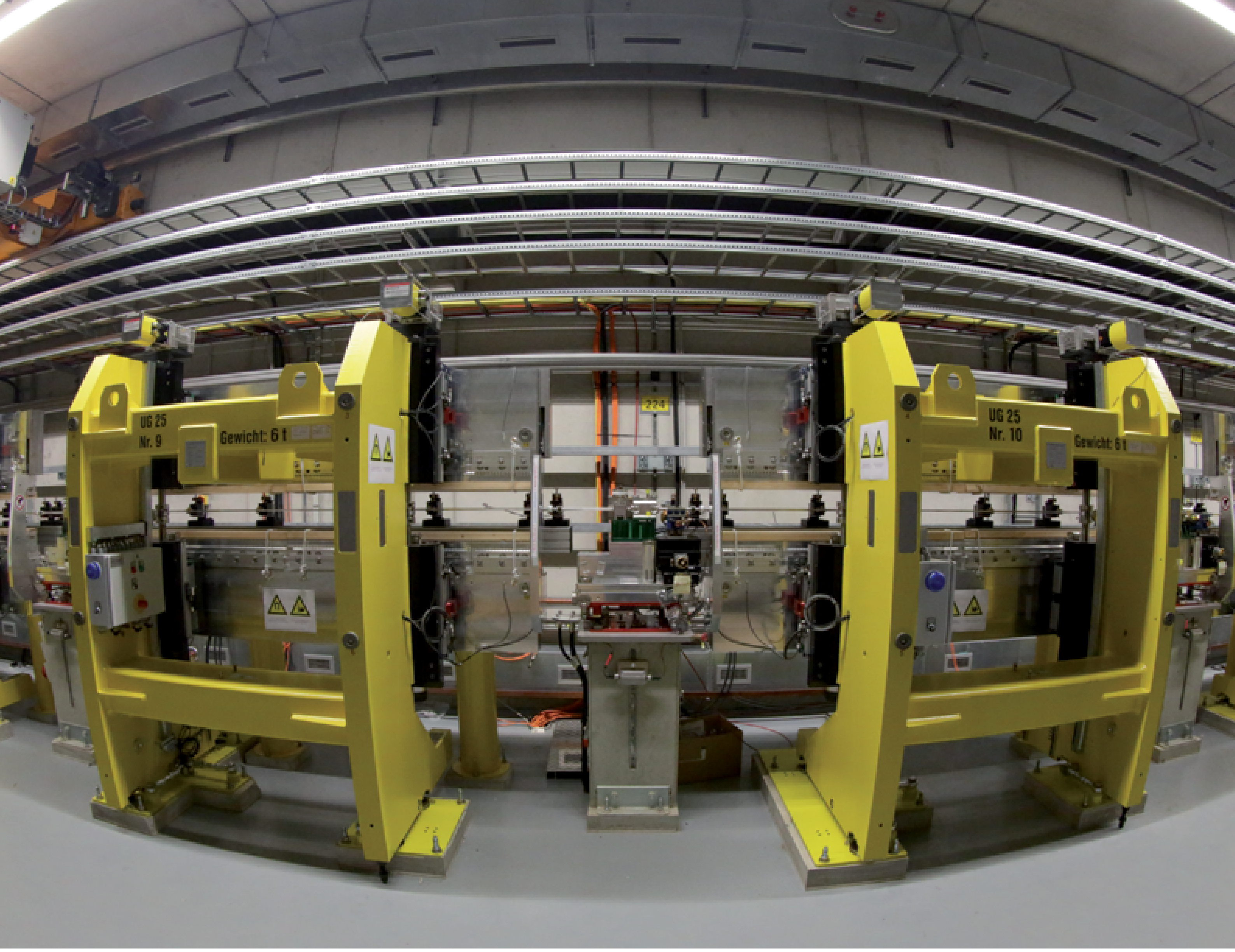

ACCELERATORS 2013.

Highlights and Annual Report

Accelerators | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

Cover

Fisheye image of the new undulator section in FLASH2 (Photo: Dirk Nölle, DESY)

ACCELERATORS 2013.

Highlights and Annual Report

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The year 2013 at DESY.

Chairman's foreword

2013 was a very busy and successful year for DESY.

The construction of the European XFEL X-ray free-electron laser is our top-priority endeavour. DESY contributes significant resources to this international prestige project. The superconducting niobium cavities devised by DESY are at the heart of the facility, and the successful implementation of their industrial series production once again underlined DESY's competence in accelerator R&D. Cavity performance tests at DESY proved that the required technical specifications were met or even exceeded. The linear accelerator infrastructure was completed, as was the installation of the injector complex.

Unfortunately, the project faces a delay due to unforeseen difficulties in the series production of the radio frequency (RF) couplers and to problems with welding seams in the assembly process. The delay amounts to 12 months, so that the commissioning of the European XFEL accelerator is due to start in the second half of 2016.

At our FLASH free-electron laser facility, the realization of the new, second beamline (FLASH2) advanced according to plan, with commissioning due to start in 2014. After the long shutdown, regular user operation of the existing FLASH1 beamline will resume in the first quarter of 2014.

The reliability of the PETRA III synchrotron radiation facility has been continuously improving. Many outstanding projects have been carried out at its various experimental stations, and I congratulate all our users and local contacts who contributed to this impressive success.

The shutdown of the DORIS storage ring at the beginning of 2013 has caused a severe bottleneck for German and European user communities that depend on extended X-ray absorption fine structure (EXAFS) technology and chemical crystallography. With the additional experimental possibilities offered by the new PETRA III extensions, the missing DORIS technologies should become available again, then with nanobeam precision.

The demands and workload the DESY Accelerator Division currently faces are very severe. In addition to the construction of the European XFEL accelerator, the Accelerator Division manages the FLASH2 project as well as the two PETRA III extensions. The DESY Board of Directors is proud of the Accelerator Division and of the way it manages this unusual situation, and extends its heartfelt thanks to all the members of the division for their unwavering efforts, which are greatly appreciated.

Celebration of the completion of civil engineering works for the European XFEL X-ray laser on 6 June 2013

Installation of klystrons in the European XFEL injector building in August 2013

DESY's expertise is essential to the IceCube neutrino telescope at the South Pole, whose discovery of extragalactic neutrinos was selected as breakthrough of the year 2013.

In parallel to the development of new user facilities, new research centres are being established at DESY, which exploit the unique properties of the DESY light sources. Construction of the new Centre for Structural Systems Biology (CSSB) started in 2013. CSSB will be an interdisciplinary centre for pathogen research, with partners from several universities and research facilities from the German federal states of Hamburg and Lower Saxony.

In the field of particle physics, the Large Hadron Collider (LHC) at the CERN research centre near Geneva, Switzerland, will resume operation in spring 2015 at energies close to the design value, and preparations to complete the detectors after maintenance are under way. For the planned high-luminosity phase of the LHC after 2020, major detector upgrades will be necessary, and an intensive upgrade programme was initiated with DESY as a central hub for German universities.

German Federal Minister of Education and Research, Johanna Wanka, speaking at the ground-breaking ceremony for the Centre for Structural Systems Biology (CSSB) at DESY on 4 September 2013

DESY is also gaining significant importance in astroparticle physics. We play a leading role in the preparation of the international CTA gamma-ray telescope, and our expertise is central to the IceCube neutrino telescope buried in the ice of the South Pole. IceCube's recent discovery of extragalactic, super-energetic neutrinos was selected worldwide as scientific breakthrough of the year 2013.

Along with other Helmholtz centres within the research field "Structure of Matter", DESY has been very busy in 2013, particularly during the last months, formulating its research plans for the upcoming Helmholtz funding period 2015–2019. This time, the Accelerator Research and Development (ARD) programme, a new initiative that was strongly pushed by DESY, will be evaluated by external reviewers. I am confident that we will convince the international reviewers of the outstanding quality of this new accelerator initiative. ●

Helmut Dosch
Chairman of the DESY Board of Directors

Accelerators at DESY.

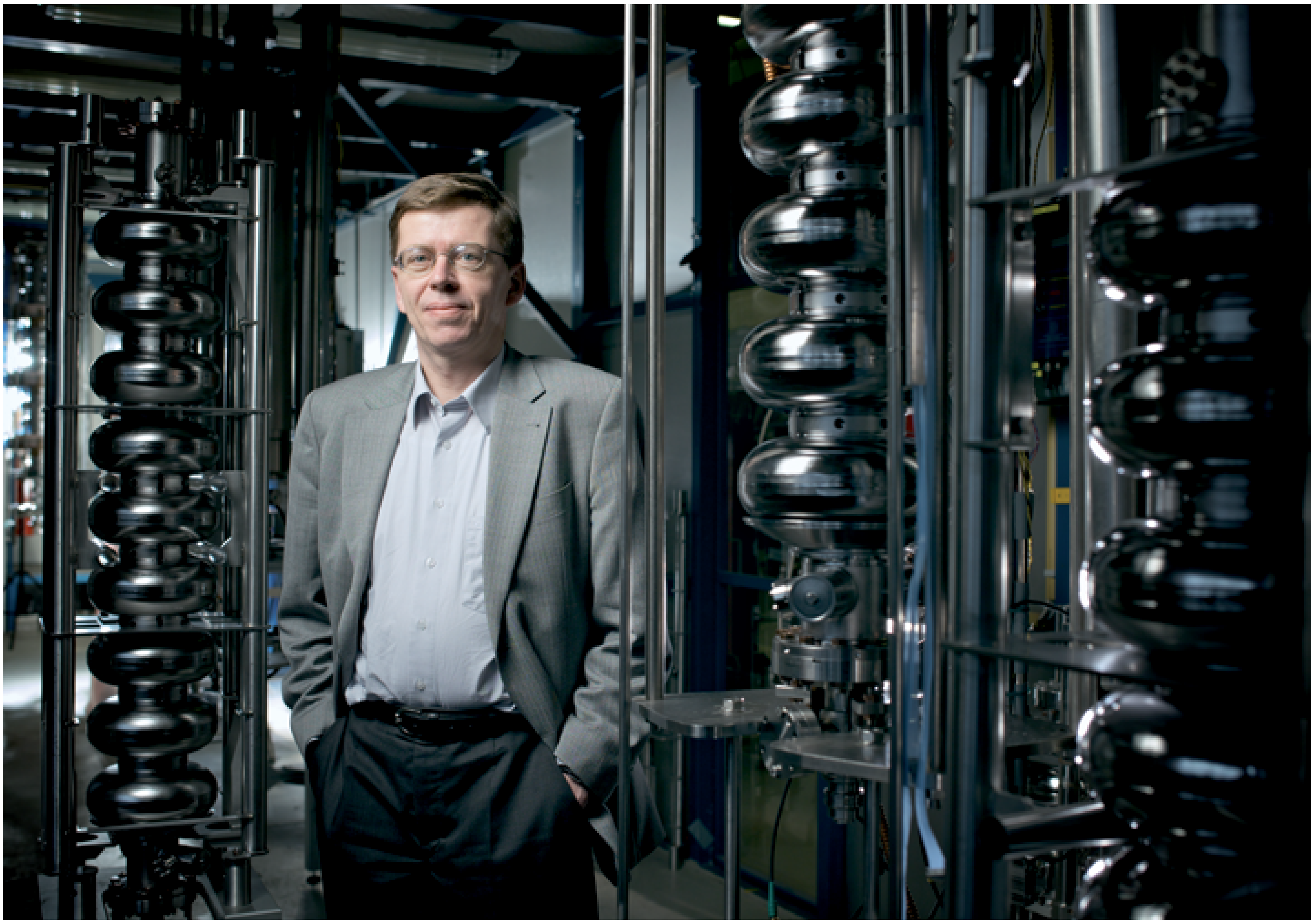
Introduction

Looking back over the year 2013 reveals tremendous progress and success with our accelerator activities at DESY, in machine operation and construction projects as well as research and development. At the same time, we had to face a few challenges in some areas.

The PETRA III synchrotron radiation source was switched from positron to electron operation during the 2012/13 Christmas shutdown. The restart in January went remarkably well and quickly, putting the machine back into regular user operation without delay. The beam dynamics issues due to electron cloud effects, which had manifested themselves during positron operation in an increase of the vertical emittance for certain bunch patterns, had disappeared, as expected. Electron beam operation now shows signs of beam–ion instability, but these occur only in a smaller range of operation modes and are generally less harmful than the previous electron cloud effects. The PETRA III user run, originally scheduled until September, was extended until Christmas 2013 because of a delay in the start of civil construction work for the PETRA III extension project. The operation of PETRA III was very satisfactory throughout most of the year, with availability slightly above the design goal of 95%. In the fourth quarter, however, a few failures caused the yearly averaged availability to drop slightly below 95%. Test beams at the DESY II synchrotron were delivered with more than 98% availability and were used heavily throughout the year. After a few challenges with the tendering for the PETRA III extension civil construction work, orders were placed and first preparatory work started in late autumn 2013. During a few-week summer break of user operation, the PETRA III team performed very interesting and successful machine studies at reduced beam energy, demonstrating a world record of 160 pm rad in horizontal emittance at 3 GeV, fully in accordance with theoretical expectations. These studies are important for future considerations of a possible upgrade of PETRA III to a diffraction-limited storage ring.

Our second facility upgrade activity, the construction of a second undulator beamline at the FLASH free-electron laser facility, proceeded essentially as planned. FLASH was shut down from mid-February to July while the civil construction work for the connection of the new tunnel, the necessary modifications of the FLASH1 beamline and the installation of the new FLASH2 beamline elements in the separation section were ongoing. The FLASH1 modifications, as well as significant ground motion caused by the relocation of large amounts of soil due to the civil construction work, made extended technical and beam commissioning necessary. In addition, new European XFEL-type µTCA low-level radio frequency (LLRF) systems were installed and required extra commissioning (with the benefit of improved energy stability for FLASH and early system tests for the European XFEL). Good beam properties could already be demonstrated in autumn 2013, but the start of regular user operation was postponed to the first quarter of 2014 in order to give the machine group sufficient time for the necessary studies and adjustments to prepare for an efficient user run. While FLASH with the FLASH1 beamline was recommissioned, installation of the FLASH2 beamline components proceeded in parallel and was to a large extent completed by the end of 2013. The RF electron source (gun) at FLASH, which had previously been conditioned and tested at the PITZ photoinjector test facility in Zeuthen, performed very well during the beam commissioning. Nevertheless, there still remains an issue with damage of RF guns in the cathode plug area, which can occur at high gradients and shows an “aging” type of behaviour, and which led to unscheduled breaks of user operation at FLASH in previous years. Tests with a modified design have started, and further improvements are necessary to guarantee reliable operation for FLASH and, in particular, for the European XFEL with its more demanding parameters.

In the European XFEL accelerator construction project, the successful start of the series production of superconducting cavities was clearly the highlight of 2013. By the end of the year, the two manufacturers had delivered some 200 niobium resonators (one quarter of the total production required). The tests performed by our project partners from Kraków, Poland, in the infrastructure of the Accelerator Module Test Facility (AMTF) at DESY show an average accelerating gradient of close to 30 MV/m, well above the European XFEL design value of 24 MV/m. Despite this very satisfying progress with these central components of the superconducting linear accelerator, the project faces a delay of about one year in the production of the complete accelerator modules, which are assembled at our project partners at CEA in Saclay, France. Two pre-series modules were successfully assembled and showed good results on the test stand at DESY, but the ramp-up of the series production was significantly slowed down. This was mainly due



to a delay in the production of RF couplers at the required rate and a problem with welding seams of titanium helium pipes that had to be overcome in the assembly process. A great deal of effort from the DESY XFEL project team went into solving these problems and supporting our partners, and by the end of 2013, significant improvements were visible, although not all obstacles on the way towards the required delivery rate of one accelerator module per week were yet completely removed. In many other areas of the project, progress is according to plan and the costs remain within the planned budget. In autumn 2013, after being tested at Zeuthen, the first small piece of the European XFEL accelerator – the RF gun – was installed in the underground injector tunnel and operated with RF power.

Activities on a much smaller scale than the European XFEL, but nevertheless highly interesting and future-oriented, are ongoing in the Accelerator Research and Development (ARD) programme of the Helmholtz Association. New tests of continuous-wave (CW) and quasi-CW operation of a superconducting accelerator module were very successful, showing a very low cryogenic load at accelerating gradients up to 15 MV/m. The μTCA technology transfer project attracted a large and increasing number of partners from science and industry, demonstrated by the attendance of close to 200 participants at its last plenary meeting. The plans for plasma acceleration that we are developing together with the University of Hamburg as our strong collaboration partner are taking more and more shape, and with the installation and technical commissioning of a 200 TW laser, we are getting closer to doing first experiments. An accelerator–photon science cooperation with colleagues from CFEL in Hamburg on sub-femtosecond beams was launched, and as a 2013 highlight, we were able to congratulate the team for acquiring substantial resources for this innovative project through a European Research Council (ERC) Synergy Grant from the EU. Last but not least, DESY coordinated the ARD part of the Programme-Oriented Funding 3 (POF3) proposal for the next five-year funding period of the Helmholtz Association, thereby for the first time including accelerator physics and technology as an own research topic in such a programme proposal.

The following pages will give you a much more comprehensive overview of our exciting accelerator activities.
Enjoy the reading! ●

R. Brinkmann

Reinhard Brinkmann
Director of the Accelerator Division

News and events.

News and events.

