model Predictive Control for Linear Systems With Adaptive Terminal Sets.
IEEE transactions on automatic control, 65(3):1044, and PUBDB-2021-00433.
doi: 10.1109/TAC.2019.2916774.

W. Decking et al.
A MHz-Repetition-Rate Hard X-Ray Free-Electron Laser Driven by a Superconducting Linear Accelerator.
Nature photonics, 14(6):391, and PUBDB-2020-04827.
doi: 10.1038/s41566-020-0607-z.

J. Engel et al.
Polymer Foil Windows for Gas-Vacuum Separation in Accelerator Applications.
AIP Advances, 10(2):025224, and PUBDB-2020-00631.
doi: 10.1063/1.5143258.

L. Fan-Chiang et al.
Gas Density Structure of Supersonic Flows Impinged on by Thin Blades for Laser–Plasma Accelerator Targets.
Physics of fluids, 32(6):066108, and PUBDB-2020-04751.
doi: 10.1063/5.0005888.

K. Floettmann.
Equivalence of Gouy and Courant-Snyder Phase.
Physical review / A, 102(3):033507, and PUBDB-2020-03121, arXiv:2006.12962. DESY-20-108. arXiv:2006.12962. DESY 20-108. DESY-20-108.
doi: 10.1103/PhysRevA.102.033507.

K. Floettmann and D. Karlovets.
Quantum Mechanical Formulation of the Busch Theorem.
Physical review / A, 102(4):043517 (1, and PUBDB-2020-03715, arXiv:2006.12948. DESY-20-107.
doi: 10.1103/PhysRevA.102.043517.

V. Gharibyan.
Experimental Hint for Gravitational CP Violation.
Modern physics letters / A A, 35(11):2050079, and PUBDB-2020-01621, DESY 16-014.
doi: 10.1142/S0217732320500790.

A. J. Gonsalves et al.
Laser-Heated Capillary Discharge Plasma Waveguides for Electron Acceleration to 8 GeV.
Physics of plasmas, 27(5):053102, and PUBDB-2020-04919.
doi: 10.1063/5.0002769.

K. Heinemann et al.
Reevaluation of Spin-Orbit Dynamics of Polarized e^+e^- Beams in High Energy Circular Accelerators and Storage Rings: An approach Based on a Bloch Equation.
International journal of modern physics / A, 35(15 & 16):2041003, and PUBDB-2021-00553.
doi: 10.1142/S0217751X20410031.

K. Heinemann et al.
The Bloch Equation for Spin Dynamics in Electron Storage Rings: Computational and Theoretical Apects.
International journal of modern physics / A Particles and fields, gravitation, cosmology A, A34(36):1942032, and PUBDB-2020-01075, DESY-19-156.
doi: 10.1142/S0217751X19420326.

P. Huang et al.
Single Shot Cathode Transverse Momentum Imaging in High Brightness Photoinjectors.
Physical review accelerators and beams, 23(4):043401, and PUBDB-2020-02152.
doi: 10.1103/PhysRevAccelBeams.23.043401.

M. I. Ivanyan et al.
Wakefields in Conducting Waveguides with a Lossy Dielectric Channel.
Physical review accelerators and beams, 23(4):041301, and PUBDB-2020-05052.
doi: 10.1103/PhysRevAccelBeams.23.041301.

M. Ivanyan et al.
On the Resonant Properties of the THz Metal-Dielectric Waveguide Impedance.
Journal of physics / Conference Series, 1596(1):012026, and PUBDB-2020-05049.
doi: 10.1088/1742-6596/1596/1/012026.

S. Jaster-Merz et al.
Development of a Beam Profile Monitor based on Silicon Strip Sensors for Low-Charge Electron Beams.
1. 4th European Advanced Accelerator Concepts Workshop, Elba (Italy), 15 Sep 2019 - 20 Sep 2019.
Journal of physics / Conference Series, vol. 15961:012047, and PUBDB-2020-04285.
IOP Publ., Bristol.
doi: 10.1088/1742-6596/1596/1/012047.

