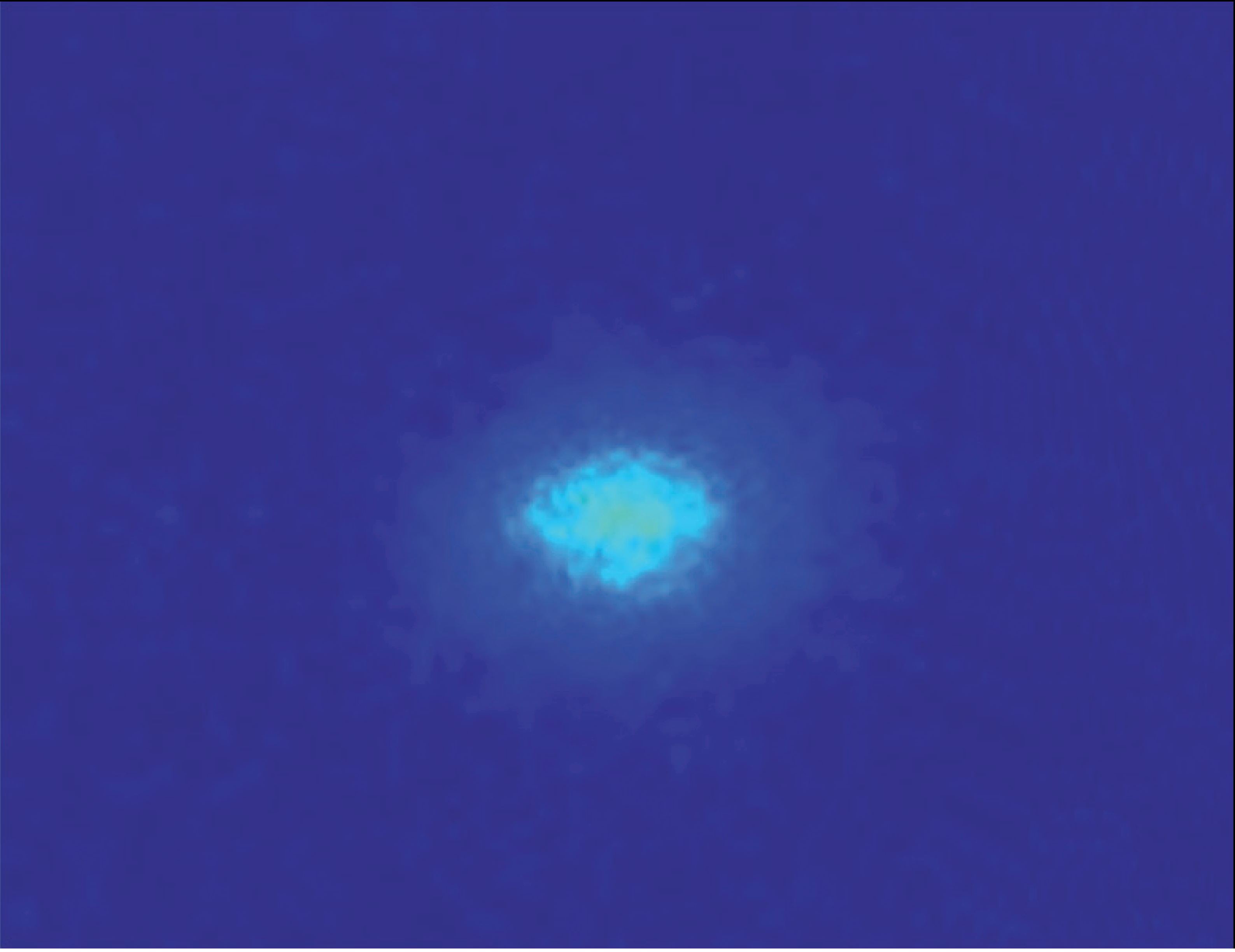

ACCELERATORS 2017.

Highlights and Annual Report

Accelerators | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

Cover

A true highlight of 2017 was the successful commissioning of the European XFEL X-ray laser, including the demonstration of first lasing and providing first laser light to the users. The picture shows the first laser light at the European XFEL at the end of the tunnel.

ACCELERATORS 2017.

Highlights and Annual Report

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The year 2017 at DESY.

Chairman's foreword

Dear Colleagues and Friends of DESY,

The year 2017 was a historical year for accelerator-based research and in particular for photon science in Hamburg. After a short commissioning period, the European XFEL—the world's most modern and powerful X-ray laser facility—produced its first laser light in May, with user operation starting in September. The official inauguration of the international facility on 1 September generated a worldwide echo in the scientific communities and the media.

As the main shareholder of European XFEL, DESY devised the facility and assumed responsibility for the construction and operation of its key component, the 2.1 km long superconducting linear accelerator that drives the X-ray laser. In cooperation with partners from all over the world, we developed the superconducting accelerator technology over the past 20 years and successfully constructed and commissioned the accelerator, which is the longest and most advanced of its kind ever built—a tremendous success that underlines DESY's leading position as one of the world's top accelerator centres. It is now upon our accelerator crew to assure stable operation of the accelerator and upon our X-ray experts to exploit the unique potential of the facility for basic research. I am most curious to see the first breakthrough results emerging from the experiments in the coming years.

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. At DESY, they enable new insights and new approaches to be produced every day. Developing the accelerator technologies and facilities of the future is one of our core competencies, in which we have been excelling since the foundation of DESY almost 60 years ago. Together with the European XFEL, our cutting-edge accelerator-based research light sources FLASH and PETRA III testify to our excellence in this field: The FLASH soft X-ray free-electron laser (FEL) facility is not only a renowned user facility in its own right, but also serves as a pioneering prototype and testing ground for the European XFEL as well as for novel accelerator and FEL concepts. Our PETRA III synchrotron radiation source is one of the world's most brilliant storage-ring-based X-ray sources, attracting thousands of scientific users from around the globe every year.

In 2017, we carried out an in-depth and comprehensive DESY strategy process. The DESY competence teams developed many brilliant ideas, which will enter into the strategy for the coming decade. Most importantly, we were able to identify not only future priorities but also posteriorities. This will render our research centre very robust, enabling it to cope with the future challenges.

Furthering accelerator development is one of the key elements of the DESY 2030 strategy. In particular, we will

upgrade the PETRA III storage ring to an ultralow-emittance facility, enabling us to realise the ultimate 3D X-ray microscope. Named PETRA IV, it will provide images of processes taking place in the nanocosm that will be 100 times more detailed than currently achievable, approaching the limit of what is physically possible. The DESY strategy process clearly positioned PETRA IV as the next large research infrastructure project of the laboratory.

In addition, it devised an ambitious future FEL plan. Together with European XFEL, we plan to comprehensively expand the X-ray laser facility, and we are continuing to develop the required technology, among other things to increase the number of X-ray pulses from 27 000 to up to one million per second.

Another major element of the DESY 2030 strategy is the further development and testing of novel concepts for building compact accelerators in the future. Activities on the campus are already rife in this area. Highlights in 2017 include first X-ray undulator radiation generated by the laser-driven plasma wakefield experiment LUX, which is operated together with the University of Hamburg, installation and testing at the electron-beam-driven plasma wakefield experiment FLASHforward, further electron-beam-driven plasma wakefield experiments at the PITZ photoinjector test facility at DESY in Zeuthen, coordination of the EU-funded multi-GeV laser plasma wakefield acceleration design study EuPRAXIA and preparations for the construction of the SINBAD accelerator R&D infrastructure at DESY in Hamburg.

All in all, the DESY campuses in Hamburg and Zeuthen are developing very dynamically. In Hamburg, DESY is making a strategic handshake with the University of Hamburg, which is planning to relocate its physics and chemistry departments on the Bahrenfeld campus, in a later stage possibly also parts of the biology department. This move will foster novel cooperations and new opportunities for the training of students and young scientists.

I would like to thank all the DESY staff members for their excellent work in the last years, and I am looking forward to the coming years, which will surely be more brilliant than ever.

Helmut Dosch
Chairman of the DESY Board of Directors

Accelerators at DESY.

Introduction

Dear Colleagues and Friends of DESY,

The year 2017 was a year of truly outstanding achievements at DESY as one of the world's leading accelerator centres, especially regarding the European XFEL X-ray laser project. The beam commissioning of the European XFEL accelerator complex, the demonstration of first hard X-ray free-electron laser (FEL) radiation and the provision of first photon beams to users are the most prominent highlights of this remarkably successful period.

In 2016, the completion of the European XFEL accelerator construction, the beginning of its technical commissioning and the successful beam commissioning of the injector had laid the foundation for the progress that was to follow in 2017. The sections of the superconducting linear accelerator were successively put into operation, and by April 2017, most of the radio frequency (RF) sections were active and the electron beam had reached the beam dump after the accelerator tunnel. Transport of the beam through the first undulator line (SASE1) was then quickly established, and after steering optimisation, a clear FEL radiation signal was observed for the first time on 2 May. The first lasing was an unplanned, but most welcome timely match with the concluding meeting of the DESY-led Accelerator Consortium on 4 May at DESY. At that event, the 17 institutes involved in the construction of the accelerator complex reviewed their joint work of the past seven years and celebrated the completion of their mission. All involved DESY staff members together with their colleagues from the collaborating institutes could look with pride and satisfaction on the achievements in one of the largest and most challenging projects in the history of DESY.

During the following months, the beam parameters were further improved, and a photon beam wavelength of 0.13 nm and a pulse energy of up to about 1 mJ were reached, both already close to the European XFEL specification. An electron beam energy of 14.9 GeV was achieved with two RF stations still inactive, which are to be commissioned in 2018. Ramping up the beam intensity has to be done with care to minimise radiation damage risk, and in this initial phase, FEL operation was limited to 30 bunches per accelerator pulse. In machine studies, however, operation with 300 bunches (3 kHz average bunch rate) was already successfully demonstrated. The rapid progress of the beam commissioning was achieved thanks to reliable and well-performing subsystems, including diagnostics and controls, and thanks to the strongly committed and competent operations team. Last but not least, the very open and constructive cooperation between the DESY XFEL team and the colleagues from European XFEL has been – and will continue to be – a crucial component for the achievements at this new world-leading facility.

Much of the success story of the European XFEL accelerator is based on past developments for and experience with the FLASH soft X-ray FEL facility at DESY. FLASH itself had again an excellent year of user operation with high availability and performance. By now, the parallel operation of the two undulator beamlines FLASH1 and FLASH2 has become routine. A refurbishment and improvement programme, supported by additional investment funding, started in 2017, and a few items on the to-do list were already completed. Operation with short bunches (down to single-spike photon pulses) has been further developed and is now being made available to users. The sFLASH seeding experiment produced several new results, including the extraction of detailed and otherwise hardly accessible properties of the electrons using time-resolved measurements with the LOLA deflecting structure, which enables a precise characterisation of the seeded FEL pulse properties. In the course of the DESY strategy process, the mid- and longer-term perspectives for improvements and upgrades at FLASH are being developed and will

Figure 1

Members of the DESY Accelerator Division and their colleagues from DESY and European XFEL gathered in the DESY accelerator control room on the occasion of the first lasing of the European XFEL X-ray laser facility in May 2017.

be further sharpened, taking into account the scientific priorities and boundary conditions regarding available resources.

The PETRA III synchrotron radiation source had a very good operation year, with the highest figure for the availability (98%) since the facility served its first users in 2010. The achievement demonstrates that previous improvements in component and subsystem reliability have paid off. Further efforts are under way to systematically address the reliability challenge and stabilise the availability at such an internationally competitive high level.

Further progress was obtained in the design studies for an upgrade of PETRA towards an ultralow-emittance storage ring (PETRA IV). The challenging task of conceiving a layout with an emittance of <20 pm rad at 6 GeV beam energy and still sufficient dynamic aperture is being addressed using different lattice design approaches. A final design decision on which the further detailed technical layout will be based will be taken after careful investigation and comparison of the different options and is foreseen for the end of 2018 or early 2019. Studies of an improved version of the DESY II synchrotron (DESY IV) have also started, and first preliminary results indicate that the emittance could be reduced by at least one order of magnitude with respect to the present machine, an improvement required for efficient electron injection into the new PETRA IV ring. In parallel to the lattice design and beam dynamics studies, first investigations of magnet, girder, vacuum and RF system concepts were also launched in the technical groups of the Accelerator Division.

Novel accelerator concepts have become a rapidly growing field at DESY. The LUX experiment led by the University of Hamburg demonstrated undulator radiation from an electron beam with an energy of several hundred MeV produced in a laser-driven plasma wakefield. Moreover, a continuous 24 h run showed that the accelerated beam had 98% uptime and was reproducible in energy to a few percent, an important step towards usable beams from plasma accelerators. Much progress was obtained with the installation of the electron-beam-driven plasma wakefield experiment FLASHforward, and a first electron beam was injected into the FLASHforward beamline in the FLASH2 tunnel. At the PITZ photoinjector test facility at DESY in Zeuthen, self-modulation experiments of the electron bunch in a plasma cell were continued. The EU-funded multi-GeV laser plasma wakefield acceleration design study EuPRAXIA, coordinated at DESY, picked up momentum. Preparations and necessary refurbishments for the construction of the SINBAD accelerator R&D infrastructure in the former DORIS building at DESY were completed, and the first components for the ARES linear accelerator were ordered. The research perspectives on plasma acceleration will be strongly boosted by the ATHENA project, for which the final funding decision within the Helmholtz Association is expected for the first half of 2018. The SINBAD infrastructure also integrates the EU-funded AXSIS experiment for THz-driven acceleration as well as the activities at DESY and the University of Hamburg within the ACHIP collaboration for laser-driven microstructure acceleration funded by the Gordon and Betty Moore Foundation.

Enjoy reading more about our exciting accelerator activities on the following pages!

Reinhard Brinkmann
Director of the Accelerator Division

News and events.

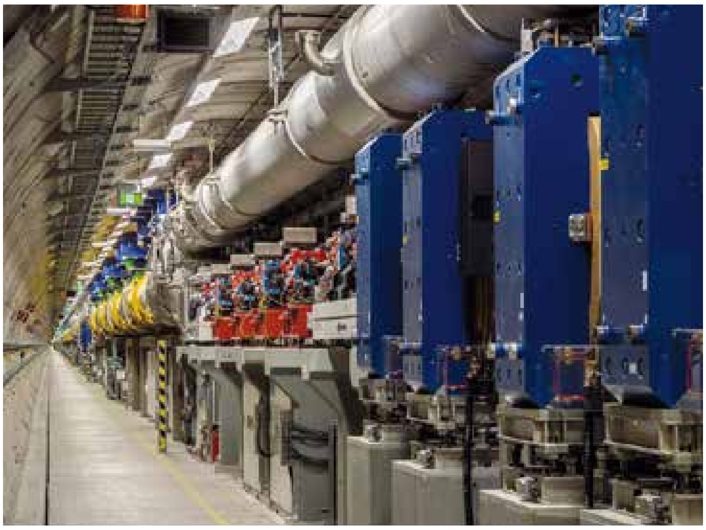
News and events.

A busy year 2017

January

First electrons in European XFEL main accelerator

In January, the European XFEL X-ray laser – the largest and most powerful X-ray free-electron laser in the world – reached an important milestone on the way to its operation phase: The accelerator team guided the first electrons from their source point in the facility's injector into the superconducting main linear accelerator. After passing through the first four accelerator modules and a subsequent section in which the electron bunches are compressed, the particles were captured in an electron dump about 150 m away. As the largest shareholder of the European XFEL, DESY is responsible for the construction and operation of the superconducting linear accelerator driving the X-ray laser.

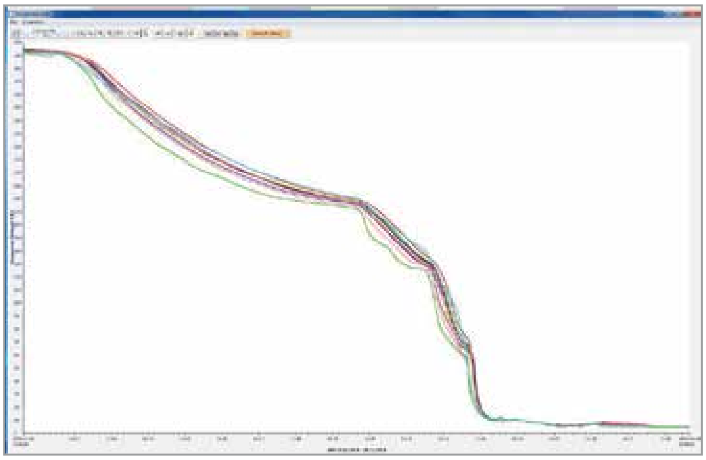


View into the European XFEL accelerator tunnel: Behind a chicane (in front) operating at room temperature, the electrons are guided into the first four superconducting accelerator modules (yellow).

"The first cooling of the accelerator was a critical phase in the commissioning of the European XFEL," said Hans Weise, leader of the Accelerator Consortium responsible for building the accelerator. "The cooling plant team has mastered this through great commitment and much outstanding intuition."

At the beginning of December 2016, the experts began to flush the cryogenic system of the accelerator and fill it with helium. On 28 December, after three weeks at the 4 K (-269°C) mark, the cold compressors were switched on. They lowered the pressure of the helium in the linear accelerator to 30 mbar so it could cool further to 2 K (-271°C, the operational temperature of the accelerator). At the beginning of January 2017, the machine physicists brought the European XFEL injector, which also includes a superconducting segment, back into service. After a successful test operation in summer 2016, the injector had been turned off so that the chicane connecting it to the main accelerator could be built. After a short time, the injector again achieved the beam quality of the test operation in summer, and the team could then direct the first particle beam through the chicane and into the main accelerator.

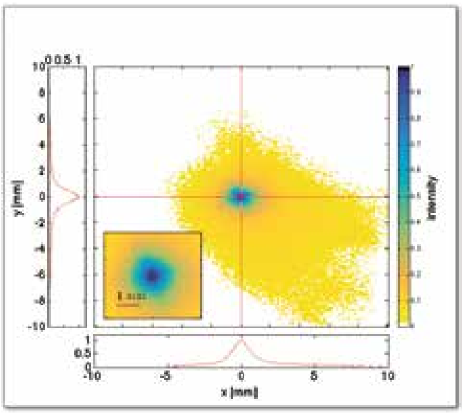
"We now have sufficient control over the pressure and temperature in the superconducting accelerator so we can feed the cavities with the first radio frequency field," Weise said. The 32 cavities in the first four modules were then brought to resonance frequency and fine-tuned to one another so that the particle bunches could be accelerated through them.



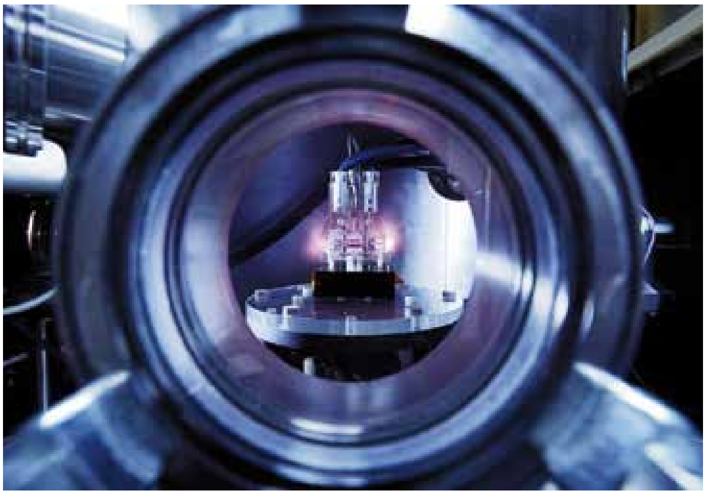
Temperature development in the different sections of the main accelerator during the cool-down phase

FLASHForward accelerates first electron bunches

The plasma accelerator project FLASHForward at DESY's FLASH free-electron laser facility accelerated electron bunches in a plasma cell for the first time. The FLASH-Forward team used a high-power laser to ignite a plasma, in which electrons were accelerated to energies of around 100 MeV within a distance of just a few millimetres. The achievement allowed important preliminary studies for the planned beam-driven plasma experiment.



Spatial distribution of the electron beam accelerated in FLASHForward



Plasma cell in which the FLASHForward scientists accelerated the first electron bunches

The electron bunches accelerated by the laser in the plasma cell had in many respects very similar properties to those the scientists later hope to accelerate with the FLASH beam in FLASHForward. The physicists were thus able to test their special diagnostic instruments before integrating them into FLASH during the summer. The diagnostics of FLASH-Forward have to fulfil some demanding requirements. The team expects having to resolve electron bunches with a charge of just a few picocoulombs – a thousand times less than in the European XFEL X-ray laser – and bunch durations in the femtosecond range. In addition, the instruments must be capable of withstanding the electromagnetic shock that is produced when the plasma is ignited.

The FLASHForward project aims to test plasma wakefield acceleration. The electric fields produced in a plasma can be a thousand times stronger than those in conventional particle accelerators. Researchers all over the world are investigating whether this highly efficient method of particle acceleration can be used to develop extremely compact particle accelerators. In FLASHForward, electron bunches produced by FLASH are to be further accelerated using a laser-generated plasma. To this end, a beamline for electron bunches including an integrated plasma cell was set up alongside the FLASH2 beamline and connected to FLASH in 2017. FLASHForward is funded by grants from the Helmholtz Impulse and Networking Fund and supported by the Alexander von Humboldt Foundation.

Construction of the beamline (left) connecting the FLASHForward experiment to the FLASH accelerator

March

European XFEL accelerator operational

By March, three months after the start of cool-down, DESY had successfully commissioned the superconducting particle accelerator that drives the European XFEL X-ray laser, sending electrons through the complete 2.1 km length of the accelerator tunnel. The accelerator is the key component of the 3.4 km long X-ray laser facility. Its superconducting TESLA technology, which was developed over the past 20 years in an international collaboration led by DESY, will enable the facility's exceptionally high repetition rate of 27 000 X-ray laser flashes per second.

From December 2016 into January 2017, the accelerator was cooled to its operating temperature of 2 K (-271°C). The electron injector and the first two sections of the main accelerator, comprising 18 out of 98 installed accelerator modules, then went into operation. Within these sections, the electron bunches were both accelerated and compressed three times, down to bunch lengths of 10 µm. Finally, the team put the third section of the accelerator with 80 modules into operation.

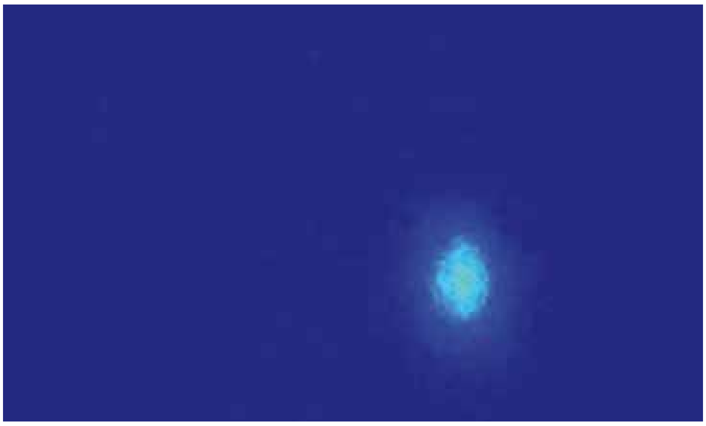
At the end of the accelerator, the electrons reached an energy of 12 GeV, which should increase to up to 17.5 GeV in regular operation. "The energy and other properties of the electron bunches are already within the range where they will be during first user operation", said DESY physicist Winfried Decking, who led the commissioning of the European XFEL accelerator.

View into the 2.1 km long accelerator tunnel of the European XFEL with the yellow superconducting accelerator modules hanging from the ceiling

May

European XFEL generates first laser light

In May, the European XFEL achieved the last major milestone before its official opening: The facility generated its first X-ray laser light. The X-ray pulses had a wavelength of 0.8 nm – about 500 times shorter than that of visible light. At first lasing, the laser had a repetition rate of one pulse per second, which will later increase to 27 000 per second.



