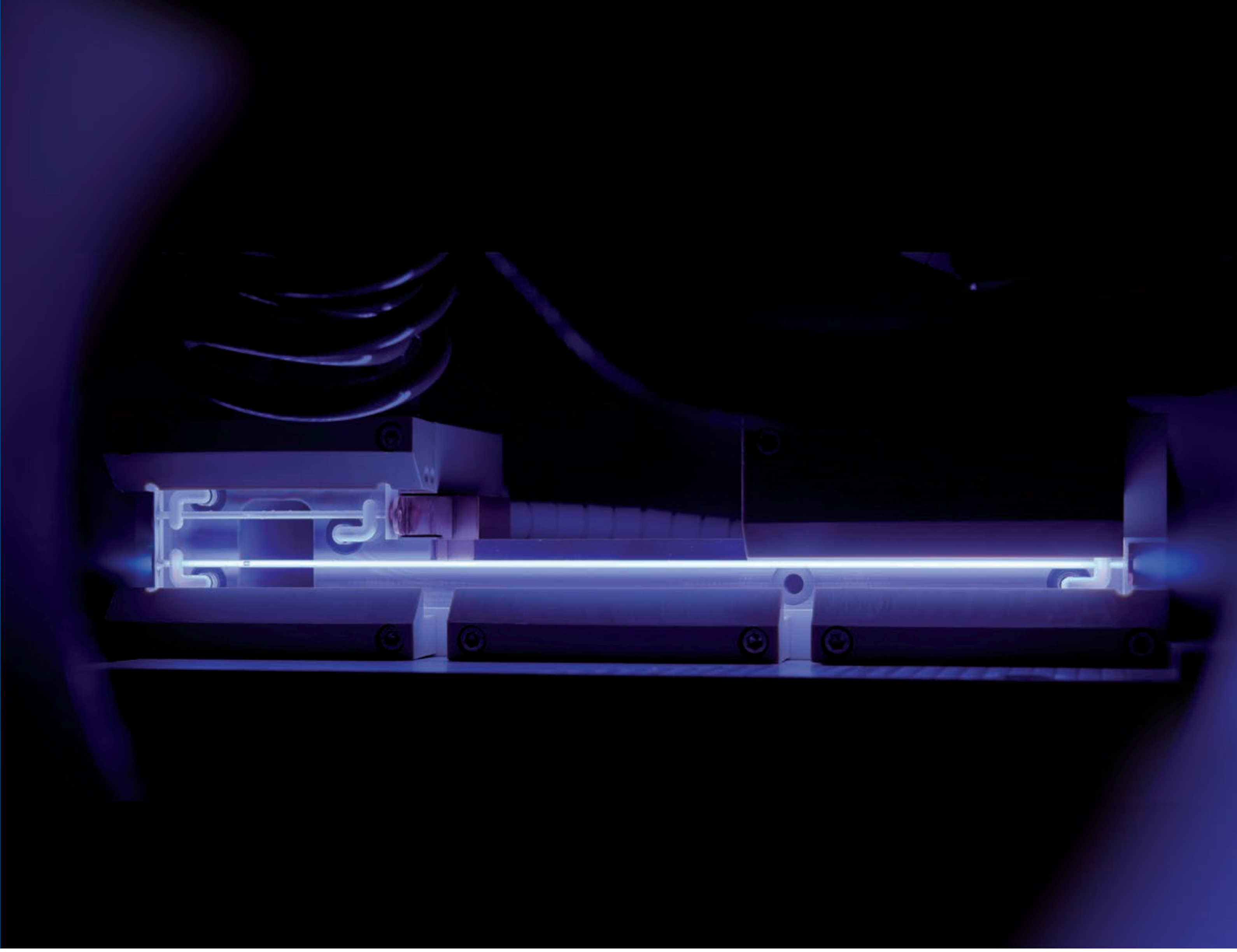

ACCELERATORS 2019.

Highlights and Annual Report

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

Cover

Many important results were achieved in 2019 in the development of new acceleration methods (see Highlights section). The cover picture shows a plasma cell at the FLASHForward beamline, which comprises two capillaries of different length that contain the plasmas used for particle acceleration.

ACCELERATORS 2019.

Highlights and Annual Report

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The year 2019 at DESY

Chairman's foreword

Dear Colleagues and
Friends of DESY,

2019 was a year with marked advances. Most prominently, DESY turned 60! The event was celebrated with a festive reception in the Hamburg city hall in the presence of Hamburg's Deputy Mayor and Senator for Science, Research and Equality Katharina Fegebank and the newly appointed State Secretary at the German Federal Ministry of Education and Research (BMBF) Wolf-Dieter Lukas. Both complimented us on our work, giving us confidence that the City of Hamburg and the German federal government will continue their support for our core business: basic research.

With Wim Leemans and Christian Stegmann, we welcomed two new directors to our laboratory: Wim has taken over the accelerator division from Reinhard Brinkmann, while Christian is heading our new astroparticle physics division. With this restructuring, we are strengthening our activities in astroparticle physics and giving more weight to synergetic topics at the boundary of particle and astroparticle physics. The appointment of Wim, one of the world's leading accelerator physicist in the field of plasma acceleration, decisively strengthens our position at the forefront of global accelerator development.

Accelerators are among the most important and versatile tools used in science, benefitting a wide range of fields, from medicine and biology through physics and materials science to art history. Developing the accelerator technologies and facilities of the future is one of the key elements of our mission. Accordingly, we are vigorously advancing both the expansion of our existing accelerator facilities and the development of novel accelerator technologies.

In particular, we will upgrade our PETRA III synchrotron radiation source – one of the most brilliant storage-ring-based X-ray sources in the world – to an ultralow-emittance facility, enabling us to realise the ultimate 3D X-ray microscope. The conceptual design report (CDR) for PETRA IV was completed in 2019 and approved by our advisory bodies. Over the next two years, we will work out the detailed technical design for the enhanced facility. DESY has also secured the necessary financial means for the upgrade of its FLASH free-electron laser, called FLASH2020+, for which the CDR was completed and approved in 2019 as well. Work has started on the technical design report for the upgrade, which will substantially improve the quality of the photon beams delivered by the facility.

Sadly, in 2019, DESY had to cope with the sudden death of Wilfried Wurth, the charismatic scientific director of FLASH and one of our pioneers in free-electron laser research. The reactions we received from colleagues and institutions from all over the world made it clear again what esteem Wilfried enjoyed in the worldwide scientific community. We owe a great deal to Wilfried Wurth and will continue his dedicated work at FLASH, making the visions for the future of this pioneering facility, which he decisively shaped, become reality.

The vision of DESY is to become the world-leading laboratory in the development of novel types of compact particle accelerators. The groundbreaking technologies of terahertz and plasma acceleration enable much higher accelerating gradients than conventional radio frequency technology. They therefore hold great potential for significantly shrinking the size and cost of future accelerator facilities, promising completely new applications, such as compact X-ray sources for materials science or medical imaging. In 2019, DESY scientists made great advances in the development of both technologies, achieving several critical steps forward towards the practical implementation of these novel types of accelerators.

Our upgraded and future accelerator facilities are central elements of our vision of the Science City Bahrenfeld: Over the next 20 years, DESY, Universität Hamburg and the City of Hamburg plan to realise a joint campus that combines science, education and training, as well as the transfer of knowledge and innovation to industry and society. At the heart of this campus, DESY will be well positioned for its next 60 years!

Finally, I would like to thank the DESY staff and all our national and international partners, who are so important for the success of our vibrant research centre.

Helmut Dosch
Chairman of the DESY Board of Directors

Accelerators at DESY

Introduction

Dear Colleagues and Friends of DESY,

2019 was an exciting year in which much progress was achieved, in the operation of our existing large-scale particle accelerator facilities FLASH, PETRA III and European XFEL, the planning of major upgrades to the latter and the development of novel technologies for the accelerator facilities of the future. Activities also included launching a new quality assurance programme, developing a detailed strategic plan for plasma acceleration, starting the KALDERA project and forming plasma acceleration and laser system groups.

At the European XFEL X-ray free-electron laser, a test with the maximum repetition rate of 4.5 MHz (27 000 X-ray pulses per second) delivered to experiments was performed in July 2019, underlining the readiness of the accelerator to operate in this mode. The simultaneous delivery of X-ray pulses from three undulator beamlines to three instruments operated in parallel – a worldwide unique trait – became the standard operation mode. In addition, the parameter space was further expanded, and the facility now regularly provides electron energies from 11 to 17 GeV, generating X-ray pulses with wavelengths down to around 0.6 Å. Extreme flexibility in the bunch pattern was demonstrated, as required for the simultaneous operation of all three undulator beamlines and the corresponding instruments.

User experiments at our FLASH soft X-ray FEL, the pioneering facility where much of the technology underlying the European XFEL was first developed and tested, were routinely carried out at two undulator beamlines (FLASH1 and FLASH2) operated in parallel. The machine availability reached a record high of 97.8%. The planning of the upgrade of FLASH proceeded well, and the FLASH2020+ conceptual design report (CDR) was approved. Upgrade plans include flexibility in photon polarisation by installing an afterburner undulator at FLASH2 and fully tuneable undulators at FLASH1. The electron beam energy will be increased to extend the wavelength reach up to the oxygen K-edge, and external seeding will be realised at the full repetition rate of 1 MHz in burst mode to make FLASH the first high-repetition-rate FEL with full longitudinal coherence. Finally, novel FEL lasing concepts based on variable undulator configurations will be exploited at FLASH2 to shorten the pulse duration and enable attosecond experiments.

The average availability of our PETRA III synchrotron radiation source reached a new record of 98.3%. From July 2019, the facility was operated in a 480-bunch mode with a 20% higher beam current of 120 mA, and low-emittance operation at a beam energy of 3 GeV was demonstrated. Planning for the successor to PETRA III, the world's brightest hard X-ray ultra-low-emittance storage ring named PETRA IV, proceeded. We will upgrade the storage ring, upgrade and refurbish the pre-accelerators, upgrade the photon beamlines and construct a new experimental building in the west of the PETRA ring. With the CDR for the PETRA IV project completed in 2019, the elaboration of the technical design report is now under way.

A central element of the DESY 2030 strategy is research into novel accelerator concepts, especially plasma wakefield acceleration and THz-driven acceleration. In 2019, all plasma acceleration activities at DESY – in Hamburg and Zeuthen – and at Universität Hamburg were assessed for strengths and weaknesses, and a strategic plan was developed that focuses all activities on key scientific goals while maximising the utilisation of world-leading infrastructure at DESY.

The laser-driven plasma acceleration experiment LUX, led by Universität Hamburg, demonstrated continuous operation, reliably providing electron beams that supported the day-long generation of spontaneous undulator radiation at few-nanometre wavelength. The facility is being upgraded to demonstrate first FEL gain. Experiments are now running at the second major experimental infrastructure, the beam-driven plasma acceleration facility FLASHForward at FLASH. Highlights in 2019 included high-precision wakefield measurements, preservation of energy spread and, most impressively, a 1 GeV energy doubling in a plasma cell in less than 20 cm. DESY scientists also proposed a new acceleration concept based on two plasma stages connected by a magnetic chicane, which could improve the energy spread of the beam by more than one order of magnitude compared to current plasma accelerators.

In another world first, a miniature THz accelerator more than doubled the energy of injected electrons, at the same time significantly improving the electron beam quality compared to earlier experiments with the technique. The coupled device produced a peak accelerating gradient of 200 MV/m, which is close to that delivered by the best state-of-the-art conventional accelerators. The achieved progress is central for the ERC-funded project AXSIS (frontiers in Attosecond X-ray Science: Imaging and Spectroscopy), which pursues short-pulse X-ray spectroscopy and imaging of complex biophysical processes with X-ray pulses generated by THz-driven electron accelerators.

At the new accelerator R&D facility SINBAD (Short Innovative Bunches and Accelerators at DESY), which DESY is currently setting up, the SINBAD-ARES linear accelerator approached the end of construction, with the electron source area already in beam commissioning. First electron bunches were produced in October 2019. ARES is expected to generate few-femtosecond-long electron bunches in 2020, which can be used to test advanced acceleration schemes and develop novel diagnostic devices in ultrafast science.

DESY also launched the KALDERA project, where the aim is to construct a high-power laser (>100 TW) that can run at a repetition rate 1 kHz and has sufficiently high stability and reproducibility to produce high-quality electron bunches from a laser plasma accelerator at this repetition rate of 1 kHz. This in turn will enable high-average-power light source experiments that build on the demonstration FEL experiment LUX and indicate the potential for this technology to power future user facilities.

At the time of writing these lines, the world is in the midst of a global pandemic. It is with pride that I can share that our PETRA III facility was operated by an extremely dedicated team of accelerator and beamline physicist to help unravel the mysteries of the SARS-CoV-2 coronavirus. The experiences gained during these challenging times will undoubtedly shape the way we will carry out our science in the future. I am very grateful to all the DESY staff and advisory committees, and I am confident that DESY will come out stronger and even more devoted to solving the greatest challenges the world faces, through the use of accelerator-based analytic tools.

Wim Leemans
Director of the Accelerator Division

News and events

News and events

A busy year 2019

January

New science district to be built around DESY

The Hamburg Senate, the Altona District, DESY and Universität Hamburg presented their plans for a science district in western Hamburg – the Science City Bahrenfeld, which is to closely link science, business and housing. The new district is to be built on an area of 125 ha around the DESY campus in Hamburg-Bahrenfeld. It will include new scientific institutes and facilities, such as the Centre for Data and Computing in Natural Sciences (CDCS), the Centre for Molecular Water Science (CMWS), the Wolfgang Pauli Centre (WPC) for theoretical physics and DESY's planned 3D X-ray microscope PETRA IV, as well as around 2500 apartments.

Virtual view of the Science City Bahrenfeld in 2040

In addition to the expansion of DESY, the plans will enable the university to move its physics, chemistry and biology departments to the science city. As a "green heart" of the new district, the Altonaer Volkspark will combine science and research with quality living, sports and health areas. First architectural competitions for the Science City Bahrenfeld are planned for 2020.

Acceleration record at the European XFEL

The particle accelerator of the European XFEL X-ray laser – the world's longest superconducting linear accelerator, which is operated by DESY – lived up to expectations by accelerating the record rate of 27 000 electron bunches per second for the first time. In 2018, it had already reached its design electron energy of 17.5 GeV. The high pulse rate at the European XFEL is unique and distinguishes the facility from the other X-ray lasers in the world. The pilot facility for the European XFEL, the FLASH free-electron laser at DESY, already achieves 8000 pulses per second.

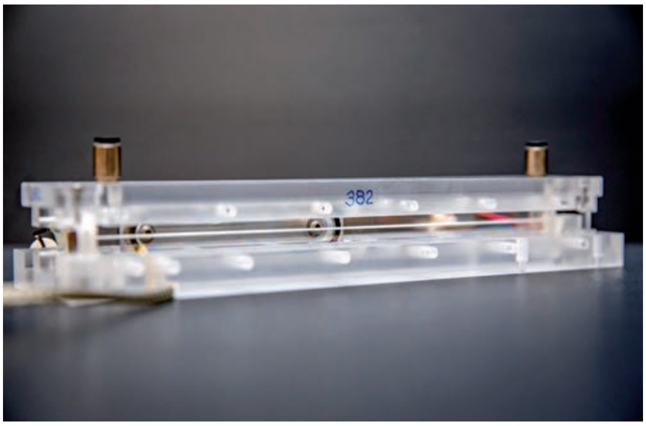
For the research operation at the European XFEL, which started in September 2017, the number of electron bunches – and thus the number of X-ray flashes – were limited to a maximum of 6000 per second in 2019 in order to be able to optimally set up and tune the scientific instruments. However, this was still at least 50 times as many X-ray pulses as any of the other large X-ray lasers in the world can generate. In the future, the pulse rate of the European XFEL will be increased to the maximum possible 27 000 per second.

View into the tunnel of the 1.7 km long superconducting linear accelerator of the European XFEL

February

Laser drill enables world record in plasma acceleration

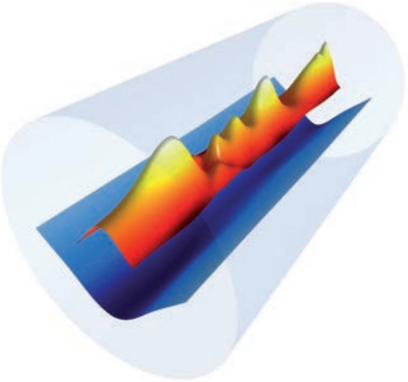
Using a laser to “drill” through a plasma, scientists at the Lawrence Berkeley National Laboratory in California, USA, set a new world record for plasma accelerators: In a plasma capillary only 20 cm long, they accelerated electrons to an energy of 7.8 GeV, a value for which today’s most advanced conventional particle accelerators require hundreds of metres. The team was led by Wim Leemans, then head of the Berkeley Lab Laser Accelerator (BELLA) Center and now director of the accelerator division at DESY.



A 20 cm long plasma capillary as used for the world record

“The development of stable plasma acceleration with energies near 10 GeV is a milestone on the route from the lab to first applications,” said Leemans, who plans to further improve the method at DESY. “We have developed a new concept in the toolbox, and together with other concepts for acceleration, beam stability and beam control existing at DESY, this will allow for compact electron sources.”

Laser plasma acceleration uses an intense, high-energy laser pulse that ploughs through a plasma, creating wakefields that can accelerate particles hundreds of times more strongly than the best conventional accelerators. The more powerful the drive laser pulse is, the stronger the acceleration in the plasma. The team at BELLA shot extremely intense and short infrared laser pulses, each with a peak power of about 850 TW and lasting just 35 fs, into a 0.8 mm wide sapphire capillary filled with hydrogen. To accelerate the electrons to high energies, the wakefields needed to be created over the full length of the 20 cm long plasma capillary. To do this required a plasma channel, which confines a laser pulse in much the same way as a fibre-optic cable channels light. In order to form such a channel, the plasma needs to be less dense in the middle of the capillary.



Snapshot of the plasma channel electron density profile (blue) formed inside a capillary (grey) with the combination of an electrical discharge and an 8 ns long laser pulse (red/yellow)

In an earlier experiment at BELLA that had set the former plasma acceleration record of 4.25 GeV, an electrical discharge was used to create the plasma channel. To reach higher energies, however, the plasma’s density profile needed to be even deeper, so the plasma is less dense in the middle of the channel. In previous attempts, the drive laser lost its tight focus and damaged the sapphire capillary. The solution to this problem was inspired by an idea from the 1990s to use a laser pulse to heat the plasma and form a channel. Leemans realised that such a laser could be combined with the discharge. If the heating laser is fed into the capillary right after the discharge, it drills through the plasma to form a deeper channel that can confine the drive laser.

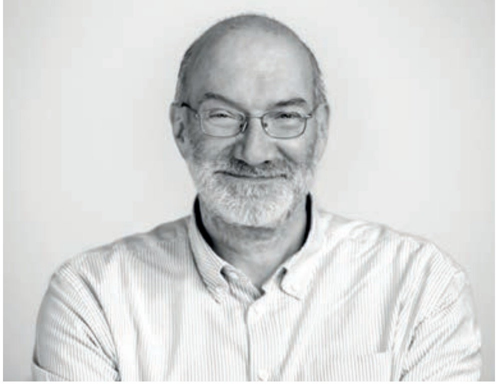
Experiments and theoretical modelling of the process showed that a laser pulse of 8 ns duration, shot through the capillary 420 ns after the electric discharge, could drill the optimal channel for the laser pulse driving the acceleration. The combined technique radically improved the confinement of the drive laser beam, preserving its intensity and focus and confining its spot size to just tens of micrometres as it moved through the plasma capillary. This enabled the use of a lower-density plasma and a longer capillary. The previous 4.25 GeV record had been achieved using a 9 cm long capillary. With a 20 cm capillary and exploiting the laser drill technique, the team reached the new record energy of 7.8 GeV.

May

DESY mourns the loss of Wilfried Wurth

DESY mourns the loss of one of its pioneers in research at free-electron lasers: Wilfried Wurth, scientific director of the FLASH free-electron laser facility and leading scientist at DESY, died suddenly and unexpectedly at the age of 62.

“Wilfried Wurth’s sudden death hit us all very hard. We are losing an excellent scientist and a very esteemed and popular colleague,” said DESY Director Helmut Dosch. “We will very much miss his positive nature and his always sharp analysis. Our deepest sympathy and our thoughts are with Wilfried Wurth’s family.”



Wilfried Wurth

Wilfried Wurth was a leading scientist at DESY and professor of experimental physics at Universität Hamburg. He made a name for himself as an expert in X-ray spectroscopy and in the investigation of ultrafast processes, such as the observation of dynamics of atoms on surfaces in real time. Already before joining DESY in 2014, he was one of the leading researchers at FLASH. He led the Advanced Study Group of Universität Hamburg at the Center for Free-Electron Laser Science (CFEL), a cooperation of DESY, the Max Planck Society and Universität Hamburg. Wilfried Wurth played an important role in the construction of CFEL as well as in the overall cooperation between the university and DESY.

From 2007 to 2013, Wilfried Wurth was the spokesman of the research priority programme FLASH of the German research ministry BMBF, the first priority programme in the field of condensed matter. It was created to bundle research at FLASH within the framework of collaborative project funding.

During Wilfried Wurth’s time as scientific director of FLASH, the second undulator line for light generation and the second experimental hall of the facility were built within the FLASH2 expansion project. In DESY’s strategy process, which was completed in 2018, Wilfried Wurth took a leading role in developing the visions for the future of the pioneering facility. He also led the creation of the conceptual design report for its further development into FLASH2020+.