A busy year 2013

February

Poland's Science Minister visits European XFEL and DESY

On 14 February, Poland's Minister of Science and Higher Education, Barbara Kudrycka, visited the European XFEL construction site and DESY. Poland is one of the eight shareholders of the European XFEL and contributes, among other things, a test facility for more than 800 superconducting cavities to the construction of the X-ray free-electron laser. Together with European XFEL Managing Director Massimo Altarelli and DESY Director Helmut Dosch, Kudrycka officially commissioned the test facility on the DESY campus.

Poland's Minister of Science and Higher Education, Barbara Kudrycka, in one of the European XFEL tunnels

"The construction of the European XFEL is – apart from research projects carried out at CERN near Geneva – the most important project that Polish scientists contribute to," said Kudrycka. "I am proud that our researchers, but also engineers and technicians are a significant part of the endeavour."

Prior to their installation into the 1.7 km long accelerator, the superconducting cavities must undergo a thorough test. To this end, the Polish experts developed and built two test benches and delivered them to DESY. In these cryostats, the cavities will be cooled down with liquid helium and tested under operating conditions. The Polish partners also built and installed the complete helium transfer line to and from the DESY helium storage tanks.

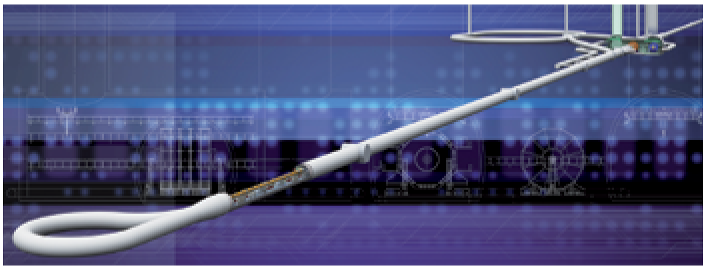
June

ILC technical design report published

The technical design report (TDR) for the International Linear Collider (ILC), a next-generation particle collider to complement and advance beyond the physics of the Large Hadron Collider (LHC) at CERN near Geneva, Switzerland, was published on 12 June. It was officially handed over to the international oversight board for projects in particle physics, the International Committee for Future Accelerators (ICFA).

The TDR marks the completion of many years of globally coordinated R&D work. It contains all the elements needed to propose the ILC to collaborating governments, including a realistic technical design and implementation plan that were optimized in terms of performance, cost and risk.

Highlights of achievements leading up to the TDR include the construction and commissioning of superconducting radio frequency test facilities for accelerators all over the world, as well as great advances in cavity production processes and plans for mass production, as 16 000 superconducting cavities will be needed to drive the ILC's particle beams.



The centrepieces of the ILC, two linear accelerators for electrons and positrons, are based on the superconducting TESLA technology originally developed at DESY. As the accelerator of the European XFEL X-ray laser relies on the same technology, the experience gained with its construction will be extremely valuable for the realization of the ILC.

Russia’s Science Minister visits European XFEL and DESY

The Minister of Education and Science of the Russian Federation, Dmitry Livanov, visited European XFEL and DESY on 28 June. The Russian Federation is an important shareholder of European XFEL and contributes about 27% of the costs, second only to the host country, Germany, which covers 58% and is represented by DESY.

Left to right: Reinhard Brinkmann (DESY Director of the Accelerator Division), Andreas S. Schwarz (European XFEL Scientific Director), Dmitry Livanov (Minister of Education and Science of the Russian Federation) and Massimo Altarelli (European XFEL Managing Director)

Like other shareholders, Russia contributes to the construction of the European XFEL X-ray laser in cash and in kind. Russian research institutes produce a number of different components, among them high-tech cryogenic components, thousands of parts for vacuum systems, 840 electromagnets weighing between 25 kg and 6 t each, and three test stands for accelerator modules.

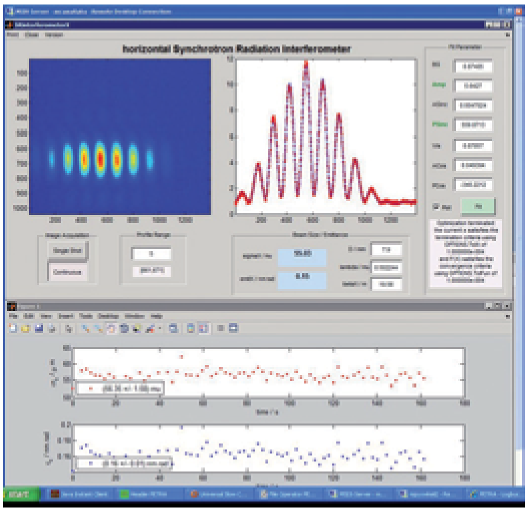
On his tour of European XFEL sites, Livanov inspected the control process for the Russian magnets, inaugurated the first test stand at the newly established Accelerator Module Test Facility (AMTF) and visited the construction site in Schenefeld, the tunnels and the experimental hall where Russian scientists will work side by side with other top international researchers when user operation starts.

August

New emittance world record at PETRA III

Machine physicists at DESY’s PETRA III storage ring set a new world record. At a beam energy of 3 GeV, they achieved a horizontal beam emittance of 160 pm rad, smaller than ever before. Defined as the product of beam area and divergence, the emittance is a measure of the size and order of a particle bunch. It significantly determines the properties of an accelerator as a light source.

The team used a three-week break of user operation to run PETRA III at energies of 3 and 5 GeV, with several hundred weakly charged electron bunches. The goal was to extend the research opportunities offered by PETRA III and take further steps on the road towards the “ultimate storage ring X-ray source”.



Beam size and emittance can be determined using a synchrotron radiation interferogram, which measures the synchrotron radiation from a dipole magnet.

A smaller emittance enables experiments with a higher resolution. With reduced emittance, the transversal coherence increases and the radiation becomes more laser-like. This is a great advantage for synchrotron radiation users, as a higher coherence allows a significant improvement of imaging procedures, such as X-ray holography. Even in the soft X-ray range, in which PETRA III already provides a relatively high degree of coherence compared to other sources, improvements can be made that result in considerably shorter measuring times and more precise and sharper reconstructions.

September

Seeding with femtosecond precision at FLASH

For the first time, researchers from the University of Hamburg and DESY operated DESY's FLASH free-electron laser in direct seeding mode. By overlapping short, extreme-ultraviolet (EUV) laser pulses with the ultrarelativistic electron bunches of FLASH in an experimental setup called sFLASH, the team improved the intensity and length of the pulses compared to unseeded flashes. The method allows the creation of fully coherent electromagnetic radiation – that is, real laser radiation – with high intensities and short wavelengths.

sFLASH undulators in the FLASH free-electron laser

For about ten years, researchers have been using the intense EUV and soft X-ray radiation from free-electron lasers (FELs) for a variety of experiments that were not possible before. The FEL radiation is created by sending a strongly compressed ultrarelativistic electron bunch through powerful magnets, the undulators, which force the electrons on a slalom course. Here, the electrons radiate spontaneous undulator light, which self-triggers an exponential gain process. This self-amplified spontaneous emission (SASE) has many advantages compared to spontaneous undulator radiation, but it suffers from poor longitudinal coherence. Many experiments would dramatically benefit from using fully coherent radiation, which is why accelerator researchers around the world are developing new schemes to improve the properties of FEL radiation for users.

The sFLASH team sent low-intensity, but fully coherent EUV laser pulses (the seed pulses) into the undulator concurrently with the electron beam. Through the interaction of the seed pulses' external laser field with the electrons within the undulator, it is possible to initiate, or "seed", the FEL process and thereby amplify the fully coherent pulses by several orders of magnitude in pulse energy. The challenge is to actually hit the short electron bunches with the even shorter EUV laser pulses, as the pulse durations involved are shorter than 50 fs. Travelling at the speed of light, this corresponds to a length shorter than the thickness of a human hair. To get the pulses to overlap, sophisticated diagnostics is needed in order to measure and control the position and arrival time of both beams.

The EUV seed beam is generated by means of non-linear frequency up-conversion of near-infrared (NIR) laser pulses in rare gases, a process called high-harmonic generation (HHG): by focusing a NIR laser pulse into a noble gas, such as argon at sFLASH, it is possible to create light with a much shorter wavelength. For sFLASH, an HHG source was developed that delivers fully coherent laser pulses at a wavelength of 38 nm.

After installation of the seeding setup in the FLASH tunnel in 2009–2010, the researchers commissioned the setup and improved some of the subsystems in order to transport sufficient pulse energy into the seeding undulator. The first observation of a seeded FEL signal at sFLASH set a new world record of the shortest wavelength ever used for directly seeded FELs. In addition, both the pulses used for seeding and the electron bunches were about one order of magnitude shorter than what had been used in previous experiments at other facilities around the world.

After optimization, the seeding process yielded a significant enhancement of the FEL pulse energy. As the seed pulses are much shorter than the electron pulses, the power difference was expected to be even larger. In spectral measurements of the second FEL harmonic at 19 nm, the power of the seeded and unseeded FEL radiation differed by a factor of 36.

In the future, the sFLASH team will improve the FEL diagnostics to allow the coherence and synchronization of the seeded radiation to be characterized directly in the time domain of the FEL pulses. This would enable the team to demonstrate to what extend the seed pulse properties are preserved in the FEL amplification process.

Topping-out for FLASH experimental hall

On 25 September, DESY, the building firms and architects celebrated the completion of the roof of the FLASH II experimental hall with a traditional topping-out ceremony. Construction of this second experimental hall started in January 2013. It is part of the FLASH II project, which involves the realization of a second undulator beamline at the FLASH free-electron laser facility to provide more users with the highly demanded X-ray radiation. The beamline branches off the existing FLASH tunnel behind the FLASH accelerator.

The tunnel for the undulators and the technical buildings for the seeding laser, cooling water and magnet power supply located on the inside of the PETRA III storage ring are already completed, including the technical infrastructure. The 2200 square metre experimental hall on the outside of the PETRA III ring should be “rainproof” in January 2014 and will then be handed over to DESY, including the technical infrastructure. DESY will then start to install the beamlines leading to the experiments. Up to seven experimental stations are planned in the hall in the long term. First experiments with the laser radiation generated by the second FLASH undulator beamline are scheduled for autumn 2014.

Topping-out ceremony for the FLASH II experimental hall

October

DESY mourns Gustav-Adolf Voss

Gustav-Adolf Voss, Director of the Accelerator Division at DESY from 1973 to 1994, passed away on 5 October 2013 in Hamburg at the age of 84. Voss greatly influenced the development of particle accelerators worldwide. He was highly respected throughout the world and a lifelong advocate of international cooperation in science.

Prof. Gustav-Adolf Voss

Under Voss’ leadership, the DORIS storage ring was successfully put into operation and expanded. Starting in 1975, Voss directed the planning and construction of the PETRA electron–positron storage ring, which achieved previously unprecedented collision energies. Thanks to Voss’ skilled leadership, the accelerator was completed sooner than its American counterpart and at a lower cost than planned. PETRA’s design and construction are still considered exemplary for modern electron storage rings. Voss also oversaw the construction of Germany’s largest particle accelerator, the HERA electron–proton storage ring, which was put into operation in 1991. He recognized early on the great potential of linear accelerators for high-energy physics, and promoted promising concepts such as wakefield acceleration.

With the death of Gustav-Adolf Voss, DESY has lost one of its most influential figures. His charismatic leadership, expert skills and foresight have greatly contributed to DESY’s current standing as an internationally leading accelerator laboratory. We owe him our sincere gratitude and will always hold him in high regard.

October

PhD thesis award 2013

The PhD thesis award 2013 of the Association of the Friends and Sponsors of DESY (VFFD) was shared by Johannes Hauk and Andrej Singer.

Johannes Hauk

Andrej Singer

Johannes Hauk graduated from the University of Hamburg with work done for the CMS group at DESY. In his PhD thesis “Measurement of Associated Z^0-Boson and *b*-Jet Production in Proton-Proton Collisions with the CMS experiment”, he presented outstanding contributions to particle physics in three separate fields. His main results provide important insights into the relationship of electroweak processes (Z^0 production) with processes involving heavy quarks (*b* quark jets) within the theory of quantum chromodynamics, and into how these relationships could be used for analyses involving Higgs pair production. He also carried out pioneering work on using Z^0 production as a reference process for the determination of the top cross section, and made an important technical contribution to the calibration of track reconstruction in the CMS tracker.

Andrej Singer studied at the University of Münster in cooperation with DESY and obtained his PhD in photon science at DESY. In his thesis “Coherence properties of third and fourth generation X-ray sources – Theory and experiment”, he studied the coherence and statistical radiation properties of new X-ray sources, such as PETRA III, FLASH and LCLS at SLAC. Singer performed theoretical studies of the transverse coherence properties based on the operating parameters and compared these with experimental results. His investigations into the coherence properties of LCLS, in particular, entered new territory. Singer also determined the coherence properties of FLASH in the soft X-ray range using intensity correlations after a procedure proposed for the visible spectrum. These experiments will be of great importance for the future use of free-electron lasers in areas such as quantum optics.

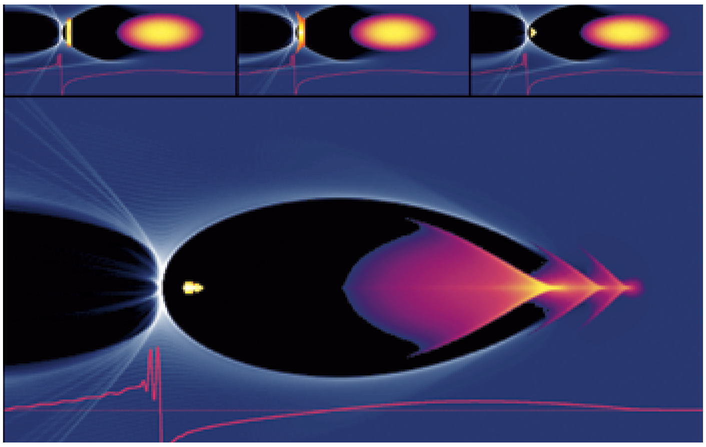
The PhD thesis award of the Association of the Friends and Sponsors of DESY includes a prize money of 3000 euro. The association presents the prize every year for one or two outstanding PhD theses.

December

New injection concept for plasma acceleration

A DESY team developed a new concept to improve electron-beam-powered plasma accelerators. Simulations suggest that the idea should enable the acceleration of very high-quality particle bunches.

Plasma wakefield acceleration is a new technology aiming to accelerate particle beams to highest energies over very short distances. The idea is to create a plasma, a highly excited state of ionized matter in which electrons and atomic nuclei can move freely, from a gas using either a particle beam or an intense laser flash, and to utilize this plasma as the acceleration medium. The particle bunch that is shot into the gas excites an electron density wake – a wakefield – travelling behind it, in which very high electric fields form. The goal is to accelerate electrons using these fields, with the electrons either originating directly from the plasma or being sent into the plasma from an external source. The technology is the subject of intensive studies, done among others within the Accelerator Research and Development (ARD) programme of the Helmholtz Association. In the long term, the research might lead to compact accelerators for particle physics or for free-electron laser operation.



Simulated propagation of a compact and ultrarelativistic electron beam through a hydrogen plasma. The top frames show a sequence of the injection process of helium electrons by means of the strong accelerating wakefields only. The main frame shows the final position within the wake of the injected electron bunch. Here, the accelerating field surpasses 100 GV/m.

A central issue in plasma acceleration is to capture the particle beams in the wakefield and further accelerate them with the quality required for the intended applications. The problem is considerable in plasma accelerators that are driven by a particle beam. Here, the wakefield propagates at almost the speed of light and is too fast to carry and accelerate the free electrons in the plasma “from rest” and form them into a usable bunch.

To solve this issue, the DESY physicists proposed to mix small quantities of helium locally into the hydrogen gas inside the plasma cell. If a particle bunch is then injected into the cell, two distinct areas are created in which the hydrogen gas is completely ionized. However, the helium atoms added to the short, front-most part of the plasma stay neutral during the passage of the electron beam and are only ionized by the following plasma wakefield. Thus, the electrons from the helium are released only in a well-defined area of the plasma wave and are immediately taken along by the high electric fields. The arrangement means that these electrons can optimally follow the strong acceleration in the wakefield area without use of any other instrumental assistance. In addition, the helium doping allows for a simple control of the number of captured electrons.

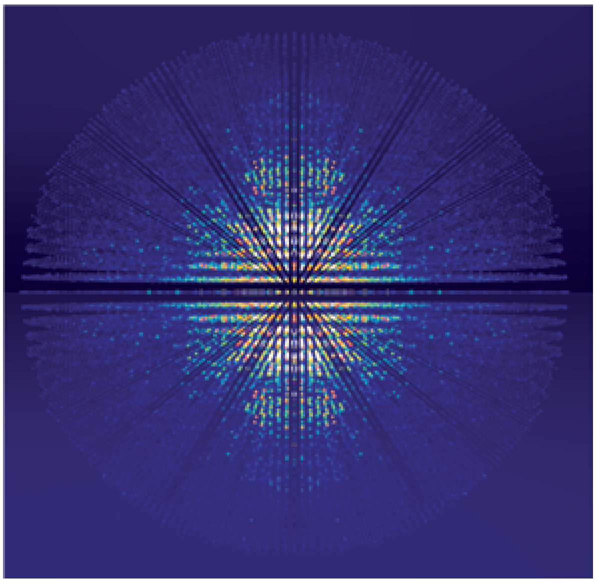
To validate their idea, the DESY team carried out 3D simulations of a particle bunch with an energy of 23 GeV and characteristics as provided by the FACET accelerator at SLAC in California, shot into a 46 cm long plasma cell. The plasma cell was set up such that it was mostly filled with pure hydrogen, with a helium–hydrogen mixture injected through a nozzle at the entrance. The field profiles predicted by the simulations were very promising. In the helium area, the wakefield featured a very high field strength, which ionized the helium and accelerated its electrons at more than 100 GV/m; the field strength was maintained when the beam propagated in the area of the pure hydrogen, so that the high-quality electron bunch was constantly accelerated further.