M. Kellermeier et al.
Towards Additive Manufacturing of Dielectric Accelerating Structures.
1. 4th European Advanced Accelerator Concepts Workshop, Isola d'Elba (Italy), 15 Sep 2019 - 21 Sep 2019.
Journal of physics / Conference Series, vol. 15961:012020 (1, and PUBDB-2020-04358.
IOP Publ., Bristol.
doi: 10.1088/1742-6596/1596/1/012020.

M. Kirchen et al.
Scalable Spectral Solver in Galilean Coordinates for Eliminating the Numerical Cherenkov Instability in Particle-in-Cell Simulations of Streaming Plasmas.
Physical review / E, 102(1):013202, and PUBDB-2020-02518.
doi: 10.1103/PhysRevE.102.013202.

T. Kroll et al.
Observation of Seeded Mn K β Stimulated X-Ray Emission Using Two-Color X-Ray Free-Electron Laser Pulses.
Physical review letters, 125(3):037404 (1, and PUBDB-2020-03698.
doi: 10.1103/PhysRevLett.125.037404.

I. V. Kuzmin et al.
Shaping Picosecond Ellipsoidal Laser Pulses with Periodic Intensity Modulation for Electron Photoinjectors.
Applied optics, 59(9):2776, and PUBDB-2020-04250.
doi: 10.1364/AO.383181.

F. Lemery et al.
Highly Scalable Multicycle THz Production with a Homemade Periodically Poled Macroscrystal.
Communications Physics, 3(1):150, and PUBDB-2020-02856.
doi: 10.1038/s42005-020-00421-2.

V. Leroux, T. Eichner and A. Maier.
Description of spatio-temporal couplings from heat-induced compressor grating deformation.
Optics express, 28(6):8257, and PUBDB-2020-00937.
doi: 10.1364/OE.386112.

N. M. Lockmann et al.
Noninvasive THz spectroscopy for bunch current profile reconstructions at MHz repetition rates.
Physical review accelerators and beams, 23(11):112801, and PUBDB-2020-04551.
doi: 10.1103/PhysRevAccelBeams.23.112801.

G. Loisch et al.
Towards Experimental Investigation of Hosing Instability Mitigation at the PITZ Facility.
Journal of physics / Conference Series, 1596(1):012003, and PUBDB-2020-03983.
doi: 10.1088/1742-6596/1596/1/012003.

J. Lorkiewicz et al.
Coating in Ultra-High Vacuum Cathodic-Arc and Processing of Pb Films on Nb Substrate as Steps in Preparation of Nb-Pb Photocathodes for Radio-frequency, Superconducting e − Guns.
Vacuum, 179:109524, and PUBDB-2021-00506.
doi: 10.1016/j.vacuum.2020.109524.

A. Maier et al.
Decoding Sources of Energy Variability in Laser-Plasma Accelerators.
Physical review / X, 10(3):031039 (1, and PUBDB-2020-02855.
doi: 10.1103/PhysRevX.10.031039.

B. Marchetti et al.
SINBAD-ARES - A Photo-Injector for External Injection Experiments in Novel Accelerators at DESY.
4th European Advanced Accelerator Concepts Workshop, Isola d’Elba (Italy), 15 Sep 2019 - 20 Sep 2019.
Journal of physics / Conference Series, vol. 1596:012036, and PUBDB-2020-04867.
IOP Publ., Bristol.
doi: 10.1088/1742-6596/1596/1/012036.

F. Mayet, R. Assmann and F. Lemery.
Longitudinal Phase Space Synthesis with Tailored 3D-Printable Dielectric-Lined Waveguides.
Physical review accelerators and beams, 23(12):121302 (1, and PUBDB-2020-05153, DESY 20-168.
doi: 10.1103/PhysRevAccelBeams.23.121302.

P. A. P. Nghiem et al.
Toward a Plasma-based Accelerator at High Beam Energy with High Beam Charge and High Beam Quality.
Physical review accelerators and beams, 23(3):031301, and PUBDB-2020-01432.
doi: 10.1103/PhysRevAccelBeams.23.031301.

F. Nguyen et al.
Free Electron Laser Performance within the EuPRAXIA Facility.
Instruments, 4(1):5, and PUBDB-2020-01007.
doi: 10.3390/instruments4010005.