June

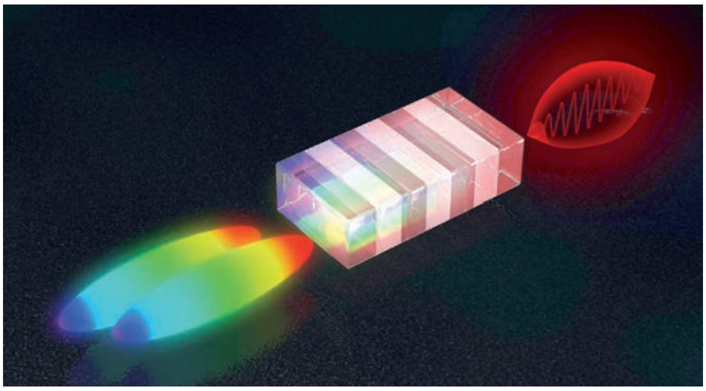
Laser trick produces high-energy terahertz pulses

A team of scientists from DESY and Universität Hamburg achieved an important milestone in the quest for a new type of compact particle accelerator. Using ultrapowerful laser pulses, they were able to produce particularly high-energy flashes of terahertz radiation with a sharply defined wavelength (colour).

Terahertz radiation lies between infrared and microwave frequencies in the electromagnetic spectrum and promises a new generation of lab-sized particle accelerators: As the wavelength of terahertz radiation is about a hundred times shorter than the radio waves currently used to accelerate particles, the components of the accelerator can also be built to be around a hundred times smaller. Accelerators based on the terahertz approach promise completely new applications, for instance as compact X-ray sources for materials science and maybe even for medical imaging. The technology is currently under development.

Chivvying along an appreciable number of particles in such accelerators calls for powerful pulses of terahertz radiation with a sharply defined wavelength – which is what the CFEL-led team managed to create. To do so, the scientists fired two powerful laser pulses into a non-linear crystal, with a minimal time delay between the two. The laser pulses had a kind of colour gradient, meaning that the wavelength at the front of the pulse was different from that at the back. The slight time shift between the two pulses therefore resulted in a slight difference in colour, which was exactly in the terahertz range. The crystal then converted the colour difference into a terahertz pulse.

The method requires the two laser pulses to be precisely synchronised. This is achieved by splitting a single pulse into two parts and sending one of them on a short detour so that it is slightly delayed before the two pulses are eventually superimposed again. However, the colour gradient along the pulses is not constant, that is, the colour does not change uniformly along the length of the pulse. Instead, it changes



From the colour difference between two slightly delayed laser pulses (left), a non-linear crystal generates an energetic terahertz pulse (right).

slowly at first and then more and more quickly, so that the colour profile has a curved outline rather than a straight one. As a result, the colour difference between the two staggered pulses is not constant and is only appropriate for producing terahertz radiation over a narrow section of the pulses.

That was a big obstacle towards creating high-energy terahertz pulses, because straightening the colour gradient of the pulses, which would have been the obvious solution, is not easy to do in practice. The crucial idea that solved the problem was to slightly stretch the colour profile of one of the two pulses along the time axis. As a result, the strength of the color gradient along the pulse still changed, but the colour difference with respect to the other pulse improved and remained constant over a wider section.

The changes that needed to be made to one of the two pulses were minimal and surprisingly easy to achieve. All that was necessary was to insert a short length of a special glass into the beam. As a result, the terahertz signal became stronger by a factor of 13. In addition, the scientists used a particularly large, specially made non-linear crystal to generate the terahertz radiation.

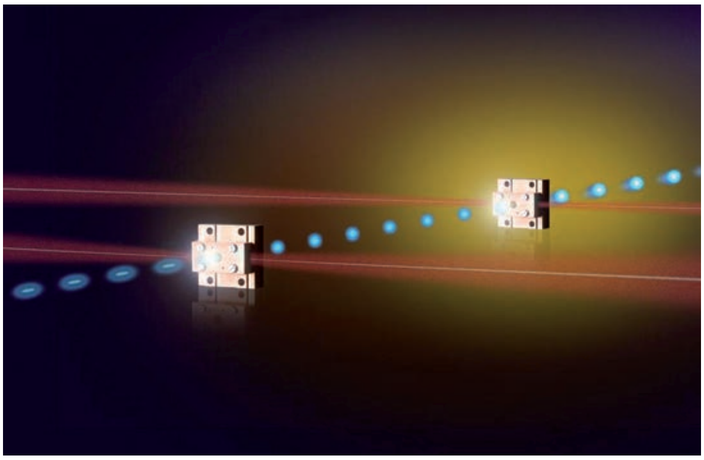
By combining these two measures, they were able to produce terahertz pulses with an energy of 0.6 mJ, which is a record for this technique and more than ten times higher than any terahertz pulse of sharply defined wavelength previously generated by optical means. The work thus demonstrates that it is possible to produce sufficiently powerful terahertz pulses with sharply defined wavelengths to operate compact particle accelerators.

July

Miniature terahertz accelerator achieves record energy

Scientists from CFEL at DESY set a new world record for terahertz accelerators: For the first time, a miniature accelerator powered by terahertz radiation more than doubled the energy of injected electrons. At the same time, the setup significantly improved the electron beam quality compared to earlier experiments with the technique, achieving the best beam parameters yet for terahertz accelerators. The result represents a critical step forward for the practical implementation of this novel type of compact particle accelerators.

Since terahertz waves oscillate so fast, all the components and every process step have to be precisely synchronised. For example, to achieve the highest energy gain, the electrons have to hit the terahertz field exactly during its accelerating half cycle. In accelerators, particles usually do not travel in a continuous beam, but are packed in bunches. Because of the fast-changing field, in terahertz accelerators these bunches have to be very short to ensure even acceleration conditions along the bunch.



The two-stage miniature accelerator is operated with terahertz radiation (shown in red). In a first step (left) the electron bunches (blue) are compressed, in a second step (right) they are accelerated. The two individual elements are each about 2 cm wide.

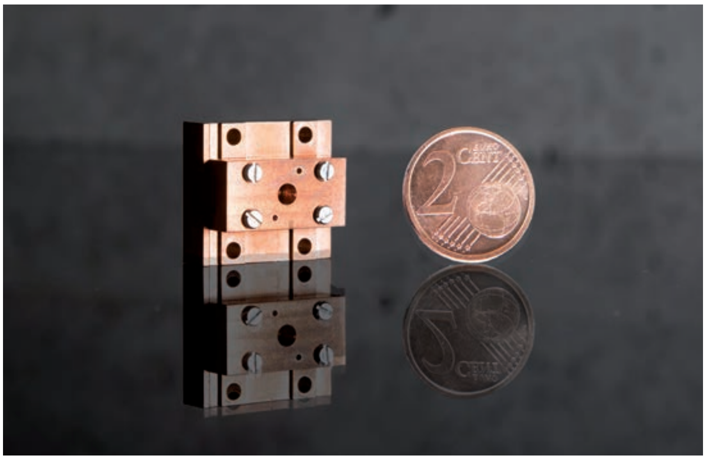
In previous experiments, the electron bunches were too long. Since the terahertz field oscillates so quickly, some of the electrons in the bunch were accelerated, while others were slowed down. In total, there was just a moderate average energy gain and, even more important, a wide energy spread, resulting in poor beam quality. To make things worse, the effect strongly increased the emittance, a measure for how well a particle beam is bundled in the transverse direction. The tighter the bundling, the better – and the smaller the emittance.

To improve the beam quality, the team built a two-step accelerator from a multipurpose device they had developed earlier: the Segmented Terahertz Electron Accelerator and

Manipulator (STEAM), which can compress, focus, accelerate and analyse electron bunches with terahertz radiation. The researchers combined two STEAM devices in line. They first compressed the incoming electron bunches from about 0.3 mm in length to 0.1 mm. With the second STEAM device, they accelerated the compressed bunches. The scheme, which required control on the level of femtoseconds, led to a fourfold reduction of the energy spread and improved the emittance sixfold, resulting in the best beam parameters of a terahertz accelerator so far.

The accelerator increased the energy of the injected electrons from 55 keV to 125 keV – the first energy gain greater than 100% in a terahertz-powered accelerator. The coupled device produced an accelerating gradient with a peak strength of 200 MV/m, which is close to that delivered by the strongest state-of-the-art conventional accelerators.

For practical applications of terahertz accelerators, both the gradient and the beam quality need to be significantly improved. The present work shows how this could be done, by demonstrating that a more than three times stronger compression of the electron bunches is possible. In combination with a higher terahertz energy, accelerating gradients in the GV/m regime seem feasible. The terahertz concept thus appears increasingly promising as a realistic option for the design of compact electron accelerators.

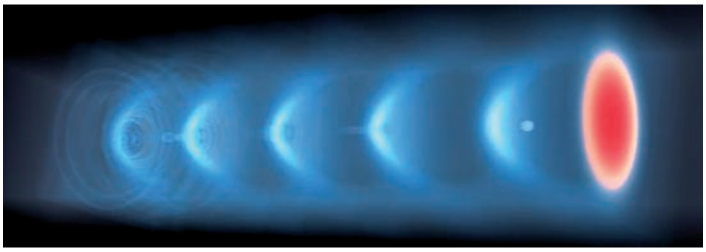


STEAM is a kind of “Swiss army knife” for electron beams – depending on the operating mode, it combines four functions in one device: It can compress, focus, analyse and accelerate electron bunches.

August

Innovative concept for better plasma accelerators

DESY scientists proposed a new plasma accelerator concept that could overcome some of the current limitations of the technology, significantly improving the quality of the accelerated particle beams. Plasma accelerators are currently in the spotlight thanks to their potential for significantly shrinking the size and cost of future accelerator facilities. However, the technology faces a number of issues that currently prevent plasma accelerators from being widely used for applications. The newly presented concept addresses the energy spread, one of the most pressing challenges of the novel technology, and could enable applications such as compact X-ray free-electron lasers that would be only a few dozen metres long instead of the several kilometres required today.



Three-dimensional view of the plasma wakefields (blue) generated by a laser pulse (red) propagating from left to right. The accelerated electron beam is represented as a blue dot in the first accelerating bucket.

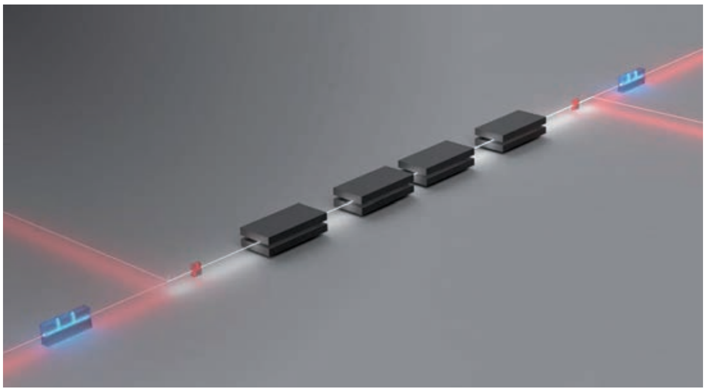
Plasma wakefield accelerators use high-intensity laser pulses to generate waves in a plasma channel that electrons can ride like a surfer rides an ocean wave. The resulting accelerating gradients are up to a thousand times higher than achievable with conventional technology. A well-known problem directly linked to these high gradients, however, is that the electrons accelerated in the plasma experience a different energy gain depending on their individual position on the plasma wave. This leads to the development of a significant correlated energy spread along the beam, which is detrimental to its quality and severely limits its applications.

The new concept proposes to perform the acceleration process in two plasma stages connected by a magnetic chicane. The magnetic detour inverts the energy correlation along the beam, allowing it to be naturally compensated for in the second plasma stage. As a result, the energy spread of the beam is drastically reduced.

Results from numerical simulations show that electron beams produced with this method exhibit an energy spread that is improved by more than one order of magnitude compared to current plasma accelerators. The study describes a first conceptual implementation of the scheme performed for the EuPRAXIA project in the framework of the Horizon2020 programme of the European Union. At a beam energy of

5.5 GeV, the simulated 1.5 m long setup is predicted to achieve a residual relative energy spread of 0.1% for the total beam and just 0.03% in a short section of the beam.

The new concept for a plasma wakefield accelerator with low energy spread – and the underlying improved understanding of the relevant accelerator physics phenomena – could be a major step forward towards building a plasma-based free-electron laser at multi-GeV beam energy. The validation of the concept requires experimental tests, however, which could partly be carried out within the Accelerator Technology Helmholtz Infrastructure (ATHENA) project at DESY, a new R&D platform on accelerator technology within the Helmholtz Association.



Conceptual implementation of the proposed plasma accelerator scheme. The two plasma acceleration stages (blue) are joined by a magnetic chicane. Two active plasma lenses (red) are used for beam transport and plasma mirrors for the laser in- and outcoupling. The trajectories of the laser pulses and the electron beam are represented in red and white, respectively.

Largest free-electron laser conference back in Hamburg

At the end of August, DESY and European XFEL co-hosted FEL2019, the 39th edition of the world's largest conference on free-electron lasers. Around 400 scientists from 25 nations discussed the latest progress in the development and application of these unique research light sources.

Free-electron lasers (FELs) are facilities fed by strong particle accelerators, in which free-flying electrons (hence the name) generate laser light on a magnetic slalom course. X-ray lasers on this basis provide unique insights into the nanocosmos: They can be used to elucidate the spatial structures of biomolecules in order to develop new drugs, film chemical reactions in order to better understand and optimise industrial processes, or simulate the conditions inside planets and stars. The European XFEL in the Hamburg metropolitan region is currently the world's most powerful X-ray FEL.

DESY last hosted the conference in 1999, at a time when X-ray FELs existed only on paper. Since then, both the field of FEL science and the science location Hamburg have evolved dramatically, with the first observation of short-wavelength FEL light at DESY's FLASH FEL facility in 2000 and the opening of the European XFEL in 2017, developed and built by a cooperation of DESY and international partners. Today, several X-ray FEL user facilities are in operation around the globe, for all of which FLASH has served as the prototype.

"The superconducting radio frequency technology developed at DESY and first deployed at FLASH opened a new era for photon-based science," said DESY Accelerator Director Wim Leemans. "It also enabled the successful construction and operation of the world-leading hard X-ray European XFEL and other high-power FELs. Together with the PETRA III hard X-ray storage ring, these Hamburg-based facilities offer one-stop shopping for X-ray users."

Hamburg's Second Mayor and Senator for Science, Research and Equality Katharina Fegebank, European XFEL Managing Director Robert Feidenhans'l and DESY Accelerator Director Wim Leemans at the opening of the FEL 2019 conference

September

"Trojan horse" trick promises ultrabrilliant electron beams

Using a trick modelled on the Trojan horse, a novel electron source based on plasma acceleration technology can generate extremely brilliant particle beams. The new method promises 100 to 10 000 times more tightly focused electron beams than conventional accelerators can currently deliver. An international team headed by the University of Strathclyde in Glasgow, Scotland, successfully tested the method at the SLAC National Accelerator Laboratory in California, USA. DESY researchers played a major role in the work.

High-energy electron beams are versatile tools for exploring the realm of molecules, atoms and elementary particles. They can either be used to collide electrons and their antiparticles, positrons, in order to unravel the secrets of the subatomic world. Or they can be fed into specialised magnet arrangements called undulators to generate extremely bright X-rays, which can be used, for example, to observe proteins at work and analyse the inner structure of new nanomaterials. For all these applications, the colder and smaller the electron beams are, the better.

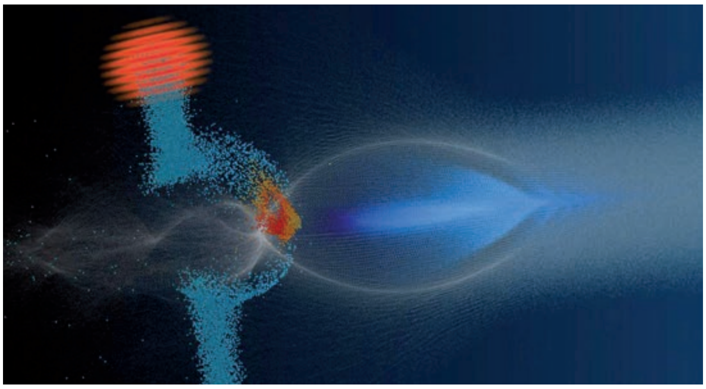
The team tested a process in which "cold" electrons with little kinetic energy are accelerated by a plasma wave. If a strong laser pulse or a high-energy electron bunch is fired into the plasma, it generates an electrically charged wave in its wake on which electrons can ride like a surfer on an ocean wave. This plasma wakefield acceleration can accelerate particles much stronger over short distances than the best conventional accelerator technology available today. However, plasma acceleration is still in the experimental phase and there are only few applications yet.

The colder the electrons are at the beginning of the acceleration, the slower they move, and the closer they stay together – an important prerequisite for strongly focused beams. For their method, the physicists released cold electrons into the hot plasma bubble in a similar way to how the Greeks allegedly once smuggled soldiers into the besieged city of Troy in a wooden horse. Instead of a wooden horse, however, helium atoms served as hiding places for the electrons.

The researchers used a mixture of hydrogen and helium as gas. The laser that generated the plasma was just energetic enough to release the electrons of the hydrogen, but not those of the helium. The scientists thus produced a plasma wave from hydrogen, while the helium remained unimpressed. With a precisely targeted second laser pulse, which had a slightly higher energy, they then released electrons from their Trojan horses, the helium atoms, right inside the plasma bubble. These still cold electrons were generated in a tiny volume of a few micrometres in diameter and compressed even more strongly by the immediately following plasma wave.

The experiment demonstrated for the first time that the Trojan horse method actually works. As one of the most promising methods for future electron sources, it could push the boundaries of current technology: The plasma setup would take over the function of the photocathode, which usually serves as the electron source in conventional particle accelerators. In these highly specialised devices, a laser knocks electrons out of a piece of metal, which are then captured by a strong electromagnetic field, bundled and packed into bunches that are finally fed into the accelerator.

The electrons from the plasma photocathode that was successfully tested could be fed into a particle accelerator, but they can also be accelerated to high energies directly in the plasma itself. In the pilot experiment, the electrons reached energies of up to 700 MeV. The team estimated that the beam quality could already compete with conventional electron sources. In further experiments, they plan to increase the quality and stability of the beam and improve the beam diagnostics.



Illustration, based on simulations, of the Trojan horse technique for the production of high-energy electron beams. A laser beam (red) strips electrons (light blue dots) off of helium atoms. Some of the freed electrons (red dots) get accelerated inside a plasma bubble (white elliptical shape) created by an electron beam (dark blue).

October

DESY strengthens cooperation with Armenia

On a three-day trip to the Republic of Armenia, a delegation from DESY intensified the scientific relations between DESY and research institutions in Armenia. Two joint declarations were signed, in the fields of accelerator physics, particle and astroparticle physics as well as on the general promotion of young scientists.

The DESY delegation was invited by Armenian President Armen Sarkissian.

A highlight of the trip was a meeting with Armenian President Armen Sarkissian. During his visit to DESY in Zeuthen in 2018, the president had issued an invitation to DESY Director Helmut Dosch to visit Armenia. In addition, a reception for Armenian research partners and members of the DESY delegation was held in Yerevan at the invitation of the German ambassador.

DESY has maintained close scientific relations with the A. Alikhanyan National Laboratory for decades. What began in the 1960s with the former Yerevan Physics Institute was sealed in 1993 with a first official cooperation agreement. In the meantime, the institute changed its name to A. Alikhanyan National Laboratory, and the collaborations were further intensified, especially in the fields of particle and astroparticle physics. DESY scientists are also collaborating closely with the CANDLE Synchrotron Research Institute, which is setting up its own accelerator-based radiation sources.

DESY nominated for Energy Efficiency Award

The German Energy Agency dena nominated DESY for the 2019 Energy Efficiency Award. DESY's project of waste heat recovery from cryogenics was one of three nominated projects in the category "Energiewende 2.0" ("Energy Turnaround 2.0"), prevailing over a total of 142 applicants in four categories.

In DESY's cryogenic hall, helium is cooled to -271°C (2 K) for the operation of the superconducting accelerators. This process generates waste heat, which has a temperature of about 70°C. Thanks to the installation of two heat exchangers that connect the cooling system of the oil-cooled rotary-screw compressors to the local heating network, this waste heat can be used for heating purposes on the entire DESY campus. Between commissioning in June 2017 and fall 2019, approx. 7.5 GWh of heat were extracted from the cryogenic plant and used for heating on the campus. This was about one third of the total heat demand at DESY.

"The use of waste heat from helium liquefaction is a big step towards more energy efficiency at DESY, and many more steps will follow," said DESY Director Helmut Dosch. "The nomination spurs us on to devote our full attention to this issue and other sustainability topics in the coming years." The further development of the accelerator facilities at DESY constantly offers new potential for energy efficiency measures. Alongside research, the operation of the facilities can thus contribute to greater sustainability as well.

The German Energy Agency dena was set up by the Federal Republic of Germany and the KfW Banking Group to increase climate efficiency in Germany and reduce absolute energy demands. The Energy Efficiency Award has been presented internationally since 2007 to honour outstanding energy efficiency achievements in private and public companies, with three finalists competing for the prize in each of four categories.

These heat exchangers in the DESY cryo plant feed heat into the DESY heating network.

Federal government supports expansion of DESY campus

The Budget Committee of the German Bundestag decided that DESY will receive a further 15 million euros in federal funding for the upgrading of its non-scientific infrastructure. The money is to be invested until 2022 into the renovation, modernisation and new construction of buildings that are crucial for day-to-day operations and for improving sustainability. The funds complement federal funding of more than 110 million euros already provided in previous years.

The aim of the funding is to strategically expand the DESY campus in Hamburg in the coming years and develop it into an interdisciplinary science centre. The campus development, which is to be as sustainable as possible, represents a cornerstone of the future vision of the Science City Bahrenfeld. DESY's long-term plans will enable a holistic further development of the campus and great scientific synergy effects.

Vision of the future DESY campus within the planned Science City Bahrenfeld

In contrast: Aerial view of the DESY campus in Hamburg-Bahrenfeld in 1963

November

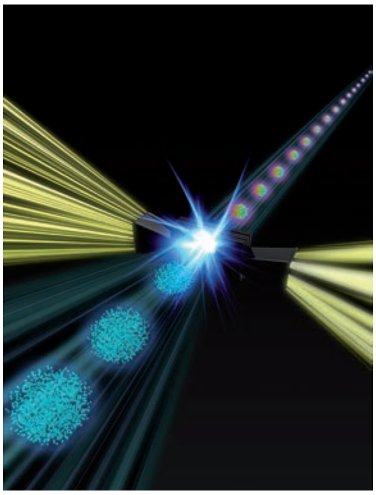
"Swiss army knife" for electrons wins innovation award

For the development of the Segmented Terahertz Electron Accelerator and Manipulator (STEAM), the team of DESY scientist Dongfang Zhang was awarded the new Prize for Frontiers of Information Optoelectronics at the International Photonics and Optoelectronics Meeting (POEM) in Wuhan, China. The jury praised the development of the multifunctional device by the group of DESY's leading scientist Franz Kärtner at CFEL as "outstanding research".