The simulations, which were carried out over an acceleration distance of 20 mm, showed that the electron bunch that was created and accelerated inside the plasma not only acquired an energy of 3 GeV over this short distance and had a pulse length of approximately 1 µm, but also displayed high quality in important properties, such as intensity, emittance and energy distribution. Theory predicts that the technique could reach twice the input energy of the beam that initiated the plasma wave. The bunch of accelerated electrons would feature an energy of 46 GeV at FACET, and its emittance would be improved by an order of magnitude compared to the driver beam.

As the next step, the researchers aim to test their gas cell under real conditions at FACET at SLAC. Starting in 2016, they will use a 10 cm long plasma cell in the FLASHForward experiment at FLASH to both accelerate particles from the plasma itself and push particle bunches from FLASH to higher energies.

EU funds slow-motion camera for the nanocosm

To trace and understand chemical and biological processes taking place in attoseconds with full atomic detail: this is the goal of four scientists of the University of Hamburg, DESY and Arizona State University, who will receive 14 million euro through a European Research Council (ERC) Synergy Grant for the coming six years.



Visualization of X-ray diffraction data from Photosystem I, a large membrane protein complex central to photosynthesis. The data was obtained by combining individual diffraction “snapshots” from many thousands of tiny protein crystals, acquired using the intense femtosecond X-ray pulses of LCLS at SLAC in California.

To film ultrafast processes in slow motion, Franz Kärtner (CFEL, DESY and University of Hamburg), Henry Chapman (CFEL, DESY and University of Hamburg), Ralph Aßmann (DESY) and Petra Fromme (Arizona State University) will develop a kind of stroboscope with ultrashort flashes in the attosecond range. To reach atomic resolution, the flashes will be short-wavelength X-rays. This will allow insights into so far unobservable processes of nature. The facility, which will be built within the Frontiers in Attosecond X-ray Science: Imaging and Spectroscopy (AXSIS) project, will be included in a new research complex for accelerator science at DESY. The attosecond source will be based on a novel, laser-driven particle accelerator technology that will emit X-ray radiation with much shorter pulses than is possible today.

The technology will revolutionize our understanding of structure and function at the molecular and atomic level and unravel fundamental processes in chemistry and biology, e.g. the dynamics of light absorption, electron transport and protein structural changes during photosynthesis – one of the major unsolved problems of structural biology.

Accelerator operation and construction.

PETRA III.

User operation and facility extension

At DESY's PETRA III synchrotron radiation source, a shift in the schedule of the planned facility extension resulted in another year fully devoted to user operation. In 2013, a total of 5236 hours of synchrotron radiation beam time was delivered to users at 14 beamlines. This is the largest number in the history of PETRA III user operation so far. Over long periods of the year, high reliability was achieved. After the shutdown of the DORIS storage ring at the end of 2012, PETRA III was switched from operation with positrons to electrons. In the course of the year, two new modes of operation were established, a continuous mode using 960 bunches and the 40-bunch timing mode operated at 100 mA beam current. Eventually, in November, the contracts for the civil construction of the PETRA III facility extension were awarded, and the contractors carried out first preparatory work. A large number of accelerator components have arrived on site, and people are raring to go.

User operation

After ten weeks of operation for the OLYMPUS experiment, the DORIS storage ring was finally shut down at the end of 2012. As DORIS and PETRA III shared the same pre-accelerators, operating DORIS with positrons forced the PETRA III operators to use the same particle type. During a short winter shutdown, the opportunity to switch to electrons was taken, and preparatory work and technical commissioning were carried out. After this thorough preparation, the actual commissioning with electron beam was accomplished in only four days of machine setup, and user operation resumed on 21 January 2013. Since the start of the PETRA III facility extension had to be shifted to 2014, user operation continued until 19 December. The necessary maintenance was done in five dedicated service weeks distributed over the year. In addition, two short breaks of user operation divided the full user period into eight run periods. On Wednesdays, user operation was interrupted by weekly regular maintenance and machine development activities for about 24 hours. The distribution of the different machine states in 2013 is shown in Fig. 1.

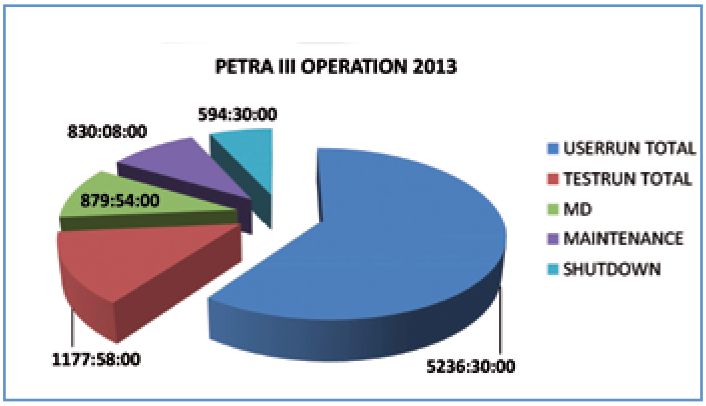


Figure 1

Contribution of different machine states to the total available time in 2013

During user runs, the storage ring was operated in two distinct modes characterized by their bunch spacing. In the “continuous mode”, 100 mA were filled in either 480 or 960 evenly filled bunches corresponding to 16 ns and 8 ns bunch spacing, respectively. Both continuous operation modes were delivered to users for the first time in 2013. The reason for changing the bunch pattern in continuous-mode operation traces back to the change in particle type. Operation of PETRA III with positrons was affected by electron cloud effects that led to a vertical emittance blow-up and prevented the use of bunch spacing smaller than 24 ns. Operation with electrons is affected by ion cloud effects. These effects turned out to be milder than expected and of different type. While standard arguments regarding ion trapping predict stronger influence at smaller bunch spacing, observations at PETRA III show the strongest effect in operation modes using 192 and 240 evenly filled bunches. This seems to indicate the existence of a kind of threshold bunch current of about 300 µA. Moreover, applying clearing gaps does not mitigate the ion cloud effect, which implies that a fast ion instability is observed. The appearance of certain multibunch modes suggests an explanation in terms of a two-stream instability. Further studies to confirm this conjecture are scheduled for the beginning of 2014 before the shutdown for the PETRA III facility extension.

The “timing mode” allows users to perform time-resolved experiments and is thus characterized by considerably larger bunch spacing. Two filling schemes are used in this mode, 100 mA in 60 bunches and 80 mA, or more recently 100 mA, in 40 bunches. The deviation from the design current in the 40-bunch mode is caused by a technical deficiency of the RF shielding in the bellows around the undulator chambers. The replacement of these bellows with a new design, which was started already in 2012, was finished in May 2013. During machine studies in July 2013, first tests with 100 mA in

40 bunches were successfully carried out. However, in subsequent tests it turned out that higher-order mode heating at diagnostic windows of the RF cavities prevented user operation in that mode. During a short shutdown at the beginning of September, a suitable RF shielding was installed to protect the diagnostic windows. In October 2013, first user operation with 100 mA in 40 bunches was possible. However, operation at very high single-bunch currents puts considerable stress on some technical components. Further improvements, in particular of the RF system and the longitudinal feedback system, will be necessary to guarantee high reliability in this mode. A corresponding list of measures is due to be implemented during the PETRA III extension shutdown.

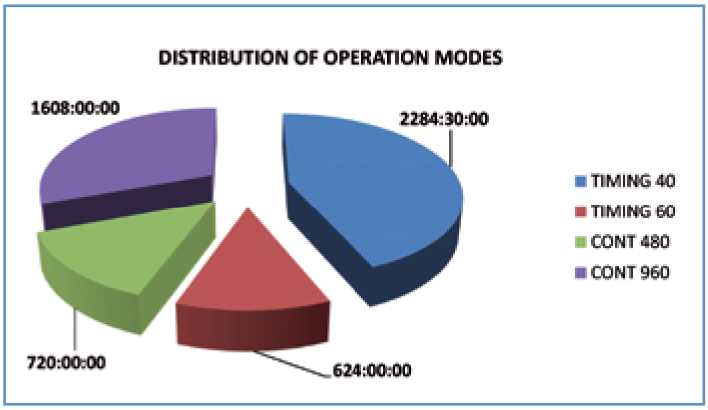


Figure 2

Contribution of different operation modes to user runs in 2013. More than 55% of the totally available time for user runs was delivered in timing mode.

High reliability is one of the key requirements of a synchrotron radiation facility. The key performance indicators, availability and mean time between failures (MTBF), for the four operation modes are summarized in Fig. 3. The 40-bunch mode shows the lowest availability and the shortest MTBF, reflecting the high stress imposed on the technical components. The fact that the 960-bunch mode also failed to reach the target availability of 95% can be traced to a period of operation affected by cumulated technical problems around mid-2013. However, these were not related to peculiarities linked to the 960-bunch mode.

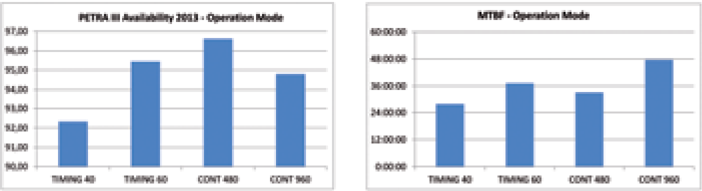


Figure 3

Key performance indicators, availability and mean time between failures (MTBF), shown for the four operation modes used in 2013

As can be seen in Fig. 4, the weekly availability exceeded the targeted 95% over long periods of the year. The figure also shows the development of the average availability over the year. The target of 95% was missed mainly due to a damaged coupler in the cavity section, which led to an interruption of machine operation for a few days and resulted in a marked dip in the weekly availability.

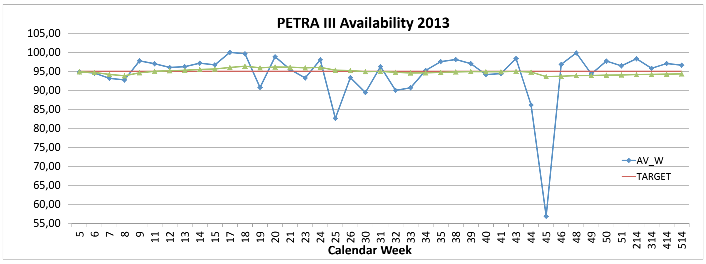


Figure 4

Availability in 2013. The blue curve shows the weekly average, the green curve the yearly average. The solid red line indicates the target availability of 95%.

In summary, the target availability of 95% has been missed in the last three years of operation, and the MTBF is not satisfactory, in particular in timing mode. Both facts are caused to a large extent by problems with the RF system and call for a strong effort to improve the reliability of the system. The issue will be tackled in 2014.

PETRA III extension

The PETRA III facility extension project faced unexpected delays in 2013. The original schedule, with civil construction starting in September 2013, had to be shifted to February 2014 due to problems with the calls for tender. Finally, the contracts with the successful tenderers were signed in November 2013. First preparatory work started in December for both extension halls, North and East. The schedule for clearing and dismantling of the tunnel was finalized. A large number of diagnostics components, magnets, vacuum chambers and power supplies have arrived on site and are currently being prepared for installation, which is expected to start in August 2014. Commissioning of the extended facility will begin at the end of 2014.

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Figure 5

View of the construction site for the PETRA III extension hall East

FLASH.

From one to two

The year 2013 at DESY's FLASH free-electron laser facility was dominated by the construction and installation work for the second undulator beamline, FLASH2. The FLASH tunnel was opened on a length of 10 m to allow the bifurcating beamline to exit the tunnel towards the new FLASH2 beamline buildings. This work forced the FLASH facility into a six-month shutdown from the end of February to mid-August. The fourth user period was concluded successfully at the end of February. The recommissioning of the accelerator and photon beamlines for FLASH1 started as scheduled in August 2013. Unfortunately, the major work for the new FLASH2 buildings was delayed, so the expected ground settlement of the existing FLASH tunnel by up to 1 cm occurred in late summer only, significantly delaying the recommissioning process. By the end of 2013, the accelerator and photon beamlines had finally been commissioned and were ready for beam delivery to users.

Fourth user period and construction work

During the fourth user period from March 2012 to February 2013, 3528 hours were scheduled for user runs. Out of this time, 84% was dedicated to beam delivery for user experiments, 7% was planned to set up the electron and photon beam, and 9% was reserved for contingency. During 75.2% of the time, FEL radiation was actually delivered. Tuning took 15.2%, and the total downtime was 9.6%. In summary, 2715 hours of FEL radiation in the wavelength range from 4.2 nm to 44 nm were provided to user experiments, corresponding to 92% of the time scheduled for them.

In parallel to the fourth user period, construction of buildings and manufacturing of beamline components proceeded for the second undulator beamline FLASH2. During the six-month shutdown starting on 18 February 2013, the connection between the existing FLASH tunnel and the new FLASH2 buildings was realized. An opening was cut into the tunnel wall on a length of 10 m. A 12 m long section of the FLASH beamline between the last accelerator module up to the collimation section was modified to provide room for the beam extraction elements, a septum magnet and three kickers, and the FLASH2 extraction beamline. Figure 1 shows the bifurcation into the FLASH1 and FLASH2 beamlines downstream of the septum magnet. The opening in the tunnel wall between the old and new buildings can be seen in the back.

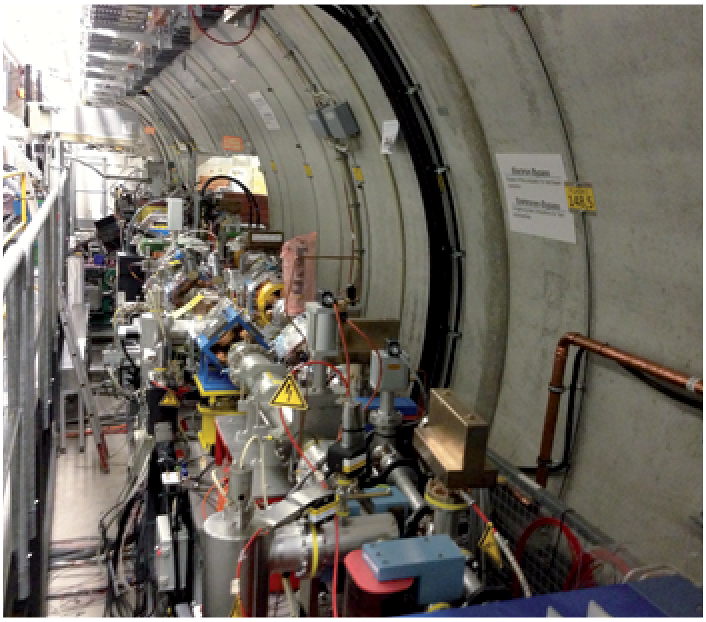

Figure 1

Bifurcation of the FLASH beamline into FLASH1 and FLASH2. The opening in the tunnel wall between the old and new buildings is visible in the back.

Recommissioning

Recommissioning of the FLASH linear accelerator and the existing FLASH1 beamline started in August 2013. The load of the new buildings and the filling of the triangular area between the old FLASH tunnel and the new buildings with sand caused a vertical settlement of the FLASH1 beamline section from the accelerating modules to the photon beamline at the PETRA III crossing. As predicted, the ground sag was between 5 and 10 mm. Due to delays in the construction of the buildings, the settlement of the electron and photon beamlines could only be corrected in late summer 2013 during commission runs. The extra time needed for survey and beamline adjustment work caused a significant delay in beamline commissioning for both electrons and photons. Because of this, and also due to significant modifications of accelerator controls and procedures to ensure compatibility with the European XFEL (e.g. upgrade

Figure 2

Brand-new variable-gap undulators installed in the FLASH2 beamline

of the accelerator low-level RF controls to the European XFEL standard), as well as upgrades to modern field bus standards (magnet controls), commissioning took more time than expected.

Commissioning was completed in December 2013. The next steps will be the integration of the safety interlock system of FLASH2 into a common FLASH system and the preparation of the fifth user period, which is due to start in February 2014. The year 2014 and the first quarter of 2015 will be dedicated to FLASH1 user operation and commissioning of the new FLASH2 beamline.

FLASH2 installation work

After completion of the FLASH2 extraction beamline, installation work continued in the FLASH2 tunnel. Additional radiation safety shielding of the extraction section allows FLASH1 to be operated during installation work in the new FLASH2 buildings. An important milestone was the installation of the new variable-gap undulators before the end of the year. Figure 2 shows the undulators and the vacuum beam pipe. The yellow support structures hold the undulator plates with their arrangement of small permanent magnets pointing to the vacuum chamber in the centre. The gap between the plates can be remotely adjusted to tune the FEL wavelength in a wide range without the need to change the electron beam energy. This is a significant advance compared to the fixed-gap undulators of the FLASH1 beamline, and makes it possible to operate both beamlines simultaneously with different wavelengths. Beam tests in early 2013 showed that FLASH can indeed produce two separate bunch trains per shot with different characteristics. One sub-train is used for FLASH1, the other for FLASH2, so that both beamlines are served with trains of FEL radiation at the 10 Hz repetition rate of the accelerator.