O. G. Olkhovskaya et al.
Plasma channel formation in the knife-like focus of laser beam.
Journal of plasma physics, 86(3):905860307 (1, and PUBDB-2020-04752.
doi: 10.1017/S0022377820000458.

E. Panofski, R. Assmann and E. Svystun.
Multi-Objective Optimization of the Matching Beamline for External Injection into a Laser-Driven Plasma Accelerator.
1. 4th European Advanced Accelerator Concepts Workshop, Isola d’Elba (Italy), 15 Sep 2019 - 21 Sep 2019.
Journal of physics / Conference Series, vol. 15961:012041 (1, and PUBDB-2020-04944.
IOP Publ., Bristol.
doi: 10.1088/1742-6596/1596/1/012041.

V. Paramonov and K. Floettmann.
Lower Limit of the Transverse Emittance Growth in Deflecting RF Fields.
Physical review accelerators and beams, 23(1):014401, and PUBDB-2020-05048.
doi: 10.1103/PhysRevAccelBeams.23.014401.

S. Pathak et al.
Tracking the Ultraviolet-induced Photochemistry of Thiophenone during and after Ultrafast Ring Opening.
Nature chemistry, 12(9):795, and PUBDB-2020-03660.
doi: 10.1038/s41557-020-0507-3.

G. Penco et al.
Enhanced seeded free electron laser performance with a “cold” electron beam.
Physical review accelerators and beams, 23(12):120704 (1, and PUBDB-2020-05305.
doi: 10.1103/PhysRevAccelBeams.23.120704.

C. V. Pieronek et al.
Laser-heated Capillary Discharge Waveguides as Tunable Structures for Laser-Plasma Acceleration.
Physics of plasmas, 27(9):093101, and PUBDB-2020-04742.
doi: 10.1063/5.0014961.

A. Potylitsyn et al.
Image of the Transverse Bunch Profile via Coherent Optical Transition Radiation.
Physical review accelerators and beams, 23(4):042804, and PUBDB-2020-02226.
doi: 10.1103/PhysRevAccelBeams.23.042804.

T. Sato et al.
Femtosecond timing synchronization at megahertz repetition rates for an x-ray free-electron laser.
Optica, 7(6):716, and PUBDB-2020-02373.
doi: 10.1364/OPTICA.396728.

S. Schröder et al.
High-resolution sampling of beam-driven plasma wakefields.
Nature Communications, 11(1):5984 (1, and PUBDB-2020-04652.
doi: 10.1038/s41467-020-19811-9.

M. B. Schwab et al.
Visualization of Relativistic Laser Pulses in Underdense Plasma.
Physical review accelerators and beams, 23(3):032801, and PUBDB-2021-00649.
doi: 10.1103/PhysRevAccelBeams.23.032801.

S. Serkez et al.
Opportunities for Two-Color Experiments in the Soft X-ray Regime at the European XFEL.
Applied Sciences, 10(8):2728, and PUBDB-2021-00607.
doi: 10.3390/app10082728.

R. Shalloo et al.
Automation and Control of Laser Wakefield Accelerators using Bayesian Optimization.
Nature Communications, 11(1):6355 (1, and PUBDB-2020-04934.
doi: 10.1038/s41467-020-20245-6.

D. Sikora et al.
Phase Drift Compensating RF Link for Femtosecond Synchronization of E-XFEL.
IEEE transactions on nuclear science, 67(9):2136, and PUBDB-2018-03737, arXiv:1806.09197.
doi: 10.1109/TNS.2020.2966018.

B. Steffen et al.
Compact Single-Shot Electro-Optic Detection System for THz Pulses with Femtosecond Time Resolution at MHz Repetition Rates.
Review of scientific instruments, 91(4):045123, and PUBDB-2021-00610.
doi: 10.1063/1.5142833.

S. V. Trofymenko et al.
Formation Region eEfects in X-ray Transition Radiation from 1 to 6 GeV Electrons in Multilayer Targets.
Nuclear instruments & methods in physics research / B Beam interactions with materials and atoms, 476:44, and PUBDB-2020-02481.
doi: 10.1016/j.nimb.2020.04.033.