The Prize for Frontiers of Information Optoelectronics was established by the Wuhan National Laboratory for Optoelectronics (WNLO) in China "to inspire cutting edge scientific discovery and technology innovation in the fields of optoelectronics, and to promote international communication and cooperation between researchers".

STEAM is a kind of "Swiss army knife" for electrons, combining four functions in one device: Depending on the mode of operation, the miniature particle accelerator can accelerate, focus, compress and analyse electron bunches. Combining multiple units of STEAM allows scientists to perform multiple consecutive actions on one electron bunch. Driven by terahertz radiation, the device is exceptionally small. The housing is only 2 cm across, and the active structures inside measure just a few millimetres.

One of the key features of the device is its perfect timing with the electron beam, which is achieved by using the same laser pulse to generate an electron bunch and drive the device. To do this, an infrared laser pulse is split into two parts, which are then fed into non-linear crystals that change the laser wavelength: For the generation of an electron bunch, the wavelength is shifted into the ultraviolet and directed onto



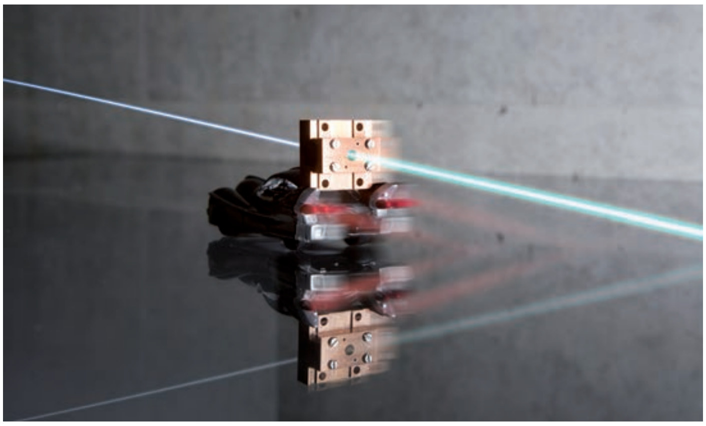
The mini accelerator STEAM (centre) is driven by terahertz radiation (yellow, coming from both sides). It can accelerate, compress, focus and analyse the incident electron bunches (blue).

a photocathode where it releases a bunch of electrons. For STEAM, the wavelength is shifted into the terahertz regime. The relative timing of the two parts of the original laser pulse only depends on the length of the path they take and can be controlled very precisely.

In this way, the scientists can control with ultrahigh precision what part of the terahertz wave an electron bunch hits when it enters the device. Depending on the arrival time of the electron bunch, STEAM performs its different functions. For instance, a bunch that hits the negative part of the terahertz electric field is accelerated. Other parts of the wave lead to focusing or defocusing of the bunch or to a compression by a factor of about 10. While compression means that the electron bunch gets shorter in the direction of flight, focusing means it shrinks perpendicular to the direction of flight.

In addition, STEAM allows the structure of the electron bunch along its path of flight to be analysed by streaking. For this technique, the incoming electron bunch is deflected sideways in such a way that it becomes smeared out perpendicular to the direction of flight. When this smeared-out bunch hits a detector, it produces a profile of the bunch along its path of flight. Streaking is regularly used in particle accelerators to analyse the bunch structure.

The technology is still at an experimental stage. The developers see STEAM as a first step on the road to a future generation of compact, terahertz-driven particle accelerators. These could enable new applications and complement today’s accelerators. However, the pocket manipulator can already be utilised today: Accelerator groups around the world are considering to use it for bunch characterisation.



STEAM compared to a matchbox car. The direction of the electron beam is symbolised.

December

DESY turns 60

The story of DESY began on 18 December 1959 with the signing of a contract in the Hamburg city hall establishing the foundation Deutsches Elektronen-Synchrotron.

18 December 1959: Siegfried Balke (left), German Federal Minister for Nuclear Energy, and Max Brauer, Mayor of Hamburg, sign the State Treaty on the establishment of the foundation Deutsches Elektronen-Synchrotron.

In those 60 years, DESY has grown from a small Hamburg accelerator laboratory into a world leader in accelerator technology, structural research, particle physics and astroparticle physics. For 60 years, DESY has developed pioneering technologies, which scientists from all over the world have used to achieve outstanding advances. Among other things, the gluon was discovered and the ribosome structure resolved at DESY.

Accelerator operation and construction

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- PITZ 26
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- European XFEL accelerator 30

PETRA III

User operation with high availability

For DESY's PETRA III synchrotron radiation source, 2019 was in many respects a very successful year. In February, the facility took up operation again after a shutdown period that had started on 21 December 2018. During the shutdown, a conventional undulator was replaced with an in-vacuum undulator for beamline P07. Furthermore, in the Peter P. Ewald experimental hall, installation of front-end components was started for the future beamlines P62 and P63, while installation was completed for the wiggler beamline P61. Regular user operation resumed on 11 March 2019 after a short commissioning period of only 2.5 weeks. In 2019, 4751 h of beam time were scheduled for the user run, which were delivered with a very good availability of more than 98%. Eventually, including test run time, a total of 5880 h of beam time was provided to the users at the beamlines throughout the year. From July 2019, the facility was operated in a 480 bunch mode with a 20% higher beam current. A three-week-long summer shutdown was used for regular maintenance work and two weeks of machine studies, which focused on low-emittance operation at a beam energy of 3 GeV. During the winter shutdown 2019/20, an additional undulator will be installed for beamline P62 in the Peter P. Ewald hall.

User operation

During the two-month-long winter shutdown 2018/19, which ended in February 2019, an in-vacuum undulator was installed for the beamline P07 in the Max von Laue experimental hall (Fig. 1). Furthermore, the installation of front-end components for the wiggler beamline P61 for materials and high-pressure science was completed, and first beam for commissioning was provided in autumn 2019. Front-end components for the beamlines P62 and P63 were also installed during the winter shutdown to prepare the set-up of the small-angle scattering beamline P62 in the Peter P. Ewald hall in 2020. Thanks to essential efforts of all the technical groups, all shutdown activities could be finished on schedule.

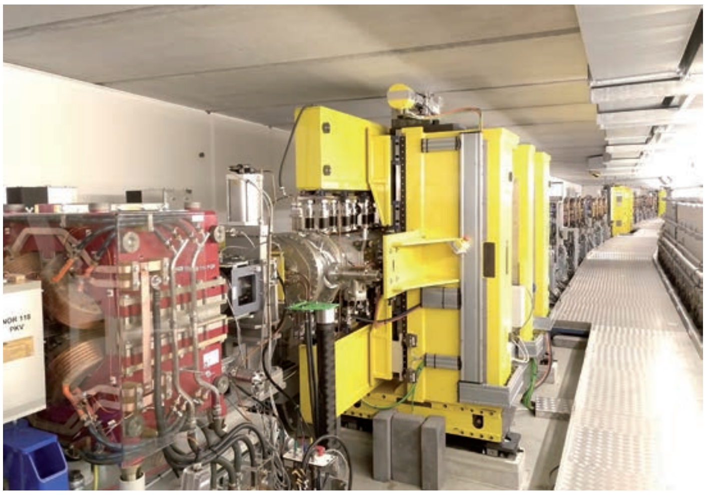

Figure 1

In 2019, an in-vacuum undulator was installed for the beamline P07 in the Max von Laue experimental hall.

Regular user operation resumed on 11 March 2019 after a short commissioning period of only 2.5 weeks.

Two weeks of the three-week-long summer shutdown were used for machine studies, which focused on low-emittance operation at a beam energy of 3 GeV. The necessary maintenance was done in five dedicated service periods distributed over the year and additionally during the summer shutdown period. 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 2019 is shown in Fig. 2. In total, about 4751 h were scheduled for the user run. In addition, 1254 h of test run time were planned for the users.

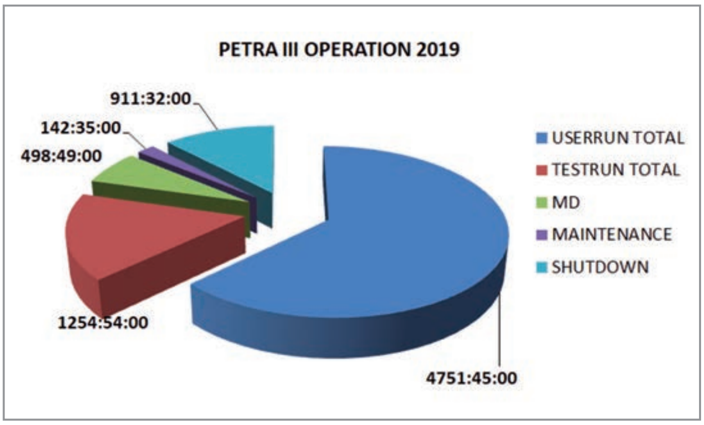

Figure 2

Distribution of the different machine states scheduled during the run period from 11 March to 20 December 2019

Figure 3

History of the PETRA III beam current from 1 to 15 July 2019. The beam current in the 480 bunch mode was increased to 120 mA.

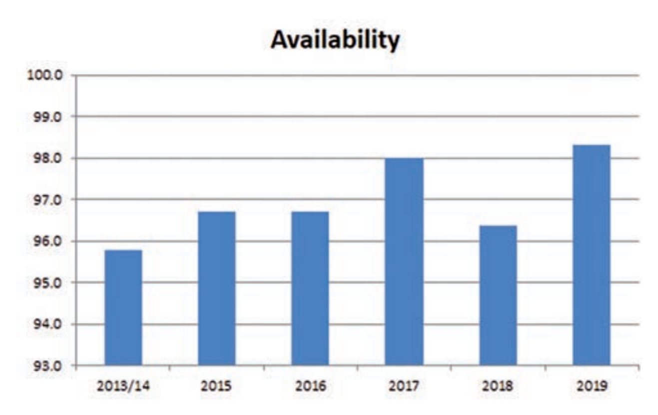

Figure 4

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

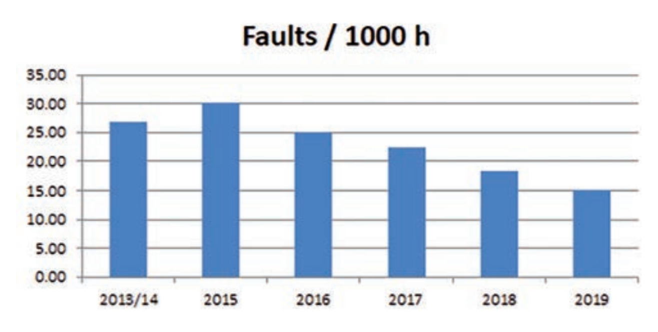

Figure 5

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

During user runs, the storage ring was operated in two distinct modes characterised by their bunch spacing. In the “continuous mode”, up to 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. The user time was split evenly between the two operation modes in blocks of five or six weeks. For beam operation in the timing mode, very good bunch purity is required. Unwanted satellite bunches were routinely cleared using the multibunch feedback system. In July 2019, the total beam current in the continuous mode was increased from 100 mA to 110 mA and finally to 120 mA (Fig. 3). The intensity increase was carefully reviewed and coordinated together with the technical groups. From July 2019, all user runs in the continuous mode with 480 bunches were performed with a total beam current of 120 mA.

High reliability is one of the key requirements for a synchrotron radiation facility. The key performance indicators are availability and mean time between failures (MTBF). In 2019, the weekly availability reached 100% for several weeks of the year. At the end of the user run, the average availability was 98.3%, the best value ever reached at 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 faults. The long-time development of the availability of PETRA III during the user run is shown in Fig. 4. In addition, the total number of faults could be further reduced in 2019. The average MTBF at the end of the year was 64 h, which is also better than in the previous year. In 2019, the overall performance of PETRA III thus 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 five years (Fig. 5), indicating that the process to improve the technical reliability of PETRA III made significant progress in the wake of an availability review held in 2016. An internal review process was implemented in 2018 to monitor the availability of the facility and guarantee a good root cause analysis of all faults during the user run. In 2019, a process was started to further harmonise the quality standards of the technical groups with respect to quality management and process documentation.

Plans for the next operation period

During the winter shutdown 2019/20, it is foreseen to replace an insertion device that suffered from radiation damage with a new undulator for the beamline P10 in the Max von Laue hall. An additional two-metre-long undulator will be installed for the new beamline P62 in the Peter P. Ewald hall. Furthermore, in the injector complex, the beam transport line from LINAC II to the booster synchrotron DESY II will be modified, opening up the possibility to bypass the accumulator ring PIA. In the long term, this modification will contribute to a better availability, as it will allow the operation of PETRA III even without PIA. One of the major challenges for 2020 will be to maintain the availability of PETRA III at the high level that was reached in 2019. This 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

High availability for user experiments at both beamlines

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 experiment. In 2019, the FLASH linear accelerator delivered beam for a total of 7476 h for user experiments, FEL studies, preparation of user experiments and accelerator R&D. In summer 2019, a prototype of the PolariX transverse deflection structure realised in a collaboration of DESY, CERN and PSI was installed in the FLASHForward beamline. Its innovative design gives full control of the streaking direction. First results demonstrate the performance of the device, which is able to measure the longitudinal phase space of electron bunches with femtosecond resolution. The same shutdown was used to install a new bunch compressor in FLASH2, significantly improving the beam properties and the flexibility of compression schemes.

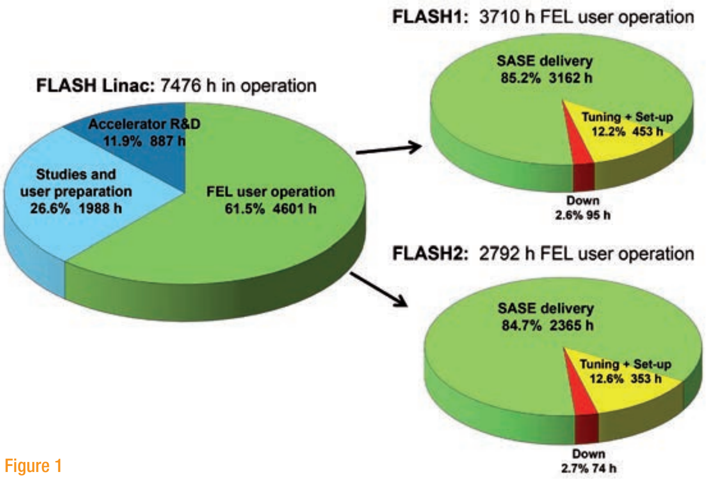

Figure 1

FLASH operation statistics in 2019. A total of 6502 h of beamtime was delivered to users.

Operation

The two FLASH undulator beamlines FLASH1 and FLASH2 are run in parallel as a tandem delivering self-amplified spontaneous emission (SASE) radiation to the experimental halls “Albert Einstein” and “Kai Siegbahn”. The third electron beamline FLASH3 was set up for the beam- and laser-driven plasma wakefield acceleration experiment FLASHForward.

In 2019, beamtime for users at FLASH was again allocated in two user periods and six beamtime blocks. The 13th user period took place from January to June and the 14th from July to December. About 60 to 70 proposals for user experiments are regularly submitted each year, of which 30 to 40 are approved.

In 2019, the FLASH linear accelerator delivered beam for 7476 h. Of these, 4601 h were devoted to user experiments, 1988 h to FEL studies and preparation of user experiments and 887 h to accelerator R&D (Fig. 1). Thanks to the simultaneous operation of the beamlines FLASH1 and FLASH2, a total of 6502 h of beamtime could be provided for user experiments: 3710 h at FLASH1 and 2792 h at FLASH2.

The beamtime for users includes the time required for set-up and tuning. The FLASH team has worked hard on streamlining the corresponding procedures. As a result, a record low of 12% of user beamtime required for set-up and tuning was achieved in 2019 for both beamlines. For comparison, 21% were required for tuning in 2014.

In 2019, the availability of the facility was at a record high of 97.8% overall. The downtime for users was 2.6% and 2.7% at FLASH1 and FLASH2, respectively, mainly due to power outages and a water leak of the radio frequency electron source (RF gun).

In the course of the year, the scientific opportunities at FLASH were further developed, in particular in the Kai Siegbahn hall. The FLASH2 optical pump–probe laser was also made available at beamline FL24 and successfully used in eight experiments. The new beamline FL21 including a THz streaking setup for pulse length diagnostics was installed. At the reaction microscope beamline FL26, a new high-harmonic generation (HHG) laser source providing vacuum-ultraviolet (VUV) laser pulses now widens the range of multi-colour pump–probe experiments on atoms and molecules.

RF gun

Gun 3.1 had been in operation at FLASH since August 2013. The gun body was built in 2004. A leak in the cooling system of the gun body appeared in December 2019, which could only be fixed temporarily to finish the user run. In the winter shutdown, the RF gun was replaced by Gun 4.4, which has an improved water-cooling system.

Figure 2

The new C-chicane bunch compressor installed in FLASH2. The dipoles are coloured in green. The beam enters from the wall and leaves towards the right.

FLASH2 bunch compressor

As part of the FLASH2020+ project, the realisation of a new bunch compression scheme was started. In summer 2019, a new bunch compressor C-chicane was installed after the extraction beamline to FLASH2 and before the FLASH2 undulators (Fig. 2). The new bunch compressor has two advantages: It allows both a soft compression before the extraction beamline with a final compression just before the SASE undulators and a more flexible compression scheme in view of FLASH1.

A difficulty in bunch compression occurs due to space-charge-induced microbunch instabilities created during the compression process. Together with the emission of coherent synchrotron radiation (CSR), both effects spoil the phase space of the electron bunches. The soft compression reduces the peak current in the extraction section and thus these effects – resulting in improved electron bunch properties. As an example, the SASE energy level could be pushed from 1 mJ to a new record of 1.5 mJ in a test run with the new bunch compression scheme.

PolariX

The PolariX TDS (Polarizable X-band Transverse Deflection Structure) is an innovative design working in the X-band frequency range. Invented at CERN, the 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. In summer 2019, a prototype cavity realised within a collaboration between DESY, CERN and PSI was installed in the FLASHForward beamline (Fig. 3).

Very promising results have already been achieved, showing an impressive reconstruction of the longitudinal phase pace with femtosecond resolution. Two such structures are planned to be installed at FLASH2 in 2020 and also at the SINBAD facility at a later stage.

The FLASH2020+ project

As strongly requested by the user community, substantial improvements of the deliverable photon beam quality are planned within the FLASH2020+ project. As an initial step, FLASH2 will gain flexibility in photon polarisation through the installation of an APPLE III-type afterburner undulator. Together with an increase in electron beam energy to 1.35 GeV, this will extend the wavelength reach up to the oxygen K-edge.

In a next step, FLASH1 will be equipped with a complete set of fully tuneable undulators providing circularly polarised radiation. A main feature of the FLASH2020+ project is external seeding at the full repetition rate of 1 MHz in burst mode. This will make FLASH the first high-repetition-rate FEL with full longitudinal coherence.

Later on, at FLASH2, we will exploit novel FEL lasing concepts based on variable undulator configurations to shorten the pulse duration and enable attosecond experiments.

In 2019, the FLASH2020+ conceptual design report (CDR) was presented to the DESY Machine Advisory Committee (MAC), Photon Science Committee (PSC) and Laser Advisory Committee (LAC). All three advisory bodies were highly supportive and suggested to start the upgrade as soon as possible. The CDR has been endorsed by the DESY Scientific Council and the Foundation Council.

FLASHForward

The installation and commissioning of the FLASHForward beamline at FLASH3 are progressing very well. After careful commissioning, experiments are now running in full swing and several milestones have been achieved. These include high-precision wakefield measurements, preservation of energy spread and, most impressively, a 1 GeV energy doubling in a plasma cell in less than 20 cm.

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

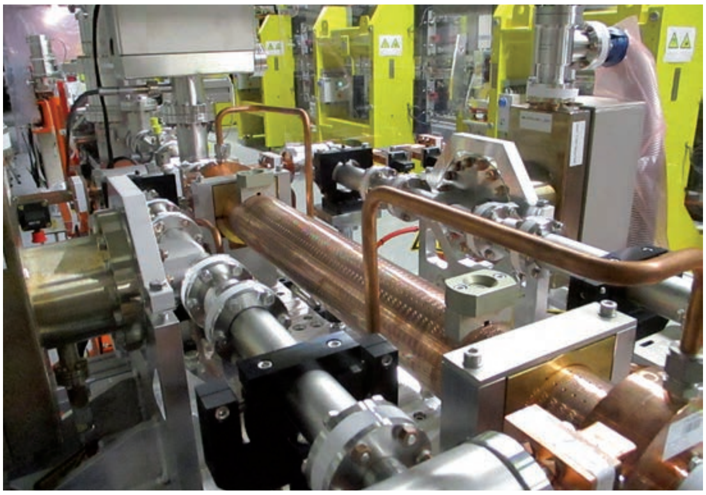

Figure 3

Prototype of the PolariX TDS installed in the FLASHForward beamline

PITZ

Accelerator R&D and applications

Throughout 2019, the PITZ photoinjector test facility at DESY in Zeuthen was operated continuously for studies supporting the operation and further improving the photoinjector of the European XFEL X-ray laser. In parallel, a number of accelerator R&D studies were conducted, as well as preparations for the extension of the facility towards a proof-of-principle THz self-amplified spontaneous emission (SASE) free-electron laser (FEL).

Preparations for THz SASE FEL experiments

The PITZ group is developing a prototype of an accelerator-based, high-power, tuneable THz source for pump–probe experiments at the European XFEL. The goal is to generate THz SASE FEL radiation with a millijoule energy level per pulse. The PITZ beamline will be extended, and an LCLS-I undulator will be installed in a tunnel annex downstream of the current accelerator tunnel.