First laser light at the European XFEL, recorded by an X-ray detector at the end of the tunnel

"This is an important moment that our partners and we have worked towards for many years," said European XFEL Managing Director Robert Feidenhans'l. "The European XFEL has generated its first X-ray laser light. The facility, to which many countries around the world contributed know-how and components, has passed its first big test with flying colours. The colleagues involved at European XFEL, DESY and our international partners have accomplished outstanding work. This is also a great success for scientific collaboration in Europe and across the world. We can now begin to direct the X-ray flashes with special mirrors through the last tunnel section into the experiment hall, and then step by step start the commissioning of the experiment stations."

"The European X-ray laser has been brought to life!" said DESY Director Helmut Dosch. "The first laser light produced today with the most advanced and most powerful linear accelerator in the world marks the beginning a new era of research in Europe. This worldwide unique high-tech facility was built in record time and within budget. This is an amazing success of science. The European XFEL will provide us with the most detailed images of the molecular structure of new materials and drugs and novel live recordings of biochemical reactions."

In the 2.1 km long accelerator tunnel, the electron bunches were accelerated and prepared for the subsequent generation of X-ray laser light. They then entered a photon tunnel containing a 210 m long undulator, with 17 290 permanent magnets with alternating poles bringing the electrons on a

The undulators generating the bright X-ray light

"slalom" course on which they emitted extremely short-wavelength X-ray radiation. In a process called self-amplified spontaneous emission (SASE), the radiation intensified across the length of the undulator. At first lasing, the X-ray pulses were absorbed and measured shortly before arriving in the underground experiment hall.

The 3.4 km long European XFEL is the largest and most powerful of the five free-electron lasers generating hard X-ray radiation worldwide. With its more than 27 000 pulses per second instead of the previous maximum of 120 per second, an extremely high luminosity and the parallel operation of several instruments, the European XFEL will enable scientists to investigate very small amounts of samples and perform their experiments more quickly. The facility will thus increase the amount of beam time globally available, as the capacity at the other X-ray lasers has been eclipsed by demand and facilities are regularly overbooked.

DESY scientist Winfried Decking explaining operations in the DESY accelerator control room

European XFEL accelerator consortium celebrates completion

As the European XFEL produced its first laser light, the international consortium of 17 research institutes that built the superconducting accelerator of the facility over the past seven years, under the leadership of DESY, celebrated the successful completion of its mission.

"The European XFEL is one of the world's largest accelerator-based research facilities, and the superconducting linear accelerator is the longest and most advanced ever built," said DESY Director Helmut Dosch. "I congratulate all those involved in the research, development and construction of this facility with passion and commitment: the employees of DESY, European XFEL and international partners. They have achieved outstanding results and demonstrated impressively what is possible in international cooperation."

"The 17 research institutions involved in the consortium have done great work under the leadership of DESY in recent years," said European XFEL Managing Director Robert Feidenhans'l. "I thank all colleagues involved for their work, which entailed a great deal of know-how and precision but also much personal commitment. The accelerator is an outstanding example of successful global cooperation, encompassing research institutions, institutes and universities alongside industrial companies in which individual components have been manufactured."

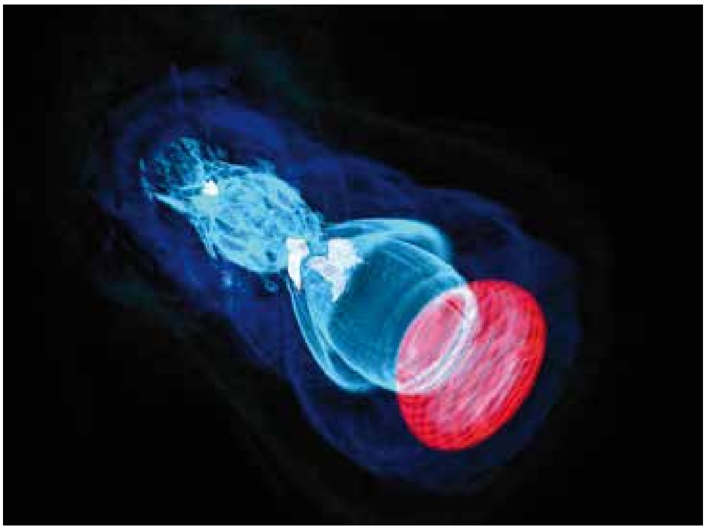
The construction of the linear accelerator had to be meticulously coordinated at the international level. The French project partner CEA in Saclay assembled the modules, which were then comprehensively tested at DESY by staff of the Polish partner institute IFJ-PAN in Kraków before installation of the modules in the accelerator tunnel. Magnets for focusing and steering the electron beam inside the modules came from CIEMAT in Madrid, Spain. The niobium resonators were manufactured by companies in Germany and Italy, supervised by DESY and INFN/LASA in Milano. Russian project partners, such as the Efremov Institute in St. Petersburg and the Budker Institute in Novosibirsk, supplied various parts for the accelerator's vacuum components as well as magnets to steer and focus the electron beam in the non-superconducting, room-temperature sections of the facility.

CNRS in Orsay, France, NCBJ in Świerk and the Wrocław University of Technology, Poland, the Institute for High Energy Physics in Protvino and the Institute for Nuclear Research in Moscow, Russia, the Universidad Politécnica de Madrid in Spain, the Manne Siegbahn Laboratory, the University of Stockholm and the University of Uppsala in Sweden as well as the Paul Scherrer Institute in Switzerland were also involved in the construction.

Periodic modulation tweaks plasma accelerators

A team of scientists from DESY, the Center for Free-Electron Laser Science (CFEL) and the University of Hamburg has come up with an ingenious way of improving plasma accelerators, which are considered promising candidates to become the particle accelerators of the future. The quality of the electron beam these innovative accelerators produce can be substantially improved by adding an oscillating component.

“Plasma accelerators can achieve up to a thousand times higher accelerations than the most cutting-edge machines in use today,” said Reinhard Brinkmann, DESY Director in charge of the Accelerator Division, on whose proposal the study was based. “This makes it possible to build more compact and more powerful devices for a wide range of applications, from fundamental research to medicine. However, the technology is still in its very early experimental stages, and we will have to solve a number of problems before it can be used in applications.”



Simulation of the plasma wave following the laser pulse (red). The electron bunch is visible as a bright patch near the trough of the wave.

In a plasma accelerator, a wave is produced inside a thin capillary containing an electrically charged gas, known as a plasma. This gas could be hydrogen, for example, subjected to extremely intense and short laser pulses. These laser pulses plough their way through the gas as thin disks, wrenching the electrons away from the hydrogen molecules and sweeping them aside. Electrons in the wake of the pulse are accelerated by the positively charged plasma wave in front of them – much like a wakesurfer riding the wave behind a boat.

The acceleration experienced is not the same for all the electrons, however, but depends on their precise position on the wave. Particles that are further forward are accelerated less than those riding further behind. The result is an unfavourably wide spread in the particles’ energies, leading to a similar problem to that encountered when focusing light made up of many different colours. A lens is only ever ideal for a single colour. Similarly, the electrons can only be focused perfectly for a very specific energy. Reducing the energy spread is thus one of the most important problems facing developers of plasma accelerators.

The solution proposed by Reinhard Brinkmann was to allow the electrons to swing to and fro across the trough of the wave. As a result, first one side of the electron bunch is accelerated more, then the other. On average, the two effects balance each other so that all the electrons experience the same acceleration – the energy spread shrinks dramatically. Also, during the process, the signs of the focusing forces alternate. This method of “alternating gradient focusing” is well established in conventional accelerators, allowing them to produce stable particle paths. Apart from leading to a small energy spread, the method also ensures that the beam is very narrowly confined, i.e. has a low emittance.

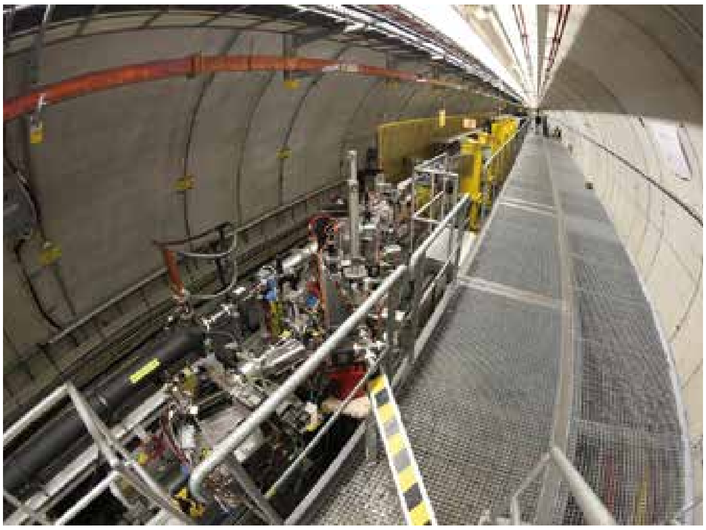
Achieving this is not that simple, however, since the entire plasma wave is just 0.1 mm or so in length, and the electrons cannot simply be moved back and forth in the short time necessary. So the physicists came up with an alternative: Instead of moving the electrons around, the plasma wave itself can be pushed to and fro, which is much easier to control. To do this, the gas-filled capillary must consist of alternating high- and low-density zones, which is achieved by positioning several nozzles along the capillaries, themselves a few millimetres long, and injecting gas through the nozzles. Each jet produces a zone of high-density gas inside the capillaries. Because of the fluctuating density, the wavelength of the plasma wave also fluctuates, so that it shifts with respect to the electrons. As a result, the particles sometimes ride further forward, and sometimes further back on the wave.

The novel principle would thus allow scientists to influence the electron beam on a micrometre scale by modifying macroscopic parameters, such as the pressure in the hydrogen inlet. In this way, the researchers hope to achieve direct control over the accelerating field, which would be a crucial step towards the development of plasma accelerators.

The scientists carried out detailed simulations of their method on the JURECA supercomputer at the Forschungszentrum Jülich in Germany, among others. However, a practical test still needed to be conducted. In a first step, the physicists planned to try out the concept on the experimental laser plasma accelerator LUX and influence the electrons directly by specifically controlling the plasma density in the capillaries. LUX is operated jointly by DESY and the University of Hamburg as part of their LAOLA collaboration.

Profiling FLASH electron bunches on a femtosecond scale

The success of free-electron lasers (FELs) relies on the capability of analysing and controlling ultrarelativistic electron beams on femtosecond time scales. One major challenge is to extract tomographic electron slice parameters for each bunch instead of projected electron beam properties. Scientists from DESY, the University of Hamburg and Michigan State University have developed a method to derive the slice emittance from snapshots of electron bunches with femtosecond resolution.



The seeding area of FLASH

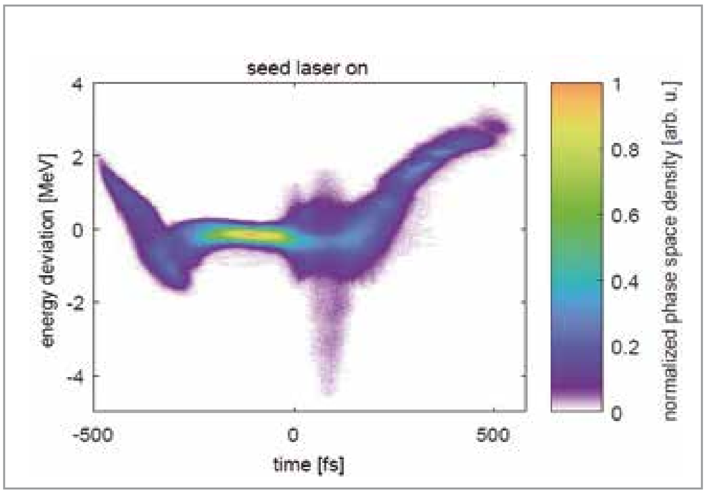
In DESY's FLASH FEL facility, ultrashort high-brilliance soft X-ray pulses are generated in an undulator by accelerated electron bunches less than 100 µm long. While synchrotron radiation sources work in a very similar way, FELs make use of a further phenomenon: During self-amplified spontaneous emission (SASE), different parts of the electron bunch organise themselves into thin microbunches at a distance equivalent to the wavelength of the emitted radiation. Several parts of the bunch undergo this process with slightly different wavelengths and phases, leading to a spiky structure of the spectrum and thus to photon pulses whose properties differ slightly from pulse to pulse. To improve the spectral properties, the scientists use a technique called seeding, based on the interaction of the relativistic electron bunches with external seed laser pulses, to arrange the electrons into microbunches even before the radiation is generated.

The power profile of the emitted photon pulse can be reconstructed in a non-invasive way by measuring the electron bunch after lasing has taken place. A radio frequency (RF) deflector maps the arrival time of the electrons onto their vertical position on a screen, yielding a time profile of the bunch. Behind the RF deflector, a dipole spectrometer maps the energy of the electrons onto their horizontal position on the screen. Overall, the particle energy along the electron bunch can thus be temporally resolved. From these data, the researchers determine how much energy the electrons are losing through light generation in various parts of the bunch, which finally enables them to reconstruct the longitudinal profile of the generated photon pulse.

This method allows the scientists not only to monitor the radiation power profile of the seeded FEL pulse, but also to map the emittance of electron slices within the bunch it was radiated from. It turns out that confined regions of the electron bunch can be seeded, i.e. stimulated to lase, very efficiently, while others only show a moderate amount or even no generated radiation at all.

The reason for the non-uniform performance in different parts of the electron bunch can be traced back to its local slice properties by superimposing the electron bunch with a seed pulse that only covers a short part of the bunch, stimulating this part to emit coherent light. Monitoring the time–energy profile of bunches stimulated in this way reveals the performance of the radiation process of single bunch slices. The measurements confirmed the reconstruction of the electron slice quality parameters and the lasing behaviour predicted by calculations.

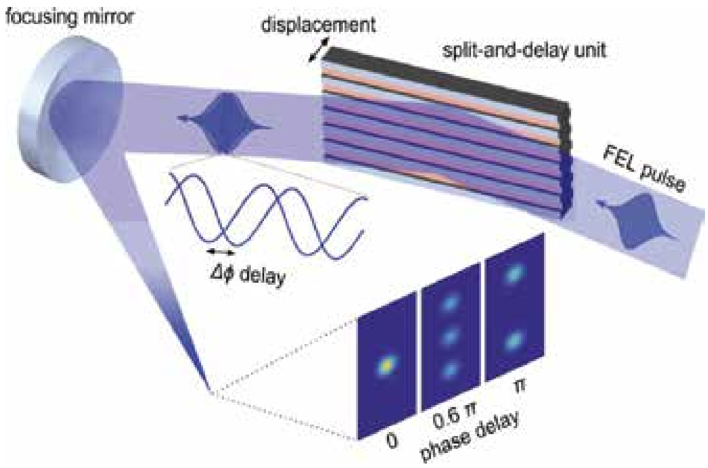
All in all, essential slice quality parameters, such as electron energy, energy spread and emittance, can thus be measured on the fly with a temporal resolution of only a few femtoseconds on electrons moving at close to the speed of light. These measurements enable the prediction of the peak power of the radiated FEL pulse. The seed pulse then serves as a microscopic probe that locally stimulates the FEL process in a longitudinal section of the electron bunch and validates the predictions.



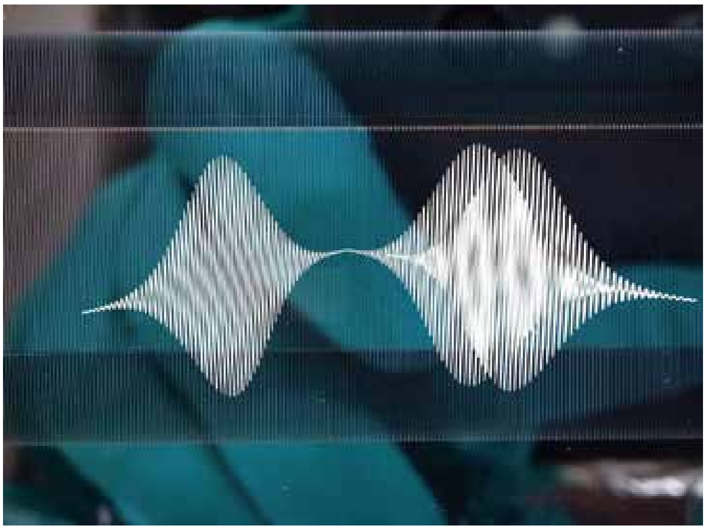
The screenshot shows the electron energy as a function of electron position (measured in femtoseconds) in the electron bunch. The colour codes the amount of electrons in the region. The spike towards lower energies in the middle of the bunch is the trace left in the electron bunch by the seeded radiation process.

Double flashes with attosecond precision

Phase-sensitive measurements using phase-controlled pulses are important to gain insight into light–matter interactions. Although phase control is an established technique in optics, the soft X-rays generated by DESY's FLASH facility oscillate a hundred times faster than visible light, requiring a hundred times better precision. Using pulse pairs created with a smart split-and-delay unit, a team of scientists led by DESY has demonstrated attosecond phase control and interferometric autocorrelation at FLASH. This successful transfer of a powerful optical method towards short wavelengths paves the way towards using advanced non-linear methodologies even at partially coherent free-electron lasers (FELs) that rely on self-amplified spontaneous emission (SASE).



Scheme of the experimental setup: An incoming X-ray pulse is doubled by a split-and-delay unit, and the resulting delayed double pulse is focused onto a sample.



The lamellar mirror splits the incoming X-ray pulse into two parts. The part reflected by the lower lamellae has a longer flight path, resulting in a delay that can be adjusted with attosecond precision.

At the heart of any atomistic understanding of complex functionality such as chemical bond formation is the ultrafast motion of electrons, dictated by the laws of quantum mechanics. In particular, information on the phase evolution of a wave packet, which describes electronic and/or nuclear structural changes, holds the key for control of the wave packet in space and time. In optics, direct phase information of the propagating light wave is derived by interferometric techniques. In the last decade, analogous methodologies have been developed to derive similar information on ultrafast electron wave packet dynamics in atoms, molecules, clusters and solid-state materials.

Prerequisites for these types of experiments, which are pursued at the Hamburg Centre for Ultrafast Imaging (CUI), are phase stability of the light source and the ability to control the temporal phase of the light wave on the corresponding sub-cycle attosecond time scale. In measurements at FLASH, the scientists now demonstrated attosecond phase control of FEL light waves by generating two phase-locked replicas of SASE pulses and observing their interference.

The exit slit with variable width of the FLASH beamline was used to select a single SASE mode with small spectral bandwidth. The radiation field passing the slit thus had a high degree of spatial and temporal coherence. A reflective split-and-delay unit (SDU) with two interleaved lamellar gratings then split the wavefront of the incoming pulse uniformly across the beam profile, creating two pulse replicas with variable delay. In contrast to a conventional half-mirror SDU, the lamellar geometry provides collinear propagation of both pulse replicas and thus constant phase difference across the beam profile, enabling phase-resolved autocorrelation signals to be recorded with maximum contrast.

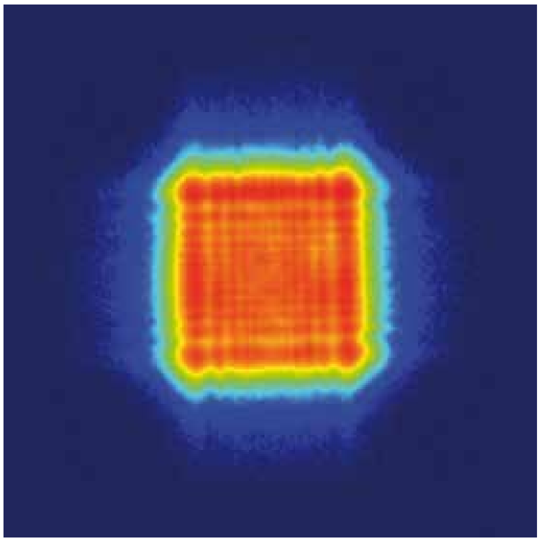
When focusing the beam e.g. on a xenon gas target, the generated spatial ion distribution depends on the relative phase (attosecond delay) between the radiation fields, i.e. their path length difference induced in the SDU. The question how precisely one can control the phase is thus transformed into how precisely one can measure the delay for each FEL pulse pair. In the present experiment, the exact auto-correlation delay was derived by simultaneously imaging the surface topography of the SDU with nanometre precision using an in-vacuum white-light interferometer.

The study opens the door for high-contrast time-domain interferometry in non-linear phase-sensitive spectroscopic studies even at partially coherent SASE sources. Full control over the relative temporal phase in FEL pulse replicas provides opportunities to trace energy and charge migration in systems of increasing complexity with unprecedented spatial and temporal resolution, making the local electronic structure and dynamics accessible and controllable.

June

European XFEL starts operation phase

The European XFEL X-ray laser entered its operation phase at the end of June. Over the previous weeks, engineers and scientists at European XFEL and DESY had worked to ensure that the first two experiment stations were equipped with instruments and that the X-ray beam met the parameters needed to start performing experiments. On 30 June, the European XFEL Council, the highest governing organ of European XFEL, agreed that the conditions for the start of operation were satisfied and consequently released the funds designated for the operation phase. First experiments were started for commissioning purposes.



One of the first diffraction patterns from the European XFEL, recorded through an approximately millimetre-wide square gap at the SPB/SFX instrument. The evenly spaced, grid-like lines of the pattern show areas of interference resulting from diffraction through the gap, demonstrating that the radiation has very high-quality laserlike properties.

Martin Meedom Nielsen, Chairman of the European XFEL Council said: “The member states are very pleased and excited about the great achievements made at the European XFEL, which mean we can now start the operation phase of this world-leading X-ray science facility. This major milestone has been eagerly awaited by the international user community, who are busily preparing for experiments that will break new scientific ground. I would like to express my sincere appreciation to the European XFEL management and staff, and to the accelerator consortium led by DESY, for their dedication and hard work.”

“Since successfully producing the first laser light in May, DESY and European XFEL have continued to make significant progress. I am very pleased that we have met the requirements to start research at the X-ray laser,” said European XFEL Managing Director Robert Feidenhans’l.

To qualify for the transition from commissioning to operation phase, the facility had to meet a number of predetermined technical requirements. The pulses of the X-ray laser at a wavelength of maximally 0.2 nm had to reach a high intensity and remain stable. In addition, the two experiment stations of the first beamline were to be sufficiently equipped so that first scientific experiments could be carried out.

Other developments since producing the first laser light in May included successfully guiding the X-ray beam via special mirrors into the experiment hutches and commissioning a number of highly specialised instruments for characterising the properties of the X-ray beam. Directly after the first X-ray beam was guided into the hutches on 23 June, teams at European XFEL started with the characterisation of the beam and experiments for the commissioning of the instruments.

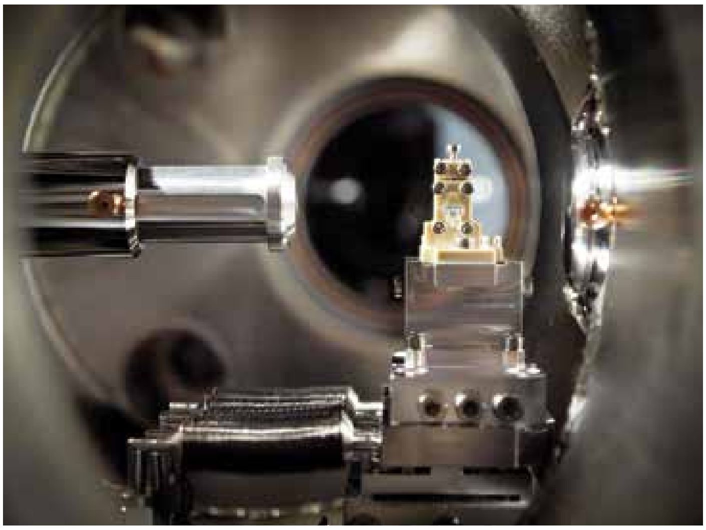
With a wavelength of initially 0.2 nm and the required peak light intensity, the X-ray radiation already allowed the recording of atomic details. First studies were possible at two experiment stations: the Femtosecond X-Ray Experiments (FXE) instrument, designed for research into extremely fast processes, and the Single Particles, Clusters, and Biomolecules and Serial Femtosecond Crystallography (SPB/SFX) instrument, designed for studying biomolecules and biological structures.