S. Usenko et al.
Auger Electron Wave Packet Interferometry on Extreme Timescales with Coherent Soft xX-Rays.
Journal of physics / B, 53(24):244008, and PUBDB-2020-04259.
doi: 10.1088/1361-6455/abc661.

T. Vinatier et al.
Feasibility Study for a THz Acceleration Experiment on the PHIL Accelerator at LAL.
Journal of physics / Conference Series, 1596(1):012033 (1, and PUBDB-2020-04684.
doi: 10.1088/1742-6596/1596/1/012033.

T. Vinatier et al.
Challenges and Tolerances for a Compact and Hybrid Ultrafast X-ray Pulse Source Based on RF and THz Technologies.
Journal of physics / Conference Series, 1596(1):012032 (1, and PUBDB-2020-04683.
doi: 10.1088/1742-6596/1596/1/012032.

M. Wenskat et al.
Nitrogen Infusion $R\&D$ at DESY - A Case Study on Cavity Cut-Outs.
Superconductor science and technology, 33(11):115017, and PUBDB-2020-02826.
doi: 10.1088/1361-6668/abb58c.

M. Wenskat et al.
Vacancy-Hydrogen Interaction in Niobium during Low-Temperature Baking.
Scientific reports, 10(1):8300, and PUBDB-2020-02437, arXiv:2004.13450. DESY-20-074.
doi: 10.1038/s41598-020-65083-0.

S. Yamin et al.
Design Considerations for Permanent Magnetic Quadrupole Triplet for Matching into Laser Driven Wake Field Acceleration Experiment at SINBAD.
Journal of physics / Conference Series, 1596(1):012010, and PUBDB-2020-04282.
doi: 10.1088/1742-6596/1596/1/012010.

M. Zeng, A. Martinez de la Ossa and J. Osterhoff.
Ponderomotively Assisted Ionization Injection in Plasma Wakefield Accelerators.
New journal of physics, 22:123003, and PUBDB-2020-04524.
doi: 10.1088/1367-2630/abc9ee.

M. Zeng et al.
Plasma eyepieces for petawatt class lasers.
Physics of plasmas, 27(2):023109 (1, and PUBDB-2020-05315, arXiv:1901.07974.
doi: 10.1063/1.5116416.

Preprints and Internal Reports

C. Albrecht et al.
Straightening of Superconducting HERA Dipoles for the Any-Light-Particle-Search Experiment ALPS II.
PUBDB-2020-01801, arXiv:2004.13441. DESY-20-070.
doi: 10.3204/PUBDB-2020-01801.

M. Ebert.
Subsequent Titanium Coating of RF Input Coupler Windows.
PUBDB-2020-01206, DESY-Technical-Note-20-01.
doi: 10.3204/PUBDB-2020-01206.

K. Floettmann.
Equivalence of Gouy and Courant-Snyder Phase.
PUBDB-2020-02700, arXiv:2006.12962. DESY-20-108.
doi: 10.3204/PUBDB-2020-02700.

K. Floettmann and D. Karlovets.
Quantum Mechanical Formulation of the Busch Theorem.
PUBDB-2020-02709, arXiv:2006.12948. DESY-20-107.
doi: 10.3204/PUBDB-2020-02709.

K. Floettmann et al.
Superradiant Cherenkov-Wakefield Radiation as THz Source for FEL Facilities.
PUBDB-2020-02166, arXiv:2005.05640. DESY-20-081.
doi: 10.3204/PUBDB-2020-02166.

M. Formela et al.
Plasma Lenses: Possible alternative OMD at the ILC.
PUBDB-2020-01080, arXiv:2003.03138. DESY-20-027.
doi: 10.3204/PUBDB-2020-01080.

V. Gharibyan.
Explaining the Universe with gravitation dependent quantum vacuum.
PUBDB-2020-02516, DESY-20-110.
doi: 10.3204/PUBDB-2020-02516.

HERMES Collaboration.
Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering by transversely polarized protons.
PUBDB-2020-02984, arXiv:2007.07755. DESY-20-119.
doi: 10.3204/PUBDB-2020-02984.