In 2019, the design process for the beamline extension was started, while preserving the functionality of the existing PITZ accelerator. The design shown in Fig. 1 includes a bunch compressor and a collimation system installed in the first tunnel. Two new screen stations allow for the characterisation of the bunch compression and for coherent transition radiation measurements.

In the tunnel annex, the beamline will start with a dipole magnet that acts as a distributor for up to three beamlines for future experiments. The LCLS-I undulator as well as quadrupole magnets for controlling the beam parameters for the FEL process will also be installed. Electron beam diagnostics will be provided by several screen stations and beam position monitors, while the THz radiation will be delivered to a diagnostics platform.

The tunnel annex was cleared out and refurbished, and installation of the infrastructure, such as cable trays, started. First parts, such as quadrupoles and power supplies, were ordered, and the design of the vacuum chambers for the bunch compressor and of the support structure for the LCLS-I undulator was finished.

Transverse pulse shaping

The emittance of the electron bunches generated at the photocathode can be decreased by using laser pulses with a flat-top transverse intensity distribution instead of the standard Gaussian. Typically, this is realised by cutting out the central part of the Gaussian distribution with an aperture along the transport beamline. The method implies a high pulse energy loss, typically of one order of magnitude. According to simulations and experiments at PITZ, LCLS-I and FLASH, cutting out a wider part of the Gaussian distribution to a “truncated Gaussian” reduces the pulse energy loss and leads to smaller emittances compared to the flat-top case.

To conduct a systematic study of this kind of transverse pulse shaping, the capabilities of the laser beam transport system from the photocathode laser (provided by the Max Born Institute (MBI) in Berlin) to the beam shaping aperture (BSA) were enhanced: A three-lens zoom telescope was added, making it possible to vary the truncation for different BSA sizes. Additionally, a mode cleaner (pinhole with 75 μm diameter) was installed to improve the transverse beam quality. First results are shown in Fig. 2, clearly demonstrating the reduced emittance.

Thermal emittance map

In state-of-the-art photoinjectors, a low thermal emittance cathode is one of the keys for further improving the beam quality. The thermal emittance normalised by the laser rms spot size, i.e. the rms transverse divergence, is an important figure of merit for cathodes, but its measurement using conventional methods is time-consuming.

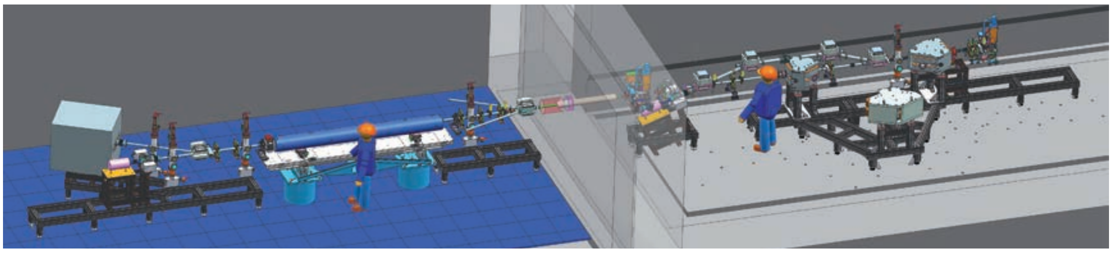

Figure 1

3D CAD model of the installations for the THz SASE FEL proof-of-principle experiments at PITZ

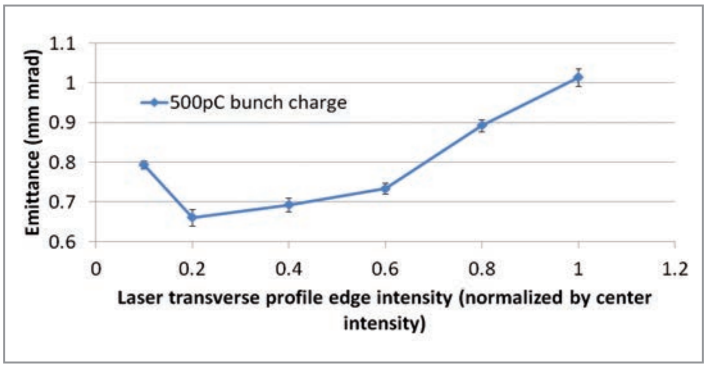

Figure 2

Projected emittance measurements with truncated Gaussian transverse profile (edge intensity: 1 means transverse flat-top)

With a proper focusing of the solenoid of the electron source (gun), the focal plane of the cathode can be imaged onto a screen downstream of the gun. This enables the beam's transverse momentum at the cathode to be imaged to a transverse electron beam distribution at that downstream screen. Once the imaging condition is met, a single-shot measurement of the beam's cathode transverse momentum can be done, and thermal emittance mapping of a cathode becomes as easy as quantum efficiency (QE) mapping.

Such a method was developed and demonstrated at PITZ. Caesium telluride (Cs_2Te) cathodes with different thicknesses were studied, and examples of QE and thermal emittance maps for a cathode with a Te thickness of 15 nm are shown in Fig. 3.

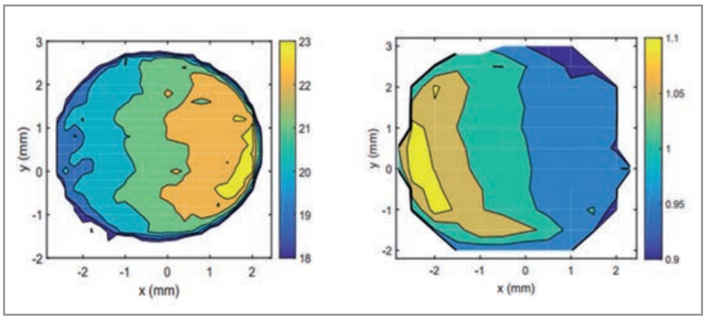

Figure 3

QE map in percent (left) and thermal emittance map in mm mrad/mm (right)

Development of green photocathodes

Together with INFN LASA in Milan, Italy, the PITZ group started an R&D project on the development of photocathodes sensitive in the green spectral range – so-called green photocathodes. This type of cathodes typically consists of alkali antimonides (e.g. K_2CsSb) and promises ultralow thermal emittance. In addition, the photocathode laser system would be significantly simplified, as the ultraviolet conversion stage would not be needed anymore, which would also simplify the laser pulse shaping.

Throughout the year, a reproducible procedure to grow alkali antimonide components on prototype samples was developed. In a next step, the recipe will be transferred to INFN plugs – the standard plug used for the photocathodes at PITZ, FLASH and the European XFEL. For that purpose, a dedicated deposition system is currently being built. The first green photocathodes are planned to be produced in spring 2020 and will then be tested at PITZ.

Gun 5 production

The next generation of pulsed L-band electron sources at DESY is currently in production. Compared to the currently used type Gun 4, Gun 5 will have an optimised cell shape for higher radio frequency (RF) efficiency and reduced peak surface field for the same cathode gradient, an RF probe for direct field measurements inside the gun, and a higher cooling efficiency allowing operation at higher average RF power. In-house production started in 2019, as the company originally foreseen stopped the gun manufacturing. After machining tests and building up the needed in-house manufacturing know-how, we expect to have produced the first Gun 5 in summer 2020. Subsequently, it will be installed at PITZ for conditioning and testing all the new features.

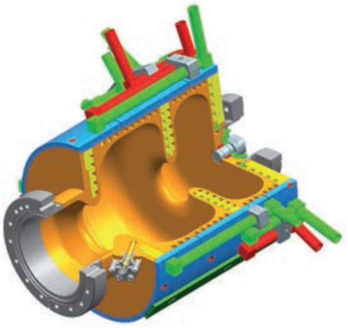

Figure 4

3D model of the new Gun 5

ELLA – first shaping with new setup

The laser shaper of the elliptical laser (ELLA) system at PITZ allows quasi free manipulation of the laser pulse energy distribution in the two spatially transverse directions and the spectral longitudinal domain, with the goal to generate quasi 3D ellipsoidal laser pulses. For demonstration, the DESY logo was carved into a Gaussian laser pulse from the top and the side. This distribution was then reconstructed from a spectrograph slit scan measurement, clearly showing the reconstructed DESY logo in both spectral–spatial projections (Fig. 5).

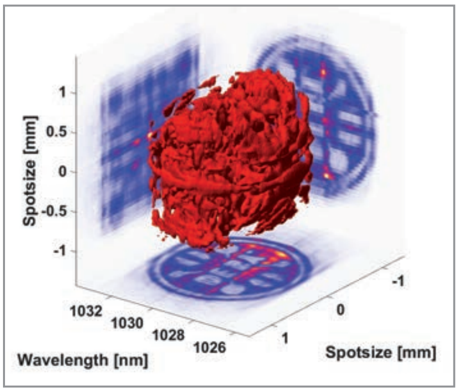

Figure 5

3D pulse shaping demonstration

Contact: Frank Stephan, frank.stephan@desy.de

REGAE

Relaunch with significantly enhanced performance and first plasma

Following a major beamline modification in 2018, DESY's Relativistic Electron Gun for Atomic Exploration (REGAE) was recommissioned in 2019. The performance of all subsystems was demonstrated with extensive tests of components and detailed beam dynamics studies. Thanks to significant improvements of the transverse beam quality, increased flexibility of the tuning capabilities and added diagnostics, a new parameter regime is now routinely available at REGAE. The first laser-ignited plasma and the operation of a plasma cell in close proximity to conventional radio frequency (RF) cavities were key achievements of the year.

After the completion of a major beamline upgrade in 2018, REGAE was restarted at the beginning of 2019. The initial phase of the relaunch was characterised by the commissioning of the numerous new elements integrated into the accelerator.

In particular, the RF system of the buncher cavity was decoupled from the RF system of the electron source (gun) by a newly installed second modulator. The new configuration enhances the flexibility and stability of the operation and significantly improves the tuneability of the longitudinal phase space parameters. Following a smooth commissioning phase, the full potential of the modified RF system could be demonstrated by reaching new records in bunch length and energy spread.

Additional diagnostic devices were added during the upgrade, such as a knife-edge scanning setup driven by high-precision piezo-based hexapod-like stages. The new tool was characterised and is in routine operation, reaching a micrometre resolution for beam size measurements at the target position.

Moreover, a specially designed transverse deflecting structure (TDS) for characterising the longitudinal beam profile was installed and successfully commissioned (Fig. 1). The TDS was built at the Armenian CANDLE institute in close collaboration with DESY. This is the first TDS that doesn't require a large and costly RF system (modulator plus klystron) for its operation. Instead, it is powered by a solid-state amplifier of the newest generation. The comparatively inexpensive system is specially tailored to the beam parameters of REGAE and reaches a temporal resolution on the order of 10 fs.

Further elements of the 2018 upgrade were included in preparation for an experimental campaign focusing on the external injection of electron bunches into laser-driven plasma waves. This project uses the wakefields generated in the plasma to further accelerate particles, taking advantage of the large accelerating gradients of the laser wakefield acceleration technique. The experiment requires gas targets, combined with an elaborate differential pumping section to reduce the gas load at the conventional accelerator cavities.

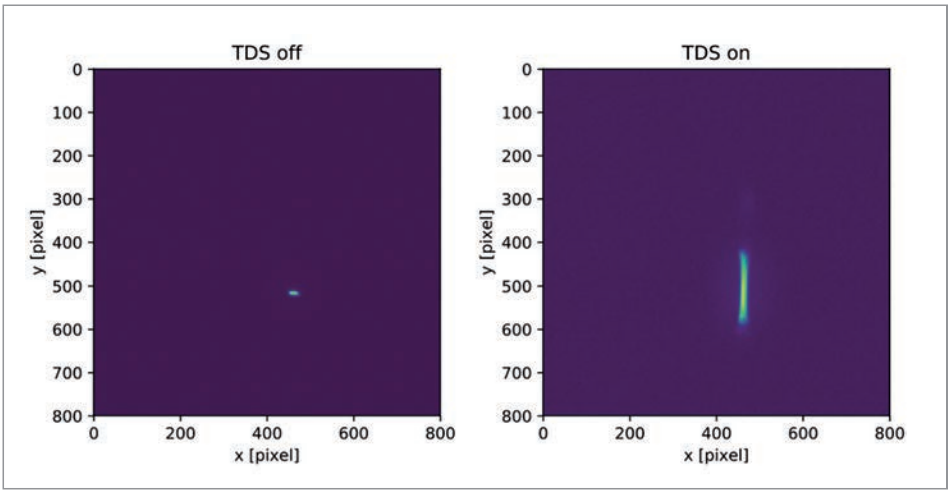

Figure 1

Streaking action of the transverse deflecting structure (TDS) installed at REGAE. The unaffected electron beam (TDS off) is shown on the left. The effect when the TDS is switched on (right) is clearly visible. The streaking of the beam is correlated to the longitudinal particle positions in the bunch.

A typical differential pumping section consists of a number of small apertures that are ideally not aligned on a common axis. However, being able to pass an electron and laser beam through this section requires a common axis of the apertures. Moreover, except for the tight focus, a multiterawatt laser reaches a beam diameter of several centimetres, in strong contradiction to the preferred conditions in a differential pumping system. Despite these challenges, the required gas pressure in the plasma capillaries could be demonstrated at REGAE while maintaining the low pressure in the nearby RF cavities. The successful tests of both the gas targets and the differential pumping scheme are a key achievement for the REGAE experiment, demonstrating the compatibility of plasma and conventional RF techniques in close proximity for the first time.

The previously mentioned multiterawatt laser is generated by the 200 TW ANGUS facility, which was connected to the REGAE vacuum system in 2018. Extensive laser diagnostic devices were installed and put into operation to match the path of the electrons to the laser axis, so that electron bunches and laser pulses pass through the gas targets transversally aligned. In order to also achieve a temporal overlap, a newly developed diagnostics concept was tested. It involves measuring the arrival time of the laser pulses and of the electron bunches on a 100 ps level using the very same detector, thus eliminating contributions from readout electronics. The high precision of this diagnostics concept is remarkable. However, it should be noted that the measurement method requires a very high dynamic range. On the one hand, the detector is hit by the strongly attenuated but still powerful laser, while on the other hand, the faint signature of scintillation photons generated by less than 500 000 electrons needs to be measured.

Significant improvements of the transverse electron beam quality could be realised by exchanging the imaging system of the photocathode laser, which led to a drastically enhanced laser spot quality on the photocathode. The transverse beam emittance – a quantity that characterises the beam quality – could be improved by about a factor of five – a performance boost of utmost important for all REGAE applications. The enhanced emittance facilitates the beam transport and leads to better focusing properties and a higher resolution of the longitudinal diagnostics. In addition, it is substantial for diffraction experiments – the initial purpose of the facility – because the emittance determines the transverse coherence of the beam, i.e. the quality of the recorded diffraction patterns. With a measured normalised transverse emittance of 30 nm at a bunch charge of 50 fC, the REGAE facility now operates close to the design values, with further potential improvements being already identified.

A direct demonstration of the improved beam quality was the measurement of a beam focus of around 5 µm rms by means of the knife-edge diagnostics. In addition, a transverse jitter of the beam relative to the knife-edge of about 3 µm rms – small enough for the external injection experiment – could be shown. The improved transverse beam quality also has a direct impact on the resolution of the TDS. The measurement of record bunch lengths below 20 fs could only be achieved thanks to the exceptional transverse beam quality.

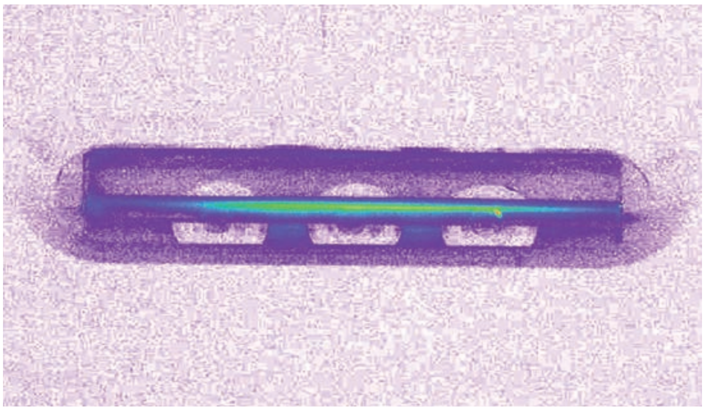
Figure 2

First plasma generated at REGAE. The image shows the 2 cm long hydrogen capillary through which the ANGUS laser passes. Due to the high fields in the laser pulses, a glowing plasma is created.

Advanced concepts for the linearisation of the longitudinal phase space allow for squeezing the bunch length further down to below 1 fs. The practical realisation of these so far theoretical concepts requires even better longitudinal diagnostics, e.g. TDSs working in the THz regime. Alternatively, the same techniques can be used to reduce the energy spread of long bunches. The demonstration of a relative energy spread of 0.014% at a mean energy of 3.25 MeV was a first step in this direction. Further improvements and measurements are required before an experimental verification of the linearisation concept can be claimed. Modifications of the photocathode laser are under way so that even longer electron bunches can be prepared for the demonstration of the energy spread compensation. Regarding the bunch length reduction, preparations to measure even shorter electron bunches by means of THz radiation are in full swing.

A special highlight of the year was the generation of the first ANGUS-induced plasma at REGAE (Fig. 2). To this end, the laser was sent into the REGAE target chamber for the first time with considerable power: 1.3 J within a time span of 40 fs were recorded, corresponding to about 30 TW.

With improved electron beam parameters and preparatory work for the plasma experiments completed, external injection of electron bunches into the laser-induced plasma is within reach. Key milestones in 2019 have been the spatial and coarse temporal overlap of electron and laser beam, the demonstrated target and differential pumping parameters and the first glowing plasma at REGAE. A rich programme of advanced beam dynamics studies and upcoming diffraction experiments complements the campaign on plasma-related experiments at the facility.

Contact: Klaus Flöttmann, klaus.floettmann@desy.de

European XFEL accelerator

User operation with six experiments

In its third year of operation, the accelerator of the European XFEL X-ray laser – which is operated by DESY – routinely served all six experimental stations installed at the three self-amplified spontaneous emission (SASE) beamlines of the facility. In addition, the facility's parameter space was further expanded by establishing new electron and photon energy working points and providing very flexible electron bunch and thus photon pulse patterns with up to 4.5 MHz repetition rate. In facility development studies, a joint team from DESY and European XFEL demonstrated self-seeding – a method to enhance the spectral brightness of the free-electron laser (FEL) radiation – at the SASE2 beamline.

Accelerator operation

In 2019, the European XFEL accelerator was operated for about 6480 h. Of these, 1656 h were used for facility development (of both accelerator and photon systems), and 3648 h were scheduled for X-ray delivery (for both user programme and experiment commissioning). Set-up and tuning accounted for the remaining 1176 h, including repair accesses outside of the scheduled maintenance periods and time needed for preparing different machine states.

Maintenance and installation periods included four weeks around the Christmas break 2018/19, three weeks in June, two single weeks in March and August, respectively, and the Christmas break 2019/20. Apart from scheduled preventive maintenance and regular interlock tests, the time was used to install new equipment at all three SASE FEL beamlines: self-seeding chicanes at SASE2, a new kicker magnet before SASE3 to better separate the electron bunches lasing in SASE1 and SASE3, beam stops for accelerator tune-up before all undulators, as well as upgrades to the photon beamline safety systems to allow for larger beam power as long as the shutters are closed. In addition, at SASE3, preparations started for the installation of a helical afterburner and a delay chicane to enable two-colour pump–probe experiments.

In 2019, simultaneous X-ray delivery to three experiments in parallel became the standard operation mode – a worldwide unique trait that implies several technical and organisational challenges. The performance of each of the three SASE FELs is interlinked with the tuning of either of the other two. Additional measures were implemented in the accelerator configuration and operation to mitigate these effects. These included operation with varying radio frequency (RF) amplitudes and phases within one 1 ms long RF pulse to allow for independent

Figure 1

Maintenance work in the European XFEL accelerator tunnel tuning of SASE1 and SASE2. The decoupling of SASE1 and SASE3 – which are located on the same beamline – was improved by means of a new kicker magnet before SASE3. Flexible bunch patterns allowed the operation to be tailored to the special needs of the experiments, either by alternating between experiments with a maximum frequency of 5 Hz or by interleaving the photon pulses in such a way as to make optimal use of the available number of bunches.

In 2019, electron bunches amounting to a total electric charge of about 24 C were accelerated. Less than 20% were used for photon production, however, as the total X-ray power that can be delivered to the experiments continued to be limited for safety reasons. A test with the maximum 4.5 MHz repetition rate delivered to experiments was performed in July, underlining the readiness of the accelerator system to operate in this mode.

During scheduled X-ray delivery time, the average accelerator availability was above 90%. However, single events led to considerably lower availabilities during four X-ray delivery weeks. The root causes of those events differed (power glitches, power failures, cold-compressor failure), but in shutting down the cryo plant, they struck the European XFEL accelerator where it is the most vulnerable. A restart involves restarting the cryo plant, retuning the linear accelerator and finally retuning all three SASE FELs, a procedure that takes at least 24 h and involves dozens of experts. We are investigating possible countermeasures to reduce the vulnerability to such faults.

FEL performance

One measure of the facility's performance is the FEL pulse energy, which is measured by a gas monitor. A statistical analysis of all 28 X-ray delivery weeks is shown in Fig. 2. Generally, all three SASE FELs performed according to specifications.

While a wide range of photon energies can be accessed and a world-record photon energy of 20 keV was reached at SASE1 in a test run, a remaining challenge is the wavelength tuneability of the hard X-ray FELs SASE1 and SASE2. The European XFEL relies on changes of undulator gaps to provide different photon wavelengths to the experiments. While this is no issue for small wavelength changes, it requires considerable set-up time for large steps as they are often required when the experiments switch operation every 12 h. To improve the set-up times, elaborate tuning procedures are being developed.

The wavelength range of the European XFEL can be extended through operation at different electron energies. In addition to operation at the standard 14 GeV working point, a user run at 16.5 GeV electron energy was performed in September. An additional working point at 11.5 GeV was established in November, thus extending the photon wavelength regime in the soft X-ray range.