Finalizing buildings and infrastructure

In parallel to the beamline installation work, the new buildings are being finalized and road infrastructure is being constructed. Figure 3 shows the FLASH2 buildings. The new buildings contain the tunnel with the FLASH2 beamline and several rooms for electricity, power supplies, air conditioning and control electronics.

Two rooms are reserved for large-scale laser systems. One laser system will serve as an external seed for seeded FEL radiation, the other system will be used for accelerator studies, especially plasma acceleration experiments in a planned third beamline housed in the FLASH2 tunnel (FLASHForward).

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Figure 3

Construction work on the FLASH2 buildings

PITZ.

Gun preparation for FLASH and the European XFEL

Throughout 2013, operation of the PITZ photoinjector test facility at DESY in Zeuthen stood under the sign of preparing electron sources (guns) for FLASH and the European XFEL. In parallel, preparations for further studies on accelerator R&D were undertaken.

Gun preparation at PITZ

A gun for FLASH: Gun 3.1

During the first weeks of 2013, Gun 3.1 was conditioned and characterized at PITZ. This gun of an older design had already formerly been used at PITZ. In the meantime, it was fitted with a new cathode spring design and was the first gun to be equipped with a Thales-type RF window. In this combination, a power level of 7.75 MW in the gun could be reached – the highest power level ever operated at PITZ. Consequently, a maximum electron beam momentum of 7 MeV/c was measured, which in turn is the highest beam momentum ever reached with a 1.6-cell gun cavity. While the power level in this gun cavity was extremely high, the dark-current emission of Gun 3.1 was the lowest ever measured. This cannot be explained only by the applied dry-ice cleaning technology. We suspect that the conditioning with long pulse trains at high peak power led to the low dark-current emission: only 50 µA were measured at full power (7.75 MW), which makes this cavity perfectly suitable for operation at FLASH. Gun 3.1 was sent to Hamburg in March 2013 and is now installed in FLASH, where it will serve as the electron source for the scheduled, more than 12-month-long user run.

The European XFEL start-up gun: Gun 4.3

On 27 February 2013, the European XFEL start-up gun was finally delivered to Zeuthen – several months later than expected, due to severe quality problems with the new Thales-type RF windows, which manifested themselves in low performance at the RF test stand in Hamburg. The gun was installed at PITZ and RF conditioning started in March 2013. After a three-month period of conditioning followed by a very short beam characterization phase, the gun was dismounted and sent to Hamburg on 25 July 2013 – exactly in time with the European XFEL schedule. Together with the gun, a detailed internal report was delivered, describing and summarizing the conditioning and gun characterization experiences at PITZ.

Figure 1

The Gun 4.3 setup was dismounted from the PITZ beamline and loaded onto the lorry for its transport from Zeuthen to Hamburg. It is now installed in the European XFEL injector building.

The gun was installed in the European XFEL injector building and operated for the first time in December 2013 during the tests of the new RF distribution system for the European XFEL. This could be called the “start of first operation at the European XFEL”.

The European XFEL spare gun: Gun 4.4

After the delivery of Gun 4.3 to the European XFEL, the next gun cavity came to Zeuthen in September 2013. This cavity, Gun 4.4, is equipped with the best Thales-type RF window produced so far. This window was successfully conditioned at the RF test stand in Hamburg to the full European XFEL power specifications: 6.5 MW RF power at 650 µs pulse length with a repetition rate of 10 Hz. The conditioning of the entire system, gun and window, consequently showed the fastest progress in the more than 10-year history of PITZ. After 12 days already, full power was reached in the cavity (at 10 µs, 5 Hz).

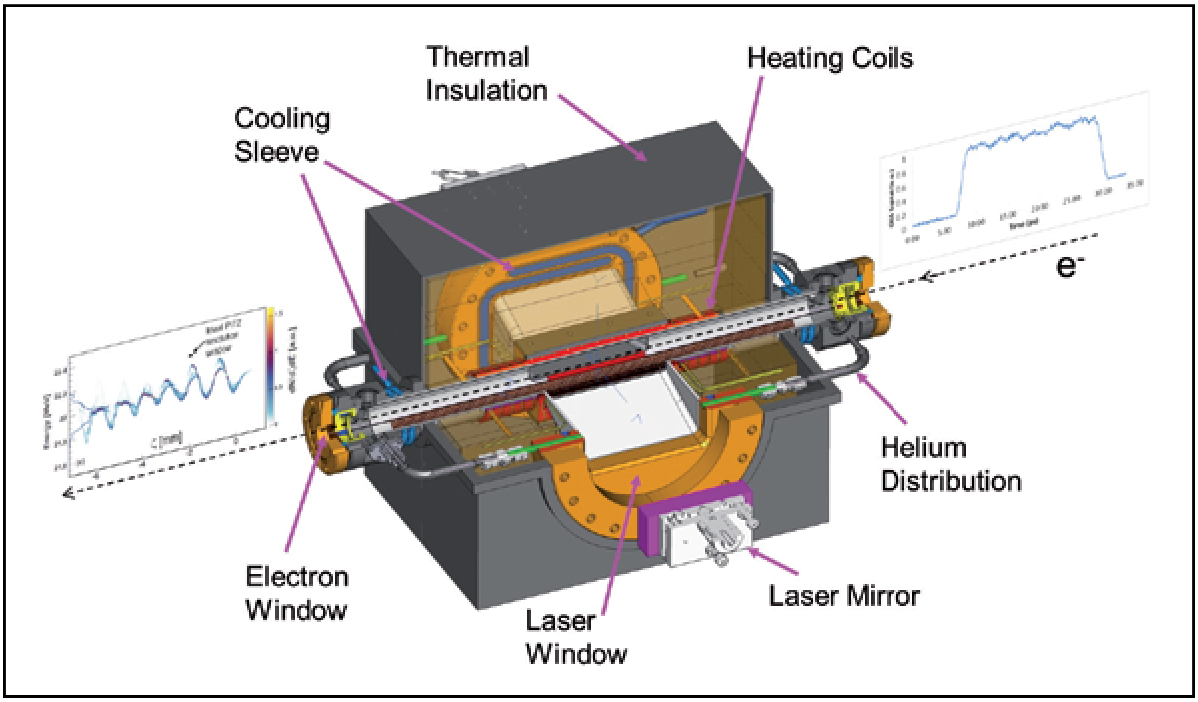

Figure 2

Design of the plasma cell. The major components are labelled. The temporal distribution of the electron beam at the entrance of the plasma cell (right insert) and the simulated energy modulation of the electron beam after passing the plasma (left insert) are shown in addition.

At the end of 2013, cavity conditioning was almost finished. First beam operation already took place in November. In December, gun performance tests for FLASH and European XFEL parameters were carried out at PITZ. In January 2014, a longer period of beam operation will start at PITZ, with a tightly booked measurement programme that includes complete beam characterization as well as studies for special European XFEL operation modes (e.g. low-charge operation) and preparatory studies for the particle-driven plasma wakefield experiments planned at PITZ. In late spring, Gun 4.4 will be dismounted from the PITZ beamline and made available as a spare gun for the European XFEL. Afterwards, another gun will be used at PITZ for the experiments planned in 2014–2016.

Accelerator R&D at PITZ

As a partner in the accelerator R&D programme of the Helmholtz Association, the PITZ team will prepare a pioneering experiment for advancing the basic understanding of particle-driven plasma wakefield acceleration. For this purpose, a plasma cell will be installed in the PITZ beamline. The goal of the experiment is to measure the energy modulation of an electron beam passing through the plasma. Thanks to the variety of electron beam diagnostics installed at PITZ, the facility is perfectly suited for such studies.

During 2013, the plasma acceleration experiment was prepared. A plasma cell was designed based on simulations and experience at related experiments (Fig. 2). The main functionality is that of a lithium heat pipe oven with helium buffers, with side ports added as a novelty. These ports will allow the coupling of the ionization laser that generates the plasma channel at the centre of the lithium column. This arrangement avoids additional optical elements along the beamline outside of the plasma cell and makes it possible to generate a plasma channel with a well-defined beginning and end. Additionally, it will be possible to use the side ports for diagnostics, e.g. to measure the plasma density.

The fabrication of the plasma cell will be finished in January 2014. The plasma cell will be inserted into the PITZ beamline later that year for first experiments.

3D ellipsoidal laser pulses

Within the framework of a German–Russian collaboration, a new laser system for PITZ is under development at the Institute of Applied Physics (IAP RAS) in Nizhny Novgorod, Russia. The laser system, which will deliver 3D ellipsoidal pulses, will be experimentally tested at PITZ.

According to simulations, the special temporal laser shaping will allow a significant improvement of the overall brightness of the photoinjector. The measurements planned at PITZ will allow a detailed characterization of the electron beam produced by the 3D ellipsoidal laser pulse, as a proof of principle for such a pulse-shaping technique.

The delivery of this laser system is foreseen for September 2014. Its installation requires a major re-arrangement of the current laser hutch, which is scheduled for late spring 2014.

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European XFEL.

Accelerator component production and first commissioning

The accelerator complex of the European XFEL is being constructed by an international Accelerator Consortium under the leadership of DESY. Seventeen European research institutes are contributing to the accelerator complex and its comprehensive infrastructure. Beamline magnets and major vacuum components are being delivered from Russia. Beam diagnostics elements are being produced at different institutes. The accelerator modules are being constructed in a shared effort by partners from several countries. DESY coordinates the Accelerator Consortium and contributes many accelerator components as well as technical building equipment and general infrastructure. With the completion of the accelerator tunnel infrastructure, the installation phase has begun.

First installed accelerator components

The production of accelerator components for the European XFEL is in full swing. In all accelerator and facility infrastructure work packages, delivery of small- or large-series orders started. With the RF electron gun, first components were made available for tunnel installation. Commissioning in the injector building began. The required RF power was generated by the first installed multibeam klystron, with energy supplied from the first commissioned modulator, located in the above-ground modulator hall (XHM) on the DESY-Bahrenfeld site.

In general, constant component delivery rates have to be guaranteed, and slight variations of the rates have to be compensated. Quick but reliable quality control is of the highest importance. Such quality control requires sufficiently high test rates in a variety of test stands, including the Accelerator Module Test Facility (AMTF) at DESY, but also using many other inspection tools.

Component integration now plays a major role. At Institut de Recherche sur les Lois Fondamentales de l'Univers (IRFU) of Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA) in Saclay, France, accelerator module assembly has started. The DESY technical coordination team is taking care of the integration of the warm beamline sections. Several stakeholders are defining the final configuration of electronics racks along the linear accelerator.

Production ramp-up

The industrial production of superconducting cavities for the accelerator started at the end of 2012. Two vendors ensure the mechanical fabrication, surface treatment and assembly of the cavities, which are then ready for "vertical testing", the qualification check at DESY. Both vendors ramped up their production in 2013 and reached the required rate of eight cavities per week. The overall industrial production within the European XFEL is remarkable, as an average rate of only one cavity per month was reached during the R&D phase. Henryk Niewodniczański Institute of Nuclear Physics (IFJ-PAN) in Kraków, Poland, is testing the finished cavities at DESY. At the end of 2013, more than 200 cavities had been delivered and almost all of them tested. In general, their performance exceeds European XFEL specifications. Many cavities can be used at an accelerating field of about 30 MV/m, which is more than 20% above the design value. About one third of the cavities still require additional high-pressure water rinsing at DESY to overcome field emission, which would otherwise limit the cavity accelerating gradient to well below the possible maximum.

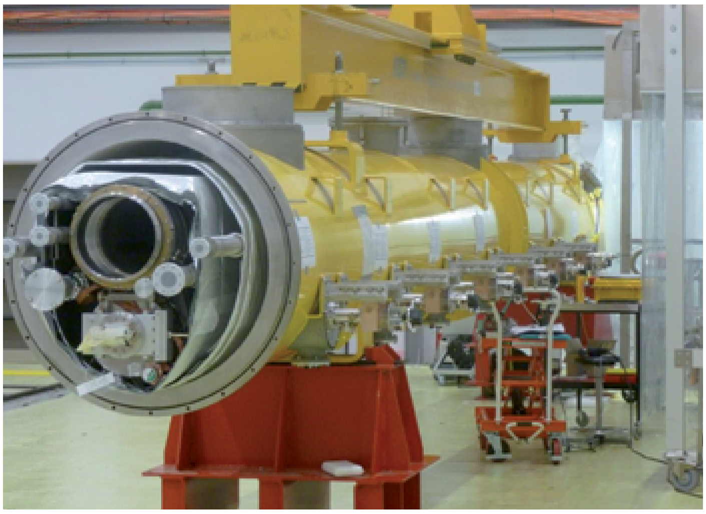

Figure 1

One of three pre-series modules assembled at IRFU of CEA in Saclay, France

High-power RF couplers have turned out to be the most challenging components needed for the accelerator modules. Brazing and copper plating during production has to be done with care. By the end of 2013, Laboratoire de l'Accélérateur

Linéaire (LAL) in Orsay, France, produced and conditioned almost 50 of 800 European XFEL couplers and made couplers for the first accelerator modules available to IRFU. The delivery rate reached four per week. The ramp-up to eight per week will require excellent quality control during all individual production steps.

Pre-series accelerator modules were used to train personnel and to start the ramp-up of module production at IRFU. The first module completely assembled by the industrial partner was shipped to DESY and tested. Its performance fulfilled all expectations.

In the last quarter of 2013, an unexpected problem related to the helium service pipe sections occurred during the assembly of the last pre-series module (XM-1). X-ray pictures of the welds revealed large pores, which were unacceptable according to the requirements of pressure equipment directives. An action plan was developed, and as a consequence, replacement of all service pipes is now required. The welding problem halted the assembly of further modules, which had a direct impact on the project schedule. Based on the currently assumed resources, the last module (XM-100) will be assembled in spring 2016. An accelerated module assembly that takes profit of additional resources could reduce the delay by a few months.

Many accelerator components are now available for installation. More than half of the RF power system's klystrons, modulators, pulse transformers and waveguides have been delivered. Many modulators are in place, while other components are ready for tunnel installation. More than half of the warm beamline magnets have been delivered, mostly by D.V. Efremov Institute of Electrophysical Apparatus (NIIEFA) in St. Petersburg, Russia. Quality control, including magnetic measurement, started at DESY and, so far, could confirm the requisite magnetic-field quality. Vacuum components are being designed and produced by DESY and Budker Institute of Nuclear Physics (BINP) in Novosibirsk, Russia. Stringent requirements for the inner surface, the material permeability and even the vacuum chamber alignment have to be met, leading to elaborate multistep production processes. The production of the about 500 m of undulator vacuum chamber with a wall thickness less than 0.5 mm is in full swing, and the installation and alignment procedures have already been tested. Almost the entire FLASH low-level RF (LLRF) system is now operated with micro-telecommunications computing architecture (μTCA) components, providing valuable input and experience for the European XFEL start-up as well as enhanced stability and performance for FLASH.

Installation of infrastructure in the modulator hall (XHM), the injector area and the main linear accelerator tunnel (XTL) is finished. The XHM hall already houses many of the delivered modulators, and a first modulator connected to the electron gun's klystron was successfully commissioned. The technical equipment for XTL was successfully installed in 2013. Accelerator installation started with a DN200 helium gas line right under the ceiling and with the steel frames required to suspend the accelerator modules from the ceiling. First modules are scheduled for tunnel installation in the second quarter of 2014.

First commissioning of electron source

One of the most crucial accelerator subsystems needed for successful operation of the European XFEL is the photocathode electron gun system. The RF gun cavity and the cathode exchange system were manufactured by DESY's vacuum group. In February 2013, the complete setup, including auxiliaries such as solenoid magnets, was transferred to the PITZ photoinjector test facility at DESY in Zeuthen, where the RF gun was conditioned to reach the peak and average RF power levels required for operation at the European XFEL. The stringent requirement on beam emittance of 0.9 mm mrad at 1 nC bunch charge in the injector had already been demonstrated at PITZ during the R&D phase.

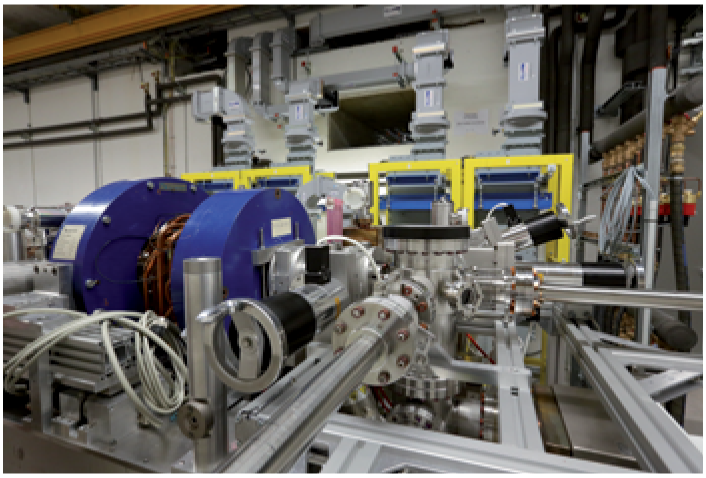

Figure 2

Installed RF gun, with the four waveguides in the background and the blue solenoid coils surrounding the gun body and the cathode exchange system in the foreground

Prior to the gun's installation and operation in the European XFEL injector building, numerous components had to be ready, such as a cooling-water circuit that stabilizes the gun water temperature to within 0.1°C while the average RF power in the gun varies between 0 and 50 kW; the radiation protection and personnel interlock system with shielding walls, radiation monitoring, temporary-access doors and so on, which had to be approved by the authorities prior to gun operation; and the high-power RF system, which ranges from the modulator in XHM, to the klystron on the fourth floor of the injector tunnel, to the RF waveguide distribution system. A crucial point of the RF distribution system is the final vacuum window, which separates the waveguides from the gun vacuum. This window differs from the one operated at FLASH or PITZ and promises an easier and more stable RF regulation. The performance evaluation of this distribution option was a major objective of the gun test that was carried out in the European XFEL injector building in December 2013.