In the medium term, scientists from around the world will be able to use six experiment stations at the X-ray laser facility, enabling new views of the structure and fast processes of the nanocosmos. Applications range from structural biology, chemistry, physics and materials science through environmental and energy research to explorations of conditions such as those found inside planets.

August

LUX plasma accelerator produces first X-rays

For the first time, a plasma accelerator at DESY has produced X-rays. The LUX installation generated ultrashort pulses of radiation with a wavelength of 9 nm, corresponding to soft X-rays – an important milestone in the development of novel accelerator-driven X-ray sources. LUX is part of the LAOLA collaboration between DESY and the University of Hamburg. The development of the next generation of compact accelerators is an essential pillar of the strategy for the future at the DESY research campus.



The plasma cell (centre) accelerating the electrons at LUX

In plasma acceleration, a pulsed laser or beam of high-energy particles creates a plasma wave inside a fine capillary. Electrons collect in the wake of each pulse and are then accelerated by the positively charged plasma wave in front of them. Although the technology is still at an experimental stage, physicists hope that it will ultimately lead to a new generation of high-performance particle accelerators with unique properties for a range of applications.

LUX uses a laser with a power of 200 TW that fires ultrashort pulses into hydrogen gas, creating a plasma in which electrons are accelerated to an energy of up to 600 MeV within a distance of just a few millimetres, the length of the plasma cell. This is more energy than is supplied by the 70 m long linear pre-accelerator LINAC II at DESY.

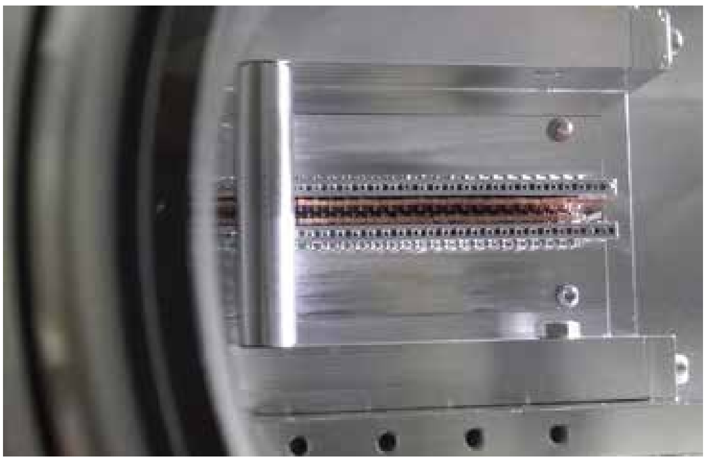
In summer 2017, the LUX team used the electrons from the plasma cell to produce X-rays for the first time. To this end, the short bunches of electrons were sent down a 50 cm long undulator, causing them to emit energy in the form of X-rays. The same principle is used at the large X-ray sources at DESY, such as the storage ring PETRA III or the European XFEL X-ray laser. However, these were the first X-rays generated on the DESY campus from a plasma accelerator – a feat that only a few research groups worldwide have achieved so far.

Although LUX does not achieve the same brightness as the large facilities, it will allow research using X-rays to expand to new areas in the future. For one thing, LUX produces extremely short X-ray pulses: As the plasma wave produced by LUX is just 0.01 mm long, the electron bunches cannot be longer than that either, meaning that the X-ray pulses last no more than 3 to 5 fs. This allows them to capture extremely rapid processes taking place in the world of atoms and molecules.

In addition, the principle behind the technique implies that the X-ray pulse and the pulse of optical laser light that creates the plasma wave are synchronised extremely precisely. Many experiments use an optical laser pulse to trigger a reaction, whose progress is then studied by scrutinising it using very precisely delayed X-ray pulses. LUX will be able to achieve synchronisations between the X-ray pulse and the optical laser pulse to within a single femtosecond.

The next step will be to further optimise the plasma accelerator and undulator so as to produce higher-energy electrons and brighter X-rays with a shorter wavelength. In the end, the scientists hope to improve the setup to a point where it reaches a self-amplifying laser process, turning the facility into a compact X-ray laser.

A number of different groups at the University of Hamburg and DESY are collaborating within LAOLA, with a view to exploring pioneering new concepts for accelerators. Another important partner is the ELI Beamlines Project in Prague, Czech Republic, which supported the project with additional manpower and resources. The concept of plasma acceleration is being studied at DESY by various projects pursuing different goals.



The undulator of LUX in which the fast electrons emit X-ray radiation

September

European XFEL inaugurated

The European XFEL X-ray laser was officially inaugurated on 1 September in an international event with musical and enlightening highlights. Research ministers and other prominent guests from across Europe joined the European XFEL Managing Directors to officially start the research operation of the facility with the first two experiments.

Speakers at the inauguration of the European XFEL cut the ribbon in front of the hutches for the SPB/SFX and FXE instruments, officially opening the facility.

Johanna Wanka, German Federal Minister of Education and Research, stressed the importance of the new international research facility: “The establishment of the European XFEL has created a unique cutting-edge research facility, which promises groundbreaking insights into the nanocosmos. The foundations for tomorrow’s innovations are laid by today’s basic research.”

European XFEL Managing Director Robert Feidenhans’l said: “We are proud to be opening the strongest X-ray laser in the world and start doing science together with our user community. The European XFEL is a unique facility that will open the door to new areas of science.”

DESY Director Helmut Dosch said: “What started as a vision and was set in motion at DESY more than 20 years ago has now become a reality: the world’s most powerful laser for X-ray light. Now scientists from around the world will conduct research at this most advanced high-speed camera for the nanocosmos in the world, and I wish them many exciting results – both fundamental and revolutionary.”

Feidenhans’l then greeted the first external users of the facility on stage. Scientists from across the world will come to European XFEL to do their research by applying for access to the instruments via a selection process. Beam time of generally one or two weeks per group and experiment is awarded according to the scientific excellence of the submitted proposals.

European XFEL scientists then informed the guests about the experiments at the first two instruments in the underground experiment hall: the Femtosecond X-Ray Experiments (FXE) instrument, which enables the study of fast reactions and is able to record molecular movies, and the Single Particles, Clusters, and Biomolecules and Serial Femtosecond Crystallography (SPB/SFX) instrument, developed for investigating the structure and transformation of biomolecules and other biological particles, such as viruses and cell components.

At the FXE instrument, scientists explained how the European XFEL’s first snapshots of a chemical reaction would be made. The reaction was to be triggered by an ultrashort pulse of visible light, while an X-ray flash, timed to reach the sample after the reaction is triggered, recorded the state of the molecule at that moment in time. During this first experiment, reacting molecules were to be studied in a watery environment in order to learn more about the influence of water on the reaction itself.

At the SPB/SFX instrument, the guests pressed a button to start the first ever experiment at the European XFEL, aimed at determining the structure of a biomolecule. In this model experiment, the structure was already known, allowing the researchers for example to check whether the X-ray laser and the instruments were optimally coordinated.

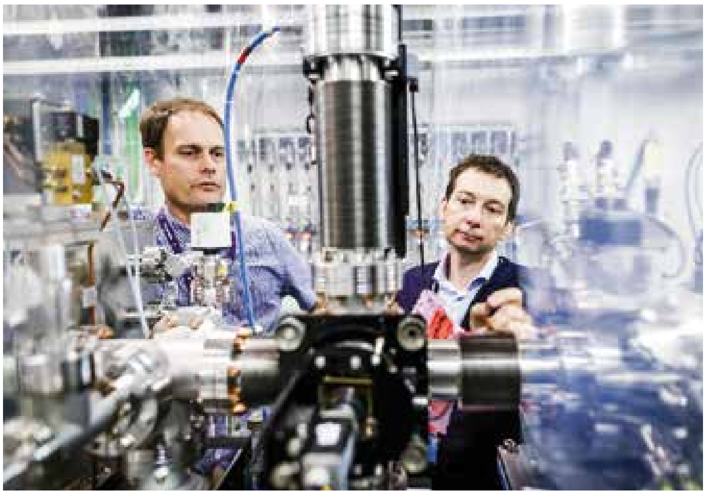
Every evening from 28 August to 3 September, laser light beams could be seen shining across Hamburg from the Elbphilharmonie concert hall, the University of Hamburg, HAW Hamburg, the Hamburg Ministry of Science, Research and Equalities, and the Planetarium to European XFEL in Schenefeld, as the City of Hamburg welcomed the international research facility to the metropolitan area.

Laser installation shining from the Elbphilharmonie concert hall to Schenefeld to welcome the European XFEL

September

First experiments at the European XFEL

A DESY-led team of researchers successfully started the first scientific experiments at the European XFEL X-ray laser. The aim of the team led by Anton Barty and Henry Chapman from the Center for Free-Electron Laser Science (CFEL) at DESY was to decode the atomic structure of different biomolecules. They used the Single Particles, Clusters, and Biomolecules and Serial Femtosecond Crystallography (SPB/SFX) instrument, which is designed to gain a better understanding of the shape and function of biomolecules, such as proteins, that are otherwise difficult and sometimes impossible to study.



Anton Barty (left) and Henry Chapman (right) at the SPB/SFX instrument of the European XFEL

During the early phase, the scientists carefully calibrated and tuned their instruments in order to learn how to use the new facility. Tuning began with the sample delivery to the X-ray beam. The X-ray flashes of the European XFEL follow one another at the extremely fast pace of 220 ns – which means that in less than a microsecond, four flashes arrive at the experiment station. The samples consist of tiny protein crystals that reveal information about their three-dimensional structure when X-rayed. However, for each crystal, this is a one-shot-only experiment, as the intense X-ray flashes vaporise the crystals almost immediately. So a new crystal has to be delivered into the X-ray beam every 220 ns.

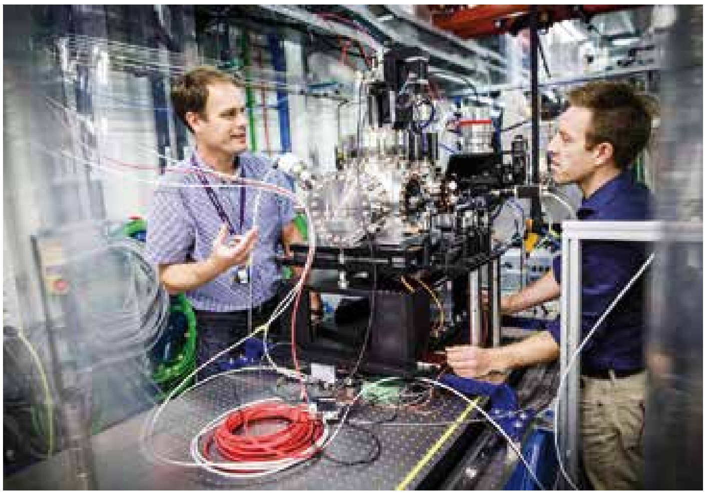
The detector too must be fast enough to record diffraction patterns from the protein crystals every 220 ns, which means obtaining four images in less than a microsecond. To accomplish this feat, the European XFEL is equipped with the fastest X-ray cameras in the world, which have been tailor-made for the individual experiment stations. The one used at the SPB/SFX instrument was designed and produced by an international consortium led by DESY's photon science detector group.

After calibration and tuning, the scientists planned to move on into uncharted territory, exposing proteins of unknown structure to the intense X-ray flashes.

In parallel to the SPB/SFX instrument, scientific experiments also started at the Femtosecond X-Ray Experiments (FXE) instrument, which is designed to create molecular movies showing the progression of chemical reactions. This will for example help to improve our understanding of how catalysts work or how plants convert light into usable chemical energy.

"The instruments and the supporting teams have made great progress in the recent weeks and months," said European XFEL Managing Director Robert Feidenhans'l. "Together with our first users, we will now do the first real commissioning experiments and collect valuable scientific data. At the same time, we will continue to further advance our facility and concentrate on further improving the integration and stability of the instrumentation."

European XFEL is an international research facility with currently 11 shareholders from 11 countries. With a share of 58 per cent, DESY is the main shareholder. Leading an international consortium, DESY has developed and built the superconducting linear accelerator at the heart of the X-ray laser and is also operating it. The vision of an X-ray laser took off at DESY two decades ago. The initial plans for the European XFEL were developed at DESY, where the prototype of all X-ray free-electron lasers worldwide, FLASH, started scientific operation in 2005.



Anton Barty (left) and European XFEL beamline scientist Richard Bean (right) discussing the experiment schedule at the SPB/SFX instrument

November

European LEAPS consortium launched in Brussels

A new strategic alliance between European accelerator-based photon sources was forged in Brussels in November. The League of European Accelerator-based Photon Sources (LEAPS) aims to offer a step change in European cooperation, through a common vision of promoting scientific excellence to solve global challenges and boost European competitiveness and integration. Representatives of 16 organisations from across Europe approved the Consortium Declaration in the presence of Robert-Jan Smits, Director General for Research and Innovation (RTD) at the European Commission.

Sixteen institutions from across Europe joined to form LEAPS.

“Light from particle accelerators plays a crucial role in studies carried out in virtually every area of the natural sciences,” said DESY Director Helmut Dosch, who put forward the idea of LEAPS and is also the chairman of the consortium. “National facilities have so far mostly been developed and operated independently of each other, yet they have much in common, because most of their scientific objectives are very similar.”

The new form of collaboration is to ensure that the large European research infrastructures can be used even more efficiently in the future and that major scientific and technological challenges can be tackled together. This will not only benefit fundamental and applied research, but also industrial research carried out at accelerator-based photon sources.

Such photon sources essentially fall into one of two categories: Synchrotrons, such as DESY’s PETRA III storage ring, produce a narrow, very brilliant beam of radiation with a range of different wavelengths, from infrared to X-rays, depending on the intended application. It can be used, for example, to examine the structure of biomolecules, to peer inside solar cells while they are operating or to reveal paintings hidden beneath other coats of paint. Free-electron lasers, such as the European XFEL, generate laserlike, extremely intense pulses of radiation that can be very brief. They can be used to take snapshots of very rapid processes occurring in the nanocosm, such as filming the precise sequence of events during (bio-)chemical reactions. Both types of photon source are unique research tools allowing experiments to be conducted that could not be carried out by any other means.

Sixteen institutions from ten European countries have joined to form LEAPS, serving a community of over 24 000 scientists from a wide range of fields. The new consortium is to encourage the exchange of ideas between its member institutions and with users, so as to speed up the development of the technology and to promote the necessary political environment for the long-term operation of the facilities. Also, it intends to strengthen the collaboration with industrial stakeholders and other scientific institutions, to pursue and advance the strategic development of key technologies in the field, to facilitate access to the photon sources, to promote education and to communicate to the general public the importance of the research photon sources for society.

December

Innovation Award on Synchrotron Radiation for DESY

A DESY team was awarded the Innovation Award on Synchrotron Radiation by the Association of Friends of Helmholtz-Zentrum Berlin (HZB). The award was presented during the ninth BER II and BESSY II user meeting in December 2017. Mikhail Yurkov, Markus Tischer, Bart Faatz, Evgeny Schneidmiller and Siegfried Schreiber received the award for their pioneering work on “innovative applications of gap-tunable undulators with integrated phase shifters in SASE X-ray FELs” at FLASH2.

Mikhail Yurkov, Markus Tischer, Bart Faatz, Evgeny Schneidmiller and Siegfried Schreiber (from left to right)

Accelerator operation and construction.

PETRA III.

User operation and challenges ahead

In March 2017, DESY's PETRA III synchrotron radiation source took up operation again after a shutdown period that started on 22 December 2016 and was mainly used to install three undulators and further components for the beamlines P22, P23 and P24 in the Ada Yonath experimental hall (extension hall East). Regular user operation resumed on 10 April 2017 after a short commissioning period of only four weeks. A four-week-long summer shutdown was used to install a photon extraction vacuum chamber and further components for the beamline P21 in the Ada Yonath hall. In 2017, a total of 4969 h of synchrotron radiation beam time was delivered to the users. During the next winter shutdown, an in-vacuum undulator will be installed, which will become operational in 2018.

User operation

During the two-month-long winter shutdown 2016/17, which ended in March 2017, three undulators and further front-end components were installed for the beamlines P22, P23 and P24 in the Ada Yonath experimental hall (Fig. 1). All accelerator components in the tunnel had been successfully realigned to correct movements of the components due to the progressive settlement of the new hall. Furthermore, the deflecting dipoles between the undulators in the Ada Yonath and Paul P. Ewald experimental halls received a new coil configuration, which improved the fringe field of the magnets. Thanks to essential efforts of the technical groups involved, all activities could be finished on schedule. Regular user operation resumed on 10 April 2017 after a short commissioning period of only four weeks.

A four-week-long summer shutdown was used to install a photon extraction vacuum chamber and further components for the beamline P21 in the Ada Yonath hall, which will become operational in 2018. After a short start-up period, regular user operation resumed on 17 August and continued until 22 December. The necessary maintenance was done in three dedicated service weeks distributed over the year and additionally during the summer shutdown period. On Wednesdays, user operation was interrupted by weekly regular maintenance, machine development activities and test runs for about 24 h.

Figure 1

Three new undulators for beamlines P22, P23 and P24 were installed in 2017 in the Ada Yonath experimental hall.

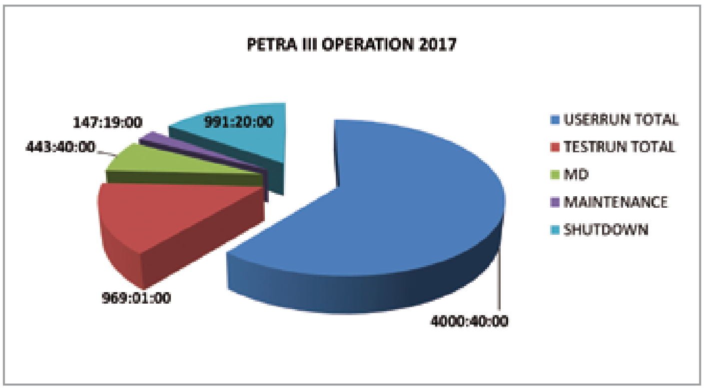


Figure 2

Distribution of the different machine states during the run period 2017

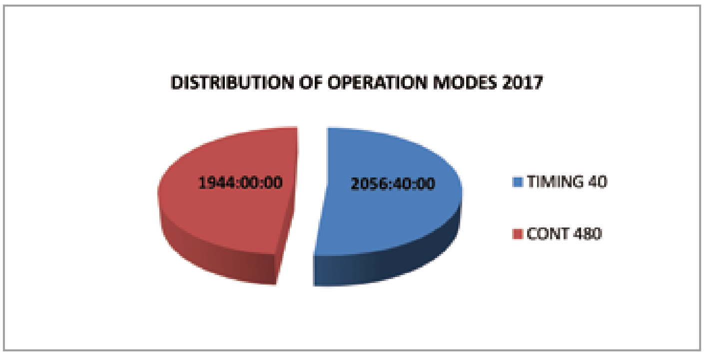


Figure 3

Distribution of the different operation modes in 2017

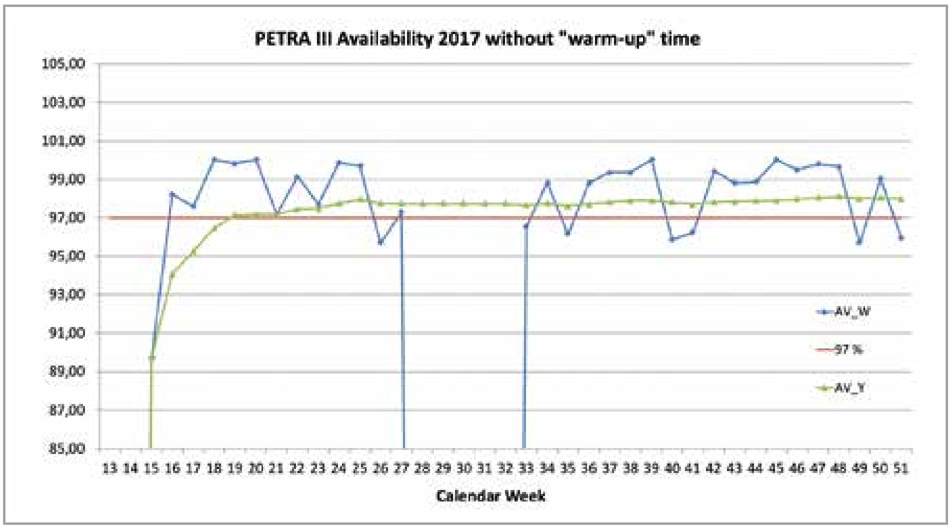


Figure 4

Availability in 2017 using the new metrics. The blue curve shows the weekly average, the green curve the yearly average. The red line indicates an availability of 97%.

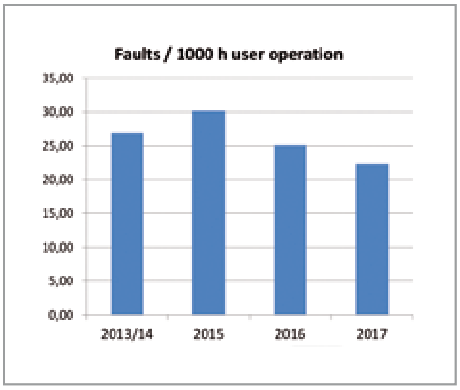


Figure 5

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

The distribution of the different machine states in 2017 is shown in Fig. 2. In total, 4000 h were scheduled for the user run. In addition, 969 h of test run time were made available to users.

During user runs, the storage ring was operated in two distinct modes, characterised by their bunch spacing. In the “continuous mode”, 100 mA were filled in 480 evenly distributed bunches, corresponding to 16 ns bunch spacing. 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. The detailed distribution of the operation modes in 2017 is shown in Fig. 3. For beam operation in the timing mode, very good bunch purity is required. Unwanted satellite bunches were routinely cleared using the multibunch feedback system.

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 2017, the weekly availability reached 100% for several weeks of the year. At the end of the user run, the average availability turned out to be 96.9%, which is almost 2% higher than the availability in the previous year. This availability statics is based on a metrics that includes a “warm-up” time after each fault of up to one hour or one downtime. If the warm-up time is not included, one obtains an availability of 98% (Fig. 4, green line). The availability calculated without warm-up time represents the availability of the beam in the storage ring and is in agreement with internationally used metrics. In all future publications, this definition of the availability will be used to make the data for PETRA III easily comparable to those for other light sources.

The number of radio frequency (RF) trips could be further reduced following recommendations of the availability review meeting, which was held in May 2016. In the summer shutdown 2017, another pair of plungers of an RF cavity was exchanged. The average MTBF at the end of the year was 42 h, which is better than in the previous year. Nevertheless, the MTBF of PETRA III is still not in line with that of other world-leading facilities and needs further improvement.

Challenges ahead

The number of faults normalised to 1000 h of user operation decreased in the last three years (Fig. 5). This number is also shown for the run period 2013/14, which was followed by a one-year-long shutdown to implement the PETRA III extension project. Since the availability review in 2016, several improvements have been implemented to decrease the number of faults.

This development led to the good availability of 98% in 2017. One of the challenges for the next run period in 2018 will be to maintain or even improve the availability of PETRA III. To achieve this goal, an internal review process will be implemented, which will guarantee a good root cause analysis of all faults during the user run. One of the challenges will be to address a multitude of minor randomly occurring faults, which seem to be uncorrelated to just a few technical causes.