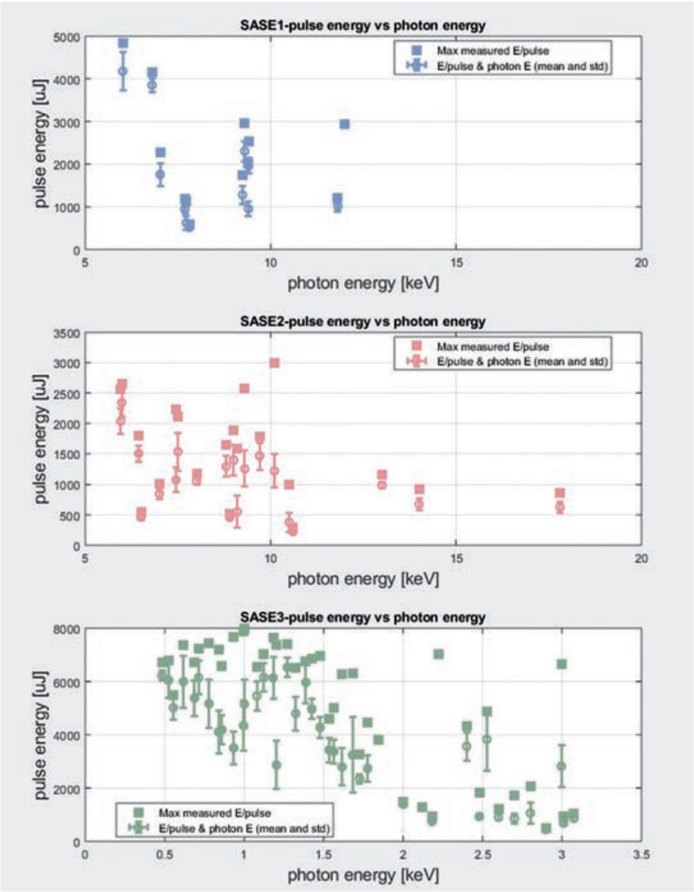

Figure 2

Maximum and average FEL pulse energy as measured during the 28 X-ray delivery weeks in 2019

The SASE2 FEL did not reach its design performance for the first three months of 2019. Commissioning time at SASE2 had been very sparse due to an alignment issue and to early X-ray delivery to experiments for commissioning. As a consequence, additional development time was devoted to SASE2 at the beginning of April 2019, yielding excellent results. SASE2 can now be operated with similar performance to SASE1.

Facility development

The facility development time was devoted to improvements of the operation of the accelerator and photon systems and to the commissioning of new hard- and software. In addition, FEL physics studies were performed with the goal to enhance the European XFEL photon parameter space. One of the most notable successes was the observation of self-seeding at SASE2. With this method, the spectral brightness and purity of the SASE radiation can be considerably enhanced. After installation of a magnetic chicane and an in-vacuum moveable crystal holder during the maintenance shutdowns in 2019, a team from European XFEL and DESY worked together to properly align the electron beam in the undulator, tune the magnetic chicane, adjust the crystal position and finally observe the self-seeded spectrum with only just commissioned photon diagnostics.

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

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PETRA IV

Conceptual design report completed

The PETRA storage ring at DESY was originally built and operated for high-energy physics starting in 1976 and later served as a pre-accelerator for the HERA electron–proton collider until 2007. Since the end of 2009, the storage ring has been operated as part of the third-generation synchrotron radiation source PETRA III. The PETRA IV project foresees to upgrade this existing source to a synchrotron radiation source with ultralow emittance. As an ultimate 3D X-ray microscope in the hard X-ray range, PETRA IV will enable highest resolution on relevant length, time and energy scales, with a very high degree of coherence, highest brightness and all the options for *in-situ/operando* analysis required for the knowledge-based design of the next generation of multifunctional materials. PETRA IV will thus contribute to finding solutions to major global challenges in the fields of energy, health, transport & technology, Earth & environment, and information technology, which rely on understanding the often complex structures and processes in matter and gaining control over them by tailoring the properties of new materials to specific needs.

Conceptual design

The ultralow-emittance synchrotron radiation source PETRA IV will enable unique new experiments and scientific opportunities. The project includes the upgrade of the storage ring PETRA III to a storage ring with ultralow emittance, the upgrade and refurbishment of the pre-accelerators, the relocation, refurbishment/upgrade and in part new construction of photon beamlines, and the construction of a new experimental building in the west of the PETRA ring (Fig. 1). The upgrade of the storage ring is the most expensive part and requires the greatest share of the investment. The conceptual design report (CDR) for the PETRA IV project was completed in 2019.

The PETRA storage ring consists of eight arcs with a total length of 1612.8 m as well as eight straight sections with lengths of 64.8 m and 108 m. This geometric arrangement was originally designed in view of the requirements of high-energy physics experiments, but was also very beneficial for the synchrotron radiation source PETRA III, since the straight sections could be used to install damping wigglers and thus improve the beam quality. The large circumference and large

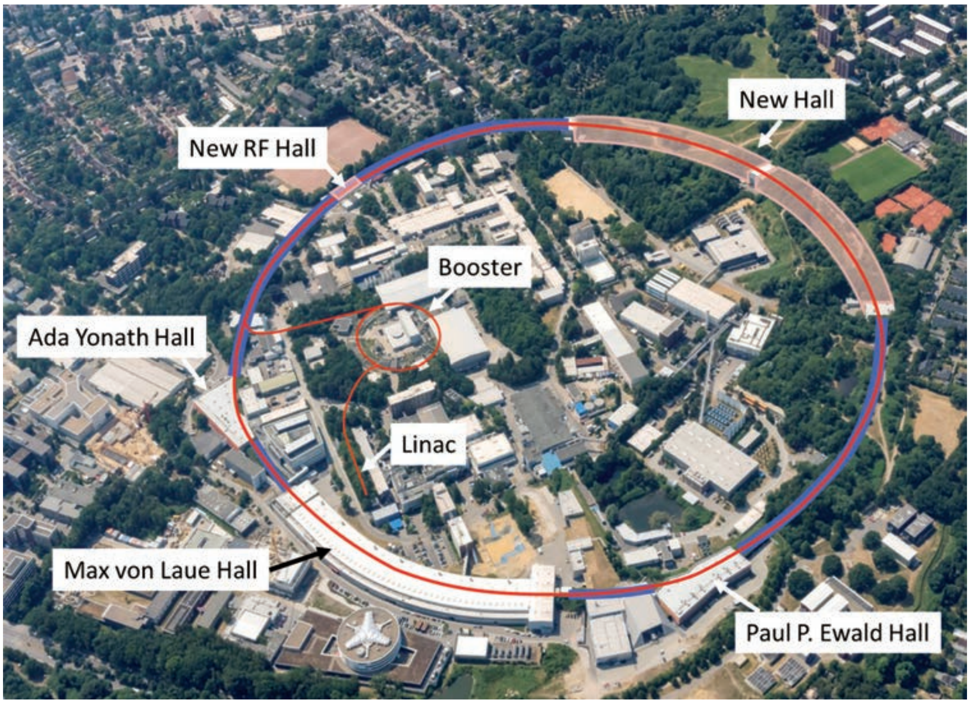

Figure 1

The DESY site with the existing PETRA III and planned PETRA IV buildings. The thick blue line indicates the sections where we plan to reuse the original accelerator tunnel.

bending radius (R = 256.68 m) of the storage ring are very advantageous for PETRA IV, as the beam emittance scales with the bending angle per arc cell cubed. The long straight sections provide space for 10-metre-long insertion devices for the so-called flagship beamlines, ease the layout of injection and extraction sections and provide more than sufficient space for the radio frequency (RF) system and other subsystems. These advantages, together with the considerable cost saving related to reusing most of the existing ring tunnel and the existing experimental hall, outweigh potential advantages of a fully symmetric ring that would be constructed entirely from identical arc cells.

The conceptual design of the PETRA IV storage ring foresees a new design for the magnet arrangement that keeps the electrons on their orbit. This new design of the electron optics is based on a hybrid seven-bend achromat (H7BA) lattice, a variant of the multibend achromat, which was developed at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, for the ESRF-EBS upgrade. Thanks to the larger bending radius of PETRA IV compared to ESRF-EBS and other planned fourth-generation synchrotron radiation sources worldwide, PETRA IV can reach by far the smallest emittance. The design parameters are summarised in Table 1.

While the design of the PETRA IV magnet lattice entails similar requirements as for ESRF-EBS, the sextupole and octupole magnets have to be stronger than those in the ESRF-EBS storage ring, and a new design of these magnets will be necessary for PETRA IV. Prototypes of these magnets will be built during the technical design phase.

The PETRA IV magnet lattice (Fig. 2) also requires a very precise alignment of the accelerator components (magnets and beam position monitors). This is due to the fact that the sensitivity of the beam dynamics to alignment errors at PETRA IV compared to PETRA III or other third-generation light sources is increased significantly because of the very strong focusing of the electron beam. Establishing the circulating beam and recovering the dynamic aperture requires an iterative procedure that involves several correction steps, similar to the procedure implemented for other upgrade projects. The demands on magnet alignment for the operation of PETRA IV are 30 µm (rms) for the transverse magnet offsets for selected and/or the most delicate magnets.

Design parameter	PETRA IV	
Operation mode	Brightness mode	Timing mode
Energy / GeV	6	
Circumference / m	2304	
Emittance (horiz./vert.) / pm rad	< 20/4	< 50/10
Total current / mA	200	80
Number of bunches	1600	80

Table 1

PETRA IV design parameters when operated in brightness mode and timing mode

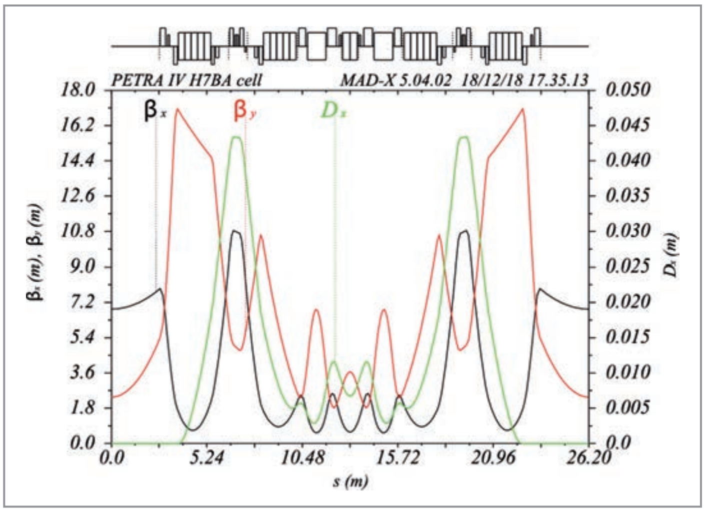

Figure 2

Optical functions of the hybrid multibend achromat lattice of PETRA IV. The figure shows the horizontal (black curve) and vertical (red curve) beta functions and the dispersion (green curve) of one arc cell.

Risk mitigation and future plans

The ambitious performance goals of PETRA IV are approaching the limits of the present state of the art in accelerator physics and technology. Therefore, a strategy for risk mitigation in this highly complex project is mandatory.

The risk of serious conceptual flaws is counteracted very efficiently through thorough analyses and detailed studies performed by the accelerator design team. A continuous exchange with other members of the worldwide accelerator community and with DESY's Machine Advisory Committee (MAC) is extremely valuable to avoid overlooking design flaws or missing opportunities for further design optimisation.

The technical risk mitigation strategy is based on two pillars: (i) building and testing of prototypes and (ii) the possibility of testing prototypical PETRA IV components or diagnostics, correction concepts and controls with beam in the PETRA III ring and the present injector complex.

The risk mitigation strategy covers all subsystems of PETRA IV, including magnets, alignment and stability of components, power supplies and utilities, vacuum system, RF system and beam diagnostics, to name only the most important subsystems.

In 2019, the PETRA III vacuum system was modified in one arc section comprising ten dipole vacuum chambers to test the properties of non-evaporable getter (NEG)-coated chambers. The aim of the study is to get a better understanding of the impact of the synchrotron radiation on the activation of the NEG coating. This study together with the R&D work, which is done by the technical groups, will be an important contribution to the technical design report (TDR) of PETRA IV. The TDR phase will start in 2020.

Contact: Rainer Wanzenberg, rainer.wanzenberg@desy.de

Drift compensation module

How to ensure long-term stability

For reliable and robust operation of free-electron lasers (FELs) with bunch arrival time variations on the sub-10 fs scale, the short- and long-term radio frequency (RF) stability of the cavity field is a crucial factor. The long-term RF stability depends mainly on temperature and humidity changes acting on various electronic subcomponents of the accelerator. For the European XFEL X-ray laser, we used drift compensation modules operating at 1.3 GHz to remove long-term amplitude and phase variations of the MicroTCA.4 low-level RF control system on the femtosecond scale. The modules showed excellent suppression of environmental temperature and humidity changes down to an amplitude and phase stability of 0.01% and 0.01 deg or 20 fs (all peak-to-peak values), respectively. This article describes the method, hardware, performance and operation of the module.

Introduction

At FEL facilities, excellent reproducibility of the amplitude and phase of the accelerating fields is the key to minimise switching times between different FEL users and achieve ultimate stability for user experiments. Uncontrolled variations of the accelerating cavity fields directly perturb the longitudinal bunch profiles and the bunch arrival times, and thus the self-amplified spontaneous emission (SASE) photon pulses at the experiments. To stabilise the accelerating fields on short and long time scales, special precaution needs to be taken in the low-level radio frequency (LLRF) control system.

Amplitude and phase drifts are especially complicated to control. These drifts are caused by environmental changes in temperature and humidity that affect various electronic subsystems, such as connectors, cables and the RF field detection circuit itself. While the ambient temperature of the electronics is regulated to a level of 0.2°C (peak-to-peak), humidity changes are uncontrolled and vary by up to 20% relative humidity (RH) within days. The impact of humidity on the field detection has been measured to 0.1 deg/% RH for 1.3 GHz.

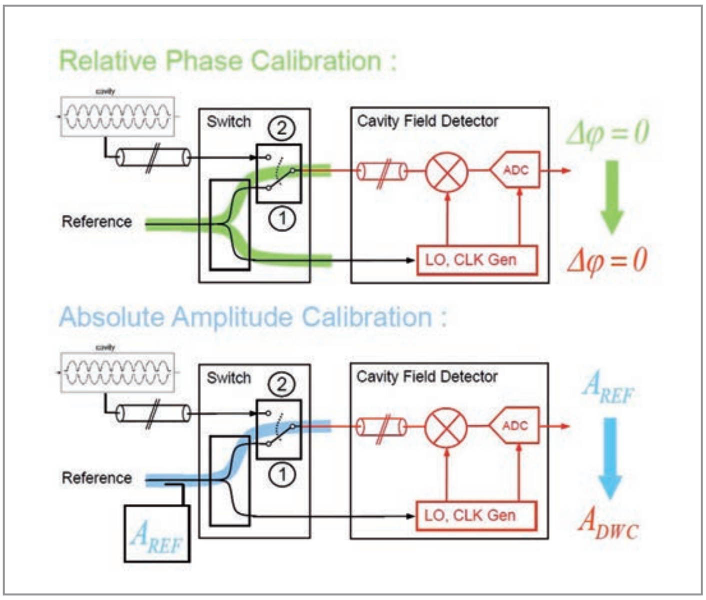

Figure 1

Phase and amplitude drift compensation method to remove drifts of cavity field detectors in LLRF systems, especially for pulsed machine operation

To be independent of humidity changes, sealed metal housings or passivated subsystems are required, which makes their packaging complicated and expensive. Because modern electronic standards like MicroTCA.4 are not sealed and the costs for a humidity-controlled accelerator are enormous, other methods are required to make the crucial subsystems stable in the long term. To actively compensate for any drifts of LLRF systems caused by temperature or humidity on the femtosecond scale, a drift compensation module (DCM) was

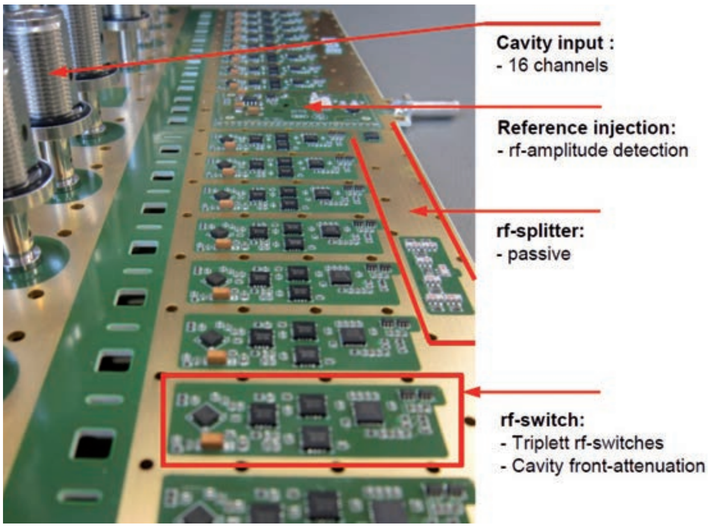

Figure 2

Main printed-circuit board for compensation of 16-cavity channels tested at FLASH and installed on a large scale at the European XFEL. From the idea to the final product, it took about 10 years of development, testing and series production.

Drift compensation module

As depicted in Fig. 1, the DCM consists of one RF splitter and one RF switch per cavity channel. To compensate for any drifts in the cavity field detector, the facility phase reference is injected into the field detection chain (switch in state 1), before the cavity phase and amplitude are measured (switch in state 2). The measured amplitudes are corrected by a specialised high-precision RF amplitude detector.

Figure 2 shows the internal main printed-circuit board (PCB), which compensates 16-cavity probe channels. For FLASH and the European XFEL, the field detection chain is realised in the industry standard MicroTCA.4 with front-end mixers (DWC8300), high-speed digitisers (SIS8300V2) and LO generation (LOGM, uLOG), which are not shown here.

Figure 3 illustrates the packaged DCM in standard 2U height 19-inch technique. All Heliax cavity RF cables are directly connected to the top of the module to provide an electromagnetic conductive (EMC) bypass of distortions. Splitters and switches are actively temperature-stabilised to about 0.02 K (peak-to-peak) using Peltier elements. This allows the module to operate also under poor rack conditions. Timing, attenuation, temperature control, power management and isolated fibre links for communication are supported by a general data acquisition module.

Figure 3

2U 19-inch packaged drift compensation module for 16-cavity probe signals. Front and rear view.

Performance verification

Figure 4 shows the DCM performance under laboratory conditions in a single device-under-test configuration for a humidity step induced using a vapour generator in the rack. The induced humidity change is about 40% RH and modulated by the rack heat exchanger. By using the DCM, the phase stability could be improved from 3.35 deg to 0.01 deg, respectively 20 fs (all peak-to-peak values) by a factor of more than 200 over 70 h. For temperature distortions, the suppression factors are about 250. The non-corrected and corrected LLRF system coefficients are 0.08 deg/% RH and 0.0005 deg/% RH, respectively.

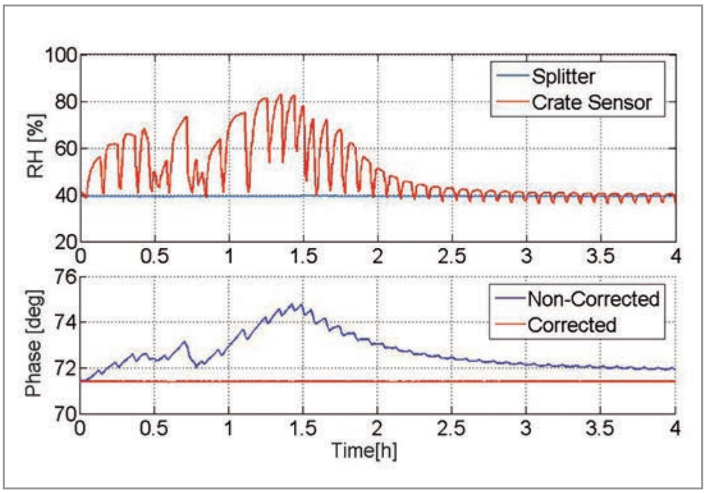

Figure 4

Corrected and uncorrected RF phase changes caused by humidity

According to Fig. 5, the operation of the DCM at the European XFEL RF station A10 shows that the major phase distortions over 40 days are caused by the humidity, which primarily induces a phase correction in the LLRF systems.

At the European XFEL, for the first time in an accelerator, all LLRF stations were equipped with DCMs to contribute to a reliable and robust long-term machine operation. A direct verification might be carried out at the European XFEL using beam-based measurements, which is planned in the near future.

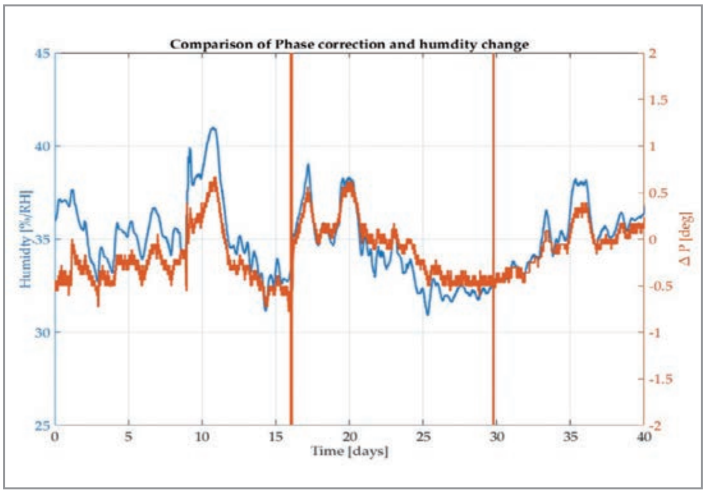

Figure 5

Correlation between humidity and phase correction at the European XFEL RF station A10

Contact: Frank Ludwig, frank.ludwig@desy.de

High-performance image processing using FPGAs

Successful technology transfer of GigE and implementation of 10 GigE Vision protocol

High-performance video data acquisition, on-the-fly image processing and real-time data evaluation have gained tremendous importance in areas such as industrial automation, process monitoring or quality inspection. For accelerator control or in photon science experiments, rapid 2D image systems are crucial assets used for fast feedbacks, target protection or *in-situ* parameterisation of experiments. Data analysis meanwhile is carried out by artificial-intelligence algorithms requiring large data throughput combined with sufficient parallel computing power, e.g. using field programmable gate arrays (FPGAs). In this article, we present our implementation of the GigE Vision protocol in FPGA, offering precise control of the execution flow. The implementation is able to acquire data from commercial off-the-shelf cameras from various vendors and allows high-speed image capture, real-time processing and distribution of the information to other components in the system.