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REGAE.

Preparing a plasma experiment

Improved machine performance and continuous user operation mark the year 2013 at REGAE, DESY's Relativistic Electron Gun for Atomic Exploration. In parallel, preparations for a challenging experiment aiming to investigate basic properties of laser-induced plasma fields were pushed forward.

First user operation

2013 marks the first year of user operation at REGAE. In contrast to large accelerators such as FLASH or PETRA III at DESY, REGAE is not operated by specialized accelerator operators but by the users themselves, with the help of the machine group working on maintenance and further improvements of the facility in the background.

Experiments at a small facility like REGAE require a direct interaction of the experimenters with the machine to optimize the measuring conditions – a challenge most users enjoy very much, but which does not come for free. Even though REGAE is of limited complexity compared to a large accelerator, users need to acquire a detailed knowledge of the machine components and the underlying beam physics to operate it successfully. On the other hand, the machine group also needs a deep understanding of the experiments to help improve experimental conditions and bring the machine to full performance.

The fruitful collaboration between DESY's accelerator group and the Max Planck Research Department for Structural Dynamics at CFEL led to significant improvements of machine operation and experimental conditions at REGAE in 2013. The facility now generates diffraction images of very high quality, and first time-resolved data have been collected.

As an example, Fig. 1 shows a diffraction pattern of a single crystal (MoS_2). The clear separation of the diffraction peaks and the visibility of higher-order peaks in this single-shot image (<200 fC charge) demonstrate the improved machine performance and the quality of the crystal under investigation.

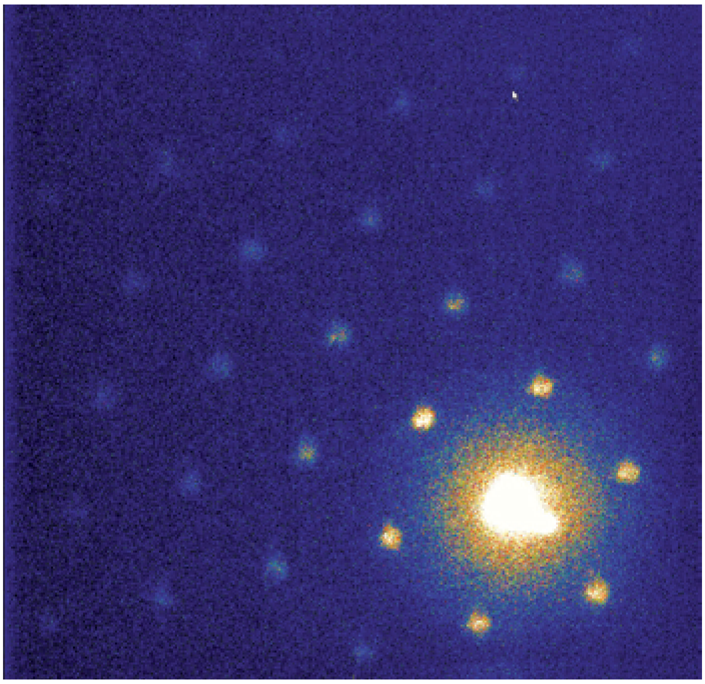

Figure 1

Single-shot diffraction pattern of MoS_2 obtained at REGAE

Preparing a new experiment

REGAE provides unique electron beam parameters with smallest emittance (<100 nm) and short bunch length (down to 7 fs) at energies of a few MeV. Even though these parameters can be achieved only at very low bunch charge (~100 fC), the beams turn out to be interesting not only for electron diffraction experiments but also for fundamental accelerator research in the field of plasma acceleration.

Plasma acceleration employs electrical fields generated in plasmas, i.e. dilute gases, to reach accelerating gradients outranging those achieved in classical resonating cavities by many orders of magnitude. The fields can be generated e.g. by a high-power laser beam passing through a gas target. The gas atoms are ionized by the laser field before the light-weight electrons are expelled by the same field, leaving behind the heavy, positively charged ions. After passage of a short laser pulse, electrons are thus found to swing around the ion cloud, forming a plasma wave that generates gradients of up to 100 GV/m. The transverse and longitudinal dimensions of the plasma wave are tiny, between some tens to some hundreds of micrometres depending on the plasma density. The gradient generated by the wave is not constant within this volume, however, but depends in a sine-like manner on the position within the wave. In addition, the high longitudinal gradients

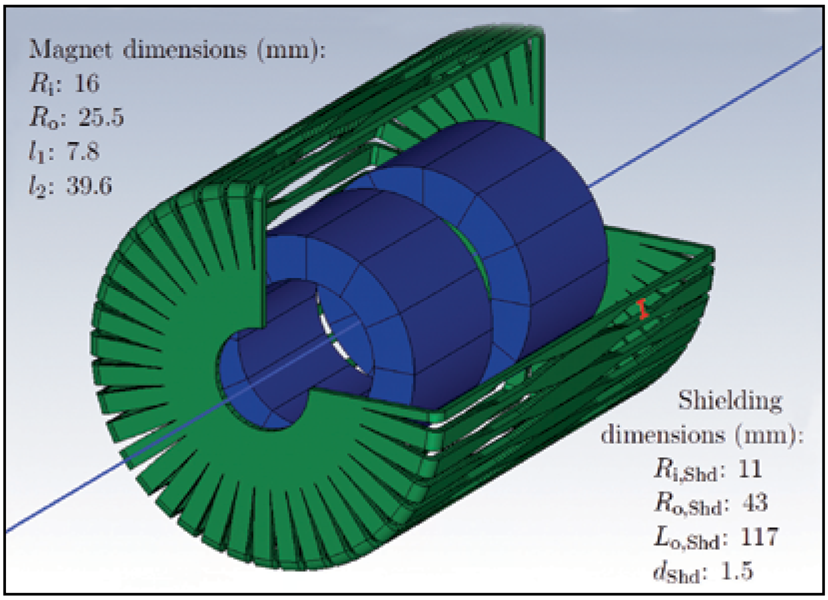

Figure 2

Permanent-magnetic in-vacuum solenoid and shielding designed for the external injection experiment

are accompanied by strong transverse fields. A well-defined and controlled acceleration of an electron bunch by the wave thus requires a bunch with dimensions significantly smaller than the plasma wavelength that would in principle be available at REGAE.

Within the LAOLA@REGAE activity, in close collaboration with the advanced accelerator group at the University of Hamburg, the DESY machine group is preparing an external plasma injection experiment to be carried out at REGAE. The goal of the experiment is to generate a plasma using a high-power laser and inject the REGAE bunch into it. The aim is not only to demonstrate injection into a plasma at the parameters available at REGAE, but to use the REGAE bunch as a probe to measure the fields inside the plasma channel, which are not accessible by other means. The experiment will thus contribute to our fundamental understanding of plasma-based acceleration.

The experiment involves tremendous challenges, as it requires modifications of the REGAE beamline, the addition of new subsystems and development work for many key components. Most notable is the addition of the high-power laser, which has already been set up in a refurbished building adjacent to REGAE. (The laser will not only drive the plasma experiment at REGAE but also independent experiments in the former transfer tunnel connecting the DESY synchrotron with the DORIS storage ring.) The laser produces light pulses with a peak power of 200 TW, which will be sent through an underground optical beamline into the REGAE tunnel. Here, the laser will be focused and mirrored into the electron beam path to generate a plasma in a modified target chamber.

To fit the electron bunches into the plasma channel, they need to be squeezed to a few micrometres in size in the longitudinal and transverse direction. The plasma experiment thus needs much stronger transverse focusing than required for the diffraction experiments. For this purpose, permanent-magnetic in-vacuum solenoid magnets have been developed (Fig. 2), which can be moved into the electron beam path. The magnet consists of two axially magnetized rings of NdFeB and generates the required focusing field without affecting the beam emittance. For the diffraction experiments, the solenoid will be retracted from the electron beam path. A shielding around the magnet guarantees that the electron beam is not perturbed by the stray fields of the magnet.

Magnet and gas target cell will be mounted on high-resolution positioning stages to allow a precise alignment of components with respect to laser and electron beam. The limited lift capacity of the positioning stages set additional constrains for the magnet and shielding design. The slotted shielding shown in Fig. 2 does not only reduce the weight of the material. The slots are designed such that the shielding material is nearly saturated at all points. It will thus not distort the fields of other magnets or bend e.g. the Earth's magnetic field in an unfavourable way.

Besides the preparation of the hardware, theoretical preparations are also in full swing. The interaction of the laser beam with the gas of the plasma target and the resulting beam dynamics of the electron beam can be understood only with complex simulation tools. To guide the experiments, it is necessary to understand beforehand the parameter space in which the electrons can be successfully accelerated.

An unavoidable complication of the injection process at low electron energies arises from the fact that the electrons don't move at the speed of light. To position the electrons at the correct distance behind the laser in the plasma, it is necessary that the laser overtake the electrons in front of the plasma target. The interaction of the laser with the electrons during this overtaking needs to be studied in detail to understand all implications for the experiment.

Many questions still need to be answered before the experiment can start to tackle the question: can future accelerators be based on laser plasma acceleration?

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Highlights · New technology · Developments.

Accelerator research.

R&D to enhance existing facilities and invent the accelerators of tomorrow

Accelerator R&D is a strong and growing field at DESY. It is part of the “Accelerator Research and Development” (ARD) programme of the Helmholtz Association, which established accelerator R&D as an independent research field in 2011. Work at DESY focuses on superconducting RF technology, ultrashort electron/photon pulses and novel accelerator technologies. Highlights achieved in 2013 include superconducting cavities with a 1.6 times higher quality factor *Q*, optical synchronization to better than 3.3 fs over 24 h and the preparation of three plasma experiments (LAOLA collaboration) at the DESY sites in Hamburg and Zeuthen. In parallel, an accelerator research plan up to 2020 was agreed, including plans for a new, dedicated accelerator research facility for Short Innovative Bunches and Accelerators at DESY (SINBAD), a Germany-wide concept for a distributed ARD test facility and plans for a novel light source with attosecond electron pulses, supported by a European Research Council (ERC) Synergy Grant.

Accelerator research for enabling science

Germany has a long tradition and history of inventing and constructing cutting-edge accelerators for science and society. The field of RF accelerators emerged in 1927 with the doctoral thesis of Rolf Wideroe in Aachen, who demonstrated, for the first time, resonant acceleration of a charged particle by a synchronously switched high voltage. Since then, facilities have been developed that accelerate electrons to tens of GeV and protons even to a few TeV. Accelerators are used as colliders for studying fundamental particles and forces, light generators for high-resolution insights into nature, neutron sources for materials studies, irradiation tools for medical treatment, and so on. Thousands of scientists and students rely on accelerator-based data for their research, including topics in particle physics, nuclear physics, engineering, biology, chemistry, medicine, photon science and other areas. Progress in the science and technology of accelerators often opens a window for innovative research in other fields. Accelerator R&D at DESY aims to enhance existing facilities and invent new frontier accelerators, thus keeping German accelerators and science at the forefront of the international research landscape.

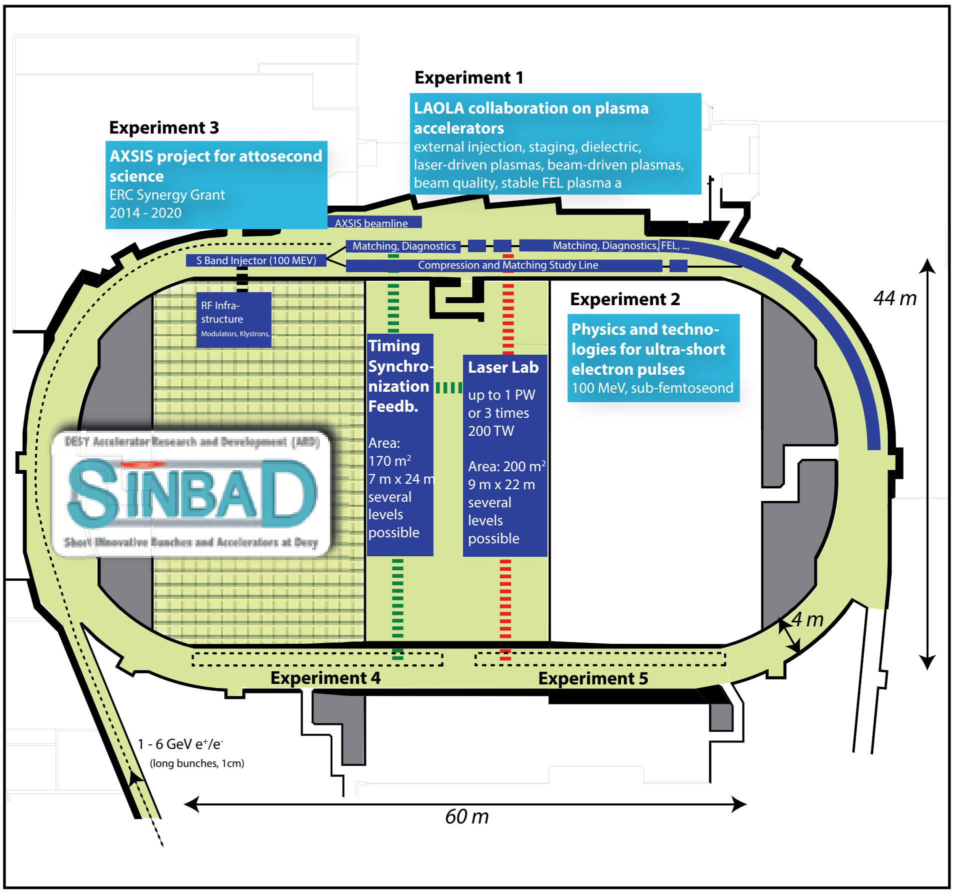


Figure 1

Sketch of a new facility for accelerator research (SINBAD) that will be set up at DESY from 2016 on within existing infrastructure (building and halls, shielded beam tunnel, photon beamlines). Several experiments can be performed in parallel while relying on the same central laser and timing infrastructure. Three experiments are funded through the Helmholtz ARD programme and an ERC Synergy Grant. The facility provides space for two additional experiments and future extensions.

Accelerator research highlights 2013

Accelerator research at DESY focuses on three areas that are critical to the research centre and its mission: (1) Superconducting RF technology and its extension to continuous-wave (CW) operation. (2) Picosecond and femtosecond particle and photon beams. (3) Novel accelerator concepts. In all three areas, important progress and world-leading results were achieved in 2013.

A highlight result in the area of superconducting RF technology was the successful operation of a superconducting cavity, installed inside a full European XFEL module, with an accelerating gradient of more than 40 MV/m. This is a new world record and illustrates the further potential of superconducting RF cavities in terms of accelerating gradients.
Research towards CW operation of superconducting cavities continued with tests of accelerator module XM-3. New results show the potential of large-grain materials for cavities, which can increase the *Q* value by up to a factor of 1.6. The ensuing lower losses would enable CW operation with higher gradients. The results demonstrate the leading, visionary role of DESY in superconducting RF technology. This is also underlined by the recent US decision to equip part of the 2 mile long SLAC linear accelerator with superconducting RF technology, operated in CW mode.

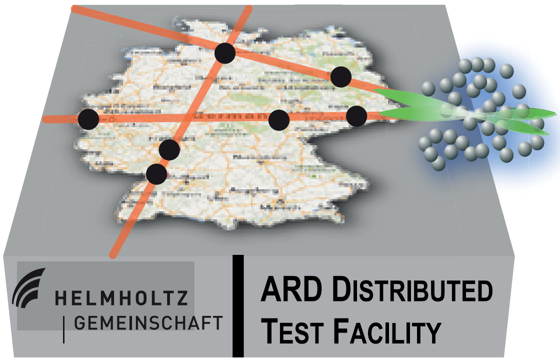
In the area of picosecond and femtosecond electron and photon beams, two outstanding results were achieved, both of which determine the present, worldwide state of the art. A digital feedback was established within a 5 ms long RF pulse in the context of the REGAE project. The phase stability of the REGAE electron beam was already reduced from 50 to 25 fs using this digital feedback, with more improvements to come.
Optical stabilization of better than 3.3 fs (peak-to-peak) was achieved over 24 h for a laser in relation to a 1.3 GHz oscillator. Both results show that DESY successfully maintains its leading role in technologies for ultrafast science.

Plans and preparations for three plasma acceleration experiments at the DESY sites in Hamburg and Zeuthen proceeded well in 2013. This work is done in the context of the LAOLA collaboration, which brings together the University of Hamburg, the DESY accelerator division and the DESY particle physics division. One highlight was the successful setup of a 200 TW laser on the DESY Hamburg site for laser-driven plasma acceleration. The laser will be used for experiments on external injection with the existing REGAE beam and for tests on FEL applications in the new LUX beamline. In parallel, experiments on beam-driven plasma acceleration at PITZ and FLASH are being prepared. The experiments at REGAE and PITZ should start at the beginning of 2015. The FLASHForward project aims at using the 1 GeV FLASH2 beam from 2016 onwards for beam-driven plasma acceleration, development of innovative plasma injection techniques (see article in this report, p. 32) and tests on FEL applications. FLASHForward is being prepared within a Helmholtz Virtual Institute for plasma acceleration, led by B. Foster.