During the winter shutdown 2017/18, it is foreseen to install two new undulators for the beamline P21 in the Ada Yonath hall. One of the undulators will be a four-metre-long in-vacuum undulator with a period length of 21.2 mm and a gap of 7 mm. This will be the first in-vacuum undulator installed in the PETRA III storage ring, and it will be a challenge to operate the device for the first time in 2018. This will be only possible with a major effort from all the technical groups involved.

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FLASH.

New schemes put into operation

FLASH2, the second undulator beamline of DESY's FLASH free-electron laser (FEL) facility, is now routinely in operation. Even though pump–probe lasers will only be ready in 2018, many user experiments have already been performed at the new beamline. In addition to the 4495 h of user runs at FLASH1, 1899 h were used at FLASH2 in 2017 for user experiments and methods and instrumentation development. A new feature – single-spike self-amplified spontaneous emission (SASE) – is increasingly requested for user experiments at both beamlines. Several experiments used these ultrashort pulses to measure ultrafast dynamics that would otherwise have been impossible to study. Other new lasing schemes being developed are double pulses with variable delay, double pulses for THz with fixed delay and various new lasing schemes using the FLASH2 variable-gap undulators, such as frequency doubling, harmonic lasing and reverse undulator tapering.

Highlights

For three years now, FLASH has been operating with two undulator beamlines in parallel as a tandem delivering SASE radiation to two experimental halls, called "Albert Einstein" and "Kai Siegbahn".

A third electron beamline, FLASH3, is being set up for the beam-driven plasma acceleration experiment FLASHForward. Major components were installed during the shutdowns in 2017, and first tests with beam were already performed. The next step will be the installation of the plasma chamber in the winter shutdown 2017/18.

The technique to produce single-spike SASE radiation is now mature enough to be offered to users. In 2016 already, an experiment measured an unexpected fast demagnetisation in nickel. The study was made possible by single SASE spikes providing a time resolution better than 10 fs.

On the request of a user experiment, the FLASH group developed a method to produce double SASE pulses with variable delay in steps of 9 ns up to 1 μs. The experiment used a delay of 221.5 ns and 470 ns to measure the recovery time of liquid jets after they were hit by an FEL pulse. The double pulses were produced by using two injector lasers simultaneously with a variable delay between them. Most beam diagnostics using 108 MHz analogue-to-digital converters (ADCs) are able to resolve the double pulses. By an appropriate gating of the two gas monitor detectors (GMDs), the SASE energy could also be measured for both pulses at the same time (Fig. 1).

To extend the options for experiments using THz radiation, a pulse doubler designed to compensate the path difference of SASE and THz radiation of 21.5 ns was brought into operation. Using a split and delay unit installed at Laser 1, two electron bunches were sent along the FLASH1 beamline with a delay of 21.5 ns (28 RF buckets). Pulse 1 produced THz radiation and no SASE, while Pulse 2 was optimised for SASE. In this first study, the FLASH group already demonstrated the suppression of the SASE pulse energy of Pulse 1 down to a level of 16% of Pulse 2. With an electro-optical encoding scheme, the group was also able to measure the time jitter between the two pulses to be less than 20 fs, limited by the resolution of the measurement.

The group of the seeding experiment sFLASH continued their experimental programme. Among others, they demonstrated the characterisation of fully coherent photon pulses in the extreme-ultraviolet (XUV) spectral range. Two different methods were used: the transverse deflecting RF structure LOLA to extract longitudinally resolved information about the

Figure 1

Double SASE pulses with variable delay. Laser 2 produces the first SASE pulse train, measured with GMD-1. Laser 1 generates the second SASE pulse train, measured with GMD-2, with a delay of 221.5 ns. Note that the SASE energy fluctuation due to its stochastic nature is different for both pulses.

seeded electron bunches, and a time-resolved characterisation of the seeded FEL pulses using the THz streaking technique, giving access to information on the optical phase.

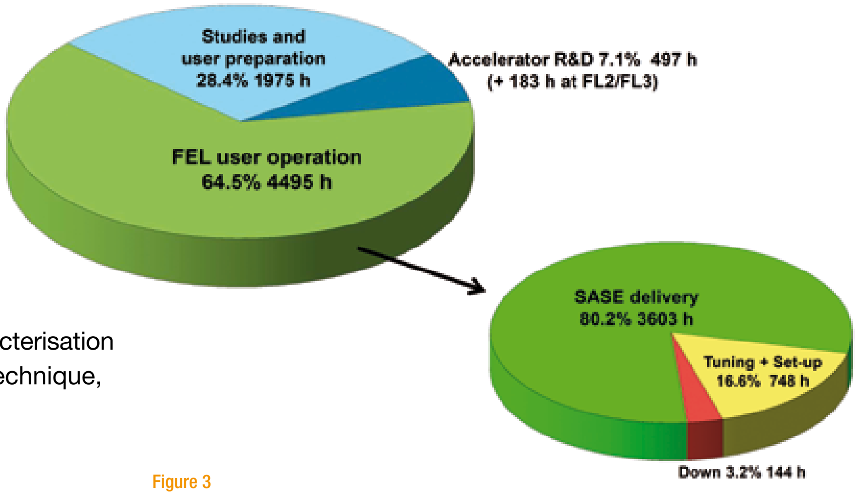

Figure 3

FLASH1 operation statistics in 2017

FLASH1 operation

In 2017, FLASH1 was operated for 6967 h. This was a bit less than in 2016 since the summer shutdown was longer than usual. Important security maintenance work on the cryogenic systems required a warm-up of the cold accelerator modules, extending the shutdown by two more weeks than originally planned. In addition, installation work was carried out for the FLASHForward experiment (Fig. 2), mainly on the bifurcation from the FLASH2 beamline to the new FLASH3 beamline. With this, FLASHForward is now ready to receive beam.

Figure 2

FLASH2 undulator beamline (left) and FLASHForward beamline under construction (right) in summer 2017

Almost 65% of the beam time was devoted to user experiments, 28% to FLASH studies, beamline commissioning and user run preparation, while 7% was reserved for open accelerator R&D. SASE radiation was delivered to users for 3603 h, i.e. 80% of the user beam time. A considerable amount of time (17%) was used for tuning the machine to specific user needs; the downtime due to component failures was only 3% (Fig. 3).

FLASH2 operation

FLASH2 user operation continued to be routine. A total of 1899 h was devoted to user operation, with 1327 h dedicated to user experiments and 572 h to methods and instrumentation developments. The remaining beam time was used for undulator beamline and photon diagnostics commissioning as well as various novel and innovative experiments with the variable-gap undulators, such as harmonic lasing self-seeding FEL, frequency doubling, and afterburner schemes.

FLASH refurbishment

After more than 13 years of operation, many FLASH components are reaching the end of their lifetime. An extensive refurbishment programme was therefore launched, not only to replace old hardware, but also to improve its performance. As an example, after the refurbishment of the beam loss monitors and the toroid systems, new electronics were installed during the summer 2017 shutdown for most beam position monitors (BPMs). The charge resolution improved to 0.2 pC. The position resolution of most BPMs improved by a considerable amount to better than 2 µm. The beam charge and position can now be measured for very small charges as well – a feature that is important for single-spike operation. The installation of new electronics for the arrival time monitors is delayed to summer 2018. Other ongoing projects are new interlock electronics for the RF couplers, vacuum system, RF stations and screen stations. Large projects include the refurbishment of two cryomodules, a new injector laser system, a deflecting X-band structure for FLASH2 and a DELTA-type undulator for circularly polarised SASE radiation.

FLASH 2020+

Within the framework of the DESY strategy process, study groups were launched to develop a long-term upgrade scheme for FLASH. On 25–27 September 2017, more than 120 participants attended a workshop on the “Future of Science at FLASH” at DESY. The workshop focused on key scientific challenges that could be solved in the future beyond 2020 with high-repetition-rate XUV and soft X-ray facilities. Based on the discussions, the community came up with parameters for a “dream” facility, which include 100 kHz continuous-wave operation, fundamental wavelength up to the oxygen K-edge, flexible pump–probe schemes (THz to XUV), few-femtosecond and sub-femtosecond Fourier-limited pulses as well as variable polarisation. On this base, the FLASH strategy will be refined further.

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PITZ.

Accelerator R&D and applications

Throughout 2017, the PITZ photoinjector facility at DESY in Zeuthen was mostly operated at the nominal operation parameters of the radio frequency photoelectron source (RF gun) for the European XFEL X-ray laser (10 Hz, 650 µs, 60 MV/m). Gun 4.6, which had been in use at PITZ since March 2016, was dismounted in October 2017 and shipped to Hamburg for installation in the European XFEL injector by the end of the year.

Laser systems for flexible laser beam shaping

In 2017, three different photocathode laser systems were in operation at PITZ. The long-used, very flexible photocathode laser system from the Max Born Institute (MBI) in Berlin was used to generate laser pulses with diverse shapes for several experiments, e.g. Gaussian shapes for emittance measurements, flat-top shapes for experiments with dielectric-lined waveguides, comb-like shapes for THz studies and double triangular shapes for experiments with the plasma cell. The second laser system from the Institute of Applied Physics (IAP) in Nizhny Novgorod, Russia, was used to generate quasi-ellipsoidal laser pulses for first electron beam studies. A spatial light modulator (SLM) mask was tuned to obtain a ~10 ps FWHM long laser pulse, and electron beam properties were measured (Fig. 1).

Higher stability is expected from an upgrade of the IAP system by combining a commercial front end with a simplified, more robust optics layout. A 1 MHz solid-state Yb:KGW PHAROS laser from Light Conversion was delivered in April and tested in the lab. Its synchronisation with the PITZ master oscillator was established with the help of colleagues from the DESY machine beam control (MSK) group in Hamburg. Electron bunches were successfully produced and characterised. In future, this system will be used in parallel to the MBI system to further develop the generation of 3D ellipsoidal laser pulses with SLMs and volume Bragg gratings.

Plasma experiments with a gas discharge cell

After the first successful results on beam-driven plasma wakefield experiments in 2016, the experimental programme at PITZ continued in 2017. Activities included investigations on acceleration with a high transformer ratio (the ratio between maximum accelerating field experienced by a witness beam and maximum decelerating field experienced by the drive beam) and more detailed studies on the self-modulation of electron bunches longer than the plasma wavelength. A low-pressure argon gas discharge plasma cell was developed and installed at the PITZ beamline to conduct these measurements (Fig. 2).

The implementation of a special bypass optics in the MBI laser system allowed the generation of a witness bunch with variable delay. In this way, transformer ratios exceeding 5 were observed – the highest value ever measured in a plasma wakefield accelerator so far. In addition, self-modulation was shown at plasma densities higher than originally planned.

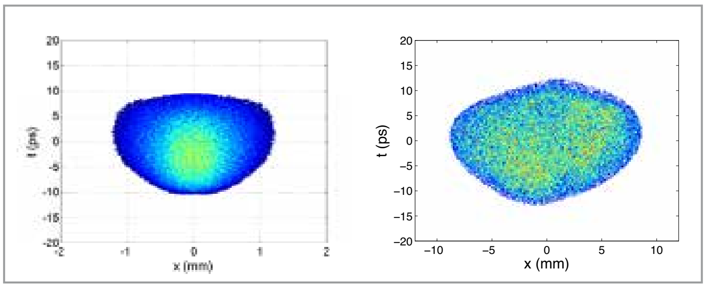

Figure 1

Simulated (left) and measured (right) electron beam distributions using a 3D ellipsoidal laser pulse shape. The simulation parameters are adapted to the measurement conditions; the bunch charge is 500 pC.

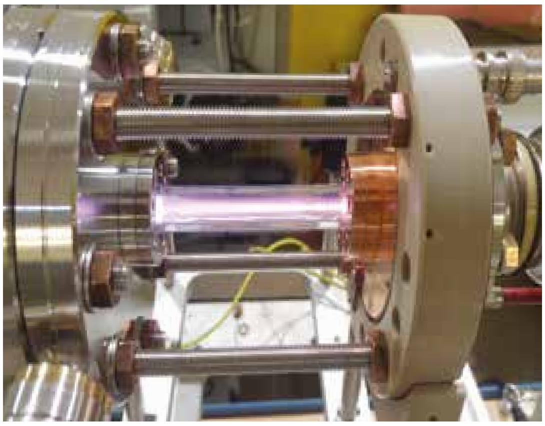

Figure 2

Newly developed gas discharge plasma cell at PITZ

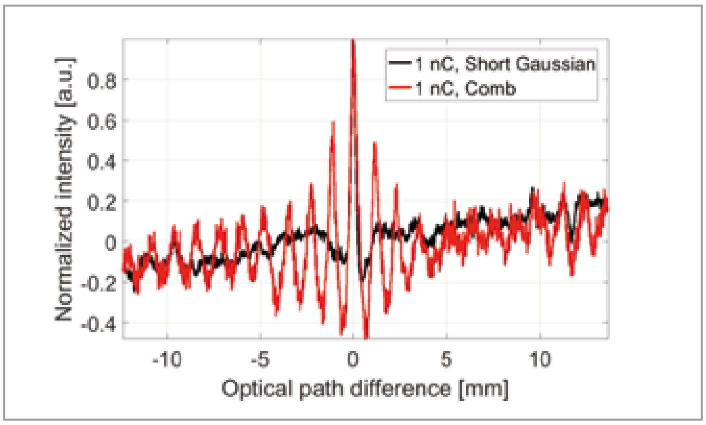

Figure 3

THz signals obtained from the Michelson interferometer

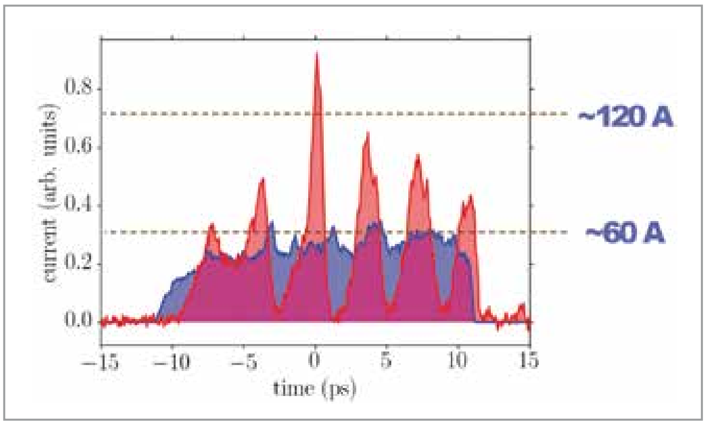

Figure 4

Current profile of the electron beam after the deflecting cavity with (red trace) and without (blue trace) the DLW

New experiments are being prepared for 2018 with an upgraded lithium plasma cell that will allow online adjustment of the plasma channel length. The goal of the experiments will be to experimentally prove that the self-modulation instability is indeed the reason for the measured electron beam modulations.

First THz CTR measurement

A reduced copy of PITZ in combination with a THz self-amplified spontaneous emission (SASE) undulator has been proposed as a tuneable accelerator-based THz source for pump–probe experiments at the European XFEL [1]. Complementing older measurements with 4 nC beams, the PITZ group used the flexibility of the MBI photocathode laser system to generate short bunches as well as electron bunches with a current profile modulation (so-called comb beams).

First THz radiation measurements using coherent transition radiation (CTR) from a specially designed screen station were performed (Fig. 3).

Ballistic bunching with dielectric-lined waveguides

Dielectric-lined waveguides (DLW) from collaborators at CFEL and Fermilab were installed in the PITZ low-energy section. A 6.5 MeV electron beam with 1.1 nC bunch charge was sent through the DLW. The beam's self-wakefields inside the DLW generated a microbunch structure by ballistic bunching. This pattern was frozen by acceleration in the subsequent booster cavity and characterised with a transverse deflecting structure (Fig. 4).

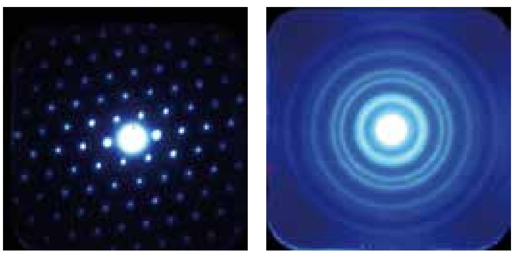

Figure 5

Diffraction patterns recorded at PITZ for single-crystal WS_2 (from FHI) and polycrystal Au (from MBI)

MeV electron diffraction tests with bunch trains

In August 2017, the PITZ group carried out first static electron diffraction experiments with low-charge (0.3 pC), ~2 ps short pulses at 4 MeV beam energy. Diffraction patterns with very high signal-to-noise ratio of thin (<100 nm) samples from collaborators in Berlin (MBI, Fritz Haber Institute) were successfully recorded. Some of the obtained images are displayed in Fig. 5.

Further gun developments at PITZ

After sending Gun 4.6 to Hamburg, the PITZ group is currently preparing a new gun setup using Gun 4.5. The RF feed of this gun will be equipped with a new T-combiner of adjusted length and two Thales windows at optimised positions. Conditioning of the new gun cavity will start in early spring 2018. The technical design of Gun 5 (Fig. 6), the next generation of pulsed guns, was finished in 2017, and its production started.

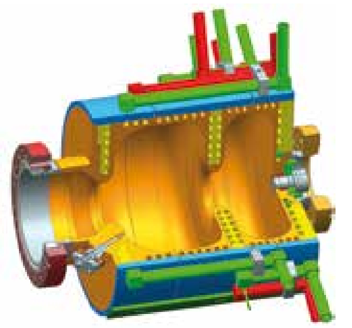

Figure 6

The next generation of pulsed RF guns: Gun 5

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References:

[1] E. Schneidmiller et al., "Tunable IR/THz source for pump-probe experiment at European XFEL", in Proc. FEL2012, Nara, Japan, pp. 503–506 (2012)

European XFEL.

From commissioning to early operation

The accelerator complex of the European XFEL X-ray free-electron laser consists of an electron injector system including bunch compressors, a 17.5 GeV superconducting linear accelerator, a beam distribution and transport system through the undulators and finally the beam dumps. In 2017, the accelerator was commissioned together with the beam distribution through the SASE1 and SASE3 undulators, leading to first observation of self-amplified spontaneous emission (SASE) on 2 May and early user operation at 9.3 keV photon energy, i.e. 0.13 nm wavelength, starting in September. This remarkable success was achieved thanks to the dedicated work of DESY, its collaboration partners in the Accelerator Consortium and the European XFEL groups responsible for the photon systems.

Commissioning of the European XFEL accelerator began in December 2016 with the start of the cool-down of the complete cryogenic system. The first electron beam was injected into the main linear accelerator in January 2017, and by March bunches with a sufficient beam quality to allow lasing were accelerated to 12 GeV and stopped in a beam dump after the 2 km long accelerator. After passing the beam through the SASE1 undulator, first lasing at 0.9 nm photon wavelength was observed on 2 May (Fig. 1). Further improvements to the electron beam quality and alignment led to lasing at 0.2 nm on 24 May. More than 90% of the installed accelerator modules are now in radio frequency (RF) operation, with effective accelerating gradients reaching the expected performance in fully commissioned RF stations.

Cryogenic system

The European XFEL cryogenic system consists of two overhauled strings of the helium cryoplant for the former HERA collider, a new distribution box and transition line to the European XFEL accelerator entrance shaft, cold compressors to reach 2 K, further distribution boxes to distribute the helium towards the injector and finally the long uninterrupted cryostring of the linear accelerator together with its transfer and bypass lines.

Cool-down of the linear accelerator from room temperature to 4 K was achieved in December 2016, with no cold leaks occurring. Start-up of the cold compressors enabled the start of accelerator commissioning at 2 K at the beginning of January 2017. Regulation loops were optimised in the following weeks, until the pressure of the 2 K helium circuit could be kept constant well below the requirement of ±1%. Most remarkable is that this stability can also be maintained during fast changes of the cryogenic load, as they do occur for instance during a sudden shutdown of the accelerator RF. In such a case, inner system heaters immediately take over the RF heat load.

Beamline commissioning

The European XFEL injector had been commissioned independently in 2016 in parallel to the ongoing accelerator installation in the remaining tunnels. Within this six-month commissioning period, most of the design parameters of the injector could be reached or even exceeded.

After the cool-down of the complete accelerator, the injector was recommissioned with fixed bunch charge, and first electrons could be injected into the main accelerator tunnel directly after authority approval was granted in mid-January 2017.

The commissioning effort was planned as a series of sequential steps with the general goal to establish beam transport to subsequent sections as soon as possible.

Beamline commissioning was performed in parallel to the low-level RF (LLRF) commissioning, with the first electron beam transported to the beam dump after the linear accelerator by the end of February. Trajectory response measurements proved very useful in validating the optics model and were possible right from day one thanks to the excellent performance of the beam position monitor (BPM) system. Other diagnostic devices such as screens, toroids, beam loss monitors and dark-current monitors were also available immediately. The BPM resolution exceeds expectations, with sub-micrometre resolution for the cavity BPMs.

Figure 1

Members of the DESY-led European XFEL Accelerator Consortium, consisting of CEA/IRFU (Saclay, France), CNRS/IN2P3 (Orsay, France), DESY (Hamburg and Zeuthen, Germany), INFN-LASA (Milano, Italy), NCBJ (Świerk, Poland), WUT (Wrocław, Poland), IFJ-PAN (Kraków, Poland), IHEP (Protvino, Russia), NIIEFA (St. Petersburg, Russia), BINP (Novosibirsk, Russia), INR (Moscow, Russia), CIEMAT (Madrid, Spain), UPM (Madrid, Spain), SU (Stockholm, Sweden), UU (Uppsala, Sweden) and PSI (Villigen, Switzerland), celebrate the completion of the accelerator complex and the successful initial commissioning on 2 May 2017.

Linear accelerator commissioning

The front-end electronics for LLRF and high-power RF as well as beam diagnostics, vacuum and cryo control are installed in shielded racks in the tunnel. The newly developed MTCA.4 standard is used throughout the installation. About 250 crates in the tunnel benefit from the enhanced remote monitoring and maintenance capabilities, thus reducing the need for time-consuming on-the-spot interventions to a minimum.

The LLRF commissioning was given highest priority. For each of the RF stations, a sequence of steps had to be performed. Frequency tuning, RF signal checks, coupler tuning, coarse power-based calibration and closed-loop operation were achieved without beam, and after establishing beam transport (typical 30 bunches, 500 pC), cavity phasing and beam-based calibration followed. While the first RF station in the linear accelerator section L1 needed one week of commissioning, the three stations in L2 could be handed over to operations after another week. Work in L3 then progressed in parallel on all 15 available stations. The possibility to time-shift the RF pulse of the stations with respect to each other allowed the parallel operation of the stations on or off the beam and thus simultaneous beam commissioning.

The phase and amplitude stability was measured within the regulation loop to be better than 0.01° and 0.01%, respectively. Preliminary beam energy jitter measurements gave an upper limit for the RMS relative energy jitter of 10^{-4} after the linear accelerator.

As of December 2017, 22 out of 24 installed RF stations are commissioned and reach about 80% of the gradient limit obtained from previous module test results. It is expected that further fine-tuning of the regulation loops will increase this value in the future. The maximum energy reached so far with all available stations on the beam is 14.9 GeV.

First lasing and user operation

After obtaining the operation permission for the “northern branch” of the beam distribution system on 26 April, the first electron beam was guided through the 1 km long beam transport line to the SASE1 undulator the next day. At long photon wavelengths, the expected FEL gain length is on the order of a few metres, thus exponential gain would be expected even without a properly aligned undulator trajectory. After some empirical tuning of the compression and the undulator trajectory, first lasing of SASE1 at a wavelength of about 0.9 nm was observed on 2 May.

Further steps to achieve lasing at shorter wavelengths included beam-based alignment and more systematic tuning of longitudinal and transverse bunch properties, leading to lasing at 0.2 nm on 24 May. Photon systems commissioning by the European XFEL commissioning team started with the availability of first photons, and the SASE1 photon beam was guided towards the experimental hutches on 21 June.