Introduction

GigE Vision is a communication protocol for transferring images and video over Gigabit and 10 Gigabit Ethernet. It is one of the most widely used protocols for connecting cameras to frame grabbers and other receivers.

Because of their internal structure, FPGAs are well suited for demanding input/output tasks and provide precise control of the execution flow compared to CPUs and GPUs. The implementation of the GigE Vision protocol in FPGA allows very high-throughput, low-latency reception of images and tight integration with image-processing algorithms.

GigE Vision specification

Strict adherence to the GigE Vision standard improves interoperability as well as user experience when connecting cameras from different vendors. To confirm the compliance of our implementation with the GigE Vision standard, we attended a plugfest hosted by the Automated Vision Association (AIA) in 2019. Our setup successfully interoperated with cameras from Allied Vision, Basler, JAI, Hamamatsu and Teledyne, confirming the compliance and interoperability with other vendor products. Meanwhile, the GigE Vision certification has been granted.

Technology stack

The right side of Fig. 1 shows the technology software and firmware stack from reception to processing of video frames. For clarity, some details are omitted. Displayed at the bottom is a GigE or 10 GigE Vision-compliant camera equipped with an Ethernet port. The camera is directly connected to an FPGA, where the Ethernet physical layer is handled by vendor-provided intellectual property (IP) cores. The data stream is then forwarded to a network stack, consisting of an Ethernet MAC and a UDP/IPv4 engine. In the next step, the data is transferred to the GigE Vision core, which extracts the image from the GigE Vision data packets. Afterwards, the image data is provided to the application over a standardised interface, the AXI4 Stream Video. Using a standardised interface increases modularity and simplifies interfacing to different modules, e.g. video direct memory access (DMA), custom logic and modules written in Vivado High-Level Synthesis (HLS) or Matlab. The data is then transferred to the CPU, either via PCI Express or internal interconnects in Xilinx Zynq devices. On the CPU, a server provides a high-level interface for the firmware. A Python library handles the application part, together with a GUI to display the images on the screen.

Performance test

To illustrate the performance, we carried out a test with a FLIR Oryx 10 GigE Vision camera (model ORX-10G-51S5C) together with our GigE Vision stack running on powerful FPGA module with a Kintex 7 FPGA (DAMC-TCK7). We configured the frame size to 1920 x 2048 pixels in RGB8 format (24-bit per pixels). The exposure time was reduced to reach a frame rate of up to 82.38 frames per second measured with an AXI4 Performance Monitor, which corresponds to a data flow of 8288 Mb/s to a DDR3 memory. Most electronic boards are equipped with fast DDR3 or DDR4 memory, the fastest being Struck SIS8160 with a total throughput of 205.3 Gb/s [1]. If hardware permits, frame rates of 1 kHz and higher can be achieved, which is of particular interest for the new DESY high-power laser system KALDERA.

Applications

Supported hardware electronic boards

The GigE Vision stack can be implemented on any Xilinx FPGA of decent size with sufficiently wide memory

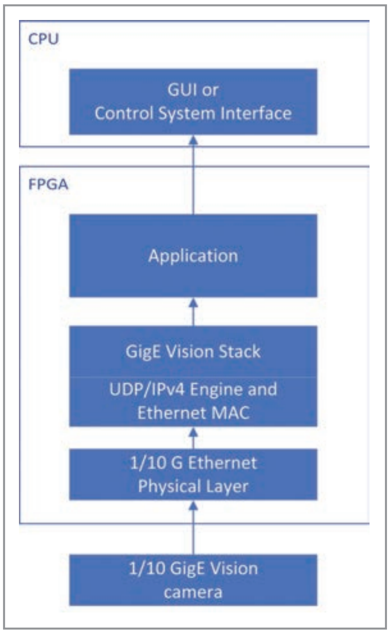

Figure 1

Left: GigE Vision application in MicroTCA crate. Right: Technology stack

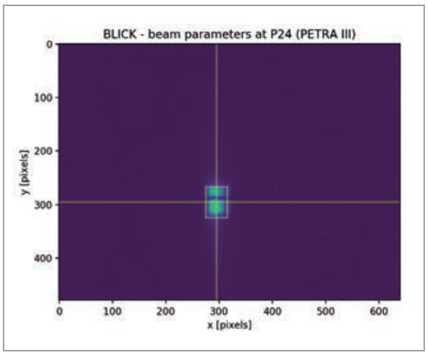

Figure 2

Output from the BLICK software

connection. So far, the stack was successfully ported and tested on the following electronic boards:

• DAMC-TCK7	licensed to N.A.T
• DAMC-FMC2ZUP	licensed to CAENels
• NAMC-ZYNQ-FMC	N.A.T
• SIS8160	Struck GmbH
• ZCU102 Evaluation Kit	Xilinx
• KCU116 Evaluation Kit	Xilinx

Several of the supported boards are advanced mezzanine cards (AMCs) compatible with the MicroTCA platform. For image acquisition and processing, the MicroTCA platform provides superior characteristics, such as:

- Aggregation of a large number of cameras [2]
- Information from the cameras can be combined with other sensors and used for fast feedback
- CPU with application software can be integrated in the crate, using PCI Express on the backplane
- Timing on the backplane to timestamp the frames
- Future developments will also allow the camera acquisition to be triggered from the backplane (e.g. from a global timing system or from other cards in the crate)

BLICK – BeamLine Instrumentation Camera Kit

BLICK is an application and a software tool kit that uses the GigE Vision stack to provide simultaneous readout of eight cameras with real-time diagnostic capabilities (e.g. 2D mean and standard deviation [3]), allowing the size and position of beams (electron, laser or X-rays) to be determined.

A Python-based GUI provides a visualisation of the images, and results of the real-time diagnostic module are displayed. An easy interface allows users to program specific functions themselves (Fig. 2). In future, BLICK will also be integrated in the areaDetector [4] framework, providing data to the Experimental Physics and Industrial Control System (EPICS).

Use cases

The GigE Vision stack can be used for any 2D imaging application where fast, deterministic or real-time data processing is needed. The stack is used as part of the European Spallation Source (ESS) target protection system [5] and at the PETRA III experiments (beamline P24) at DESY. It is of particular interest when frame rates of 100 Hz to 1 kHz are required or low latency is mandatory, e.g. for fast feedbacks.

The development has a high technology transfer potential. The MicroTCA Technology Lab at DESY has licensed the GigE Vision IP core to several industry customers and provides customisation regarding online processing algorithms, implementation and porting to new hardware platforms. Algorithms are written in C++ and compiled to FPGA logic with Vivado HLS, allowing for easy and fast developments.

Contact: Jan Marjanovic, jan.marjanovic@desy.de
Sven Stubbe, sven.stubbe@desy.de
https://techlab.desy.de/products/gige_vision_solutions/

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Beam profile measurement at the European XFEL

Fast wire scanner system for the X-ray laser facility

Fourteen wire scanner systems are installed in the European XFEL to measure the transverse electron beam profiles in the high-energy sections of the facility. These scanners provide a slow scan mode for beam size and halo studies as well as beam optics matching. When operating with long bunch trains (>100 bunches), fast scans can be used to measure the beam profiles in an almost non-destructive manner, revealing the transverse electron bunch size of one macropulse and the substructures within it. First slow scans had been performed in 2017, and fast scans were commissioned in 2019.

Wire scanners at accelerators

In particle accelerators, wire scanners are used to image transverse beam profiles. The wire scanner drives a thin wire inside the vacuum pipe through the electron beam, producing scattered electrons, other charged particles and bremsstrahlung. The electrons and particles can be detected downstream outside of the vacuum pipe by scintillation detectors equipped with photomultipliers. Plotting the detector signal over the wire position reveals the beam profile in the scanned plane. Figure 1 shows a typical result of a transverse beam profile measurement in slow scan mode by a European XFEL wire scanner.

The European XFEL with its superconducting linear accelerator can be operated with long bunch trains (up to 2700 electron bunches per train, 10 times per second). This enables extremely fast measurements of the beam profile.

European XFEL wire scanner system

Wire scanner units developed for the European XFEL consist of one horizontally oriented and one vertically oriented titanium fork carrying different wires. Each fork is equipped with three straight tungsten wires of 20, 30 and 50 µm thickness, allowing adaption to different beam charges. Two 10 µm wires angled by 60° allow a 30°-angled tomography of the electron beam at one position (needs six subsequent measurements). The orthogonal arrangement of the forks reduces the sensitivity of the measurement to mechanical vibrations of the forks and their support while moving. Linear servomotors are used to drive the forks, and an optical ruler measures the fork position during motion. Figure 2 shows a wire scanner unit installed in the European XFEL, Fig. 3 a titanium fork with the wires displayed in red.

The mechanics of the motion unit as well as the electronics and firmware for the motion unit and the detector readout are custom-made and fully integrated into the MicroTCA.4 environment and the DOOCS control system. Using a digital field-programmable gate array (FPGA) advanced mezzanine

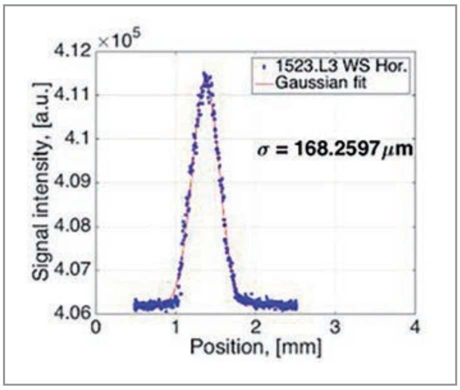

Figure 1
Transverse horizontal beam profile measured by a wire scanner in slow scan mode at the European XFEL

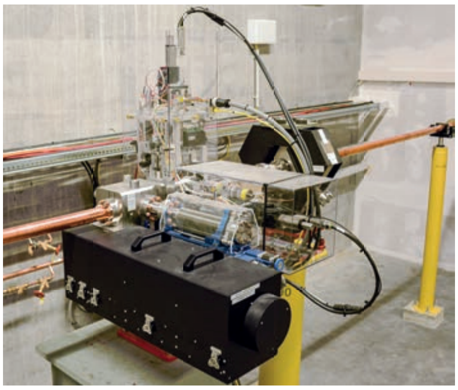

Figure 2
Wire scanner unit with horizontal and vertical plane installed in the European XFEL, with a screen station in the foreground (black box)

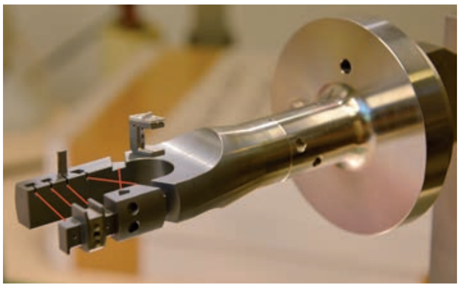

Figure 3
Titanium fork in the mounting support with wires displayed in red. Wire thicknesses from left to right are 50, 30 and 20 µm. Two further 10 µm wires are crossed at 60°.

card (AMC) and digitiser AMC, both motor start and readouts are synchronised to the general timing system of the European XFEL. A repetitive accuracy of the motor start trigger on the order of microseconds is important to hit preselected parts of the bunch train and select the wire when performing a fast scan. Figure 4 shows a custom-developed rear transition module (RTM) for the detector readout and surrounding components.

Installation in the European XFEL

Wire scanner units are installed in the European XFEL in groups of three upstream of the collimation section and upstream of the undulator systems. Several dedicated photomultiplier-based detectors are installed downstream of each group of wire scanner unit to detect the scattered particles. These detectors are connected to a scintillating fibre wrapped around the beam pipe or to a scintillating paddle. Their readout system is designed for a high dynamic range. Additionally, regular beam loss monitors can be used.

Figure 4

Readout electronics for the photomultiplier signal: Wire scanner detector RTM (left) and photomultiplier tube with base (right) standing on a commercial off-the-shelf high-voltage power supply. The photomultiplier signals are relayed to the RTM using differential cables with standard RJ45 connectors. A black wrapped-up scintillating paddle is partially visible in the background.

First fast scan measurements

Slow scan measurements typically take several minutes and are used in single-bunch operation only for dedicated purposes. When operating the European XFEL with long bunch trains, the wire scanners can be used to check and optimise the transverse beam profiles in an almost non-destructive manner within one bunch train during user experiments. For this purpose, the fork is driven through the beam – under the control of the general timing system – with a constant speed of 1 m/s, hitting hundreds of subsequent electron bunches. This makes it possible to measure a complete transverse beam profile within less than 600 µs. Figure 5 shows one of the first fast scans.

Beam orbit drift and jitter compensation

During data acquisition, the position of each individual electron bunch at the wire might vary. Without correction, the measured beam profile could be distorted, depending on the direction and speed of the drift and the direction of the wire motion. For this reason, the effective wire position relative to the beam is used for the beam profile measurement instead of just the wire position. Since there is no beam position monitor installed directly at the wire scanner unit, the data of two adjacent beam position monitors is used to calculate a virtual beam position (bunch-by-bunch) at the position of the wire. While fast scans suffer from beam orbit drifts, slow scans are affected by beam orbit jitter. Both drift and jitter can be compensated in this way.

Contact: Timmy Lensch, timmy.lensch@desy.de

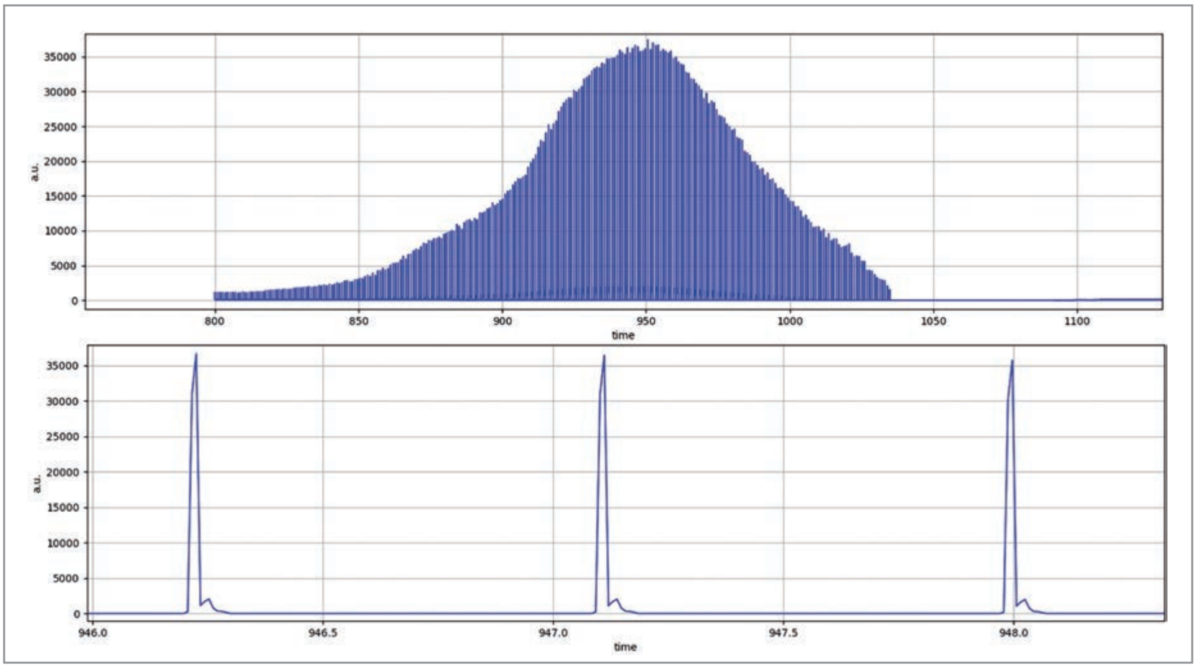

Figure 5

Fast scan detector read-out. The upper plot shows a corrected transverse beam profile measured from a bunch train with about 300 bunches (bunch repetition rate of 1.1 MHz, i.e. 909 ns bunch separation, 250 pC per bunch) hitting a tungsten wire that passes by at 1 m/s. The bunch train starts at 800 µs, the wire hits the beam core at around 950 µs. The lower plot is a zoomed view of three bunches near the beam centre.

European XFEL high-power RF system

Optimising availability

The high-power radio frequency (RF) system of the European XFEL X-ray laser has now been in operation for three years. During this time, an efficient monitoring system has been developed to record the operating states of the high-power RF stations and determine the causes of failures. For the year 2019, a complete recording and analysis of the failures of all 26 RF stations was available for the first time. By analysing the data, optimisation potentials were identified and measures to increase the availability were derived, most of which were implemented in the winter shutdown 2019/2020.

Monitoring

In order to optimise a technical system, a precise knowledge of its behaviour during operation is necessary. The operation of the RF stations of the European XFEL is therefore monitored very closely. Software developed especially for this purpose enables us to record to the minute which of the stations fail and for what reasons. The focus here is on the failures that have an effect on the electron beam operation.

In the following, downtime is defined as follows: The downtime of the high-power RF system is the duration in the off-state of one or more RF stations that were “on beam”, so that the total energy gain of the electrons is reduced and X-ray generation is lost. All off-states are counted regardless of whether the user X-ray programme is active or not. The total downtime of the European XFEL facility is higher, because even if all RF stations are running, other accelerator components can cause a loss of the electron and photon beams.

Basically, there are two reasons for RF station failure, internal or external. Internal reasons are e.g. failures of subsystems of an RF station or emergency shutdowns triggered by the internal interlock systems. External reasons for off-states are malfunctions and interlocks of other accelerator subsystems, which inhibit the operation of the associated RF station.

Analysis, identification and prioritisation

The high-power RF system proved to be very reliable, as it caused less than 10% of the total downtime in 2019. This is probably largely due to the extensive testing of the RF station subsystems prior to installation and to preventive maintenance during shutdowns. It is particularly remarkable that, in three years of operation, no klystron had to be replaced due to irreparable breakdown. In order to further increase the reliability in the future, the type, duration and frequency of the failures caused by the RF systems themselves were analysed in detail. With the analysis results, optimisation potentials could be easily identified and prioritised, depending on the time required for repair.

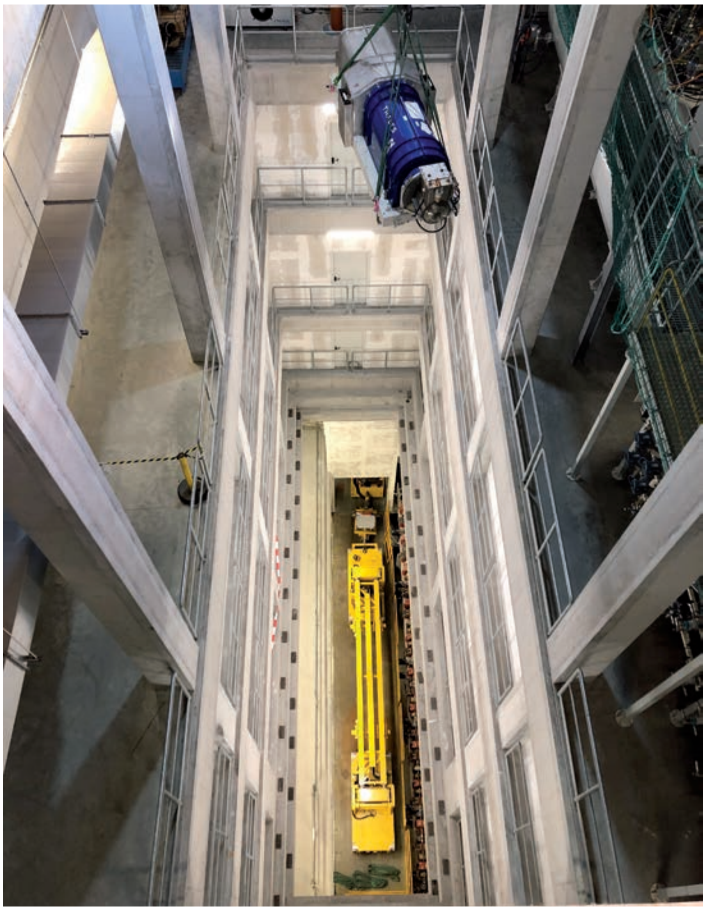

Figure 1

Insertion of a spare klystron (top) into the European XFEL tunnel using a crane and the special transport vehicle “Mullewupp” (bottom)

- Priority 1: Failures that might require a break of several days. For example, if a klystron has to be replaced, this can take several days.
- Priority 2: Failures that require breaks on the order of hours. For example, if smaller subcomponents fail whose repair requires tunnel access, it takes about 1 h to correct the fault.

For the Priority 2 case, four subcomponents were identified that required repeated access to the accelerator tunnel:

- Circuit breakers tripped after power outages due to current peaks during the switch-on procedure.
- A communication module (YAU41) failed repeatedly.
- At the end of 2018 and the beginning of 2019, bursts occurred in three klystron water hoses in the solenoid cooling circuit.
- Some flow monitors of the water-cooling circuit of the waveguide distribution did not release the interlock after pressure fluctuations in the cooling water system.

On the basis of this analysis, measures to optimise the availability were derived and, for the most part, already implemented.

System optimisation

Priority 1, the programme to accelerate klystron exchange, started in mid-2018. Due to their limited lifetime, klystrons have to be replaced sooner or later. The first replacement was done in December 2018, and the duration of the necessary work steps was recorded on the occasion. A total of five working days was required. Two days alone were needed to get the – currently only and very large – transport vehicle, named “Mullewupp” (the Low German word for “mole”), into the accelerator tunnel. The replacement klystron then also had to be brought in (Fig. 1). In addition, there was the fundamental problem that, in their original configuration, all the klystrons were difficult to manoeuvre on their own wheels.