Accelerator research plan up to 2020

An accelerator research plan up to 2020 was worked out in 2013 and agreed on. This plan is also being presented in the ongoing Helmholtz POF3 (Programme-Oriented Funding 3) evaluation of ARD as part of the “Matter and Technology” research programme. The plan foresees the further development of the main DESY research directions: superconducting RF, pico/femtosecond electron/photon pulses and novel accelerator concepts. The latter research topics will be supported by a new, multipurpose accelerator research facility, called SINBAD (Short Innovative Bunches and Accelerators at DESY). This facility will be set up in existing, presently idle infrastructure on the DESY site in Hamburg. SINBAD will provide much more space than what is available at other ongoing DESY experiments, combined with a 100 MeV conventionally generated electron beam, a high-power laser and modern timing and synchronization technology.

Scientific goals include, amongst others, accelerator physics of ultrashort beams, conventional generation of sub-femtosecond electron bunches, engineering of plasma accelerators for usability, pilot user tests of an FEL based on novel accelerators and possibly FEL seeding tests. The AXSIS project aims at establishing science with attosecond electron/photon pulses generated with THz lasers and novel accelerating structures (without the use of plasmas). AXSIS will be located in the SINBAD complex and is supported by an ERC Synergy Grant (principal investigators F. Kärtner, R. Assmann, H. Chapman, P. Fromme from DESY, CFEL, University of Hamburg and University of Arizona). A first schedule has been established for the setup of SINBAD and the relocation of various accelerator research activities to this central facility.



Distributed ARD test facility

The 2011 Helmholtz roadmap for large infrastructures includes a proposal for a distributed ARD test facility. The basic concept for such a facility has been agreed between DESY, GSI, HZB, HZDR with HIJ, HZJ and KIT, and brings together accelerator research infrastructure at these laboratories. The proposal for the distributed ARD test facility will be prepared by 2015, implementing better coordination of accelerator experiments (collaboration), upgraded facilities for common usage (synergy) and a limited number of common flagship projects (leadership). The agreed direction for the flagship projects is the advancement of ultracompact accelerators and radiation sources for science and medicine.

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Wakefield injection.

New injection technique for plasma wakefield accelerators

A new concept for the injection of high-quality electron beams into beam-driven plasma wakefield accelerators has been developed by the plasma acceleration group (FLA-PWA) at DESY. The new method significantly simplifies the plasma-based production of ultrashort, low-emittance and high-brightness electron bunches at multi-GeV energies. This strategy exploits the natural wakefield structure to trigger the ionization of a neutral atomic species within the plasma and the capturing of the released electrons into the optimal accelerating phase. As a result, femtosecond-duration electron bunches are accelerated up to energies that double the initial driver energy. The bunches also feature a much improved quality.

Plasma wakefield acceleration

Plasma wakefield acceleration is a novel technology that allows for ultrahigh field strengths (>10 GV/m) suitable for the acceleration of electrons up to GeV energies over distances of much less than a metre. The high accelerating fields are generated in the wake produced by a high-intensity laser or a charged particle beam travelling through a stationary plasma. The system can effectively operate as a transformer, in which the energy from the driver is transferred to the witness electrons via the plasma wake. This technique seems promising, but before actual applications will be possible there are still a number of technical challenges to overcome. One of the most important is the injection of witness electrons into the proper accelerating phase of the wake. Recently, a group of DESY researchers developed a new concept to achieve injection of high-quality electron bunches into beam-driven plasma wakes using a relatively simple experimental setup termed wakefield-induced ionization injection [1].

Wakefield-induced ionization injection

Compact electron beams of lengths shorter than the plasma wavelength and of sufficiently high currents can develop accelerating fields in plasma, which are strong enough to capture electrons from rest and accelerate them to near the speed of light. These electrons may originate from field-induced ionization of a neutral dopant component, such as helium, coexisting inside the plasma. In order to achieve trapping, these electrons must be released in a precise and well-defined phase range of the wakefield. This selective ionization could be performed with a laser co-propagating with the beam, which would require femtosecond-level synchronization [2]. In contrast, the novel technique described in the following exploits the natural structure of the wakefields to selectively ionize and trap electrons from a narrow phase range without the need for any additional technological elements. The key idea is to ionize using the plasma wakefields only, while preventing any contribution from the space charge field of the driver beam.

These conditions can be achieved with state-of-the-art electron accelerator facilities around the world. For instance, FACET at SLAC is able to routinely produce 23 GeV energy electron beams of an approximate Gaussian longitudinal current profile with peak currents of 23 kA and a duration of 47 fs (rms) [3]. According

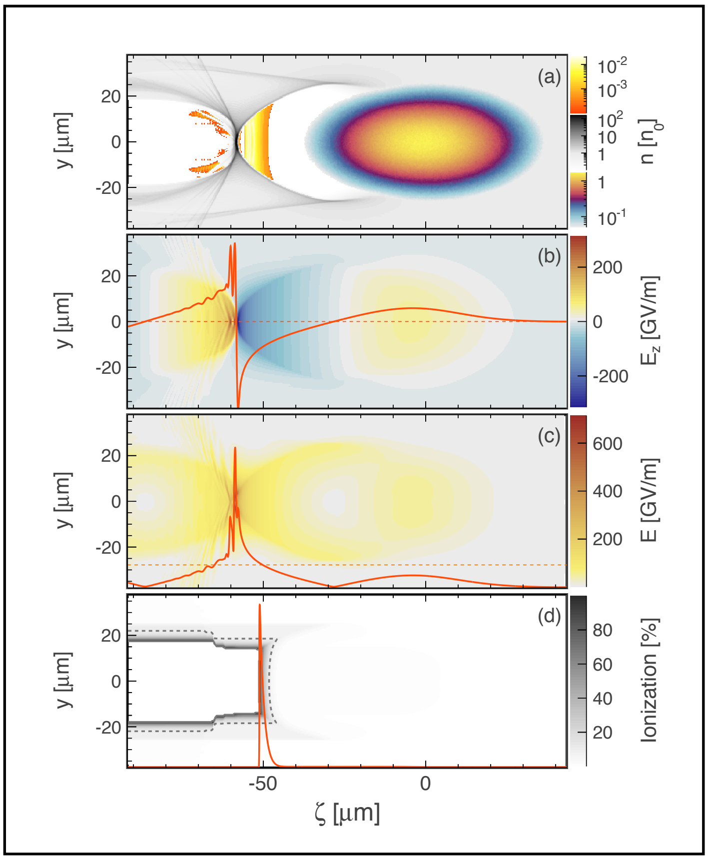

Figure 1

OSIRIS 3D simulation of wakefield-induced ionization injection of He electrons into a plasma wake driven by a FACET-type electron beam. (a) Spatial particle density. (b) Longitudinal electric field and on-axis values (solid line). (c) Total electric field and on-axis values (solid line). (d) ADK ionization probability of the first level of He and on-axis values (solid line).

to three-dimensional particle-in-cell calculations using the code OSIRIS [4], the FACET beam can drive plasma wakefields with an electron density of n_0 = 5x10^{17} cm^{-3} that largely exceed the ionization threshold of helium (E_{He} = 93 GV/m) and reach peak values higher than 200 GV/m (Fig. 1(b)). At the beginning of the driver beam propagation, the magnitude of the electric fields associated with the beam is well below E_{He}, and thus incapable of ionizing the helium (Fig. 1(c)). In this first phase, just the wakefield itself is responsible for the ionization of electrons from helium, which only occurs in a narrow and well-defined wakefield phase situated close to the back of the first plasma cavity (Fig. 1(d)). This situation lasts until the driver beam adjusts to the focusing forces of the plasma wake, and hence is being transversely compressed. Once this happens, the transverse fields of the driver become large enough to completely ionize the helium, and thus impede the functioning of the method. This can be avoided by confining the helium in a thin gas column immersed into the plasma at its boundary, just before the compression of the driver takes place. The amount of injection may be easily tuned by changing the helium concentration. In this example, the number density of the helium is 5x10^{15} cm^{-3} and the total length of the helium region is 100 µm. As a result of the passage of the plasma wake through the helium, a total charge of 40 pC of electrons is trapped. Figure 2(a) shows the situation of this compact electron bunch after 15 mm of propagation in the plasma wake. The average accelerating field along the bunch is ~130 GV/m (Fig. 2(b)).

High-quality electron beams

The properties of the injected bunch after 15 mm of acceleration from the simulation are summarized in Fig. 3. The longitudinal phase space is shown in Fig. 3(a), with an average energy of 2 GeV and a total relative energy spread of 5% rms. In Fig. 3(b), additional properties are shown for several slices along the bunch. With a length of just 0.8 µm (rms), the current profile exhibits a maximum of ~10 kA at the back, and smoothly decreases towards its front. The relative uncorrelated energy spread is less than 1%, while its transverse normalized emittance is smaller than 1 µm along the bunch. Further acceleration of the captured beam is possible until the driver has exhausted its energy. In the shown example, the FACET beam with an initial energy of 23 GeV can propagate for approximately 46 cm.

Assuming a constant acceleration of the trailing bunch at a continuing rate of 100 GV/m, a maximum energy of 46 GeV is expected. These values are in agreement with previous experimental observations demonstrating energy doubling [5]. The characteristics of these beams have no precedents in beam-driven wakefield accelerator research. First experiments demonstrating such beam quality will be regarded as important milestones in the ongoing endeavour to advance plasma-based particle accelerators for their future application in photon science and high-energy physics.

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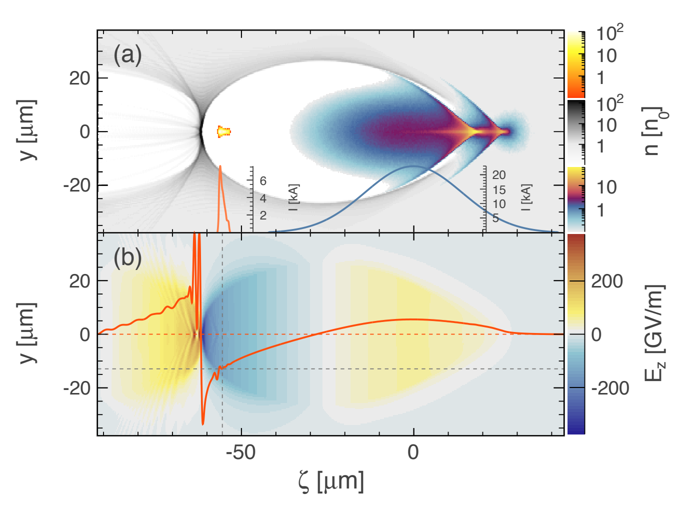

Figure 2

A short bunch of electrons injected from He into the plasma wakefield driven by a FACET-type electron beam after 15 mm of propagation. (a) Spatial particle density. Current profiles are shown at the bottom. (b) Longitudinal electric field and on-axis values (solid line).

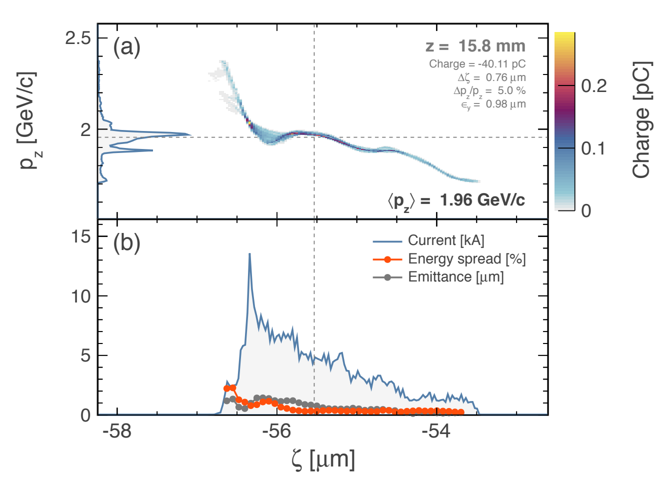

Figure 3

Witness bunch properties after 15 mm of acceleration. (a) Longitudinal phase space. (b) Current, transverse normalized emittance and relative energy spread.

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Low-emittance studies at PETRA III.

Exploring the physics of diffraction-limited synchrotron light sources

Recent years have seen enormous progress in research and development towards nearly diffraction-limited storage-ring-based synchrotron light sources. With the design of the MAX IV facility in Lund, Sweden, a blueprint for the layout and construction of synchrotron light sources with ultralow emittance is available. Several projects based on modified multibend achromat lattices are currently under investigation, pushing the limits even further. In view of these developments, a careful study of the physics of ultralow-emittance rings becomes crucial. Operating PETRA III at an energy of 3 GeV results in an emittance of 160 pm rad, which represents the smallest emittance value measured in a storage ring to date. This provides a perfect test bed to explore and study the physics of diffraction-limited synchrotron light sources.

Ultralow-emittance rings

Achieving ultralow emittance in electron storage rings is by now a mature field of accelerator physics that enjoys a history of several decades. On the one hand, the requirements for ultra-high luminosity drive the development of damping rings for future linear colliders. On the other hand, the quest for ever brighter light sources generates increasing momentum for the development of ultralow-emittance storage rings. Although sharing the common goal of reaching low emittance, the considerations regarding beam dynamics may be quite different. In damping rings, the particles are typically only stored for a few damping times, while stability of the stored current is of major importance in synchrotron light sources.

Only recently, it has been realized that modified theoretical minimum emittance (TME)-type lattices, known as multibend achromat lattices, pave the way to designing machines that aim at very low emittance while providing beam stability at a feasible level of complexity and robustness. A number of projects, most notably the Swedish MAX IV facility, have embarked on this strategy, proposing a new generation of light sources, all in the sub-nanometre emittance regime.

This naturally raises the question whether well-established modelling strategies and tools like simulation codes still perform accurately at ultralow emittance and provide the necessary guidance in the design stage of such machines. A phenomenon of particular interest in that context is intra-beam scattering (IBS), usually a process of minor importance in (moderately) high-energy electron storage rings. However, at ultralow emittance, IBS may become a performance limitation. While the principles of the underlying physical process are well understood, modelling real measurements has its pitfalls. In particular for round beams, as proposed by many light source projects to maximize the brightness, no experimental data seem to be available. Understanding and modelling of IBS at ultralow emittance has been the subject of dedicated low-energy studies at DESY since 2013.

PETRA III at low energy

The natural emittance in electron storage rings scales (at least to lowest order, keeping the focusing fixed) like the energy squared. Therefore, lowering the energy is a powerful way to reduce the natural emittance of an existing machine, which provides a welcome opportunity to investigate interesting machine physics at low emittance without having to change machine hardware. On the other hand, the behaviour of the machine can be very different when the energy is varied. Lowering the particle beam energy in PETRA III becomes even more intricate due to the presence of strong damping wigglers. Being permanent-magnet devices, their field cannot be scaled with the energy. Their focusing and inherent non-linearities (dynamic multipoles) increase at least quadratically when the energy is lowered. On the bright side, the wigglers also contribute stronger damping at lower energies, enhancing the effect on the natural emittance.

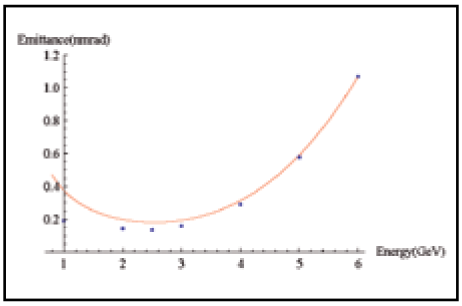

Figure 1

Scaling of the horizontal emittance with energy. The red curve shows a simple scaling argument, while the blue dots correspond to values computed for matched optics using the MAD-X code.

Figure 1 shows a simple scaling argument for the energy dependence of the emittance, together with a number of values for matched optics calculated using the accelerator design code MAD-X. The natural emittance at the nominal energy of 6 GeV is 1 nm rad. When lowering the energy, the emittance rapidly decreases, reaching a minimum of approximately 135 pm rad at around 2.5 GeV. Since this minimum is rather flat, 3 GeV was chosen as target energy for the studies. At this energy, a value of 158 pm rad is expected, which was indeed confirmed experimentally.

A typical picture of the interference pattern measured with double slits at the PETRA III diagnostic beamline is shown in Fig. 2. The source size is reconstructed from fitting the fringes assuming a Gaussian beam profile.

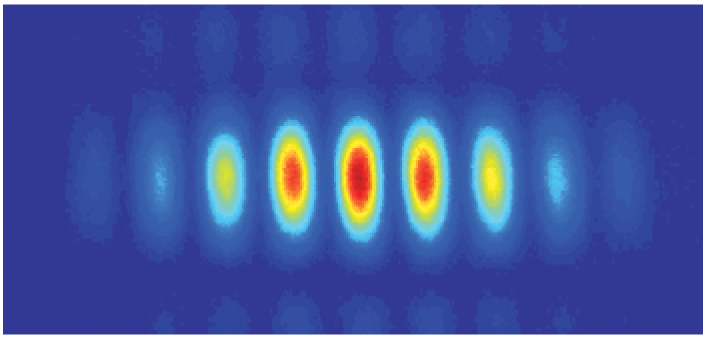

Figure 2

Interference pattern measuring the electron beam emittance at 3 GeV observed at the PETRA III diagnostic beamline. The beam size is deduced from the visibility of the pattern, which is a measure of the source size. The value measured is 160 pm rad, corresponding to the expected natural emittance at 3 GeV.