M. Wenskat et al.
Vacancy-Hydrogen Interaction in Niobium during Low-Temperature Baking.
PUBDB-2020-01797, arXiv:2004.13450. DESY-20-074.
doi: 10.3204/PUBDB-2020-01797.

I. Zagorodnov et al.
Collective Effects at the Injector Section of the European X-Ray Free-Electron Laser.
PUBDB-2020-04829, arXiv:2010.1020.
doi: 10.3204/PUBDB-2020-04829.

Conference Contributions

MIKON 2020

B. Gasowski et al.
Concept of Master Oscillator Upgrade for FLASH.
23rd International Microwave and Radar Conference, Warsaw (Poland), 5 Oct 2020 - 8 Oct 2020.
PUBDB-2020-05296.
IEEE.
doi: 10.23919/MIKON48703.2020.9253858.

B. Gasowski et al.
Concept of Redundancy Subsystem for Master Oscillator of European-XFEL.
23rd International Microwave and Radar Conference, Warsaw (Poland), 5 Oct 2020 - 8 Oct 2020.
PUBDB-2020-05297.
IEEE.
doi: 10.23919/MIKON48703.2020.9253781.

M. Urbanski et al.
Voltage Driven Phase Shifters for Phase Reference Distribution System in SINBAD.
23rd International Microwave and Radar Conference, Warsaw (Poland), 5 Oct 2020 - 7 Oct 2020.
PUBDB-2020-05294.
IEEE.
doi: 10.23919/MIKON48703.2020.9253786.

IBIC 2020

S. Bielawski et al.
A New Scheme for Recording Electron Bunch Shapes With High Resolution and Record Recording Length - Principle and Tests at EuXFEL.
9th International Beam Instrumentation Conference, Santos (Brazil), 14 Sep 2020 - 18 Sep 2020.
PUBDB-2020-04931.

D. Lipka.
Influence of a Bellow to a Cavity BPM for SINBAD.
IBIC. 9th International Beam Instrumentation Conference, Santos (remote) (Brazil), 14 Sep 2020 - 18 Sep 2020.
PUBDB-2020-04391.
JACoW, Geneve.

B. E. J. Scheible et al.
Evaluation of a Novel Pickup Concept for Ultra-Low Charged Short Bunches in X-Ray Free-Electron Lasers.
9th International Beam Instrumentation Conference, Santos (Brazil), 14 Sep 2020 - 18 Sep 2020.
PUBDB-2020-04926.
JACoW Publishing, Geneva, Switzerland.
doi: 10.18429/JACOW-IBIC2020-WEPP21.

9th MicroTCA Workshop for Industry and Research

J. Branlard.
Operational Statistics with MTCA LLRF Systems at FLASH and XFEL.
9th MicroTCA Workshop for Industry and Research, Hamburg (Germany), 1 Dec 2020 - 3 Dec 2020.
PUBDB-2020-05312.

A. Brunzel.
MicroTCA Technology Lab at DESY: Report on Completed and Ongoing Projects.
9th MicroTCA Workshop for Industry and Research, Hamburg (Germany), 1 Dec 2020 - 3 Dec 2020.
PUBDB-2020-05313.

S. Farina and M. Fenner.
Next Generation SoC-based AMC Developments at DESY.
9th MicroTCA Workshop for Industry and Research, Hamburg (Germany), 1 Dec 2020 - 3 Dec 2020.
PUBDB-2020-05314.

P. Huesmann and M. Fenner.
Modernization of MMC Software Development at DESY Using Open-Source Tools.
9th MicroTCA Workshop for Industry and Research, Hamburg (Germany), 1 Dec 2020 - 3 Dec 2020.
PUBDB-2020-05319.

M. Killenberg et al.
A New Major Release of ChimeraTK ApplicationCore and DeviceAccess.
9th MicroTCA Workshop for Industry and Research, Hamburg (Germany), 1 Dec 2020 - 3 Dec 2020.
PUBDB-2020-05318.

N. Radakovic.
MicroTCA Motion Controller.
9th MicroTCA Workshop for Industry and Research, Hamburg (Germany), 1 Dec 2020 - 3 Dec 2020.
PUBDB-2020-05316.