User operation started at a wavelength of 0.13 nm on 14 September. Seven user blocks of five days each had been scheduled, and towards the last user blocks, the European XFEL accelerator delivered SASE radiation with an intensity of 800 µJ during well over 90% of the scheduled time.

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Highlights · New technology · Developments.

High-gradient operation in continuous-wave mode.

Superconducting radio frequency results from the cryomodule test bench

Operating superconducting radio frequency (SRF) cavities in continuous-waveform (CW) or long-pulse (LP) mode offers interesting possibilities for beam acceleration. However, it also entails a new set of challenges compared to pulsed-operation SRF linear accelerators, such as the ones driving the European XFEL and FLASH X-ray laser facilities. The cryomodule test bench (CMTB) at DESY offers the opportunity to conduct CW tests on a European XFEL pre-series cryomodule (XM-3), pushing the limits in terms of cavity loaded quality factor and accelerating gradient. This article provides an insight into the results obtained in 2017 in terms of accelerating-field regulation performance. During these tests, the cavities were operated at bandwidths as narrow as 12 Hz in CW, making them very sensitive to any external mechanical disturbances. The article also explains some details on the techniques used to suppress microphonics.

Benefits and challenges of CW operation

While pulsed accelerators such as the ones driving the European XFEL or FLASH have a duty factor of around 1% (i.e. the SRF cavities are charged to accelerate beam only 1 ms every tenth of a second), CW accelerators such as LCLS-II at SLAC in the USA benefit from a continuous RF field to accelerate beam, allowing for relaxed beam injection patterns and simplified detection schemes on the experimental side.

Having RF on all the time comes at a cost, however. First, for the European XFEL series production, the dynamic heat load is limited to 20 W per cryomodule. Second, in their current design, the fundamental input power couplers can sustain a maximum of 2 kW average power, above which overheating could cause permanent damage. These two limitations put an upper bound on the gradient that can be achieved in CW operation. This limit can be increased by operating in LP mode, i.e. with duty factors in the 10–50% range.

Furthermore, CW operation requires an increase of the cavity loaded quality factor (Q_L) to optimise the input-power-to-gradient efficiency. As a side effect, the cavity bandwidth is reduced, making the cavity more sensitive to external mechanical disturbances such as microphonics or helium bath pressure fluctuations. Finally, strong hysteresis behaviour in the cavity tuning as a function of gradient results in so-called ponderomotive oscillations, which introduce a complex non-linear coupling between the accelerating field and the resonance control feedback algorithms.

European XFEL pre-series cryomodule at CMTB

The European XFEL pre-series cryomodule XM-3 is currently installed at CMTB. This module offers many interesting characteristics since it comprises a mix of large- and fine-grain SRF cavities, some of which can sustain accelerating fields in excess of 40 MV/m. XM-3 has demonstrated an unloaded quality factor (Q_0) of up to 4.3×10^{10}, making it a strong candidate for CW studies since the dynamic heat load is inversely proportional to Q_0. Furthermore, the warm parts of the XM-3 couplers were recently modified to shift the coupling tuning range towards higher Q_L (up to 1.1×10^8, corresponding to a cavity half bandwidth of 6 Hz) in order to investigate the challenges of narrow-bandwidth, high-gradient CW operation.

Vector sum, RF and piezo feedback

CMTB is also equipped with two independent low-level radio frequency (LLRF) systems, allowing for single-cavity or vector sum control of the accelerating field in CW, LP and short-pulse mode. Both systems are performing cavity resonance control using piezoelectric actuator feedback. The RF feedback guarantees the stability of the accelerating field (typical requirements are 0.01% and 0.01° in amplitude and phase, respectively), while the piezo feedback aims at keeping the cavity on resonance, compensating the detuning induced by Lorentz forces or microphonics. Operating a cryomodule in vector sum mode adds a layer of complexity, since the behaviour of individual cavities (detuning, ponderomotive oscillations, etc.) influences the behaviour of all the cavities in the vector sum, compromising the regulation performance of the cryomodule.

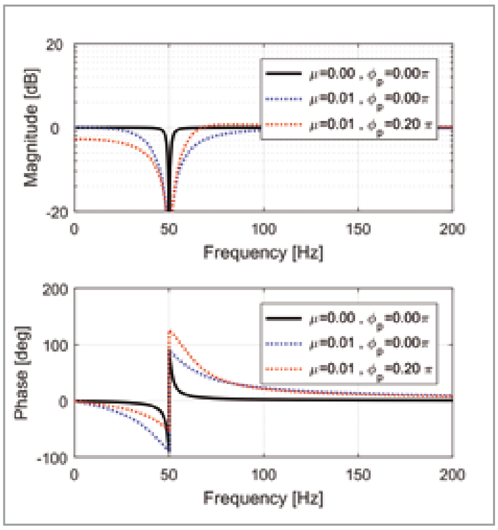

Figure 1
ANC transfer function with reference frequency of 50 Hz and various adaptation speeds (μ) and phase delays (ϕ)

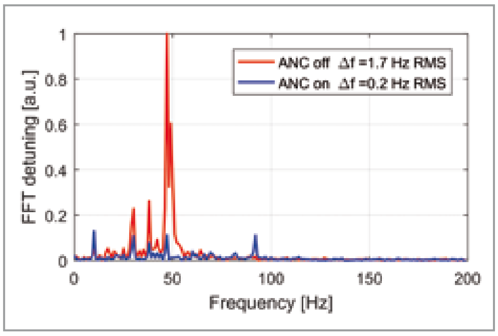

Figure 2

Detuning measurements with ANC algorithm enabled (blue) and disabled (red)

Disturbance rejection using active noise control

Adaptive algorithms are commonly used in active noise and vibration control (ANC) to compensate microphonics-induced detuning. ANC algorithms typically require a reference signal specific to each disturbance. By taking advantage of the fact that the microphonic noise measured on the cavities is narrow-bandwidth, the reference signal can be generated as a sine wave digitally synthesised on the main LLRF controller board. The ANC algorithm adjusts coefficients iteratively in order to track changes in the amplitude and phase of the disturbances. The coefficient adaptation is based on detuning information estimated from the RF signals.

The main advantage of this method is its simplicity. Identification of the cavity mechanical modes is not required to run the algorithm. Instead, the method relies on only three parameters for each disturbance: frequency of the disturbance, adaptation speed and phase delay. The first parameter can be taken directly from the fast Fourier transform spectrum of the error signal, while the second and third can be set manually or automatically using optimisation methods. The ANC algorithm then iteratively adapts the amplitude and phase of the piezo control signal. A properly configured ANC algorithm acts as a notch filter with its centre frequency equal to the reference signal, while its bandwidth is set by the adaptation speed parameter, as shown in Fig. 1.

The algorithm was successfully tested in CW operation at CMTB, together with a conventional integrator feedback, compensating for low-frequency disturbances below 5 Hz. The current ANC implementation allows the compensation of up to four disturbance frequencies for each cavity. As illustrated in Fig. 2, the use of ANC reduced the cavity detuning well below 1 Hz RMS. Two reference signals were used for the tests, at frequencies of 30 Hz and 49 Hz, respectively.

Field regulation in vector sum operation

The accelerating-field regulation performance was evaluated for eight cavities (single module) controlled as a vector sum. Due to several boundary conditions (limitation in Q_L range and high radiation level for high-gradient operation), the operating parameters listed in Table 1 were chosen.

Parameter	C1	C2	C3	C4	C5	C6	C7	C8
E_{acc} [MV/m]	16	16	8	16	16	16	11	11
Q_L [x10^7]	6	6	1.4	6	6	6	2.5	2.5

Table 1: Individual cavity settings for vector sum test

The amplitude and phase regulation level achieved during the study met the European XFEL specifications of 0.01% and 0.01°, respectively. Figure 3 shows the RMS amplitude stability (dA/A) over 1.5 h. The best results in phase were around 0.009°.

The vector sum field stability was guaranteed by the RF feedback, while the resonance control of individual cavities was achieved using an integral feedback together with ANC filters acting on the cavity piezos (set to suppress 31 Hz oscillations).

Field regulation in single-cavity operation

Single-cavity studies pursued two objectives. The first goal was to push towards higher gradients (above 20 MV/m) for a constant Q_L. The second goal was to push towards higher Q_L for a gradient set point of 16 MV/m. Due to its high-gradient potential, Cavity 3 in XM-3 was used for the first goal. An amplitude and phase regulation of dA/A = 0.019% and dP = 0.014°, respectively, was achieved for a maximum gradient of 23.5 MV/m in CW – still a factor of 2 away from the target specifications. RF and piezo feedback along with ANC set to suppress 31 Hz and 49 Hz were used. In the second single-cavity study, Cavity 4 was chosen due to its high Q_L tuning range. In this study, Q_L was set to 8.2x10^7 (corresponding to a half bandwidth of ~8 Hz). The achieved performance was dA/A = 0.015% and dP = 0.017°.

Conclusion

Both studies have confirmed the potential of the current systems to operate in CW mode (without significant hardware modification with respect to short-pulse operation), under various conditions and with very encouraging performance results. The algorithms used for RF field and resonance control are still under development. Further improvement of the results presented in this report is to be expected.

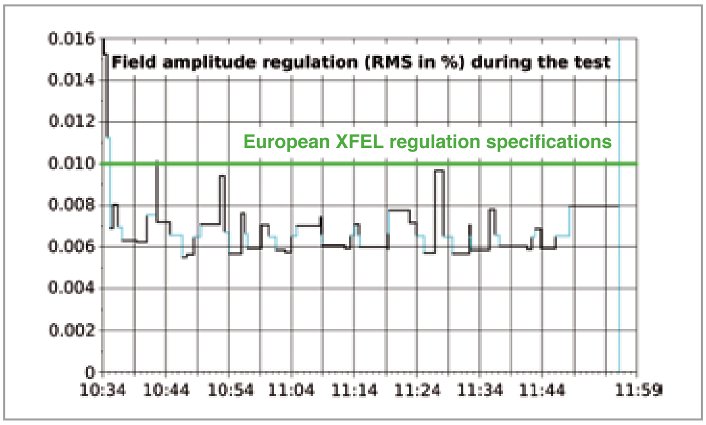

Figure 3

Vector sum signal amplitude regulation dA/A (RMS)

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EuPRAXIA.

Conceptual design study for a European plasma accelerator facility picks up steam

The Horizon2020 project "European Plasma Research Accelerator with eXcellence In Applications" (EuPRAXIA) aims at producing a conceptual design report for a highly compact and cost-effective European research infrastructure. Based on plasma acceleration, the goal is to provide a 5 GeV electron beam for high-energy physics detector tests, pilot free-electron laser (FEL) experiments and other compact X-ray sources. Funded by the European Union, the project started in 2015. The final design report will be completed in October 2019.

Introduction

The EuPRAXIA collaboration is investigating two paths towards a stable 5 GeV electron beam using plasma acceleration. The first approach uses a high-quality electron beam provided by a radio frequency (RF) accelerator and boosts the beam's energy from a few hundred MeV to 5 GeV in plasma stages while maintaining the original beam quality (Fig. 1). The second method uses only plasma modules, both for the injector and for the accelerator stages. In 2017, the 125 scientists of EuPRAXIA worked out the preliminary designs for the RF and laser injectors (Fig. 2), the accelerator modules and the overall PW laser system infrastructure powering all plasma modules. Several options are being considered. In 2018, the primary and backup solutions will be discussed, with a decision to be made during the collaboration week and symposium in Liverpool in July 2018.

Laser plasma injector and accelerator

Using separate stages to inject and accelerate the electrons allows for controlling and shaping the bunch inside the injection stage before it enters the accelerator stage. In 2017, the collaboration compared all published experimental results regarding achieved electron beam reliability, stability, scalability to larger electron energy, and repetition rate. It concluded that gas cells are the most promising media for stable operation of a plasma injector and that plasma

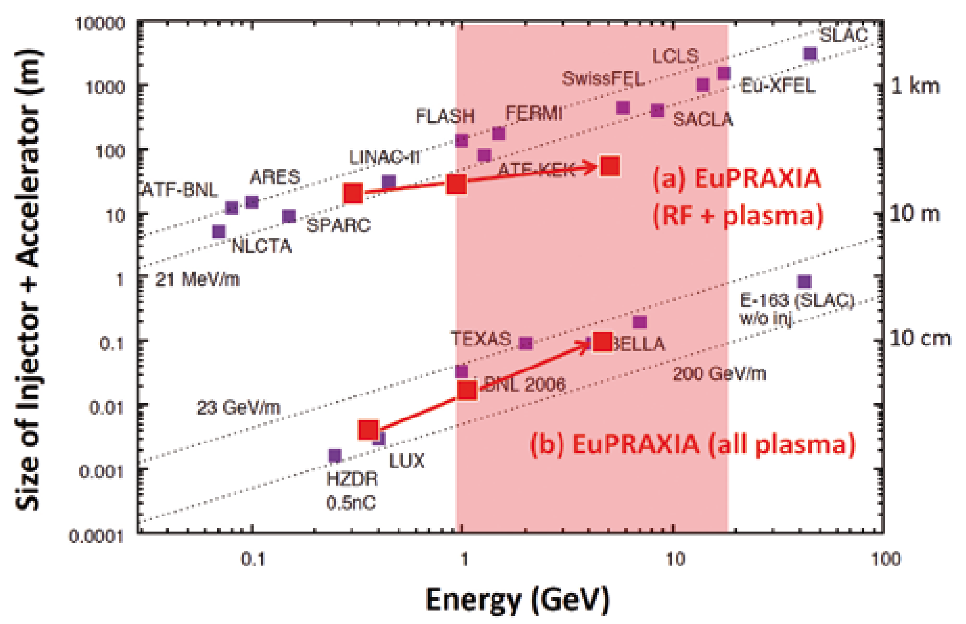


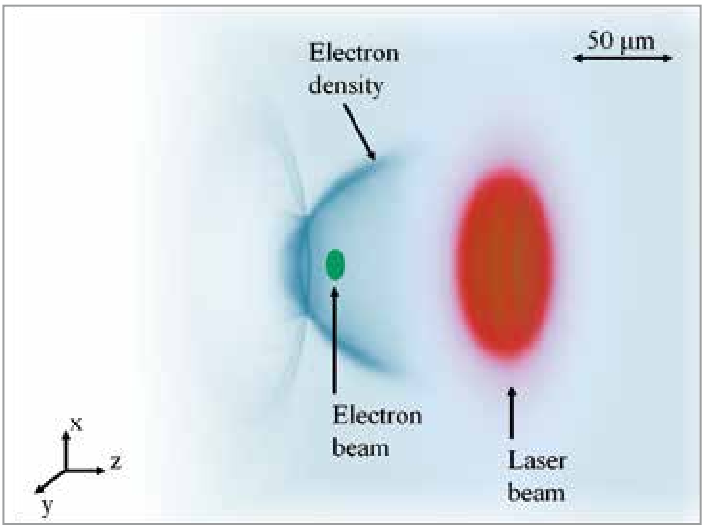
Figure 1

Total size of injector and accelerator of different RF and plasma accelerators versus achieved energy. Two bands are visible: RF accelerators are located in the upper band, with very high-quality beams (low emittances, narrow energy spread) and decades of experience in building stable electron sources. The plasma accelerators are located in the bottom band, with lower-quality beams but potential for shorter accelerator stages and new techniques usable for both plasma and RF accelerators. Both EuPRAXIA approaches (using only plasma stages or using a combination of RF power and plasma accelerators) are sketched out.

(Plot courtesy of R. A. Aßmann)

Figure 2

Particle-in-cell simulation of a laser wakefield acceleration case. The laser pulse (red) propagates the plasma from left to right (electron density shown in blue) and excites a wakefield, which accelerates electrons (shown in green) from 0.1 to 1 GeV in 2.5 cm.
(Plot courtesy of A. Ferran Pousa)



channels and grazing-incidence capillary tubes provide adequate structures for plasma guiding over long distances. Alternative plasma injector schemes could be provided by sources using ionisation-assisted injection and structured density profiles. The final plasma injector beam will have an energy of 150 MeV, charges between 30 and 100 pC, 5 fs bunch length (RMS), a total energy spread of 1% or below and a transverse normalised emittance of below 1 mm mrad.

RF injector

Two RF injector designs were proposed and simulated – one at 240 MeV and one at 540 MeV, both with beam charges of 30 pC and pulse lengths of ~10 fs. The relative energy spread in both cases is well below 1% (0.25% and 0.06%, respectively), which is crucial for FEL radiation generation, one of the main user experiments planned for the facility. The normalised emittances are below 0.5 mm mrad. One benefit of the RF injector is that using well-established RF technology allows optimal control over the injection beam before acceleration to 5 GeV can occur in the acceleration module. For example, triangular-shaped beams are possible, which would be useful for beam-driven acceleration.

Laser design

The design of the EuPRAXIA facility requires tens of kW average laser power, PW peak power, up to 100 Hz repetition rate and short (20–50 fs) laser pulse lengths. While the technology is rapidly evolving, a laser system with all these combined properties does not yet exist. Scaling the technology of existing high-peak-power lasers to higher average power in a five-year time frame while maintaining key technological performance is rather challenging. In light of this, EuPRAXIA is basing its design on the most established laser technologies currently available that are scalable to the required specifications – that is, the titanium sapphire technology pumped by diode-pumped solid-state lasers. The laser system will be able to deliver pulses with energies of 5 J, 15 J (both with 30 fs pulse length, FWHM) and 50 J (at 60 fs pulse length, FWHM) at a repetition rate of 20 Hz.

Workshops and conferences

In 2017, two collaboration weeks were held in Hamburg and Lisbon, during which the overall EuPRAXIA operating parameters were discussed and tuned. Right before the collaboration week in Lisbon, the collaboration held its second yearly meeting, in which the scientific advisory committee gave advice for the first time on the tasks ahead. EuPRAXIA scientists also presented the project in several invited and contributed talks worldwide and published their first collaboration-wide paper [1]. In July, Ralph Aßmann (EuPRAXIA coordinator) and Leo Gizzi (laser design and optimisation work package leader) organised a dedicated laser plasma school, which was attended by 35 students and scientists.

Outlook

In 2018, the collaboration will continue its simulations and experiments. Work will focus on selecting the primary options and backup solutions for the design report, with a decision to be made in July during the EuPRAXIA collaboration week and symposium in Liverpool.

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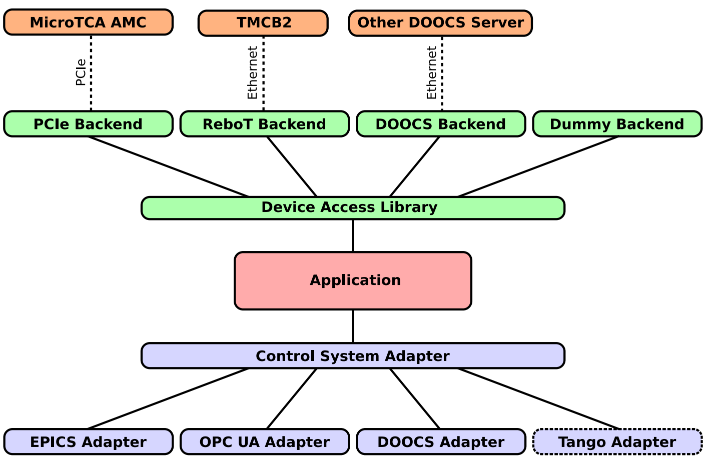
Digital RF control for the ELBE accelerator.

ChimeraTK software facilitates seamless integration into foreign control systems

In the context of the Helmholtz Accelerator Research and Development (ARD) programme, DESY is collaborating with partners to install MicroTCA-based digital low-level radio frequency (LLRF) control at the ELBE accelerator of the Helmholtz-Zentrum Dresden-Rossendorf (HZDR). The technology was developed at DESY for the free-electron laser facilities FLASH and European XFEL, where the application software is based on the DOOCS control system software framework. The newly developed ChimeraTK control system adapter now allows developers to write applications that can easily be integrated into other control system environments. The LLRF control server was ported to ChimeraTK and successfully tested in the WinCC-based control system at ELBE.

Accelerator controls not only for DESY

The MicroTCA-based digital LLRF control developed at DESY is now being adapted to several other accelerators, such as ELBE at HZDR, FLUTE at the Karlsruhe Institute of Technology (KIT) and the Turkish Accelerator and Radiation Laboratory in Ankara (TARLA). All those facilities use different software for their control systems. Usually, when a component is ported into a different software environment, the existing application code is copied and modified to adapt it to the new facility. This requires a significant amount of work and duplicates the workload each time a new feature is introduced: It always has to be ported manually. In the long run, this maintenance overhead cannot be kept, and both applications start to develop independently. Each of them will have features that the other one does not have, and neither of them will have all the features. In addition, bugs have to be fixed for both applications individually, which can even increase the downtime of the facilities.



As the LLRF control application is supposed to run at multiple facilities, the idea came up to introduce an adapter layer that would make it easy to integrate the application into different environments. The goal was to decouple the application logic that implements the features so that it can be used at all the facilities without having to change the source code. The control system adapter is part of the Control system and Hardware Interface with Mapped and Extensible Register-based device Abstraction Tool Kit (ChimeraTK, Fig. 1). ChimeraTK started as a C++ hardware access library for components in a MicroTCA crate and introduced an abstraction layer allowing the use of different hardware protocols and devices with the same application. It evolved into a tool kit to facilitate the development of control applications that also includes libraries for writing mocks and dummies for testing and, as the latest additions, the control system adapter and a library called ApplicationCore, which helps to define internal interfaces and application modules. ChimeraTK is an open-source software that evolved from a DESY-only project into a community project hosted on github.

Control system adapter for ChimeraTK

Work on the control system adapter started in early 2014 and included several iterations from a proof-of-principle prototype to a version that implements all the features needed by the LLRF control application. The development was a collaborative effort of HZDR, which hosts the ELBE accelerator, the company Aquenos, which is working on the EPICS-based control system for the FLUTE accelerator at KIT, and DESY,

Figure 1

The ChimeraTK device access library and the control system adapter are abstraction layers for decoupling the application from the hardware and the middleware, respectively.

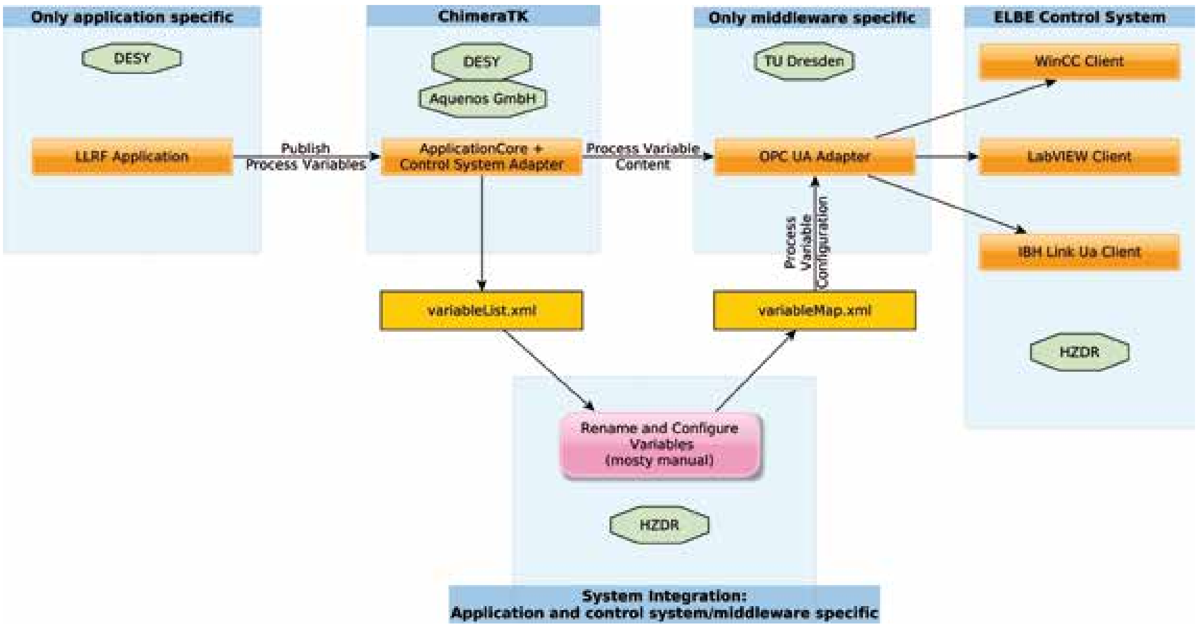


Figure 2
DESY, the company Aquenos, the chairperson of process control systems of TU Dresden, and HZDR have been working together to integrate the digital LLRF control application into the ELBE control system.

which provided the original implementation and the expertise on DOOCS. The chairperson of process control systems of the Technical University (TU) Dresden, a leading developer of the Open62541 OPC UA software stack, joined the project in 2016. Only thanks to the combined experience with several control system frameworks was it possible to get the required abstraction for the adapter to work.