To remedy the situation, a smaller transport vehicle is currently being developed that can be brought into the European XFEL tunnel much faster through the elevator. The manoeuvrability of all klystrons was considerably improved by replacing the original fixed castors with swivel castors. Furthermore, two replacement klystrons were stored in the European XFEL tunnel in August 2019 (Fig. 2). The latter two measures paid off right away in December 2019, as another klystron unexpectedly had to be replaced, which was then possible with considerably less effort.

The optimisations with Priority 2 were all tackled or completed in the shutdown 2019/2020. In November 2019, the circuit breakers were replaced. This action was prepared in the summer shutdown, during which the inrush currents were measured. Based on the measurement results, other circuit breakers were selected that only switch off after a longer delay. These new circuit breakers tolerate the length of the expected inrush currents and should no longer trip in the event of power outages.

Figure 2

Spare klystron with equipment in the European XFEL tunnel

It turned out that the faults of the communication module (YAU41) could be eliminated by switching the mains voltage on and off. Since this was only possible with tunnel access in the past, a remote-controlled power interruption was integrated into all communication modules.

The original plastic hoses of the klystrons, some of which burst, were quickly exchanged in March for better, but still not permanently suitable types. We then looked for a hose that would be permanently suitable for the deionised cooling water of the European XFEL and finally found a flexible stainless-steel hose that met the requirements. This type of hose was installed in almost all the klystrons during the winter shutdown.

We also found a promising alternative for the flow monitors of the water-cooling circuit of the waveguide distribution, which was extensively tested on a test stand. This type of flow monitor seems to reliably re-enable the interlock after pressure fluctuations in the cooling water system. Three of these new flow monitors were installed in an RF station for long-term testing. If they prove to be reliable there, they should also help at the other problematic positions.

All the recurring problems have thus either been dealt with conclusively or been processed to the extent that they can be finally solved in the course of 2020. These efforts and other unmentioned work on the high-power RF system would not have been possible without the support from 11 DESY groups (MKK, MKK1, MKK2, MKK6, ZM5, MR, MEA, MDI, MCS, D3 and MHF-p) and a very extensive shutdown planning and management by the High-Power RF group.

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

Seeding R&D at sFLASH

Generating coherent photon pulses

The sFLASH experiment at the FLASH1 beamline of DESY's free-electron laser (FEL) user facility FLASH is dedicated to the investigation of external seeding techniques. It was installed in 2010 and is being operated in a collaboration of DESY, Universität Hamburg and TU Dortmund University. The experiment is currently operated with high-gain harmonic generation (HGHG) seeding. In the last two shutdowns of the FLASH facility, the laser injection beamline and the diagnostics around the first modulator were upgraded. A hardware upgrade of the first chicane is currently being manufactured, which will enable the exploration of the advanced echo-enabled harmonic generation (EEHG) seeding technique.

Seeding of FELs

High-gain FELs generate photon pulses with extreme intensities. The exponential amplification process in these devices is typically initiated by spontaneous undulator radiation emitted by the high-brightness electron bunches at the beginning of the undulator. This self-amplified spontaneous emission (SASE) mode of operation results in photon pulses with poor longitudinal coherence. In the extreme ultraviolet (XUV) and soft X-ray wavelength ranges, seeding techniques greatly improve the longitudinal coherence by initiating the FEL amplification process using coherent light pulses from an external source.

The sFLASH experiment was installed in 2010. Figure 1 shows the schematic layout of the experiment. Currently, the HGHG [1] seeding scheme is employed, with typical harmonic numbers being 7 and 8. External ultraviolet laser pulses (wavelength 270 nm) are interacting with the electron bunches arriving from the FLASH linear accelerator in a short undulator called the modulator. A subsequent chicane turns the resulting sinusoidal energy modulation into a periodic density modulation carrying rich harmonic content. This electron bunch is then injected into the 10-metre-long variable-gap radiator where the FEL emission takes place. The energy and spectrum of the generated photon pulses can be measured already in the accelerator tunnel. For more sophisticated analysis techniques such as THz streaking, the pulses can be transported into a dedicated photon diagnostics laboratory.

Hardware upgrades

In the 2019 summer shutdown of the FLASH facility, the seed laser injection beamline was upgraded [2]. The vacuum chambers housing the seed injection and focusing optics installed for the experiments that demonstrated direct high-harmonic generation (HHG) seeding at 38 nm [3] were removed, and a new laser beamline section was installed. This upgrade also included relocating the thin vacuum window separating the accelerator vacuum and the laser beamline vacuum further downstream in the laser beamline. Thanks to this modification, all optical components are now located in the laser beamline vacuum, making them readily accessible for maintenance.

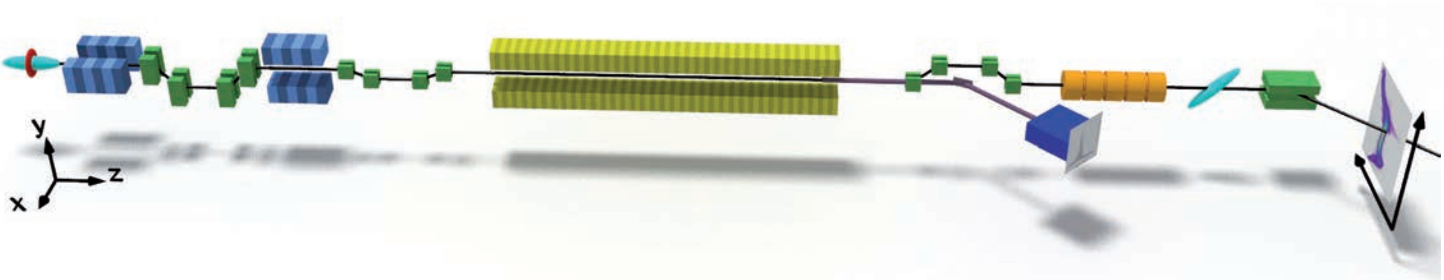

Figure 1

Schematic layout of the seeding experiment sFLASH. The electron bunches and the seed laser pulses propagate from left to right through two five-period undulators (blue) and two four-dipole chicanes (green). Here, the electron bunches are microstructured before they enter the 10-metre-long undulator (yellow) in which the FEL emission takes place. The generated photon pulses are transported to in-tunnel photon diagnostics or an external laboratory, while the longitudinal phase space distribution of the electron bunch can be diagnosed with a transverse-deflecting structure (orange) and a dipole spectrometer.

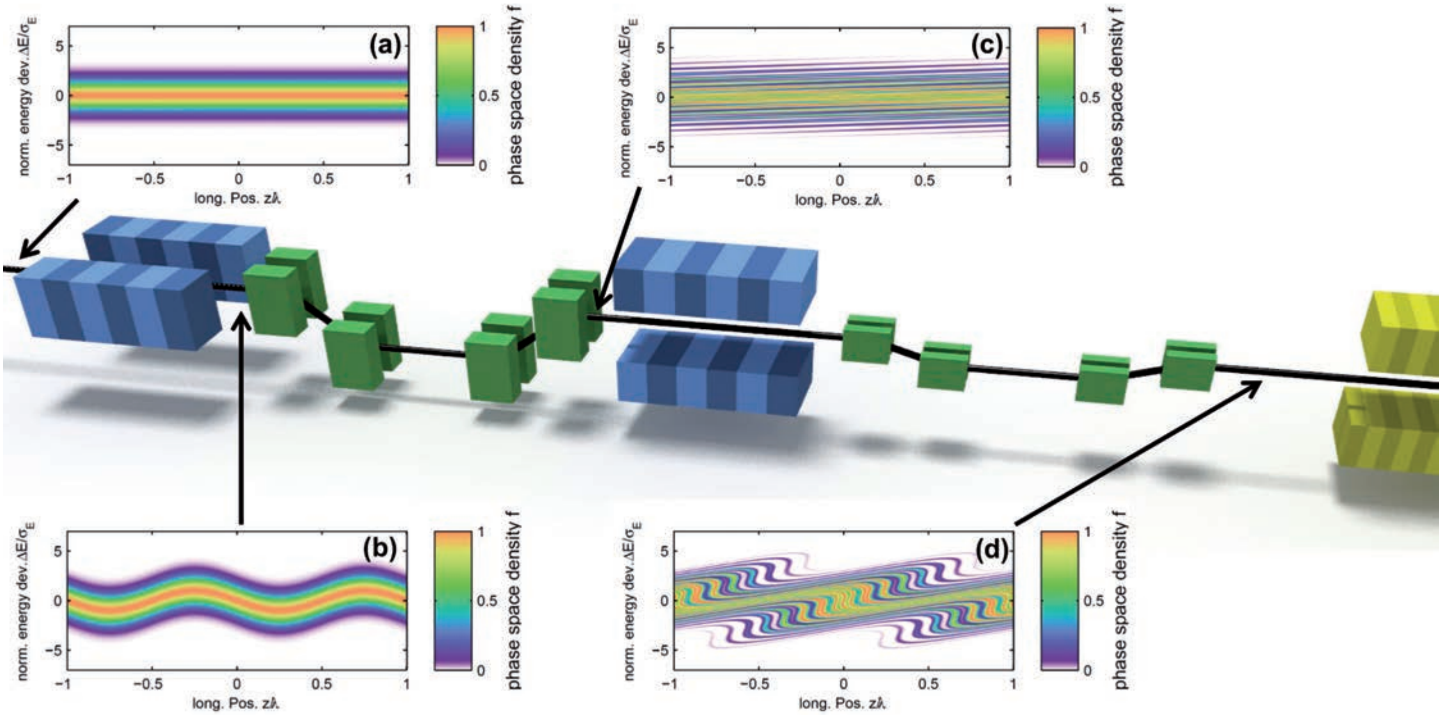

Figure 2

Evolution of the longitudinal phase space distribution in the EEHG seeding scheme. In the first modulator, the initially uniform electron beam (inset (a)) interacts with the first laser pulse (wavelength λ), resulting in a sinusoidal energy modulation (b). This energy modulation is sheared over in the first chicane, which typically has a longitudinal dispersion of a few millimetres, resulting in a filamented longitudinal phase space distribution (c). After a second laser-based beam manipulation, the beam is microstructured at the desired harmonic (d) and injected into the radiator (yellow).

In addition, the newly installed beamline section permits the extraction of a fraction of the seed laser pulses for online diagnostics as the pulses propagate from the final mirror to the interaction region in the modulator. In January 2020, an initial laser diagnostics setup was installed. This includes (i) the "beam sampler", a thin glass element inserted into the laser beamline to extract a fraction of the seed laser pulses for online measurements, and (ii) the optical components for the characterisation of the seed laser pulses.

In addition, in January 2020, the diagnostics installed in the accelerator beamline were upgraded. So far, the spatial overlap of the electron bunches and the ultraviolet seed laser pulses could only be directly diagnosed for the second modulator. There, cerium-doped yttrium aluminium garnet (Ce:YAG) crystals are available before and after the modulator to image the transverse beam profiles. In January 2020, an additional pair of Ce:YAG screens was installed before and after the first modulator of the seeding experiment. This enables direct measurements of the spatial laser–electron overlap also in the first modulator, which is expected to reduce the setup time needed to establish laser–electron interaction in the first modulator.

Towards echo-enabled harmonic generation

With single-stage HGHG, harmonic numbers up to approx. 15 are accessible. The advanced EEHG seeding scheme allows the beam to be efficiently bunched at higher harmonics [4]. Figure 2 illustrates the manipulations of the electron beam. Recently, the seeded FEL user facility FERMI in Italy demonstrated EEHG-seeded FEL operation at 5.9 nm [5].

At high harmonics, EEHG calls for significant overshearing of the electron bunches in the first chicane. The longitudinal dispersion of the first chicane currently installed at sFLASH is insufficient for EEHG-seeded FEL operation at high harmonics, being limited both by the vacuum chamber aperture and by the first field integral of the installed dipole magnets. To lift these restrictions, a hardware upgrade comprising a flat vacuum chamber and new dipole magnets is currently being manufactured. In combination with the already installed Ce:YAG screens, this chicane upgrade will enable the exploration of EEHG-seeded FEL operation at higher harmonics.

Contact: Christoph Lechner, christoph.lechner@desy.de

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The SINBAD-ARES linear accelerator

First electron beam at the SINBAD accelerator R&D facility

Accelerator R&D was identified as one the core tasks of the Helmholtz Association. In line with this objective, DESY is setting up the dedicated, long-term accelerator R&D facility SINBAD (Short Innovative Bunches and Accelerators at DESY) in the premises of the old DORIS accelerator complex. The first experiment, the SINBAD-ARES linear accelerator (linac), is approaching the end of construction, with the electron source (gun) area already in beam commissioning. First electron bunches were produced in October 2019. The ARES linac will enable the generation of ultrashort electron bunches. The few-femtosecond-long electron bunches are an R&D topic in itself, but can also be used to test advanced acceleration schemes and develop novel diagnostic devices in ultrafast science.

Construction of the ARES linac

Starting in 2015, DESY's old DORIS accelerator and its outdated infrastructure were removed. The SINBAD facility for dedicated accelerator R&D was designed and implemented in the refurbished space. One part of SINBAD is occupied by the ARES linac, which will produce and accelerate electron bunches up to 100 MeV while compressing them to few-femtosecond bunch length. This is the first of multiple experiments in the SINBAD area. For electron acceleration, ARES relies on S-band radio frequency (RF) systems produced in industry. At the beginning of 2019, it received TüV approval and commissioning started. The hardware of the first stage of the linac, the 5 MeV electron gun section, was commissioned in the following months. Meanwhile, the DESY technical groups have installed the next stages of the linac, including two travelling-wave RF structures, the matching area and the high-energy spectrometer section (Fig. 1).

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 deflection structures, which will be installed in early 2021. These so-called PolariX TDS devices were conceived, developed and procured in collaboration with CERN and PSI. Their novel polarisation feature will allow

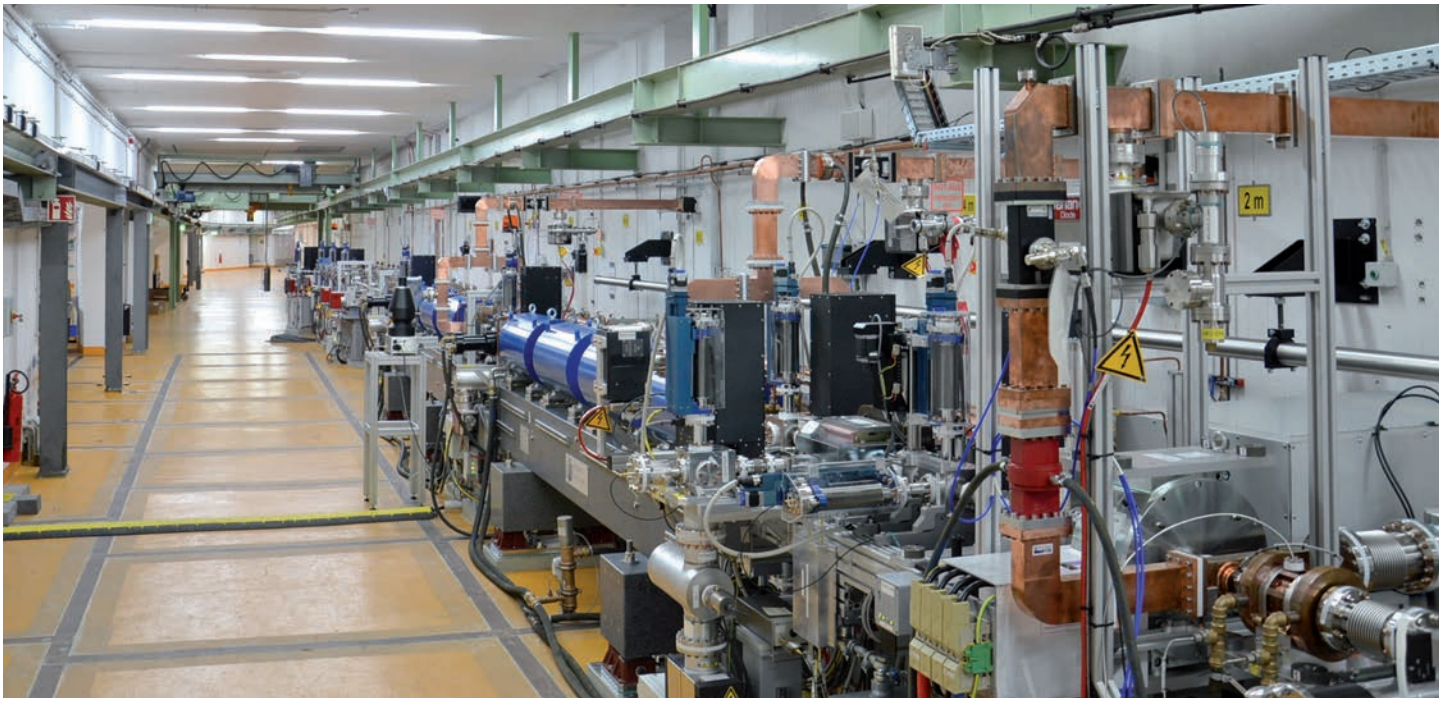

Figure 1

The ARES linac at the SINBAD facility as installed in 2019 the streaking of bunch characteristics with femtosecond resolution in 2D instead of 1D. With their tuneable characteristics, the high-brightness ultrashort electron bunches from ARES will be ideally suited to test novel accelerators, such as laser-driven dielectric structures, or to develop new diagnostics devices for ultrafast science.

Beam commissioning of the gun section

On 30 October 2019, scientists produced and detected the first electron bunch from the ARES photoinjector after acceleration up to 4 MeV. Figure 2 shows the screen station camera picture of this first electron bunch at ARES. The beam is further characterised in emittance, charge, energy and energy spread in the gun diagnostic section. Once its properties are optimised, the electron beam will be sent into two S-band structures for acceleration to the final beam energy of 100 MeV.

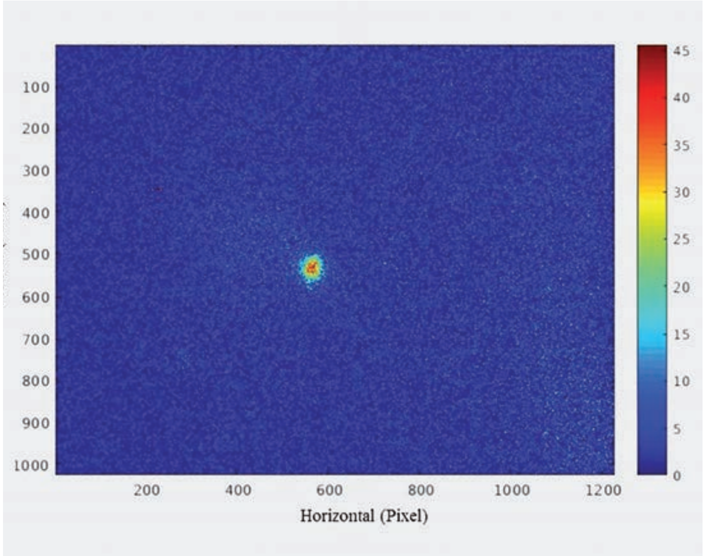

Figure 2

First electron beam at ARES, measured with a screen station in the gun diagnostic section

At the beginning of 2020, the experimental area – including a triplet magnet system for matching, beam diagnostics and an experimental chamber (Fig. 3) – will be installed, allowing first experiments for internal and external users. In autumn 2020, the bunch compressor stage and the PolariX TDS will be installed and commissioned. At this point, the ARES team will be aiming for the detection of world-record short electron pulses.

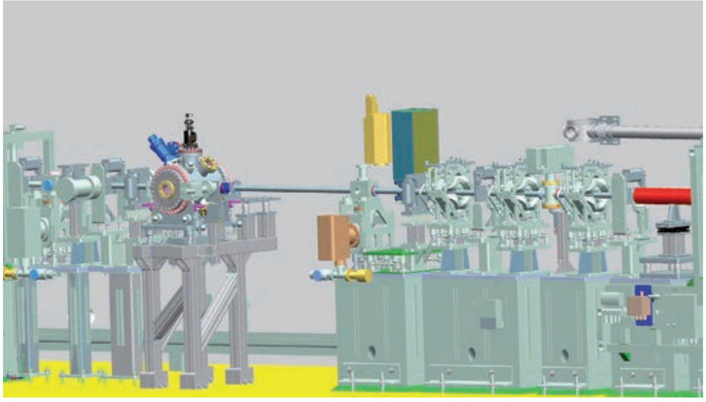

Figure 3

CAD model of the experimental area, including a triplet magnet system to focus the beam, beam diagnostics and an experimental chamber (from right to left)

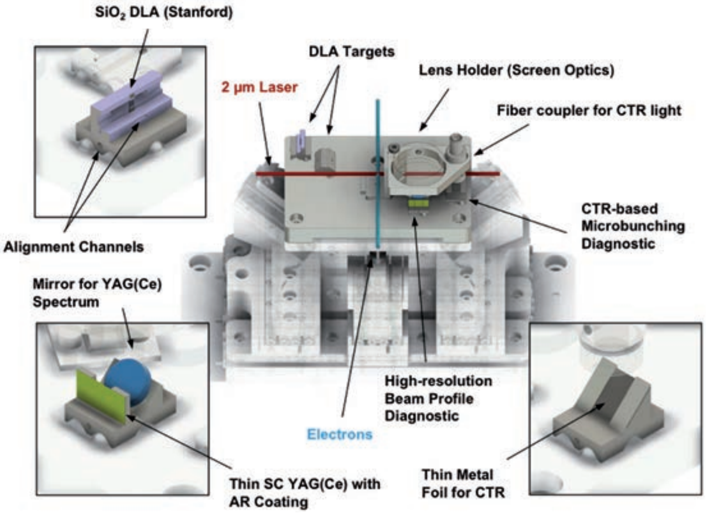

Figure 4

Sketch of the experimental ACHIP setup in the experimental chamber

First experiment at ARES – the ACHIP collaboration

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). The main goal is to show for the first time an energy spectrum shift of about 1 MeV for externally injected relativistic electron bunches in DLA. This is to be achieved by generating accelerating fields of around GV/m in a 1 mm long, laser-illuminated dielectric grating structure. As the structures used at ARES have a period of 2 µm, the accelerating buckets are only about 1 fs long. In a future upgrade of the experimental area, a new premodulation technique will be employed in the longitudinal phase space. With this technique being applied to the injected bunches, it is predicted that stable shot-to-shot operation can be achieved. Figure 4 shows the ACHIP setup in the experimental chamber.