Other Conference Contributions

A. Bellandi et al.
Integral Resonance Control In Continuous Wave Superconducting Particle Accelerators.
1st Virtual IFAC World Congress, Berlin (Germany), 11 Jul 2020 - 17 Jul 2020.
PUBDB-2020-04937.

J. Keil.
Lattice Design, Commissioning and Operation Challenges for PETRA IV.
Editorial Series on Accelerator Science. ARIES-ICFA Workshop ”Beam Tests and Commissioning of Low Emittance Rings”, Karlsruhe (Germany), 18 Feb 2019 - 20 Feb 2019.
PUBDB-2020-04471.
Insitute of Electronic Systems, Wasaw University of Technology, Warsaw.
doi: 10.5281/zenodo.3889903.

Conference Presentations

IBIC 2020

N. M. Lockmann et al.
Non-invasive Longitudinal Profile Measurements of Electron Bunches Simultaneously to FEL Operation at MHz Rates.
9th International Beam Instrumentation Conference, Santos (Brazil), 14 Sep 2020 - 18 Sep 2020.
PUBDB-2020-04933.

Virtual MT ARD ST3 Meeting in Karlsruhe

M. Gross et al.
Emittance Reduction of RF Photoinjector Generated Electron Beams by Transverse Laser Beam Shaping.
Virtual MT ARD ST3 Meeting in Karlsruhe, Karlsruhe (Germany), 24 Sep 2020 - 24 Sep 2020.
PUBDB-2020-04561.

M. Krasilnikov.
Status and Future Plans of PITZ.
Virtual MT ARD ST3 Meeting in Karlsruhe, Karlsruhe (Germany), 23 Sep 2020 - 24 Sep 2020.
PUBDB-2020-04559.

M. Krasilnikov et al.
LCLS-I Undulator Horizontal Gradient Modeling for THz@PITZ.
Virtual MT ARD ST3 Meeting in Karlsruhe, Karlsruhe (Germany), 23 Sep 2020 - 24 Sep 2020.
PUBDB-2020-04560.

G. Loisch et al.
Cathode Response Time Measurements in a High Gradient Photo Injector.
Virtual MT ARD ST3 Meeting in Karlsruhe, Karlsruhe (Germany), 23 Sep 2020 - 24 Sep 2020.
PUBDB-2020-04562.

A. Lueangaramwong and M. Krasilnikov.
Beam Dynamics Simulations for PITZ Bunch Compressor.
Virtual MT ARD ST3 Meeting in Karlsruhe, Karlsruhe (Germany), 23 Sep 2020 - 24 Sep 2020.
PUBDB-2020-04563.

Other Conference Presentations

N. Aftab.
Transverse Phase Space Characterization of High Brightness Electron Beams at PITZ.
Physikerinnentagung 2020, Hamburg (Germany), 5 Nov 2020 - 7 Nov 2020.
PUBDB-2020-04870.

E. Allaria.
Perspectives for Seeded FELs.
2nd Forum on Advanced FEL Techniques, Hamburg (Germany), 17 Sep 2020 - 18 Sep 2020.
PUBDB-2020-04989.

S. Diederichs et al.
High-Quality Positron Beams in Beam-Driven Plasma Wakefield Accelerators using a Plasma Column.
62nd Annual Meeting of the APS Division of Plasma Physics, Remote (USA), 9 Nov 2020 - 13 Nov 2020.
PUBDB-2020-05300.

D. Kostin.
Experience with the Eu-XFEL RF Couplers.
Americas Workshop on Linear Colliders 2020, Online (USA), 19 Oct 2020 - 22 Oct 2020.
PUBDB-2020-03966.

M. Krasilnikov et al.
Preparation of a Proof-of-Principle Experiment on SASE THz FEL at PITZ.
European XFEL Users’ Meeting 2020, Hamburg (Germany), 29 Jan 2020 - 31 Jan 2020.
PUBDB-2020-04566.