An important step was to identify and separate the responsibilities of the application's business logic and the integration into the control system environment. The task of the application logic is to provide algorithms to steer the LLRF controller and to define the process variables used for this. In the system integration step, the variables are matched with the naming scheme of the facility and published in the control system through the corresponding communication protocol. This led to the development of the ChimeraTK ApplicationCore library, which together with the control system adapter introduces the abstraction layers necessary to separate the tasks.

Software improvement through modularity

The re-organisation of the code when porting the LLRF application to ChimeraTK has not only allowed its use at other facilities. The accelerators at DESY already have several flavours of LLRF device servers. The European XFEL, for instance, has one for the electron source (gun) and one for the accelerator itself, and other DESY facilities such as REGAE again have their own flavours. The modular design introduced by the application core library will enable those servers to be unified, while still providing the flexibility to configure them to the specific needs of each accelerator. This significantly reduces the maintenance effort and makes new features available faster at all the facilities.

Integration at the ELBE accelerator

The LLRF application has originally been developed and tested by DESY using the DOOCS adapter. The application itself does not know about the control system environment and publishes its process variables using the ChimeraTK libraries. Figure 2 shows how the LLRF control application is integrated into the ELBE control system. The OPC UA adapter, which was developed by TU Dresden, is application-independent. It does not know about the LLRF control. The only part that is application- *and* control-system-dependent is the configuration file for the adapter. The fact that it is a simple xml file allowed the system engineer at HZDR to carry out the system integration without having to write a single line of C++ code.

More facilities and applications on the horizon

The integration of the LLRF application into the ELBE control system proceeded smoothly and without major problems, although the application had been developed using a different middleware and environment. First tests with beam were successfully completed in 2017, with long-term operation planned for mid-2018. Preparations are ongoing to use the application at FLUTE and TARLA with the EPICS adapter.

The ChimeraTK framework is certainly not limited to the LLRF control application, or even to accelerator controls. The DESY Machine Beam Controls group has already started porting other device servers to use the ChimeraTK control system adapter and is looking forward to many exciting applications at various facilities all over the world.

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LUX.

First generation of X-ray pulses

The Laser-Plasma Driven Undulator X-Ray Source (LUX) is a novel laser plasma accelerator driving a miniature undulator for the generation of few-femtosecond X-ray pulses at compact scales and with unprecedented time resolution for pump–probe experiments. After commissioning of the plasma accelerator, 2017 saw the first generation of X-ray pulses from a laser-plasma-driven undulator on the DESY campus, with photon energies reaching into the water window.

The LUX beamline is developed and operated within a close collaboration of DESY and its strategic partner, the University of Hamburg. Building on the combined expertise of both partners in plasma acceleration and state-of-the-art accelerator technology, the mission of LUX is to advance the technology from single-shot experiments towards stable operation of a laser plasma accelerator and thus demonstrate the possibility of first pilot applications.

The LUX plasma accelerator focuses ultrashort pulses from the 200 TW high-intensity laser system ANGUS into a hydrogen-filled capillary only a few hundred micrometres in diameter to create a plasma and then plasma waves trailing the main laser pulse. Figure 1 shows a simulation of the laser-driven wake, which captures electrons from the background and forms short bunches of electrons that are accelerated within millimetre lengths to GeV-scale energies. The electron beams are then extracted from the capillary with a set of high-gradient quadrupole magnets and transported to a miniature undulator, in which they generate short bursts of radiation with wavelengths of only a few nanometres.

With its 15 m length, the LUX beamline is still very compact but features state-of-the-art diagnostic instruments, such as beam profile and position monitors, to study the properties of the electron beams as a result of the complex dynamics inside the plasma. Stable operation of the plasma accelerator requires precise control over all the parameters of the machine, especially a well-controlled operation of the driver laser. At LUX, the laser and the plasma accelerator are integrated into the same machine control system that operates the large facilities on the DESY campus. At the end

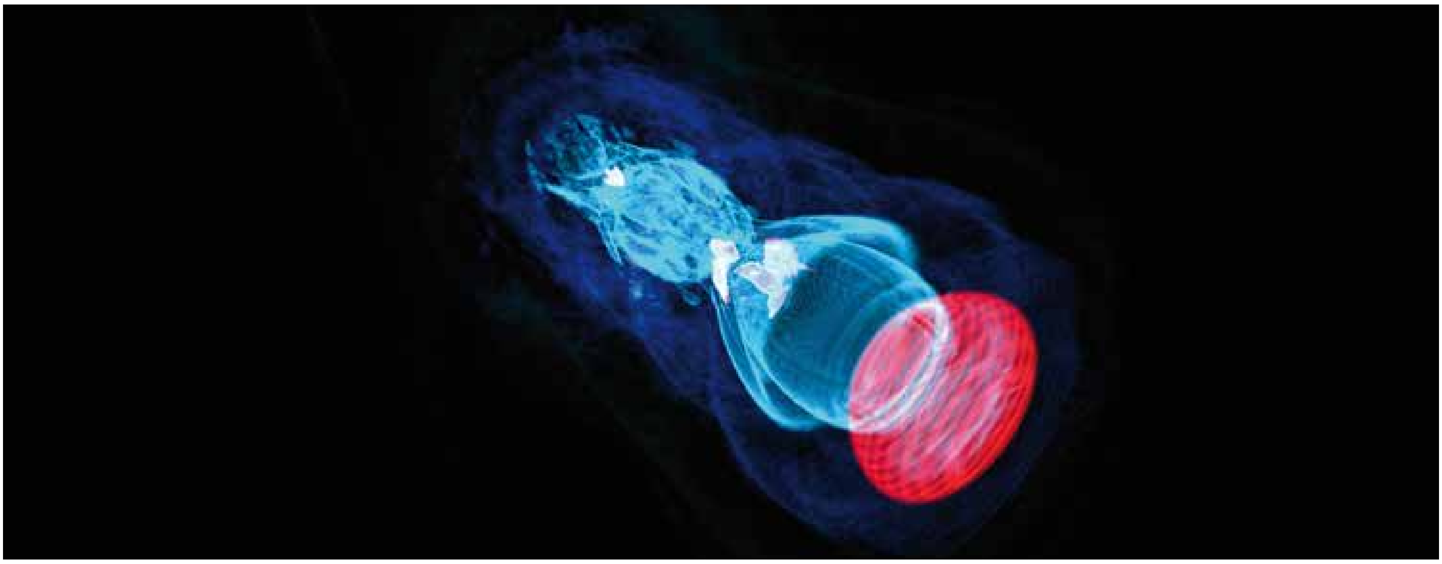

Figure 1

Simulation of a plasma wave (blue) driven by an intense laser pulse (red)

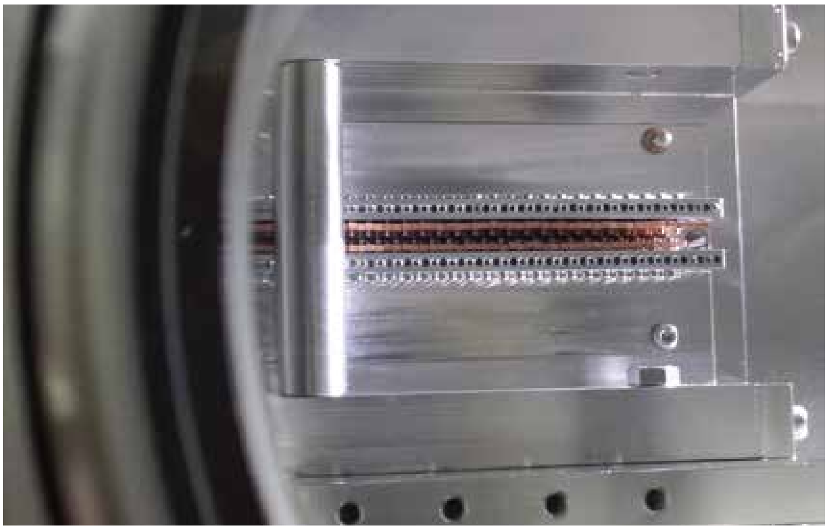

Figure 2

View through a vacuum window onto the BEAST II undulator, which was used to generate first X-ray pulses from the plasma electron beams at LUX

of 2017, the great success of this pioneering approach was demonstrated by operating LUX, as the first plasma accelerator of its kind, continuously for more than 24 h, while generating electron beams from the plasma accelerator with high availability and several 10 000 consecutive shots.

In a campaign earlier in 2017, the LUX electron beams were used to generate synchrotron-type radiation from the miniature in-vacuum undulator BEAST II (Fig. 2). With the first pulses recorded at a wavelength of 9 nm (Fig. 3), water-window radiation at 4 nm could be demonstrated after carefully tuning the machine. Together with an auxiliary optical pump/probe beam of several 10 mJ pulse energy that is derived from the main laser driver and thus synchronised with few-femtosecond accuracy to the X-ray pulses from the undulator, this enables exciting new possibilities for experiments to be performed at LUX, advancing our understanding of the machine and of the complex dynamics of the laser–plasma interaction.

As a future upgrade to LUX, the cryogenically cooled in-vacuum undulator FROSTY is currently being built. FROSTY is specifically designed for a first demonstration of free-electron laser (FEL) amplification using laser-plasma-generated beams. The demonstration of plasma-driven FEL gain is extremely challenging, as the quality of the plasma beams is still limited. Further diagnostic upgrades and extensive machine studies will be used in combination with theoretical models and simulations to further improve the control over the LUX electron beams.

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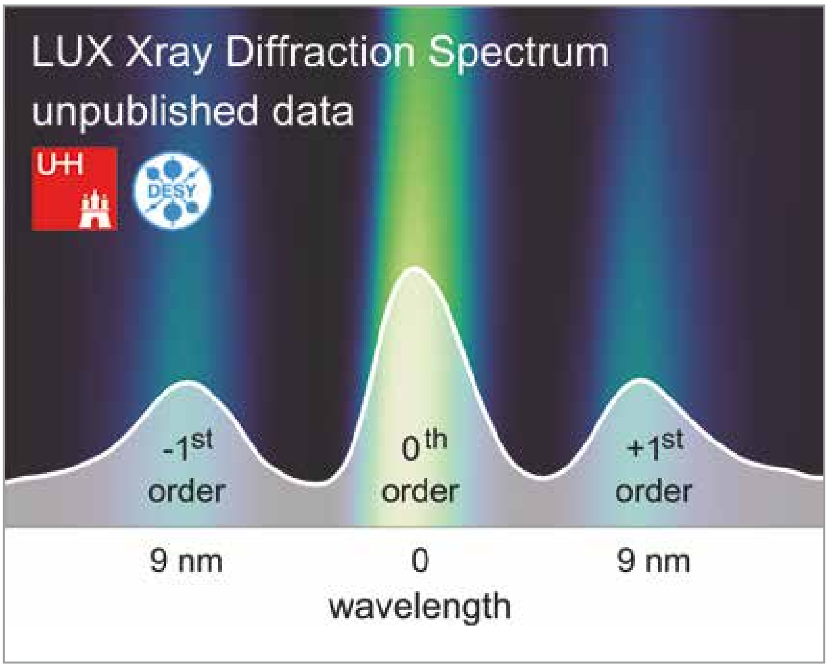

Figure 3

LUX undulator radiation spectrum at 9 nm wavelength, showing the minus and plus first diffraction order of the X-ray pulse passing a gold transmission grating. Analysis by C. Werle (UHH) and P. Winkler (DESY).

Burning lenses.

Achieving extreme focusing with active plasma lenses

Electron acceleration in plasma is a promising concept for shrinking the size and cost of high-energy accelerators, owing to the achievable extreme accelerating fields – which are about 1000 times stronger than in conventional radio frequency cavities. One key feature of beams generated and accelerated in plasma is a low beam emittance. This feature is challenging to preserve in the drift section after the beam extraction from the plasma module, however, due to the inherent beam properties of bunches accelerated in plasma: a high beam divergence and a typical energy spread on the percent level. Capturing those beams as close as possible to the plasma source would allow the beam quality to be conserved. This requires novel types of magnetic beam optics, which are currently being developed by the DESY plasma acceleration group. Plasma-based lenses enable focusing strengths an order of magnitude higher than conventional magnetic lens assemblies. In the future, such beam optics will play a crucial part in the development of plasma accelerators for high-energy physics and photon science.

Active plasma lenses

The idea of using a round plasma channel as a conductor for a high current flowing collinearly with a passing particle beam in order to achieve focusing has been thoroughly tested for heavy-particle beams. Referred to as an active plasma lens (APL), it enables an azimuthal, radially symmetric magnetic field configuration for focusing the charged particle beams. New experiments show that the same concept can be applied to electron beams in plasma structures orders of magnitude smaller. The underlying principle is fundamentally different from the passive beam focusing that occurs in transverse plasma wakefields excited by high-current-density particle beams or strong lasers.

The APL, as sketched in Fig. 1, consists of a gas channel typically hundreds of micrometres in diameter and a few centimetres in length. When applying a voltage of a few ten kilovolts, electrical breakdown is induced, leading to the formation of a plasma. The plasma supports current transport along the channel, which induces a magnetic field. The magnetic field configuration of such a system can easily be shown through Ampère’s law as being radially symmetric. This allows for symmetric focusing of co-propagating charged particle beams in a single optical element – a considerable advantage of the APL over the most widely used conventional device, the magnetic quadrupole.

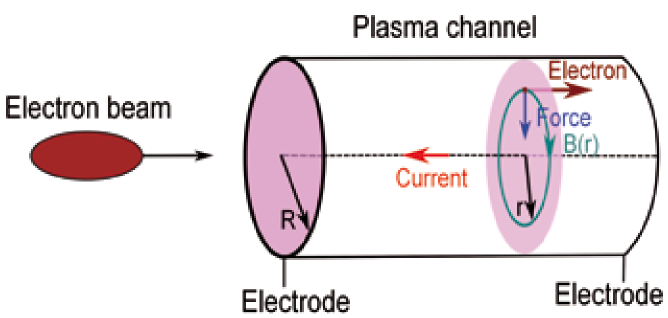

Figure 1

Schematic drawing of the APL setup. The current density in the cylindrical channel creates a focusing magnetic field configuration.

For a plasma channel of 250 µm diameter with a 250 A current, a focusing gradient of g = 3840 T/m was experimentally demonstrated [1], which surpasses the gradient of commonly used electromagnetic quadrupole lenses by an order of magnitude. These gradients allow for focusing of high-divergence beams over short longitudinal distances – as is crucial for electron beams from plasma accelerators – allowing the staging of multiple independent accelerators [2]. In addition to focusing strength, beam quality preservation is a paramount aspect of focusing elements. Measuring the emittance – an indicator of beam quality – of a beam focused by an APL is, therefore, an important step towards understanding and improving APLs for everyday experimental use.

An alternative technique that can achieve focusing in both transverse dimensions simultaneously – the solenoid lens – has the disadvantage of a quadratic scaling of the focusing strength with the energy. However, APLs and quadrupoles rely on the same focusing mechanism and have a more favourable linear scaling, making them less prone to chromatic effects.

While the focusing force due to the plasma current can be relatively strong, the forces acting inside a plasma wakefield can be orders of magnitude higher. Therefore, it is important to design the plasma lens in such a way that the traversing electron beam drives no wake.

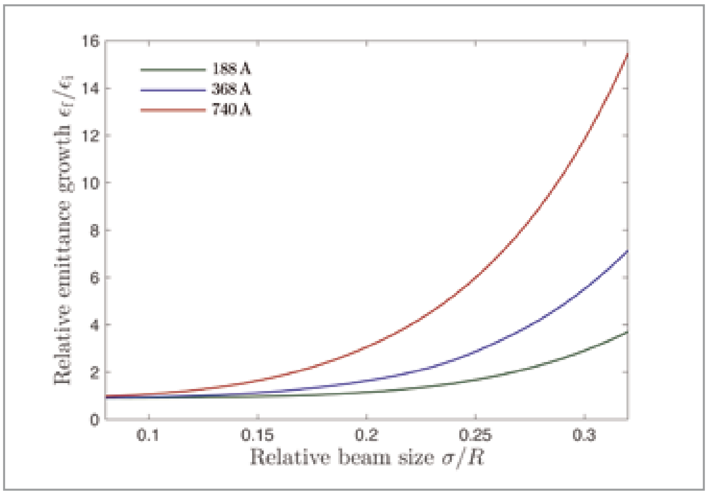

Figure 2

Relative emittance growth of a MAMI-type beam, induced by an APL of three different settings. The emittance growth strongly depends on the beam size. Also, the core part of the beam is degraded less than the wings.

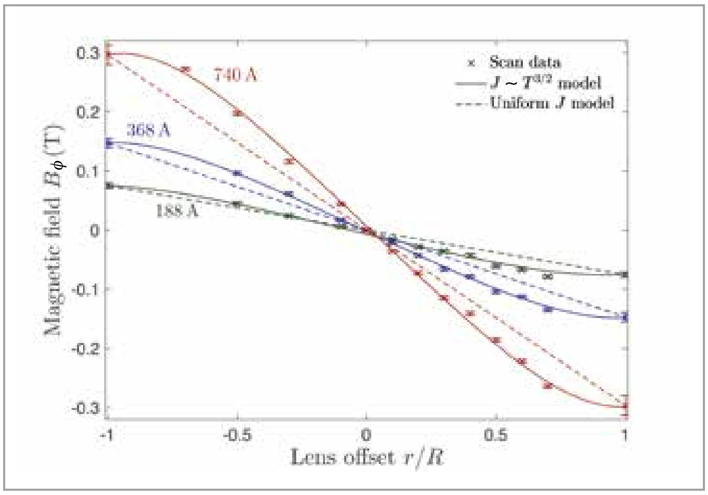

Figure 3

Direct measurement of the magnetic field gradient. The scan was performed by moving the APL transversally, introducing a dipole kick depending on the gradient and the distance moved. The best fit of the measured data yields a core gradient of g = 823 T/m for a current of 740 A.

Probing the quality of plasma lenses

To test the stability of APLs, the DESY plasma acceleration group used the stable and well-characterised electron beams provided by the MAMI microtron at the University of Mainz in Germany. During an experimental campaign in cooperation with the universities of Hamburg and Mainz as well as Lawrence Berkeley National Laboratory (LBNL) in the USA, the focusing gradient and the impact of the APL on electron beam stability and emittance were measured.

The electron beam emittance was measured with and without the APL in the beamline. The measurements show a degradation of the initial emittance of 1.4 mm mrad in dependence of the focusing strength. The results of a quadrupole scan – a widely used method of probing a beam's emittance – can be found in Table 1. However, this scan was performed using a large, unfocused electron beam to sample over a large fraction of the lens diameter. Using beams with smaller transverse size will decrease the emittance growth considerably, as illustrated in Fig. 2.

Additionally, the APL was moved transversally to probe the focusing gradient as well as its reproducibility. This was achieved by measuring the transversal kick the electron beam experiences when passing the lens off-centre as a function of the radial coordinate, i.e. the lens offset. The results of this scan are also shown in Table 1 as well as in Fig. 3.

Current [A]	Gradient [T/m]	Emittance [mm mrad]
188	206 ± 4	2.2 ± 0.1
368	473 ± 5	3.9 ± 0.1
740	823 ± 9	8.2 ± 0.1

Table 1: Focusing gradient and electron beam emittance determined for different APL current settings

The offset scan also yielded the first direct measurement of the magnetic field gradient of an APL. The core gradient in the uniform case (dashed lines in Fig. 3) can be derived from a measurement of the total current through the APL and the channel radius. The disparity between the uniform case (dashed lines) and the measurements was explained using the recently discussed $J \sim T^{3/2}$ model [3]. The APL did not have a deleterious effect on the pointing stability, with respect to the beam size, which demonstrates the excellent reproducibility and stability of the system.

These results show that APLs have the potential to play an integral role in advanced accelerator techniques. They allow for compact capturing of electron beams from plasma accelerators while potentially maintaining their high beam quality.

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PolariX TDS – X-band RF deflector project.

An international effort towards testing a novel variable-polarisation feature

A collaboration between DESY, PSI and CERN was formed [1] with the aim of developing and building an advanced modular X-band radio frequency (RF) deflector system called PolariX TDS (Polarizable X-Band Transverse Deflecting Structure). The cavity has the new feature of providing variable polarisation of the deflecting field. The possibility of changing the orientation of the streaking field of the structure to an arbitrary azimuthal angle allows for improved diagnostic capabilities and possibly full 6D characterisation of the electron beam phase space. As this new cavity design requires very high manufacturing precision, the tuning-free assembly procedures developed at PSI for the SwissFEL C-band accelerating structures will be used. The high-power RF system is based on the X-band test stands at CERN. This article presents an overview of the application of such RF deflectors in the different experiments at DESY.

RF deflector diagnostics

RF deflectors, also called transverse deflecting structures (TDS), are well-known diagnostic devices for characterising the longitudinal properties of electron bunches in a linear accelerator. The resolution of such devices depends, among other parameters, on the RF frequency [2,3]. Using a conventional system, it is possible to characterise the slice properties of an electron beam in the direction perpendicular to the one of the time-dependent streaking. Therefore, typically only either the horizontal or the vertical slice envelopes can be measured.

Recently, an innovative design for a TDS that gives full control of the transverse streaking direction was proposed at CERN [4]. The possibility of changing the orientation of the streaking field of the structure to an arbitrary azimuthal angle (Fig. 1) allows for exciting new opportunities for characterising the electron bunch. By collecting measurements of the beam streaked at different angles and combining them using tomographic techniques, it is possible, in principle, to retrieve 3D distributions of the bunch properties, such as the charge. As an example, Fig. 2 shows the retrieved bunch distribution in a simulation of the measurement in the SINBAD-ARES linear accelerator [5].

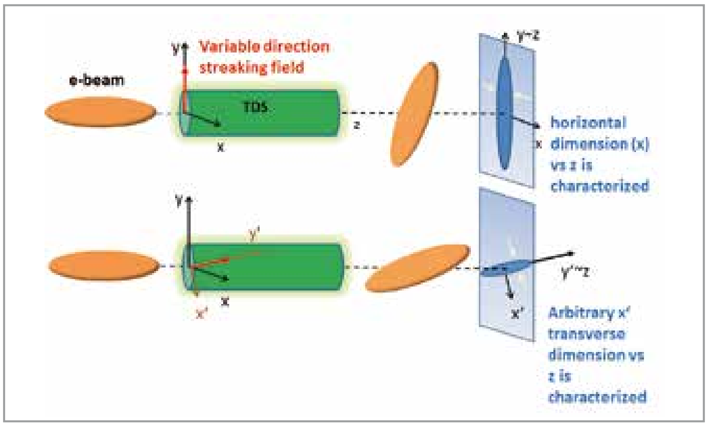

Figure 1

Working principle of a variable-polarisation RF deflector. The cavity provides a time-dependent, sinusoidal streaking field in the transverse direction. The angle of the streaking field can be varied continuously, thus allowing for the characterisation of an arbitrary transverse beam slice profile versus *z*.