IBS studies

The beam physics of ultralow-emittance storage rings is dominated by the non-linearities of the strong sextupole fields needed to compensate the chromatic effects of the strong focusing inherent in these machines. On the other hand, the small beam size and small momentum compaction typically arising in low-emittance rings drive collective effects, such as IBS. The physics behind IBS is multiple small-angle Coulomb scattering within a single bunch. Its effect is a dilution of the phase space density, resulting in an increase of the beam size and energy spread. Since IBS worsens with smaller emittance and lower energy, it strongly manifested itself in the PETRA III low-energy studies. A summary of the measured variation of transverse emittance with single-bunch current is shown in Fig. 3. The natural horizontal emittance of 160 pm rad is measured at single-bunch intensities of ~5 μA. It grows to approximately 600 pm rad when increasing the single-bunch current to 600 μA. Together with the data, Fig. 3 shows a preliminary result of modelling the emittance increase due to IBS (blue curve).

One of the uncertainties in modelling the IBS effect is the precise contribution of coupling to the vertical emittance. The model shown assumes a coupling contribution of 20%, expressed by the parameter $r = 0.2$ to the zero-current vertical emittance. Many projects propose to use round beams to maximize the performance of nearly diffraction-limited synchrotron light sources. One possibility to generate round beams is by deliberately introducing coupling. This improves the matching between the particle beam and radiation phase space and thus maximizes the convolution of the beam distribution, the single-particle radiation distribution and hence the brightness. In addition, it has the benefit that the horizontal emittance can be further reduced.

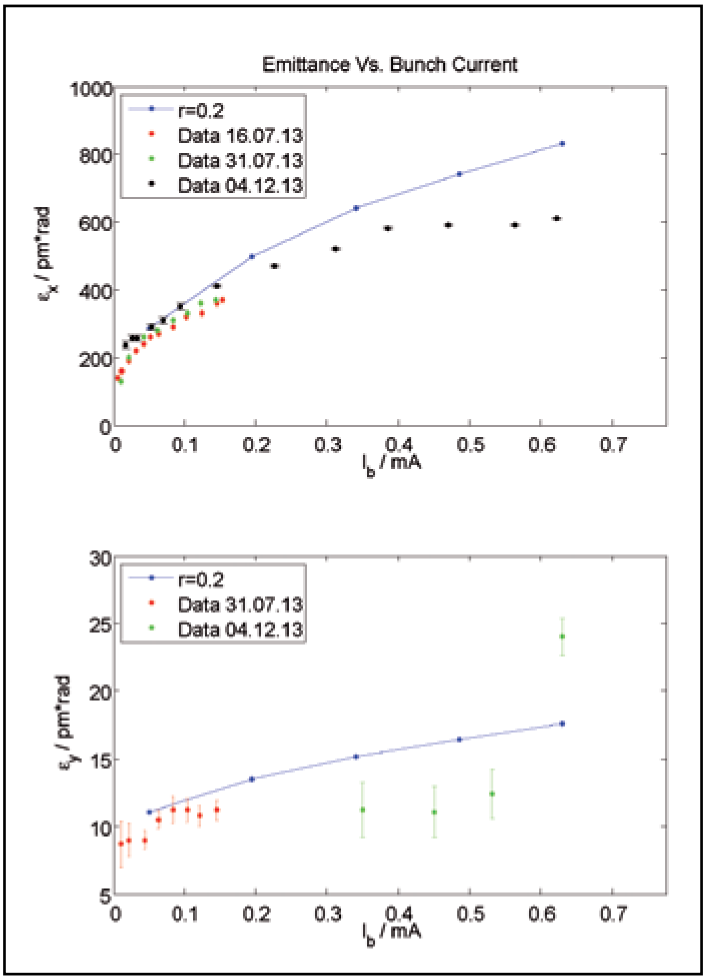

Figure 3

Variation of the horizontal and vertical emittance with single-bunch current measured at 3 GeV (red, green and black) and a preliminary model (blue). The IBS effect is dominant in the horizontal plane where the dispersion is large. The parameter $r = 0.2$ expresses the coupling contribution to the zero-current vertical emittance.

Recently, a beam with horizontal and vertical emittance of approximately 90 pm rad was generated during studies by moving the betatron tunes close to the coupling resonance and tuning the coupling using skew quadrupoles. The corresponding beam size measurements are shown in Fig. 4. Another benefit of round beams is that the bunch volume is increased, which mitigates detrimental effects like IBS. A quantitative analysis of IBS using the round beam at PETRA III is currently in progress.

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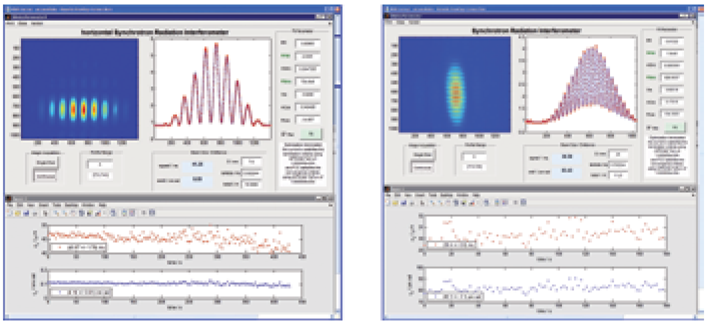

Figure 4

Horizontal and vertical beam size measurement of a round beam generated by coupling the horizontal and vertical betatron motions. The resulting emittance is approximately 90 pm rad in both planes.

Circular polarization at X-ray FELs via reverse undulator taper.

Full radiation power with ultimate degree of circular polarization

The baseline design of a typical X-ray FEL undulator assumes a planar configuration, which results in a linear polarization of the FEL radiation. However, many experiments at X-ray FEL user facilities would profit from circularly polarized radiation. As a cheap upgrade, installing a short helical (or cross-planar) afterburner can be considered, but this requires an efficient method to suppress powerful linearly polarized background from the main undulator. A new method to achieve such suppression is based on the application of a reverse taper in the main undulator. We discovered that in a certain range of the taper strength, the density modulation (bunching) at saturation is practically the same as in the case of a non-tapered undulator, while the power of the linearly polarized radiation is suppressed by orders of magnitude. The strongly modulated electron beam then radiates at full power in the afterburner. Considering the SASE3 undulator of the European XFEL as a practical example, we demonstrated that soft X-ray radiation pulses with a peak power in excess of 100 GW and an ultimately high degree of circular polarization can be produced. The proposed method is rather universal, i.e. it can be used at SASE FELs and seeded (self-seeded) FELs, with any wavelength of interest, in a wide range of electron beam parameters and at any repetition rate. It can thus be used at different X-ray FEL facilities.

Description of the scheme

In a short-wavelength SASE FEL, undulator tapering is used for two purposes: to compensate an electron beam energy loss in the undulator due to wakefields and spontaneous undulator radiation; and to increase the FEL power (post-saturation taper). In both cases, the undulator parameter K decreases along the undulator length. The essence of our method is that we use the opposite way of tapering: the parameter K increases, a configuration that is usually called reverse (or negative) taper.

We discovered that in some range of the taper strength, the bunching factor at saturation is practically the same as in the reference case of the non-tapered undulator, the saturation length increases slightly, while the saturation power is suppressed by orders of magnitude. Therefore, our scheme is conceptually very simple (Fig. 1): in a tapered main (planar) undulator, saturation is achieved with strong microbunching and suppressed radiation power; the modulated beam then radiates at full power in a helical afterburner, tuned to the resonance.

Figure 1

Conceptual scheme for obtaining circular polarization at X-ray FELs

Figure 2 shows the bunching factor and normalized FEL efficiency at the saturation point as a function of the tapering strength. For negative tapering, the saturation power quickly decreases while the bunching factor remains at a high level. The price to be paid for the suppression of the radiation power in the main undulator is some degradation of the FEL gain and a moderate increase of the undulator length.

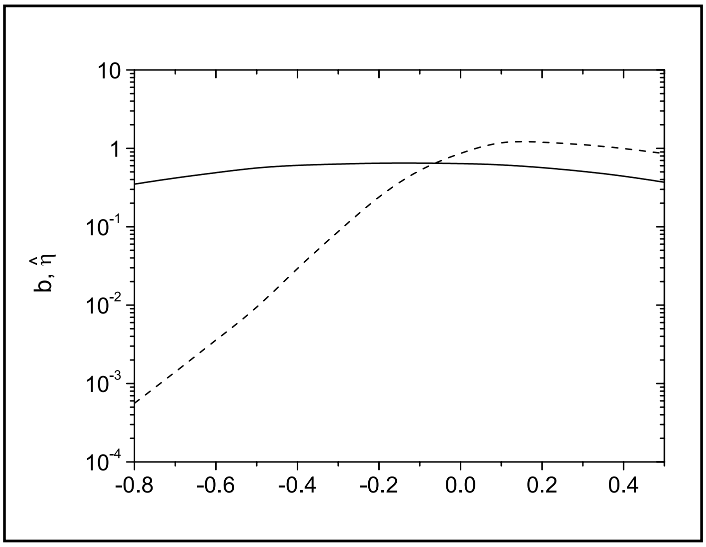

Figure 2

Ensemble-averaged rms bunching factor (solid line) and normalized FEL efficiency (dashed line) at the saturation point (position with maximum bunching factor) as a function of the taper strength parameter

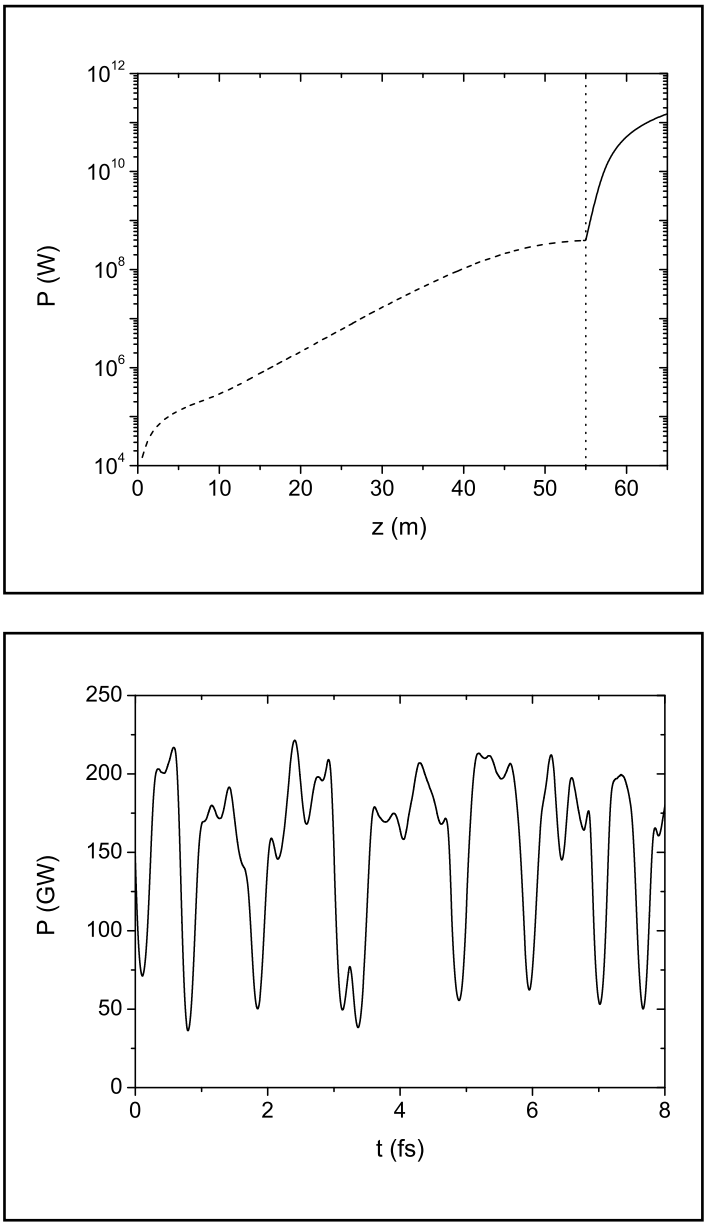

Figure 3

Top: average FEL power as a function of the length of the planar main undulator SASE3 (dashed line) and the helical afterburner (solid line). Bottom: peak power of circularly polarized radiation at the exit of the afterburner (a central part of the X-ray pulse is shown).

Reverse taper at European XFEL undulator SASE3

We illustrate the operation of the proposed scheme with the parameters of the soft X-ray SASE3 undulator of the European XFEL, which operates at a radiation wavelength of 1.5 nm. The radiation power as a function of position in the planar main undulator and in the helical afterburner is shown in Fig. 3. Linearly polarized radiation from the main undulator is strongly suppressed (it amounts to about 0.4 GW), and the powerful circularly polarized radiation quickly builds up in the afterburner. This happens because the bunching is strongly detuned from the resonance within the last part of the planar undulator, but the *K* value of the afterburner is optimized in such a way that it is close to the resonance, and maximum power is achieved at the end of the afterburner.

The averaged peak power from the helical afterburner reaches 155 GW. The level of the radiation power from the main undulator is only 0.4 GW. Thus, we achieve an ultimate degree of circular polarization of 0.999 at full radiation power.

The proposed method for generating powerful circularly polarized radiation is universal and can be easily implemented at all beamlines of the European XFEL and other X-ray FEL facilities.

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References:

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Upgrade of FLASH LLRF controls to MicroTCA.

Key milestone for the European XFEL

The FLASH free-electron laser requires a high-precision control of the electron beam to generate the femtosecond-pulsed laser light delivered to user experiments. The low-level radio frequency (LLRF) control system is certainly one of the key subsystems affecting the overall laser stability. To achieve the stability goals, the LLRF system was developed based on a new electronic platform, the Micro Telecommunications Computing Architecture (MTCA.4). FLASH was recently upgraded to this new LLRF system standard. First experimental results show excellent system performance capabilities. The FLASH upgrade is also a key milestone for the European XFEL. Permanent operation of the system in a regular accelerator environment was demonstrated, allowing new functionalities and system behaviour to be studied. The improvement in measurement accuracy and detection bandwidth increased the regulation performance and enabled the integration of further control subsystems.

The LLRF control system

The FLASH facility at DESY is based on superconducting accelerator technology, controlled by a digital LLRF system. The scope of the LLRF is to achieve a stable RF field inside the accelerating cavities. RF field regulation is done by measuring the electromagnetic field stored inside the cavities. This information is then processed by the feedback controller to modulate the driving RF source.

Numerous steps within the regulation loop must be optimized to achieve the RF field stability requirements set by user demands. Detection and real-time processing are performed using most recent FPGA techniques. The system design of FLASH and the European XFEL requires the regulation of the field vector sum, where up to 32 cavities are driven by a single RF source. Special calibration and processing techniques of the RF signals inside the system are required. Performance increase demands a powerful and fast digital system, which was found with the MTCA.4 standard. The upgrade to MTCA.4 offers the following advantages:

- System performance and processing
    - o Precision of measurements
    - o High resolution and low latency
    - o Number of RF signals
- In-tunnel installation
    - o Compact system standard
    - o Redundancy
    - o Radiation resistance / shielding
    - o Remote software updates
- Modularity of the systems
    - o Maintenance and upgradability

Installation inside the accelerator tunnel, in particular, poses new challenges. Possible radiation-driven events, e.g. single event upsets (SEU), might cause sudden malfunction of the system. Effective shielding and redundant layout of critical components are essential to guarantee the reliability of the system. The installation at FLASH provides experience in a radiation-prone environment, where access for maintenance is also limited.

This is the first time that permanent operation of an MTCA-based LLRF system in an accelerator facility of this scale is demonstrated. Five RF stations have been equipped with the new system and operated for about four months. The experience that has been gained during this time directly affects ongoing upgrades, but also serves as a system demonstration for the proper operation of the European XFEL.

Figure 1

Installation of MTCA crates inside the FLASH tunnel underneath the first accelerator module (ACC1). The radiation shielding (yellow cabinet) protects the electronic rack inside. The insert shows the MTCA crate installed in this rack.

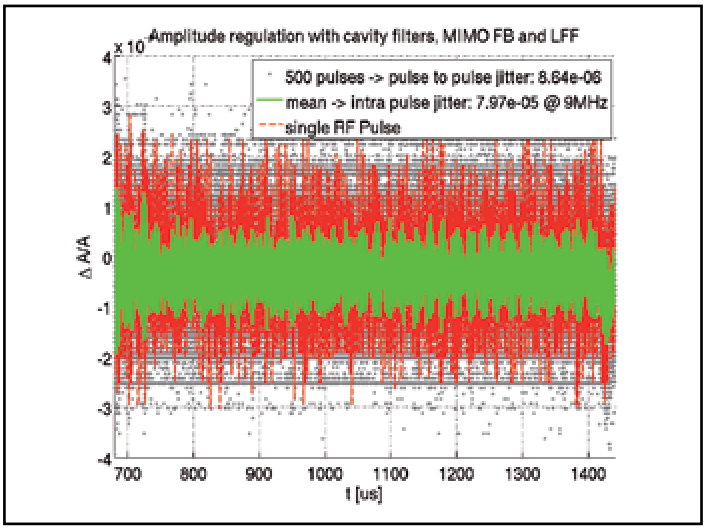

Figure 2

Measurement of the relative amplitude stability during the flat top of 500 consecutive RF pulses. The plot shows the individual measurement points (grey), the mean value (green) of these data points and an exemplary single pulse (red).