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

Towards high-quality plasma accelerators

Rapid experimental progress at FLASHForward

Promising high-gradient, high-efficiency and high-quality acceleration of electrons, plasma wakefield accelerators may revolutionise photon science and high-energy physics. While many important aspects have already been demonstrated, others have not. The FLASHForward facility at DESY's FLASH free-electron laser (FEL) aims to show high-quality acceleration in a plasma, thanks to its world-class electron driver beams. After years of careful commissioning, experiments are now running and several milestones have been achieved – including high-precision wakefield measurements, preservation of energy spread and 1 GeV energy doubling in less than 20 cm.

Plasma accelerators for high-energy physics and photon science

High-energy physicists crave particle collisions, or events. Faced with limited funds, they are always looking to minimise the cost per event. Photon scientists using FELs have a similar criterion – the cost per photon. Particle accelerators have gotten better and better at these aspect over the past 100 years. Now, as machines are being pushed to the limit, we are asking ourselves: How can we produce more brilliant beams at even lower cost? The answer is simple: We need to accelerate particle bunches with higher quality – bunches that can be focused down to small sizes and that have a small energy spread. We also need to reduce the construction cost as well as the running cost – requiring more compact and more energy-efficient accelerators.

Plasma accelerators promise to solve all these problems simultaneously. With large GV/m-scale electric fields, inherently strong focusing and the ability to achieve high energy efficiency, the theoretical basis for plasma acceleration is clear. What's left is to demonstrate all this in practice. This is one of the main goals of DESY's FLASHForward facility [1] and in particular the X-2 experiment.

High quality, high efficiency

Accelerating particles in a plasma wakefield is nothing new [2] – it is done routinely in dozens of labs worldwide, normally using high-power lasers fired at a plasma. The ion–electron charge separation caused by the intense laser pulse leads to a trailing charge density wave (a wake) with very strong electric fields. These fields can accelerate particles to several GeV in a few centimetres or less. However, the beam quality and energy efficiency of *laser-driven* plasma accelerators are currently suboptimal. While several groups have made headway on the beam quality, the wall plug efficiency of lasers is orders of magnitude lower than that of conventional accelerators.

For applications where energy efficiency is key (as for high-energy physics and FELs), the solution is straightforward: use an intense particle beam from a conventional accelerator to drive the plasma wake. This *beam-driven* plasma accelerator concept has shown great promise in the past decades, with demonstrations of high energy gain [3] and high instantaneous efficiency [4] at SLAC's FFTB and FACET facilities. What's lacking, however, is to demonstrate high-quality acceleration and high overall efficiency (driver energy depletion).

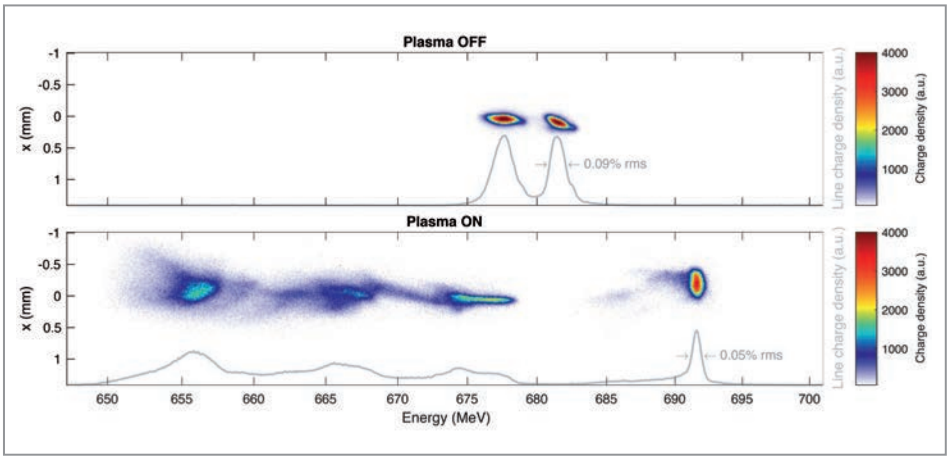

Figure 1

Two-bunch acceleration with a driver (left) and a trailing bunch (right). The bunches and the plasma were optimised to preserve (and even reduce) the energy spread in a 33 mm long plasma accelerator.

In technical terms, we split beam quality into two component parts. *Longitudinal* beam quality means low energy spread – vital to both FELs and particle colliders – which ideally should be less than 1%. *Transverse* beam quality, also known as *emittance*, is more abstract: It is the area of the beam in transverse phase space. In practice, this equates to the beam's ability to be focused down to small beam sizes – especially important in the interaction region of a collider.

In detail, therefore, the goal at FLASHForward is to accelerate an electron bunch by 1 GeV with high energy efficiency, while preserving both energy spread and emittance. This is no easy task, as both the plasma and the beam need to be controlled at the micrometre level. While certainly an ambitious goal, this *can* be achieved thanks to the stable and high-quality bunches provided by the FLASH linear accelerator. After several years of careful commissioning, the FLASHForward facility is now regularly running experiments, and it already reached several important milestones in 2019.

Precision wakefield measurements

Understanding the detailed structure of the electric field in the plasma wake was an important first step towards optimising the FLASHForward plasma accelerator. Using a novel technique based on progressively collimating an electron bunch from the tail to the head, we could measure the temporal structure of the wakefield with unprecedented resolution (few femtoseconds). High statistics and very stable beams resulted in percent-level accuracy, which paired with simulation enabled us to verify and improve our understanding of the detailed experimental setup.

Preserving the energy spread

Experimental optimisation studies and multiparameter scans were performed, making use of the highly tuneable and reproducible electron bunches at FLASHForward. This campaign resulted in a preliminary demonstration of energy spread preservation (Fig. 1), at a moderate accelerating gradient of 300 MV/m – that is, 10 MeV was gained in 33 mm of plasma. While this is already an order of magnitude larger than the accelerating gradient of the superconducting radio frequency cavities at FLASH, the goal is to extend this result to higher gradients and longer plasmas.

Energy doubling in 20 cm

In mid-2019, a significantly longer plasma cell was commissioned (Fig. 2). This enabled us to demonstrate energy doubling of a part of the bunch (Fig. 3) – a significant milestone for FLASHForward. Starting from 1.1 GeV, which took more than 200 m to accelerate, particles were boosted to 2.2 GeV in less than 20 cm of plasma. This corresponds to an accelerating field of approximately 6 GV/m. Full energy depletion of 1.1 GeV particles (deceleration to rest) was also achieved.

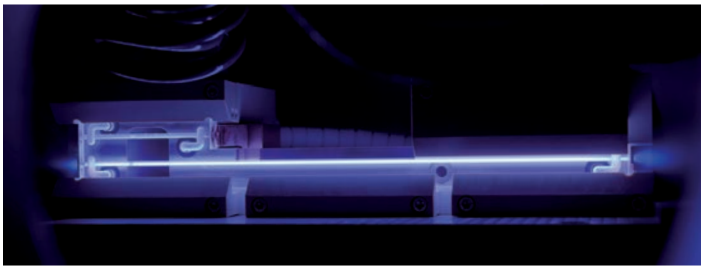

Figure 2

The plasma cell recently installed at FLASHForward, ionised using a high-voltage discharge in argon, with both a short capillary (50 × 1.5 mm^2) and a long capillary (195 × 1.5 mm^2).

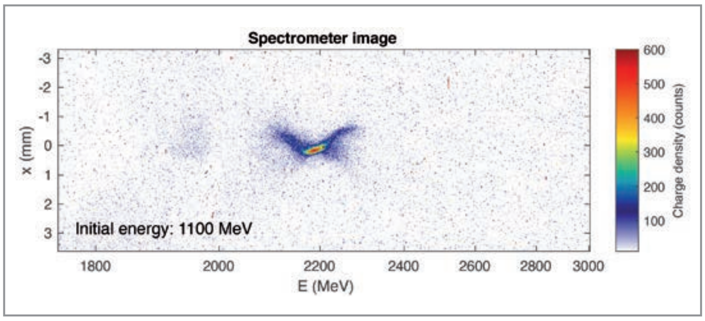

Figure 3

Energy doubling – accelerating some particles from 1.1 to 2.2 GeV. A set of quadrupoles focuses particles at 2.2 GeV onto the spectrometer.

Tight focusing and tilted beams

As a final preparatory step towards realising the perhaps most challenging goal, emittance preservation, much effort was put into detailed beam shaping. For the beam emittance to be preserved in a strongly focusing ion channel, the beam must be focused to millimetre-scale beta functions in both planes within a few millimetres of the plasma entrance. Moreover, any beam dispersion combined with an energy chirp will manifest as a beam tilt – this will lead to violent oscillation (hosing) if not cancelled. Solutions were found for both these problems, with a new technique for fast beta function measurement using only beam position monitors and beam jitter, as well as direct observation and cancellation of beam tilts and curvatures using the newly commissioned polarisable X-band transverse deflecting structure (PolariX).

Building on these first results, the goal for 2020 and beyond is clear: to combine the preservation of emittance and energy spread with a large energy gain. The race is on!

Contact: Carl A. Lindstrøm, carl.a.lindstroem@desy.de

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The PolariX TDS project

Prototype structure installed in the FLASHForward beamline

The PolariX TDS (Polarizable X-band Transverse Deflection Structure) is an innovative TDS design working in the X-band frequency range that was invented at CERN [1]. The design gives full control of the streaking direction, which can be tuned continuously to characterise the projections of the beam distribution on all the transverse axes. A prototype of such a novel structure was realised in a collaboration between DESY, CERN and PSI. In 2019, the prototype was installed in the FLASHForward beamline at DESY's FLASH free-electron laser (FEL) facility for first commissioning with the electron beam. Technical studies and numerical simulations for the installation of copies of such structures at FLASH2 and SINBAD at DESY also progressed.

The PolariX TDS project

Transverse deflection structures (often called RF deflectors) are well-known diagnostic devices for characterising the longitudinal properties of electron bunches in a linear accelerator.

TDSs deflect electrons along a well-defined direction, which is perpendicular to the velocity of the electrons. When an electron bunch travels through such a device, each electron receives a kick – for example in the vertical direction – that is proportional to its longitudinal distance from the centre of the bunch. By taking a picture of the transverse distribution of the bunch after the TDS, it is possible to extrapolate information concerning the properties of longitudinal slices of the electron beam in the direction perpendicular to the one along which they have been streaked.

In the PolariX TDS, the direction of the streaking field can be tuned continuously, as sketched in Fig. 1. This novel feature opens new opportunities for the complete characterisation of the electron beam, including for example the 3D reconstruction of the charge density distribution of the bunch [2].

In 2017, a collaboration was set up that includes the three research institutes mentioned above and four experiments: FLASHForward, FLASH2 and SINBAD (DESY) as well as ATHOS at SwissFEL (PSI). The collaboration partners have since collected the specifications and worked towards a common mechanical design of the PolariX TDS [3].

The new RF cavity design requires very high manufacturing precision guaranteeing highest azimuthal symmetry of the structure in order to avoid the deterioration of the quality of the field inside the cavity. At PSI, a high-precision tuning-free assembly procedure was developed for the SwissFEL C-band accelerating structures, which was recently used to produce the prototype of the PolariX TDS [4].

The prototype was then characterised, conditioned and finally installed in the FLASHForward beamline [5] in

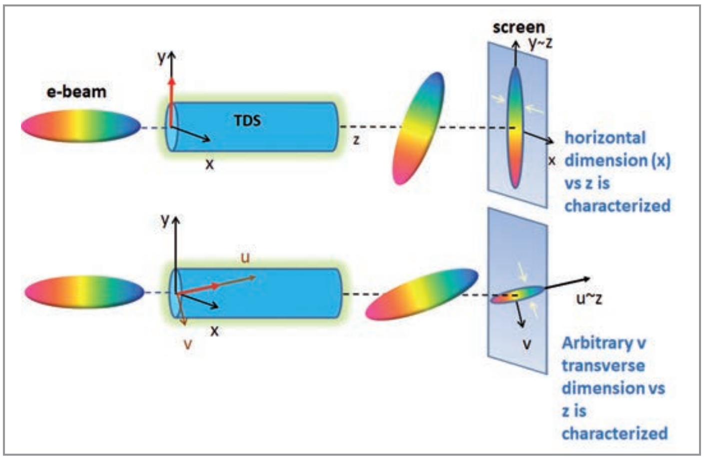

Figure 1

Illustration of the working principle of a conventional TDS (top) compared to the PolariX TDS (top and bottom). In a conventional TDS, the direction of the streaking field is fixed and it is typically chosen to be either vertical or horizontal. In the PolariX TDS, it is possible to tune the angle of the direction of the streaking in a continuous way, enabling the characterisation of beam slice parameters in an arbitrary transverse direction.

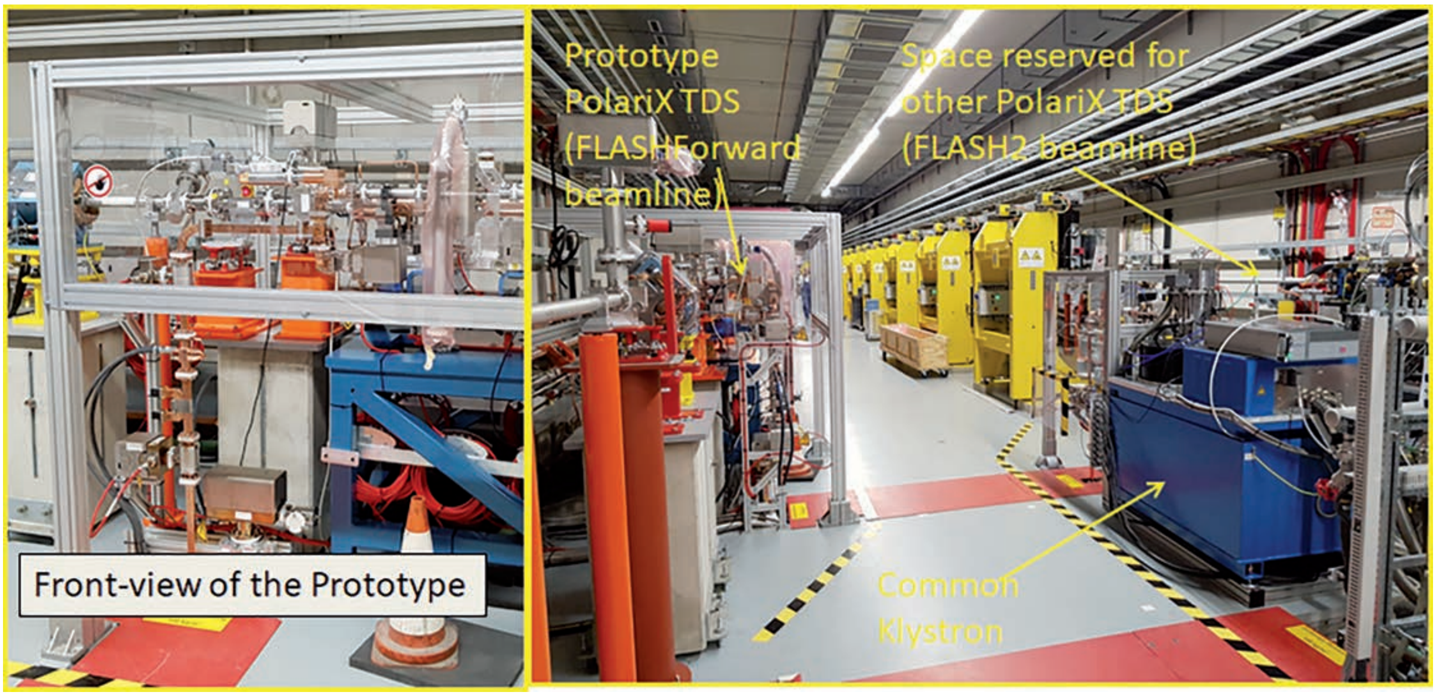

Figure 2

Left: Prototype of the PolariX TDS that was installed in the FLASHForward beamline. Right: Location of the common klystron that will serve the TDS for FLASHForward and the future ones for the FLASH2 beamline.

summer 2019 (Fig. 2). In September 2019, a mixed team from FLASHForward, FLASH2 and SINBAD operated the structure for the first time and started its experimental characterisation, which will be reported in future publications.

Two PolariX TDS cavities for the FLASH2 beamline and two cavities for the SINBAD-ARES linear accelerator are currently being manufactured, and the collaboration is looking forward to their installation and characterisation starting in 2020.

Installation of the prototype at FLASH

The FLASHForward and FLASH2 groups have been working on the design of a shared RF station to feed either the FLASHForward TDS or the FLASH2 TDSs installed in the two beamlines (Fig. 2, right). On the one hand, FLASHForward aims at the longitudinal characterisation of GeV electron beams used for driving plasma wakefield experiments or accelerated in a beam-driven plasma channel [5]. The goal of FLASH2, on the other hand, is to establish femtosecond-scale photon pulses through meticulous optimisation of the longitudinal bunch slice parameters to enhance the FEL performance. The photon pulse length can also be reconstructed [6].

Both experiments share the need for femtosecond-scale longitudinal beam diagnostics, which will be achieved thanks to the installation of one or two PolariX TDSs, respectively. The installation of the first structure in the FLASH2 beamline is planned for the summer shutdown 2020.

Numerical studies for SINBAD-ARES

Two PolariX TDSs are to be installed in the SINBAD-ARES linear accelerator. In this setup, the characterisation of 100 MeV electron bunches with sub-femtosecond resolution will be tested. In 2019, the collaboration ran detailed numerical studies, which show the feasibility of a longitudinal resolution of 200 as for the characterisation of the longitudinal profile of the ARES beam. The reconstruction of the 3D charge distribution of the beam will be possible with a longitudinal resolution of 2 fs. Those studies were recently published [7]. The diagnostics beamline for SINBAD-ARES is to be installed in late fall 2020.

Contact: Barbara Marchetti, barbara.marchetti@desy.de
Richard D'Arcy, richard.darcy@desy.de
Mathias Vogt, mathias.vogt@desy.de
Florian Christie, florian.christie@desy.de

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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. In 2019, LUX demonstrated continuous operation, reliably providing electron beams that supported the day-long generation of spontaneous undulator radiation at few-nanometre wavelength. With the facility fully integrated into the DESY accelerator control system, the correlation of measured laser and electron data enabled the fine-tuning of the machine to improve the quality of the generated electron beams. A detailed analysis provides a better understanding of which laser parameters are responsible for the bulk of residual shot-to-shot energy variations. Currently, LUX is being upgraded to demonstrate first free-electron laser (FEL) gain.

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. Electrons are generated by the interaction of the ultrashort (few 10 fs) pulses of the 200 TW ANGUS high-intensity laser system with a small volume of hydrogen gas. The laser drives a plasma wave, which traps electrons from the plasma background and, in typical operation, accelerates them to 300 MeV energy within only a few millimetres. After generation, the beams are captured by a transport optic, carefully diagnosed and then sent through a miniature in-vacuum undulator to generate spontaneous undulator radiation.

Figure 1

The magnet structure of the FROSTY undulator at LUX, assembled and ready for field measurements

In 2019, the LUX team concentrated on the demonstration of continuous accelerator operation. Several successful campaigns demonstrated extensive runs generating large data sets of 100 000 consecutive shots each. Correlating the laser, electron and X-ray properties yielded a deeper understanding of which laser parameters dominantly cause residual instabilities in the plasma electron beam. These insights provide a crucial guideline for the development and improvement of both the laser and the electron beamline. Furthermore, the steady operation enabled the team to perform high-statistics measurements of important beam properties, such as the emittance, and to set up and live-tune the electron parameters. As a direct consequence, the team was able to enter a new operation regime, which provides 1%-level energy spread beams of sufficient peak current to drive a first FEL experiment.

The goal of this demonstrator, which was proposed by members of the LUX team, is not to reach saturation, but to show that a plasma-accelerated beam can in principle drive FEL amplification. LUX is currently being extended with additional beam optics and a decompression chicane to manipulate the electron phase space and then match it into a dedicated undulator. The undulator, called FROSTY, is an in-vacuum, cryogenically cooled device, which was developed in a close collaboration of Universität Hamburg and Helmholtz-Zentrum Berlin (HZB). The cryogenic cooling increases the on-axis magnetic field and enhances the resistance to radiation damage. Completion of the beamline extension and first experiments are expected in the second half of 2020.

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

In addition to research, sustainability and efficient use of energy are becoming increasingly important topics at DESY, especially in connection with the operation of its large-scale facilities. In 2019, DESY was nominated for the Energy Efficiency Award 2019 for the use of waste heat from its cryogenic plant in the DESY heating network (see News and Events section). The picture shows the heat exchangers in the cryogenic plant feeding the waste heat into the DESY heating network.

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Photographs and graphics
DESY
European XFEL

Gennadiy Bagdasarov, Keldysh Institute of Applied Mathematics; Anthony Gonsalves and Jean-Luc Vay, Berkeley Lab

Werner Bartsch, DESY
Marilyn Chung, Berkeley Lab
Lucid Berlin, DESY
Gesine Born, DESY
Thomas Heinemann, DESY
Heiner Müller-Elsner, DESY
Rüdiger Nehmzow, DESY
Dirk Nölle, DESY

Angel Ferran Pousa, DESY/UHH
Max Trunk, UHH

Spengler Wiescholek Architekten Stadtplaner, WES GmbH Landschaftsarchitekten, Urban Catalyst GmbH; Visualisation: Moka-studio; Aerial image: Matthias Friedel

Office to the President of the Republic of Armenia

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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 978-3-945931-29-5
doi 10.3204/PUBDB-2019-05178

Editing
Klaus Balewski
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 2020

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

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

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