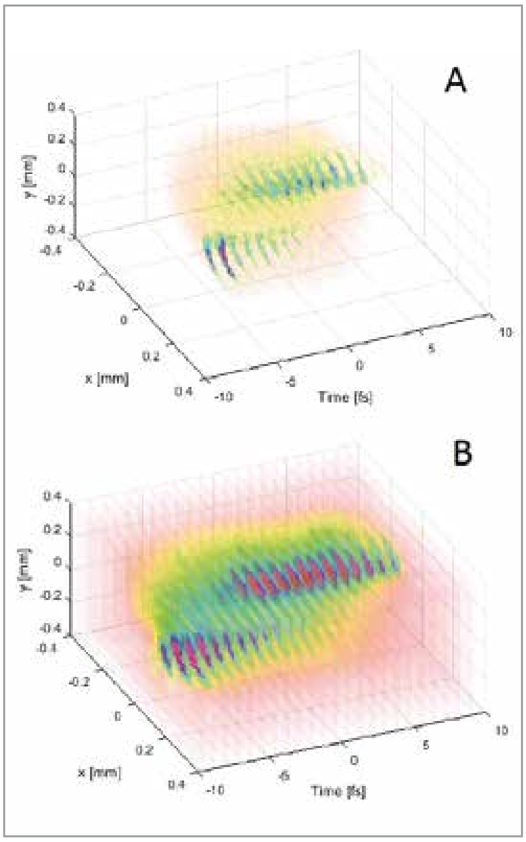

Figure 2

(A) Example of initial electron bunch distribution at the measurement screen of the SINBAD-ARES beamline. (B) Reconstructed 3D charge distribution from a simulation described in [5].

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 polarisation of the streaking field. At PSI, a high-precision tuning-free assembly procedure was developed for the SwissFEL C-band accelerating structures [6] and recently applied to CLIC X-band cavities.

Experiments involved in the project

Four experiments have collected their specifications for a common design of the cavity [1]: FLASHForward, FLASH2 and SINBAD at DESY as well as ATHOS at SwissFEL (PSI) [7]. Moreover, in the near future, the European XFEL project could possibly also benefit from such diagnostic devices. The following paragraphs present an overview of the requirements of the experiments located at DESY.

FLASHForward

The FLASHForward project [8] is an innovative plasma wakefield acceleration experiment, aiming to accelerate electron beams to GeV energies over a few centimetres of ionised gas. To demonstrate free-electron laser gain, the accelerated beams must be of sufficient quality, which is achievable only through rigorous analysis of the longitudinal phase space of both the drive beam and the accelerated beam.

The pulse duration of the accelerated beams is typically in the few-femtosecond range and thus difficult to resolve with traditional diagnostic methods. To longitudinally resolve these extremely short bunch lengths, it is necessary to use the properties of an X-band transverse RF deflector with high frequency and power, mapping longitudinal onto transverse coordinates. The conceptual RF scheme for such a system, shared between FLASH2 and FLASHForward, is shown in Fig. 3.

FLASH2

At FLASH1, measuring the longitudinal phase space directly with a deflecting RF structure has proven to be of utmost importance for establishing femtosecond-scale photon pulses. We plan to also install such a transverse deflecting cavity at FLASH2 [9] and to combine it with an existing dipole as a spectrometer in order to exploit the full longitudinal phase space. With this setup, we will be able to optimise longitudinal bunch parameters for both self-amplified spontaneous emission (SASE) and seeding processes.

In contrast to FLASH1, the RF deflector at FLASH2 will be located downstream of the undulators (Fig. 4). In such a configuration, the lasing part of the electron bunch can be measured directly, thus also providing an estimate of the photon pulse duration. The temporal resolution will be better than 10 fs.

SINBAD

The Short Innovative Bunches and Accelerators at DESY (SINBAD) facility [10] will be dedicated to accelerator research and development, building upon DESY's recent investment in this area in the framework of the Helmholtz Accelerator Research and Development (ARD) programme.

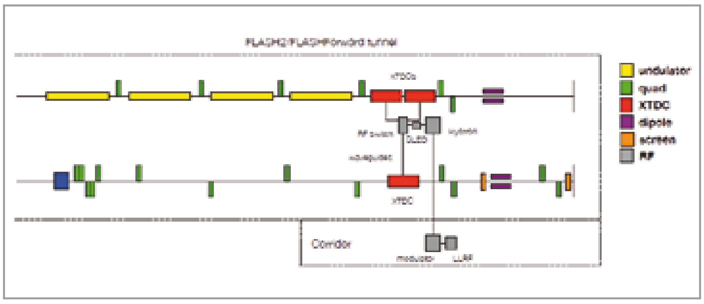

Figure 3

Sketch of the proposed X-band scheme for FLASH2 and FLASHForward: A shared DESY-designed low-level RF source and off-the-shelf high-level RF unit supply X-band cavities (called XTDC) on each beamline through a high-power-acceptance RF switch.

Figure 4

Exit of the SASE undulator section at FLASH2. Two 0.8 m long TDS cavities are foreseen to be installed in the free space downstream of the undulator.

It will be used for experiments on plasma wakefield acceleration, dielectric accelerating structures and other novel accelerators.

A 100 MeV electron linear accelerator (ARES) will be able to provide very short (sub-femtosecond) electron bunches with low (sub-picocoulomb) charge, as required for plasma and dielectric experiments. The planned X-band RF deflector with variable polarisation will enable the characterisation of the ARES bunches at the end of the linear accelerator, which is essential for these experiments.

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Seeding R&D at sFLASH.

Probing high-quality electron and photon beam parameters

sFLASH, the experimental setup to investigate external seeding methods at DESY's FLASH free-electron laser (FEL), has been operated since 2010 in a collaboration between DESY, the University of Hamburg and TU Dortmund University. In 2012, the sFLASH experiment demonstrated direct seeding at a wavelength of 38 nm, which is to date the shortest wavelength of a directly seeded FEL. Currently, the setup is operated in the high-gain harmonic generation seeding scheme and emits fully coherent FEL radiation at harmonics of the 267 nm seed laser. Recently, the characterisation of fully coherent photon pulses in the extreme-ultraviolet (XUV) spectral range was demonstrated using two different methods, a transverse deflecting radio frequency (RF) structure to extract longitudinally resolved information about the seeded electron bunches and a time-resolved scheme referred to as THz streaking that gives access to information on the optical phase.

External seeding of FELs

X-ray FELs have become powerful tools for exploring matter with unprecedented temporal and spatial resolution. The process generating the intense and ultrashort X-ray pulses is typically driven by self-amplified spontaneous emission of radiation (SASE), resulting in transversely coherent radiation pulses with multi-GW peak power. For the soft X-ray and XUV spectral range, different external seeding techniques have been developed in recent years. These enable the generation of fully coherent radiation pulses for wavelengths down to a few nanometres.

The sFLASH experiment dedicated to studies of external seeding schemes was installed at FLASH in 2010. It comprises optical injection beamlines for ultraviolet laser pulses, magnetic chicanes and undulators for manipulating the phase space distribution of the FLASH electron beam. Downstream of the experiment, advanced diagnostic instrumentation gives access to crucial information on the seeded electron beam and the generated photon pulses. Figure 1 schematically depicts the relevant elements of the experimental seeding setup.

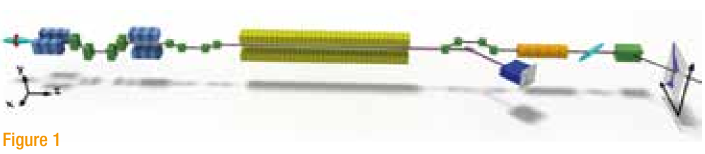

Figure 1

Illustration of the experimental seeding setup at FLASH. The electron and laser pulses travel from left to right through short five-period undulators (blue) and two magnetic chicanes (green dipole magnets) to modify the microstructure of the electron pulses. The 10 m long undulator (yellow) is used to amplify radiation pulses in the XUV spectral range. The electron bunches are guided around the FEL extraction mirror by a magnetic chicane. A transverse deflecting structure (orange) and a horizontally deflecting dipole spectrometer guide the electron beam to an observation screen. This unique hardware configuration allows the performance of the seeded FEL to be measured by analysing the longitudinal phase space distribution of the electron bunches leaving the undulator.

Recently, the sFLASH setup has been operated in the high-gain harmonic generation (HGHG) seeding scheme. In this mode, the 267 nm seed laser pulse interacts with the ultrarelativistic electron beam in a short undulator called a modulator. In the subsequent magnetic chicane, a periodic density modulation at the seed laser wavelength is generated. This current modulation enables the controlled initiation of the FEL amplification process. In this way, the sFLASH setup generates seeded FEL radiation up to the ninth harmonic of the 267 nm seed wavelength with GW-level peak intensities.

The advanced diagnostic instruments available at sFLASH allow for a detailed characterisation of the seeding process. A transverse deflecting RF structure (TDS) gives the possibility to measure the longitudinal phase space distribution of the electron bunches. This reveals the energy extracted from the electrons by the FEL process, enabling the reconstruction of the FEL pulse power profile. Independently of that, the temporal properties of the FEL photon pulses are characterised by THz streaking, a method widely used in the X-ray photon science community. Here, the highly intense FEL radiation hits a noble-gas target and extracts photoelectrons from the atoms. A co-propagating THz field accelerates these electrons, and their kinetic energy is measured. The energy spectrum allows the reconstruction of the temporal profile of the electric field of the initial FEL pulses.

Detailed electron bunch characterisation

In addition to allowing the generation of highly intense FEL pulses, the external seeding technique also gives the

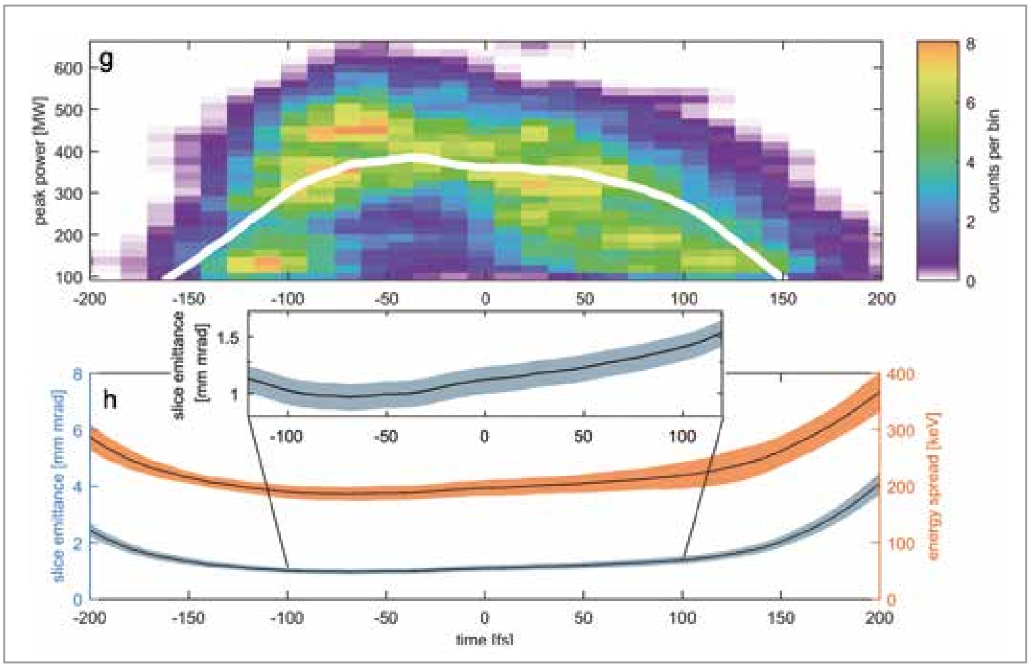

Figure 2

Histogram of the peak powers of 1979 seeded photon pulses and their longitudinal positions within the seeded electron bunch (upper panel). The white curve shows the predicted FEL performance as a function of the relative laser–electron timing. This prediction based on theoretical considerations uses independently measured electron bunch parameters, such as peak current, energy spread and slice emittance, as shown in the lower panel. Figure reproduced from [2] under Creative Commons Attribution 4.0 International License [4].

possibility to precisely diagnose the beam parameters of the involved electron bunches. Operating the linear accelerator in a low electron peak current mode enables the generation of coherent harmonic radiation up to very high harmonic numbers. Starting at the 267 nm seed laser wavelength, harmonic numbers up to the 19th order were observed. The distribution of the radiation power as a function of the harmonic number allows information to be retrieved about the local energy spread, which is one of the key parameters for the performance of the FEL process. Comparison with FEL simulations has shown that the value of the slice energy spread of the electron bunches in the seeded region is 13 ± 3 keV at a peak current of 160 A [1].

Besides the slice energy spread, another essential parameter of the electron bunches is their transverse slice emittance. The sFLASH team developed a method that allows the extraction of slice emittance profiles from single-shot data acquired using the TDS setup at FLASH. The results were used to calculate the expected FEL performance of sFLASH. Figure 2 shows the comparison of the expected and measured FEL output power as well as the extracted slice emittance. The theoretical prediction (white line) by the FEL model and the measurement data were found to agree remarkably well [2]. The seeding process therefore also serves as a perfect benchmark for the theoretical understanding of the FEL.

FEL pulse characterisation

The measurements of the temporal profile of the FEL pulse using the TDS were compared to data obtained with the THz streaking method. Figure 3 shows the histograms for the pulse durations acquired by both methods, which agree well within their respective errors.

In addition to the pulse duration, the THz streaking method allows the extraction of information about the temporal phase of the FEL pulse and its chirp. In recent measurements, the chirp of the FEL pulse was determined with its absolute value and sign to be -1940 ± 800 THz/ps [3].

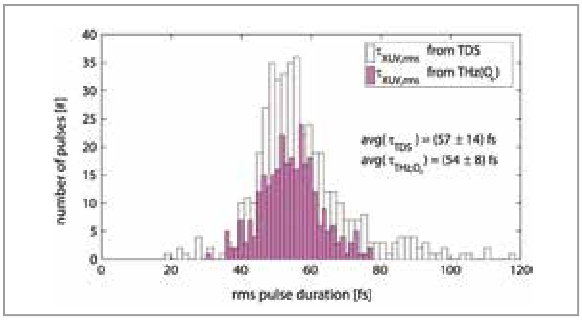

Figure 3

Comparison of single-shot measurements of the XUV pulse duration with two different diagnostic techniques. The magenta histogram displays data recorded with the THz streaking method. The pulse duration data extracted from measurements with the TDS are shown in white. Figure reproduced from [3] under Creative Commons Attribution 3.0 License [4].

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[4] https://creativecommons.org/licenses/by/4.0/; https://creativecommons.org/licenses/by/3.0/

Sub-10 fs pulses for FLASH users.

Single-spike operation at FLASH

The generation of single-spike self-amplified spontaneous emission (SASE) pulses in the soft X-ray regime at free-electron lasers (FELs) allows detailed investigations of ultrafast reaction dynamics on the time scale of a few tens of femtoseconds. The shortest possible pulse duration is the so-called single spike, which is longitudinally completely coherent. Measuring the duration of such single-spike pulses is challenging. The DESY FLASH group determined the pulse duration of ultrashort pulses with two different methods and compared the results. Even though the technique is new, ultrashort pulses have already been delivered to several user experiments.

Measurement of ultrashort FEL pulses at FLASH1

About 40% of the experiments proposed at DESY's FLASH FEL facility request pulse durations shorter than 50 fs (FWHM). The FLASH group therefore furthers stable and reproducible operation with the shortest-possible SASE pulses. To ensure the generation of short FEL pulses, short electron bunches are required. Figure 1 shows an example of an electron bunch measured using a coherent radiation intensity spectrometer with a FWHM of 7 fs (3 fs RMS, neglecting the tails). The shortest radiation pulse duration at the end of the exponential gain regime during the amplification process is proportional to the number of longitudinal modes, the radiation wavelength and the saturation length. In the optimal case, the pulse contains only one longitudinal mode.

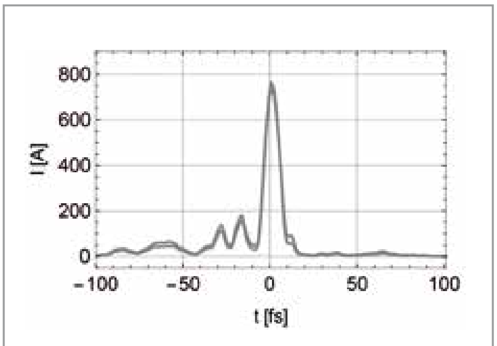

Figure 1

Temporal distribution of the electron bunch reconstructed from a measurement using a coherent radiation intensity spectrometer. The FWHM bunch duration is 7 fs in this example.

In an experiment to precisely measure the FEL pulse length, the FLASH group set up the FLASH1 beamline with a bunch charge of 70 pC for a wavelength of 6.8 nm. The strength of the bunch compression was modified in steps by changing the phase of the accelerator module ACC23 before the second bunch compressor from 7.9° to 8.9°.

The FEL pulse duration was determined using the THz streaking technique. Figure 2 shows the measured pulse duration for about 500 FEL pulses at six different phases. A pulse duration of 7 ± 4 fs (FWHM) was measured in the case of an ACC23 phase of 8.9°. This corresponds to an RMS pulse duration of 3 ± 1.7 fs assuming a Gaussian distribution.

The spectral distribution of the FEL pulses was determined with a high-resolution spectrometer in parallel to the THz streaking measurements. For the shortest FEL pulses, the number of modes was counted in all spectra. Figure 3 shows the result of the mode counting. On average, 1.6 modes were measured. More than 50% of the spectra contained only one mode. Applying 1.6 modes to the theory and assuming a saturation length of 35 ± 3 m, a pulse duration of 9 ± 1 fs (FWHM) is expected for a wavelength of 6.8 nm. The FEL pulse durations determined with different methods thus agree within the measurement errors.

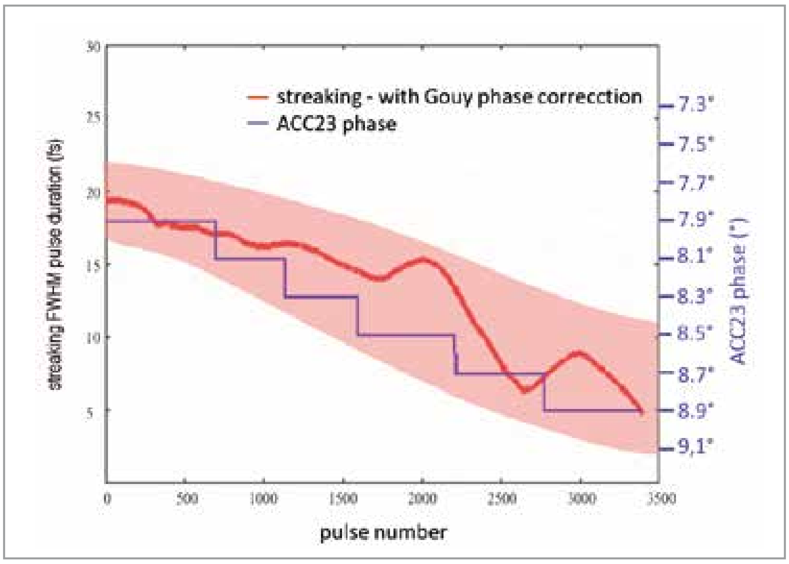

Figure 2

Measured pulse duration using the THz streaking technique for six different compression settings

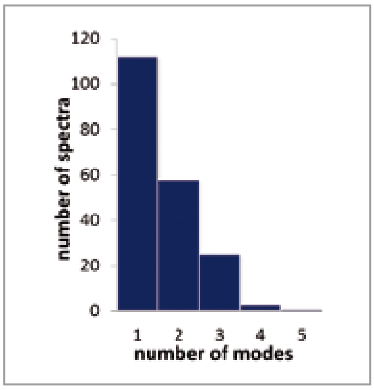

Figure 3

Histogram of the number of modes for an ultrashort FEL pulse measured using a high-resolution spectrometer

Measurement of ultrashort FEL pulses at FLASH2

Ultrashort pulses were also generated and analysed at the FLASH2 beamline. Although FLASH2 is not yet equipped with a high-resolution spectrometer and THz streaking setup, FEL pulses with 1.05 longitudinal modes on average were proven by analysing the statistics of the FEL pulses – in this specific case at a wavelength of 40.5 nm, a beam energy of 689 MeV and a bunch charge of 88 pC. The saturation length was determined to be 16.25 ± 0.63 m. From these data, the pulse duration at the end of the exponential gain was estimated to be 14.7 ± 0.6 fs (FWHM) and 6 fs (RMS).

From simulations, single-spike operation can also be expected with these parameters. Figure 4 presents four different simulation runs for the conditions during the measurement. The simulation shows three pure single-spike distributions.

Ultrashort pulses for users

The technique to generate ultrashort pulses is now mature enough to be offered to users. One experiment measured for the first time the demagnetisation in nickel with a time resolution better than 10 fs, providing a new understanding of ultrafast magnetic dynamics. Another experiment measured the dynamics of proton transfer through a hydrogen bond.

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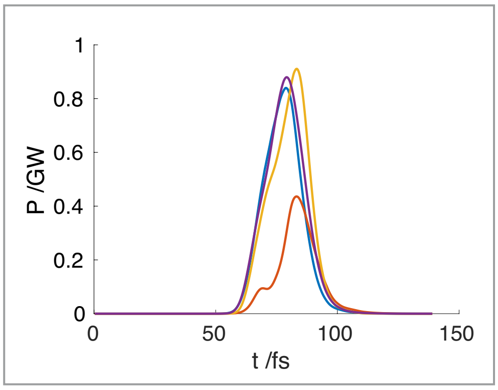

Figure 4

Simulated temporal distribution of the FEL pulse for short-pulse operation conditions

European XFEL cool-down.

Operation of the European XFEL linear accelerator at 2 K

The operation of the superconducting linear accelerator of the European XFEL X-ray laser requires cooling at liquid-helium temperatures. In particular, 768 superconducting 1.3 GHz nine-cell radio frequency (RF) cavities need to be cooled in a liquid-helium bath at 2 K. The cool-down of the accelerator started in December 2016, and operation at 2 K began in January 2017. Aside from the technical aspect, the cool-down required 2.8 t of matter to be put into an exotic quantum state.

Helium II – 2.8 t of macroscopic quantum state

The operation of the European XFEL linear accelerator requires the cooling of 768 superconducting 1.3 GHz nine-cell RF cavities at a temperature of 2 K in a liquid-helium bath. At this temperature, only helium is still in the liquid phase, in contrast to all other fluids. In particular, helium undergoes a phase transition in the liquid phase to helium II, showing quite exotic properties as soon as the temperature falls below 2.17 K. This phase change is known as the λ-transition because of the characteristic shape of the specific heat at this temperature. From the quantum physics point of view, at the λ-transition, all helium atoms fall into the same ground state and form a "macroscopic quantum-mechanical state" (within the boundaries of the correlation length). Helium II shows several unique properties, such as superfluidity, film creeping or "second sound". The cooling of the cavities takes advantage of the very large heat conductivity of helium II.

The helium vessels around the eight cavities and the superconducting quadrupole magnet of each accelerator cryomodule contain about 200 l of liquid helium II. Hence, all 96 cryomodules in the main European XFEL accelerator tunnel contain about 2.8 t of helium II – all in this particular macroscopic quantum state. Certainly, only a few visitors of the European XFEL accelerator will notice this when passing the about 1.5 km long chain of yellow cryomodule tubes in the tunnel.

From the technical point of view, helium II is used in the European XFEL accelerator merely as a coolant. The thermodynamic efficiency of cooling at 2 K is quite poor and hence quite expensive. Therefore, any kind of heat transfer from the warm environment to the inner parts of the cryomodules at 2 K has to be reduced as much as possible: Each cryomodule is under vacuum and equipped with two thermal shields, at 5–8 K and 40–80 K temperature levels, respectively. The thermal shields are covered with several layers of multilayer insulation.