N. M. Lockmann et al.
Non-invasive Longitudinal Profile Measurements of Electron Bunches Simultaneously to FEL Operation at MHz Rates.
9th International Beam Instrumentation Conference, Santos (Brazil), 14 Sep 2020 - 18 Sep 2020.
PUBDB-2020-04933.

N. Schirmel et al.
Femtosecond Arrival Time Stability of Pump Probe Laser System at the FLASH Free Electron Laser.
9th EPS-QEOD Europhoton Conference EUROPHOTON SOLID-STATE, FIBRE, and WAVEGUIDE COHERENT LIGHT SOURCES, Prague (Czech Republic), 30 Aug 2020 - 4 Sep 2020.
PUBDB-2020-05290.

F. Stephan.
New FLASH Radiation Therapy $R\&D$ Options at the Photo Injector Test facility at DESY in Zeuthen (PITZ).
Very High Energy Electron Radiotherapy Workshop (VHEE’2020), Geneva (Switzerland), 5 Oct 2020 - 7 Oct 2020.
PUBDB-2021-00695.

Thesis

Ph.D. Thesis

P. Boonpornprasert.
Investigations on the Capabilities of THz Production at the PITZ Facility.
Universität Hamburg, 2020.

A. Ferran Pousa.
Novel Concepts and Theoretical Studies for High-Quality Plasma-Based Accelerators.
Universität Hamburg, Hamburg, 2020.

J. D. Good.
Experimental Characterization of the Photocathode Laser System for Advanced 3D Pulse Shaping at PITZ.
Universität Hamburg, 2020.

V. Grattoni.
Advanced Seeding Methods for Generation of Fully-Coherent Ultra-Short Soft X-Ray Pulses.
University of Hamburg, 2020.

W. Kuropka.
Studies towards Acceleration of Relativistic Electron Beamsin Laser-driven Dielectric Microstructures.
Universität Hamburg, Hamburg, 2020.

P. V. Winkler.
Emittance Measurements at Laser-Wakefield Accelerators.
University of Hamburg, 2020.

Master Thesis

J. L. Dresselhaus.
Paving the way of high repetition rate laser wakefield acceleration by solving heat induced grating deformation issues.
University of Hamburg, 2020.

Photographs and graphics
DESY
European XFEL
KIT
Imperial College London
Science Communication Lab

Florian Burkart, DESY
Ángel Ferran Pousa, DESY
Claudia Höhne, DESY
Thomas Hülsenbusch, DESY
Sonja Jaster-Merz, DESY
Alexander Knetsch, DESY
Carl A. Lindstrøm, DESY
Marta Mayer, DESY
Frank Mayet, DESY
Heiner Müller-Elsner, DESY
Dirk Nölle, DESY
Inga Pfeffer, DESY
Olaf Rasmussen, DESY
Daniel Reinhardt, DESY
Paul A. Walker, DESY
Antonio de Zubiaurre-Wagner, DESY

Niels Delbos, Universität Hamburg
Axel Heimken, European XFEL
Jarli & Jordan, University of Oslo

The figures were reproduced by permission of authors or journals.

Acknowledgement

We would like to thank all authors and everyone who helped in the creation of this annual report. ●

Imprint

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

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

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

www.desy.de
ISBN 978-3-945931-36-3
doi: 10.3204/PUBDB-2020-04948

Editing
Inga Pfeffer
Ilka Flegel, Kapellendorf

Layout
Sabine Kuhls-Dawideit, Büro für Grafik und Design, Halstenbek

Production
Britta Liebaug

Printing
EHS Druck GmbH, Schenefeld

Editorial deadline
1 May 2021

Editorial note
The authors of the individual scientific contributions published in this report are fully responsible for the contents.

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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

The Helmholtz Association is a community of 18 scientific-technical and biological-medical research centres. These centres have been commissioned with pursuing long-term research goals on behalf of the state and society. The Association strives to gain insights and knowledge so that it can help to preserve and improve the foundations of human life. It does this by identifying and working on the grand challenges faced by society, science and industry. Helmholtz Centres perform top-class research in strategic programmes in six core fields: Energy, Earth & Environment, Health, Aeronautics, Space and Transport, Matter, and Key Technologies.

www.helmholtz.de