The European XFEL cryogenic plant

The European XFEL refrigerator facility provides the required cooling capacities at 40–80 K, 5–8 K and 2 K temperature levels for the operation of the European XFEL accelerator. For each temperature level, helium is supplied to the injector and the main linac and returned to the refrigerator in a closed loop. (For the cryogenic supply, the linear accelerator sections L1, L2 and L3 in the main accelerator tunnel are referred to as "main linac"). By means of cryogenic valve boxes, the injector and the main linac can be supplied independently of each other.

Two existing helium refrigerators of the former HERA electron–proton collider at DESY were overhauled and modified to provide the required European XFEL accelerator cooling capacities, including some design overhead margin. In particular, a 2 K cold box had to be added. The 2 K cold box contains four stages of cold compressors, which are used to lower the vapour pressure of the helium in the cavity helium vessels to 31 mbar. This vapour pressure of 31 mbar corresponds to a liquid-helium bath temperature of 2 K.

The helium vapour is then compressed to a pressure of about 1 bar and returned to the heat exchangers of the European XFEL refrigerator to recycle the cooling capacity of the cold vapour. The cold compressors are operated within a very narrow operation range by means of sophisticated process controls. The resulting compression is coupled to specific conditions of helium vapour temperature, pressure and mass flow. Moreover, the RF operation of the cavities requires very stable helium pressure with variations smaller than ±0.3 mbar.

Cool-down of the European XFEL accelerator

Before the cool-down of the main linac started in December 2016, the European XFEL refrigerator and the injector branch had already been commissioned and all cryomodules cold-tested in the Accelerator Module Test Facility (AMTF) at DESY prior to their installation in the tunnel. Other components of the cold linac – valve boxes, transfer lines and module interconnections, including more than thousand welds – had been carefully leak- and pressure-tested, while some components had even undergone cold tests at liquid-nitrogen temperature. However, the complete system had never been cooled down to the final operation temperatures before.

The cool-down started on 12 December 2016, after all helium process tubes had been evacuated and purged several times with pure helium gas (Section 0 in Fig.1). The cool-down rate was limited to avoid compromising the alignment of the cavities and superconducting quadrupoles. The helium supply temperature of each cooling circuit was constantly adjusted by mixing cold and warm helium in the valve box to limit thermal stresses on the cryomodule components.

Figure 1 shows the return temperatures of all the cryogenic circuits during the cool-down. At the beginning, only one refrigerator was in operation and switched to the so-called 80 K mode, until a temperature of 40 K was reached. In this mode, only six of the seven expansion turbines are operated, allowing a better cooling efficiency.

As long as quite warm gas returns to the refrigerator, the heat exchangers have to be bypassed and the cooling capacity is limited (Section 1 in Fig. 1). This process was boosted by switching on the second refrigerator, which took over the cool-down of the 40–80 K shield circuit (Section 2 in Fig. 1). Soon afterwards, the return gas was cold enough to be fed into the heat exchangers of the refrigerators (Section 3 in Fig. 1).

Once the circuits reached the temperature of 80 K, one refrigerator was switched to regular operation mode and the cool-down of the 5–8 K and 2 K circuits continued until they reached a temperature of 4.5 K (Section 4 in Fig. 1). Around Christmas, all cavity helium vessels of the linac were filled with liquid helium at about 4.5 K.

The cool-down proceeded smoothly without any major technical problem. In particular, no helium leaks were observed in the cryogenic process tubes. Also, the static cryogenic heat loads appeared as calculated, and no extra cooling capacity overhead was required. As a result, the cryogenic supply could be continued with only one of the two European XFEL refrigerators in operation, and the primary power consumption could be decreased.

Operation at 2 K

In January 2017, the stage was set for the final step towards cool-down to 2 K. Valuable experience for the operation of the cold compressor system had already been gained during the commissioning of the European XFEL refrigerator in stand-alone mode and during the commissioning of the injector, but the supply of the 2 K circuit of the linac added about two orders of magnitude of volume to the system. As a consequence, all operation parameters for the process controls of the cold compressors had to be adapted to the larger system.

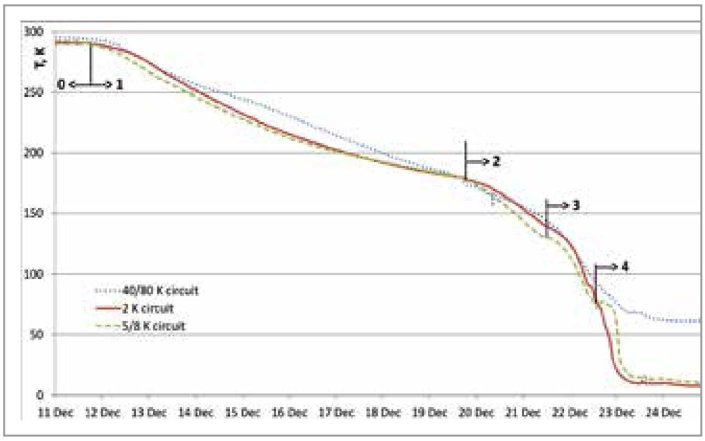

Figure 1

Return temperatures of all cryogenic circuits during cool-down of the European XFEL accelerator

During the cool-down of the liquid helium from 4.5 K to 2 K, the operation of the refrigerator has to deal with changing process conditions, including variable liquefaction rates and helium vapour mass flows. At the same time, the operation of the cold compressors needs stable boundary conditions. It took a few hours until the liquid helium in the linac was cooled down to 2 K for the first time.

After two months of intense commissioning, stable operation conditions of the helium II bath at 2 K were established in the linac, and RF operation and beam commissioning could start. In particular, the pressure stability of the helium II bath was kept within the specified boundaries.

As soon as the RF supply of the linac is switched on, the cryogenic heat load in the helium II bath increases by a factor of about 1.5. As a consequence, more helium evaporates and more vapour is returned to the cold compressors. The cold compressors can deal with mass flow changes by means of an internal bypass regulation and by adaption of the rotation frequency within narrow limits. To avoid a break of cold compressor operation, sudden RF load changes are compensated by means of electrical heaters in the helium bath. In this way, even quite strong load changes can be compensated without break-down of the cold compressor operation. (A restart of the cold compressors would take about 5 h).

After the cool-down and first cold operation of the linac, some conclusions could be drawn: Stationary cryogenic operation can be conducted with one refrigerator only (leaving the second refrigerator for redundancy and saving primary power); stable pressure conditions for RF cavity operation can be established and RF load changes can be compensated without break of cold compressor operation.

The stable stationary helium II supply of the European XFEL linac was continued throughout 2017, meaning that 2.8 t of helium were kept in a macroscopic quantum state.

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Laser-to-RF synchronisation with femtosecond precision.

How to provide femtosecond stability in free-electron lasers

Phase-stable radio frequency (RF) reference signals are essential to achieve low beam jitter and high performance at free-electron lasers (FELs). RF reference signals are distributed through coaxial cables, which are robust and provide the required availability. However, they suffer from phase drifts due to temperature and humidity variations in the accelerator tunnel. These drifts can easily exceed tens of picoseconds, whereas femtosecond stability is required. At the European XFEL X-ray laser, the phase drifts are overcome by locally resynchronising the RF reference signals with femtosecond precision using an optical reference module. This module connects the RF reference signals to the optical synchronisation system, which provides the required femtosecond stability. In this way, RF phase drifts are successfully removed with femtosecond precision for selected subsystems of the European XFEL.

Introduction

In FELs, the accelerating fields have significant influence on the beam energy, peak current, pulse shape and particularly the bunch arrival times. Sophisticated RF control systems have been developed at DESY for the European XFEL to stabilise and control the accelerating fields with so-far unrivalled precision. However, an RF control system can never exceed the precision of its RF reference signals. Therefore, a key to achieving femtosecond stability is to supply femtosecond-stable RF reference signals at numerous points along the accelerator. Unfortunately, conventional RF transport suffers from temperature-, vibration- and humidity-induced phase drifts, which easily exceed the desired femtosecond accuracy.

At the European XFEL, the 1.3 GHz RF reference phase stability is therefore continuously measured and actively corrected with respect to a femtosecond-stable optical synchronisation by a so-called optical reference module (REFM-OPT). The optical synchronisation system provides the desired femtosecond short- and long-term stability. The core component of the REFM-OPT is a laser-to-RF (L2RF) phase detector, which allows the phase of the 1.3 GHz RF reference signal to be measured with femtosecond precision with respect to the optical synchronisation system.

Optical synchronisation system

The optical reference system comprises a mode-locked low-jitter short-pulse laser (master laser oscillator, MLO) with a pulse repetition rate of 216 MHz. To guarantee long-term frequency stability, the MLO is tightly phase-locked to the RF master oscillator (RF-MO) of the accelerator. Optical pulses from the MLO are distributed throughout the accelerator facility by optical fibres. The propagation time in these fibres is actively stabilised by measuring the round-trip time of the laser pulses using optical cross-correlation techniques. Fibre length changes are compensated by a motorised delay stage (slow, nanosecond range) or a piezo-based fibre stretcher (fast, picosecond range). The optical synchronisation system provides optical reference signals to different end stations such as the REFM-OPT. A total of eight REFM-OPTs are currently installed and operated in the European XFEL.

RF resynchronisation in the REFM-OPT

The REFM-OPT is an engineered, fully integrated and remotely controllable unit, built for operation in the accelerator tunnel (Fig. 1). Its core component is an opto-electrical L2RF phase detector invented at DESY. It consists of an integrated readout electronics and an optical setup with free-space and fibre components. The optical baseplate is actively temperature-stabilised by Peltier elements (<10 mK), its housing is thermally isolated and sealed against humidity variations.

The L2RF phase detector is based on a commercially available Mach–Zehnder amplitude modulator (MZM), which modulates the laser pulse amplitude relative to the applied voltage. The laser pulse length of 100 fs is much shorter than the 1.3 GHz period of about 0.7 ns. The amplitude of the laser pulses is therefore modulated by the momentary RF voltage, which depends on the RF phase relative to the optical pulse train. This modulation of the optical amplitude allows the

Figure 1

Final hardware layout of the REFM-OPT

relative phase between the optical signal and the RF signal to be measured using conventional photodiodes. To overcome potential error sources, the laser beam is preprocessed so that the RF signal is sampled by the laser pulses at zero-crossings with opposite slopes. This suppresses the influence of power fluctuations of either the RF or the laser pulse train and allows compensation of bias drifts of the MZM.

The 1.3 GHz actuator contains a tuneable attenuator to actively stabilise the RF output power and a phase shifter controlled in a phase-locked loop (PLL) configuration. If the optical reference fails, the phase shifter is frozen to prevent accelerator downtime.

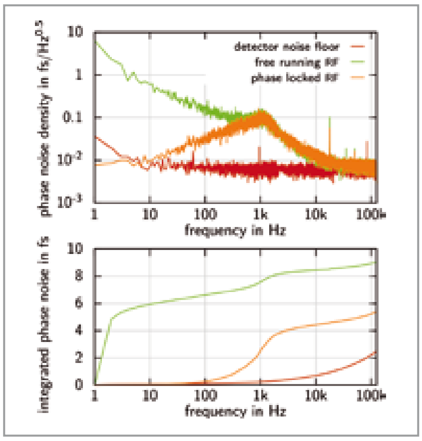

Figure 2

Short-term REFM-OPT performance. The in-loop jitter (orange) amounts to 9.5 fs (integrated).

REFM-OPT performance

The short-term performance of the REFM-OPT is presented in Fig. 2. The detector noise floor (red curve) was determined with the 1.3 GHz RF reference signal turned off. The measured voltage noise from the detector was converted to its equivalent in femtoseconds using the previously determined conversion constant K_ϕ of 1.5 V/ps. The integrated detector noise floor – and thus the achievable detection accuracy – amounts to 2.5 fs RMS in a bandwidth from 1 Hz to 125 kHz. The bandwidth is limited by the 250 kS/s sampling rate of the analogue-to-digital converters (ADCs) on the controller board.

The jitter between the reference pulse train from the optical synchronisation system and the 1.3 GHz RF signal (green curve) is observed after the RF has been switched on. The relative integrated jitter amounts to typically 9 fs RMS (1 Hz – 125 kHz bandwidth).

The orange curve shows the performance when the RF is phase-locked to the optical reference. Drifts and low-frequency jitter are corrected. The integrated jitter drops to 5.4 fs. Within the locking bandwidth (~300 Hz), the residual integrated in-loop jitter is only 0.8 fs, while the integrated detector noise floor amounts to 130 as. The remaining peak at 1 kHz is caused by an imperfect synchronisation of the MLO to the RF-MO, which cannot be removed by the REFM-OPT.

The long-term measurement presented in Fig. 3 was started at the end of a maintenance day for the duration of one week. When accelerator operation is resumed, the tunnel heats up. The RF cables from the RF-MO suffer from phase drifts induced by this temperature change. The peak-to-peak RF phase drift corrected by the REFM-OPT at the LLRF station A8 amounts to 14.2 ps.

The largest temperature change after the maintenance period occurs during the first three days. The temperature variations afterwards are much smaller. The peak-to-peak corrected phase change at A8 from day four to the end of the measurement amounts to only 2.9 ps.

The RF connection to the injector (LLRF station A1I1) is shorter and guided through a different area. The peak-to-peak corrected phase drift at the REFM-OPT at A1I1 amounts to 2.1 ps. This is on the same order as the phase drifts in the accelerator tunnel – if one disregards the heat-up after the maintenance day, which is not applicable to the injector.

Conclusion

At the European XFEL, the quality of the RF reference signals throughout the accelerator is analysed and continuously monitored with femtosecond precision. Supplying low-drift high-precision RF reference signals is uniquely possible thanks to the implementation of a drift-free L2RF phase detector that uses the femtosecond-stable optical synchronisation system as its reference.

Without the active correction by the REFM-OPT, the RF reference phase stability at the European XFEL would be on the order of a few picoseconds peak-to-peak during normal operation and more than 10 ps peak-to-peak after maintenance days. The residual phase jitter of the 1.3 GHz RF in the detector bandwidth of 1 Hz to 125 kHz amounts to 5.4 fs, while the jitter up to the locking bandwidth of 300 Hz is 0.8 fs. The synchronisation of the MLO to the RF-MO will be improved in 2018 in order to further reduce the residual jitter measured in the REFM-OPT in the 1 kHz range.

The successful implementation and operation of the REFM-OPT have increased the accuracy of the 1.3 GHz RF reference signals at the European XFEL by more than three orders of magnitude, enabling low beam jitter and high-performance FEL operation.

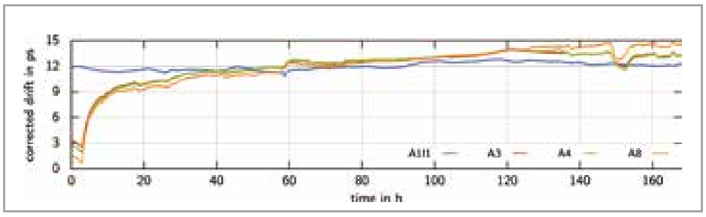

Figure 3

Long-term corrected phase drift at multiple LLRF stations of the European XFEL

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LLRF commissioning of the European XFEL.

Preparing the RF stations for beam acceleration

After cool-down of the main linear accelerator of the European XFEL X-ray laser, which took place in December 2016, all radio frequency (RF) stations were ready to operate and provide power to the superconducting cavities for the first time since their installation in the tunnel. Many steps were still required to prepare the RF stations for beam acceleration, the final objective being to achieve self-amplified spontaneous emission (SASE) to deliver X-ray radiation to the experimental hall. This article provides an insight into the low-level radio frequency (LLRF) cold commissioning of the largest number of superconducting cavities (>700) ever operated in an accelerator, which was completed in a record time of less than three months.

Commissioning overview

The European XFEL accelerator is depicted in Fig. 1, showing the RF stations in the injector (I1) and the three linear accelerator sections (L1–3). The commissioning of LLRF systems relies on many pre-commissioning steps performed during tunnel installation, at the board, crate, rack and system level. These are referred to as warm commissioning since they are performed before accelerator cool-down.

The LLRF cold commissioning can be subdivided as follows: 1) initial LLRF system verification, 2) LLRF signal dynamic range optimisation, 3) cavity frequency tuning, 4) coupler tuning, 5) power-based calibration, 6) closed-loop operation, 7) cavity phasing and beam-based calibration. The cold commissioning started on 2 January 2017. The injector had already been commissioned in cold conditions in 2016, so that its nominal energy was reached within a week. Commissioning of L1 (one RF station) took two weeks, L2 (three RF stations) another two weeks and L3 (up to RF station A23 only) roughly two months.

Initial LLRF system verification

This preliminary step consists in checking that the LLRF system functions properly and is ready for commissioning. The process starts by verifying that about 400 boards are loaded with the correct firmware, all servers are running properly, and all signals can be read. At this stage, all critical server properties (≈ 20 000) are systematically initialised to guarantee that the starting point is identical for all stations. The installation phase lasted about two years; ensuring a uniform firmware and software distribution across the accelerator is mandatory before starting any commissioning work.

LLRF signal dynamic range optimisation

In this phase, the forward power is increased to its nominal level, typically 150–250 kW per coupler, corresponding to the nominal operation gradient. Adjustable attenuators are then automatically set for all forward and reflected channels so that the signal amplitude uses 75% of the digitiser dynamic range. In most cases, the 31.5 dB range of the programmable attenuators was sufficient. If not, fixed-value attenuators were inserted manually upstream of the LLRF down-converters (less than 1 per mill of cases).

Cavity frequency tuning

After a series of checks to guarantee proper motor function and cavity detuning by the expected amount and in the expected direction, cavities are tuned from their parking position to resonance. This step is performed at a moderate forward power (≈10 kW per coupler, corresponding to 5–10 MV/m per cavity) to avoid any potential quench once the cavity comes close to resonance. A tool for computing and monitoring the cavity resonance during tuning was developed to guide the operator. If no errors were found, tuning a complete RF station (32 cavities) could be done in less than 2 h.

Coupler tuning

The cavity coupling ratio (loaded quality factor Q_L) is then adjusted to its target value $Q_L = 4.6\text{x}10^6$. This task has been automated using a middle-layer server and typically takes a few minutes per RF station. At this point, the cavities are tuned to resonance and have the desired bandwidth. Before proceeding to the next step, a signal validation check is systematically performed. First, a waveform recognition algorithm verifies that forward, reflected and transmitted waveforms have

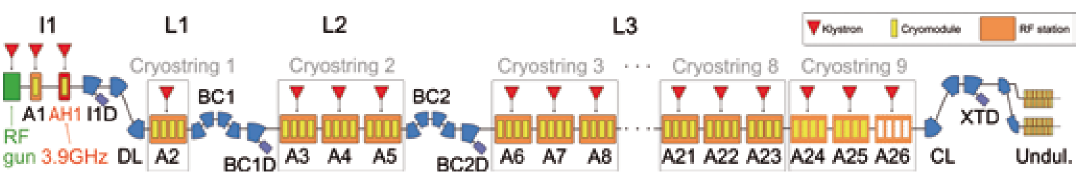

Figure 1

European XFEL accelerator layout, showing the injector I1 and the three linear accelerator sections L1–L3, separated by the bunch compressor sections BC1 and BC2 and their respective beam dumps the expected shapes in order to catch potential cabling mistakes. Second, the script exercises individual waveguide phase shifters while measuring the resulting phase shift on forward, reflected and probe signals. Overall, this helped identify ≈ 20 cable swaps (<1%), which were corrected during the following maintenance days (Fig. 2).

Power-based calibration

The LLRF system requires calibration of over 2400 RF signals, so that displayed waveforms show actual kW or MV. The power at the input of each of the 32 cavity couplers is calculated based on the reported klystron output power and the attenuation of the waveguide distribution measured during assembly. The calibration script retrieves the waveguide attenuation from the cryomodule database and automatically scales the LLRF waveforms to match the calculated power. Reflected and probe signals are then scaled using the calibrated forward power signal as reference. This approach provides a first-order cavity gradient calibration with an accuracy of 10–15%.

Closed-loop operation

When all cavity gradients are calibrated, the phases are aligned (i.e. rotated to a common phase value, still arbitrary with respect to the beam phase). The complete vector sum is computed, combining four cryomodule-wise partial vector sums. An automated procedure measures the system behaviour and defines the parameters of the multiple-inputs-multiple-outputs (MIMO) feedback controller. The system can then be operated in closed loop. The learning feed-forward coefficients are computed based on the measured closed-loop system behaviour.

Cavity phasing and beam-based calibration

For this last step, beam transmission is required: typically 30 electron bunches, 0.5 nC at 4.5 MHz repetition rate. Beam-induced voltage transients are measured to establish the phase relationship between cavities. Phase shifters are adjusted to align the cavity phases relative to the beam. Absolute gradient calibration is achieved by scaling the LLRF operating gradient to match the energy gain measured by the beam energy monitor. A phase scan is performed, measuring the beam energy as a function of phase to validate the 0° on-crest setting. The LLRF system is then in a state where all cavity phases are aligned with respect to the beam, the 0° set point corresponds to on-crest acceleration, and the RF station amplitude set point matches the measured energy gain. This beam-based approach provides an absolute calibration within 1% in amplitude and a few degrees in phase.

Typical issues to be addressed

The error most commonly found was cable swaps, but these could be easily identified and corrected during the commissioning phase. One cryogenic incident was triggered because of undetected quenches, but did not result in any downtime. Cavity quenches due to multipacting appearing for gradients above 17–18 MV/m were observed on nearly all stations, affecting up to 50% of cavities in the worst case. The effect could always be processed away within 2–3 h of conditioning (i.e. controlled quenches). Four couplers out of 720 in use so far had to be shorted because of overheating, six cavities out of 720 had to be detuned out of operation because of high field emission. During the early beam steering, several electronic components were irradiated due to beam losses and triggered false alarms. Although some LLRF electronic failures remain unexplained and could be attributed to radiation, no LLRF component seems to have endured irrevocable damage.

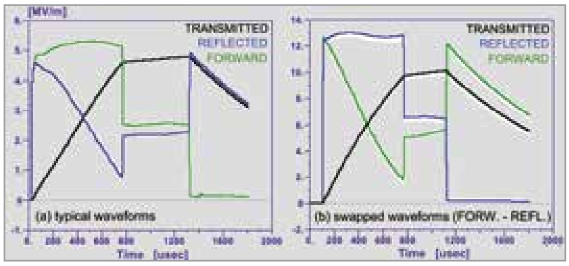

Figure 2

The left panel shows the expected colour code, where the forward signal is depicted in green and the reflected signal in blue. The right panel shows that the forward and reflected cables for that cavity were swapped.

Lessons learnt

The effort put into testing components and performing system checks early on paid off. The experience gathered at FLASH with the MicroTCA.4 LLRF system installed as a prototype for the European XFEL also proved beneficial. A strong commissioning team, reinforced by external colleagues, boosted the work force during the peak commissioning time. The high level of automation, organised as simple modular scripts, was key to performing most of the commissioning tasks in a systematic and reproducible way. Having easy access to the information gathered during cryomodule tests proved essential. Weaker points of the commissioning include the fact that some steps had to be repeated due to incomplete documentation or revised commissioning procedure. Finally, although tracker tools such as Redmine proved very useful, a tool to measure and report the overall commissioning progress was missing.

Overall, the baseline LLRF commissioning went very smoothly. Standard accelerator operation – in which RF station ramp-up, down and recovery after trip events is handled automatically by a finite-state machine, with LLRF expertise and support available as on-call service – was handed over to European XFEL operators after three months.

Since summer 2017, one main effort has consisted in assessing the maximum operational gradients for every RF station. A few other LLRF milestones also remain to be met, such as installing and commissioning the piezo drivers, improving the system start-up time after shutdown and understanding the long-term stability of the system – in particular, measuring the performance of the optical RF synchronisation and the drift compensation modules. Finally, a higher level of automation for LLRF operations, diagnostics and fault detection is also on the agenda.

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Photographs and graphics
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