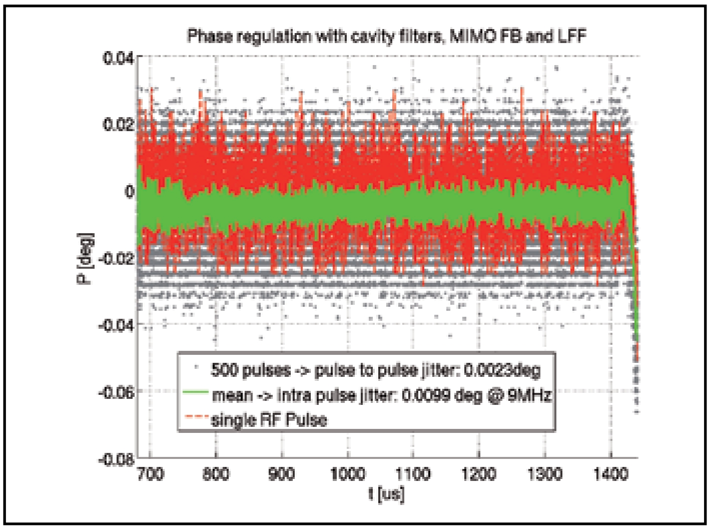

Figure 3

Measurement of the phase stability during the flat top of 500 consecutive RF pulses

FLASH installation and first operation experience

Since 2010, MTCA test systems had been installed at FLASH, which were temporarily used to operate dedicated RF stations during special measurement opportunities. During the FLASH shutdown in 2013, the complete LLRF system for all superconducting RF stations was upgraded to the MTCA.4 standard.

All measurement signals are split between the MTCA.4 and the previous LLRF system, which is kept in standby mode to offer the possibility of a fast backup at any time. Furthermore, this setup allows for an independent observer system to qualify the regulation performance. Further development, mainly on the software side, is ongoing and can be easily adapted to this environment. The experience gathered at FLASH during the installation and commissioning phase can be directly applied to the European XFEL. Demonstration of reliable operation was as important a task as the FLASH upgrade to the most recent LLRF system. In addition, operation and use case scenarios can be tested, bugs need to be identified and solved, and necessary automation routines can be implemented.

Measured system performance

The scope of the LLRF system is to provide a stable RF field, both during a single RF pulse and for several consecutive pulses. A typical pulse takes about 1.3 ms and continuously recurs with 100 ms intervals. It consists of three phases, where the second, flat-top phase is used for beam acceleration. Here, the RF field must be kept constant to provide each electron bunch with the same amount of energy. Figures 2 and 3 show the regulated RF field in amplitude and phase during the flat-top phase as an example for accelerator module ACC45.

This in-loop measurement was performed for all RF stations. The given field stability requirements of $\mathrm{d}A/A < 0.01\%$ in amplitude and $\mathrm{d}P < 0.01°$ in phase are fulfilled.

Stability (rms) @ 9 MHz	ACC1	ACC39	ACC23	ACC45	ACC67
Amplitude intra pulse [%]	**0.0067**	**0.0266**	**0.0055**	**0.0079**	**0.0069**
Amplitude pulse to pulse [%]	**0.0017**	**0.0053**	**0.0012**	**0.0009**	**0.0019**
Phase intra pulse [°]	**0.0100**	**0.0233**	**0.0074**	**0.0099**	**0.0089**
Phase pulse to pulse [°]	**0.0028**	**0.0108**	**0.0017**	**0.0023**	**0.0031**

Summary and outlook

The installation of the MTCA-based LLRF system at FLASH demonstrated the capability of reliable operation and showed a performance increase of the RF field regulation.

Recently, the system has been upgraded to support future operation extensions. In addition, an MTCA-based LLRF system for the normal-conducting RF gun has been installed. First measurements and tests are currently in progress. For 2014, several user runs at FLASH and installations of the first LLRF systems for the European XFEL are planned.

The MTCA-based LLRF system is evolving from prototyping stage to large-scale production. Several research centres within the Helmholtz Association, as well as external partners, consider using the system as a new technology standard. Within DESY, the MTCA technology has also been chosen for several subsystems, besides LLRF, for the European XFEL.

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Lorentz force detuning compensation for high-performance SRF cavities.

Performance test of European XFEL pre-series cryomodules

Before installation into the European XFEL tunnel, all superconducting cryomodules are tested to verify their functionality and assess the gradient performance of individual cavities. As the accelerating field is increased, superconducting radio frequency (SRF) cavities experience a shift in their resonance frequency induced by Lorentz forces. This detuning prevents keeping a constant gradient inside the cavity and degrades the beam acceleration. To compensate for this Lorentz force detuning, piezoelectric tuners are installed on every cavity, taking counteractive action by mechanically deforming the cavity. During one of the last cryomodule tests, a high-performance cavity reached an accelerating gradient of 42 MV/m, experiencing over 700 Hz Lorentz force detuning. With piezo tuner compensation, the detuning was controlled within 50 Hz of the cavity resonance, hence maintaining the accelerating gradient constant over the entire beam pulse.

Testing cavities of European XFEL cryomodules

Every accelerating cryomodule for the European XFEL undergoes a series of tests and measurements to assess and validate its performance before installation into the tunnel. These tests are carried out in the Accelerator Module Test Facility (AMTF) at DESY. During the commissioning phase of this new test facility, pre-series modules were also tested at DESY’s Cryomodule Test Bench (CMTB). The RF tests of cryomodules include measurement and characterization of cavity tuners, motorized power couplers and piezo tuners. After coupler conditioning, the cavities’ gradient performance is evaluated by gradually increasing the forward power to individual cavities until a cavity quench is observed. During this phase, large detuning due to Lorentz forces can occur.

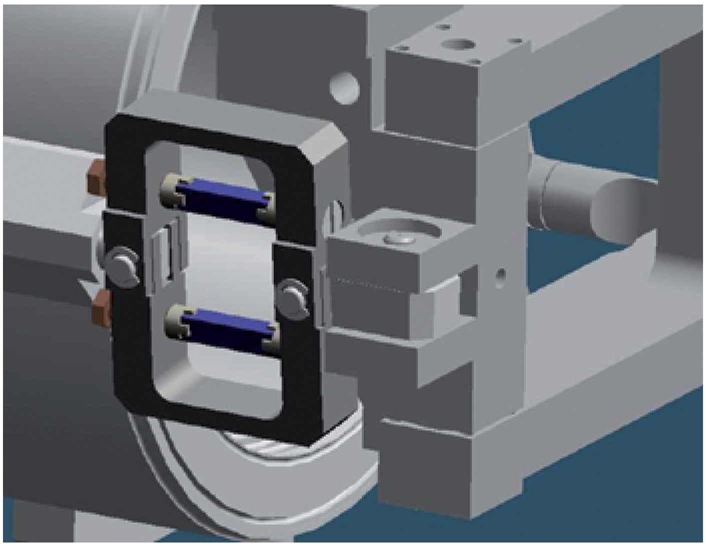

Figure 1

Redundant piezo tuner mounted on the cavity frequency tuner

Lorentz force detuning and piezo tuner

The RF magnetic field in a cavity interacts with the RF currents flowing along the cavity walls, resulting in a Lorentz mechanical force that effectively changes the shape of the cavity and hence modifies its resonance frequency. This Lorentz-force-induced detuning (LFD) is proportional to the square of the accelerating field inside the cavity and can be characterized by an LFD coefficient, typically in the range of several Hz/(MV/m)^2 for TESLA-type cavities. Stiffening rings are mounted around the cavity iris region to increase the mechanical stiffness of the cavity. This reinforcement is insufficient for gradients above ~10 MV/m, where LFD can still be observed in European XFEL cavities. Active compensation using the piezo tuner is then applied, mechanically exciting the cavity before each RF pulse. The compensation is optimized by adjusting several parameters of the piezo sinusoidal stimulus: frequency, amplitude, offset and delay.

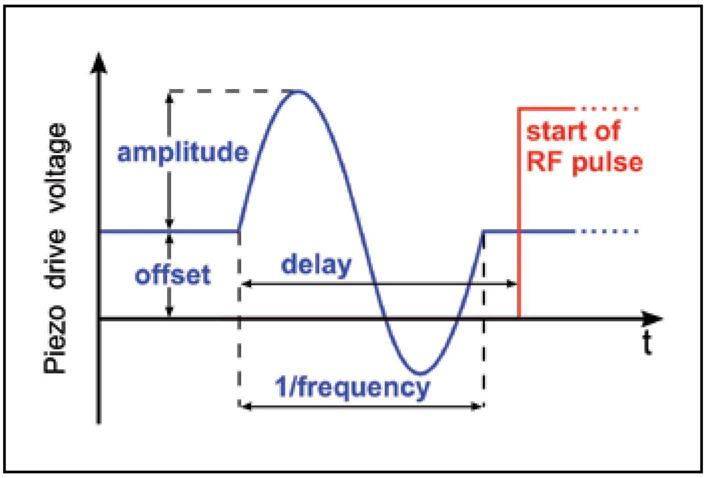

Figure 2

Piezo stimulus tuning parameters to optimize LFD compensation

European XFEL piezo driver

A 16-channel piezo driver (PZ16M) was developed for the European XFEL. This module can handle piezo signals from two cryomodules (i.e. 16 piezo actuators and 16 piezo sensors). The piezo driver module is used to sample and digitize the signals coming from each piezo sensor and drive the stimulus waveforms to excite each piezo actuator in order to compensate for LFD. Communication between the module and the low-level radio frequency system is performed through a low-latency fibre link. Such piezo driver modules are also installed in the AMTF and CMTB, one module dedicated to each test stand, to perform piezo control and piezo sensor data analysis.

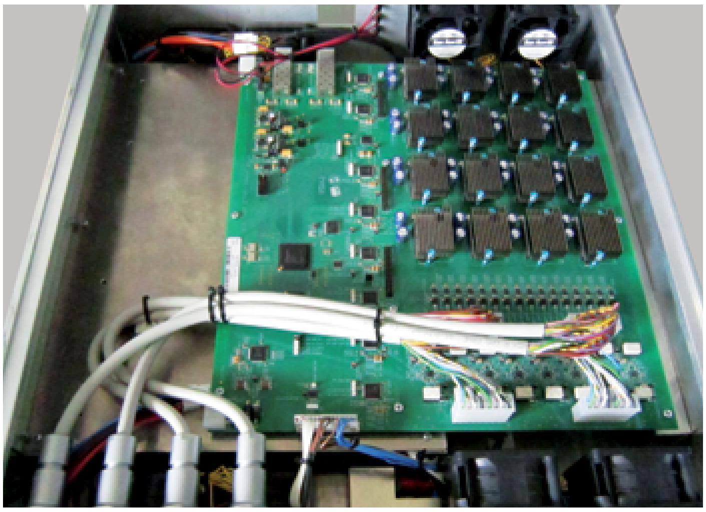

Figure 3

Top view of the 16-channel piezo driver prototype for the European XFEL

Results

Most qualified European XFEL SRF cavities can sustain gradients in excess of 24.5 MV/m, which is the nominal average accelerating gradient for the European XFEL. Some high-performance cavities, however, can sustain much higher gradients. During the test of the first pre-series cryomodule (XM-3) at the CMTB, cavity #3 (AC146) could be driven up to 42.1 MV/m before quenching. At this high gradient, the cavity experienced over 700 Hz Lorentz force detuning, inducing a gradient drop of 7 MV/m. This corresponds to an LFD coefficient of 0.4 Hz/(MV/m)^2. With active piezo compensation, this detuning was controlled within 50 Hz of the cavity resonance, maintaining the maximum achievable gradient of 42.1 MV/m during the entire duration of the flat top (800 µs), at a repetition rate of 2 Hz. The steps leading to this result are as follows:

1. All cavities except the cavity under test are purposefully detuned to allow an increase of the power to the high-performance cavity only, without quenching lower-gradient cavities. This restriction comes from the fact that the forward RF power at the test bench cannot be distributed unevenly among cavities.
2. The cavity under test is placed at a mid-range gradient (~20 MV/m) where LFD is already observed.
3. The cavity is tuned to its resonance using the stepper tuner motor. This provides a coarse frequency tuning of the cavity.
4. A finer frequency tuning is performed by adjusting the offset on the DC bias driving the piezo actuator for this cavity.
5. The piezo sensor information is used to identify the main mechanical mode of the LFD for this cavity (~200 Hz).
6. A single sine wave excitation is played on the piezo actuator, with a frequency matching the main mechanical mode measured from the piezo sensor.
7. Piezo stimulus parameters are adjusted to optimize the detuning compensation (delay and amplitude).
8. The gradient is gradually increased; fine adjustments to the piezo stimulus parameters are applied to track the detuning changes induced by the gradient increase.

In this particular case, a delay of 5 ms, a frequency of 200 Hz and an amplitude of +/-45 V (maximum +/-70 V available) were applied. The offset adjustments were on the order of a few volts. Stable operation (no cavity quench) under these conditions was observed and recorded for several minutes. Although LFD compensation using piezo tuners has been routinely performed for several years at FLASH, this is the first time, to the authors' knowledge, that this compensation technique is performed at such a high gradient for TESLA-type cavities.

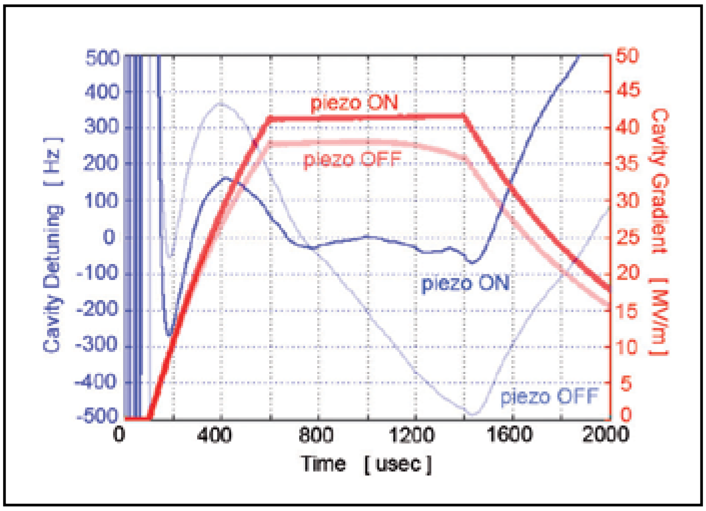

Figure 4

Cavity detuning and gradient without and with piezo LFD compensation

During normal accelerator operation at FLASH, for example, and as planned for the European XFEL, LFD compensation using piezo tuners is automated to minimize the cavity detuning for the entire duration of the beam acceleration time period. The static, dynamic and curvature (second order) characteristics of the detuning are measured and used to optimize the piezo drive waveform.

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Compact laser synchronization using a MicroTCA chassis.

Synchronization of laser to accelerator RF with femtosecond precision

Optical lasers have become an integral part of free-electron laser (FEL) facilities, for the purposes of electron bunch generation, external seeding, diagnostics and pump–probe experiments. The ultrashort electron bunches and FEL photon pulses demand that the optical lasers be synchronized to the accelerator RF with femtosecond precision. A laser synchronization scheme was developed based on MTCA.4-compliant modules that were commercially available or developed for other applications within the particle accelerator community. The first realization of laser synchronization to an external RF source based on MTCA.4 technology was demonstrated for an ytterbium fibre laser that was developed for electro-optical electron beam diagnostics. This article also gives an outlook on further system development in laser-to-RF synchronization.

Introduction to MTCA.4

MTCA.4 (Micro Telecommunications Computing Architecture – Enhancements for Rear I/O and Precision Timing) has become a viable standard for demanding applications in large-scale research facilities of the high-energy physics and photon science communities. Originally derived from AdvancedTCA™ or ATCA™ (Advanced Telecommunications Computing Architecture), the MTCA standard has gained popularity as a compact, versatile and cost-efficient alternative wherever low-noise analogue and ultrahigh-speed digital signal processing is required.

The basic architecture follows the idea of a centralized powerful processing unit (CPU board) that is connected to various advanced mezzanine cards (AMCs) over the backplane. The platform is managed by the MTCA carrier hub (MCH), which takes care of crate management (power, cooling), port switching and generation of timing signals.

System components

Besides the basic MTCA.4 crate infrastructure composed of MCH, CPU, power supply, AMC backplane and cooling, the developed laser-locking application comprises four boards in MTCA.4 standard that are used to process analogue and digital signals (Fig. 1). The laser pulses are translated to RF and processed accordingly in an external RF front-end 19'' chassis. The output is then fed to the DRTM-DWC10 downconverter board that is placed as a rear-transition module (RTM) in the MTCA.4 crate. The signals are downconverted and the intermediated frequency (IF) is transmitted via the Zone 3 connector to the AMC side of the crate, where it is sampled by a 10-channel SIS8300refL digitizer.

Processing includes I/Q detection of the sampled signals, amplitude and phase transformation, feedback controller and feed-forward table. In order to achieve suppression of eigenmodes of the piezo, a digital notch filter has been included. The output of the controller is routed to the DAC outputs on the digitizer (for monitoring purposes) and transmitted over low-latency links on the AMC backplane to the neighbouring DAMC-FMC20 AMC board. The DAMC-FMC20 is a low-cost

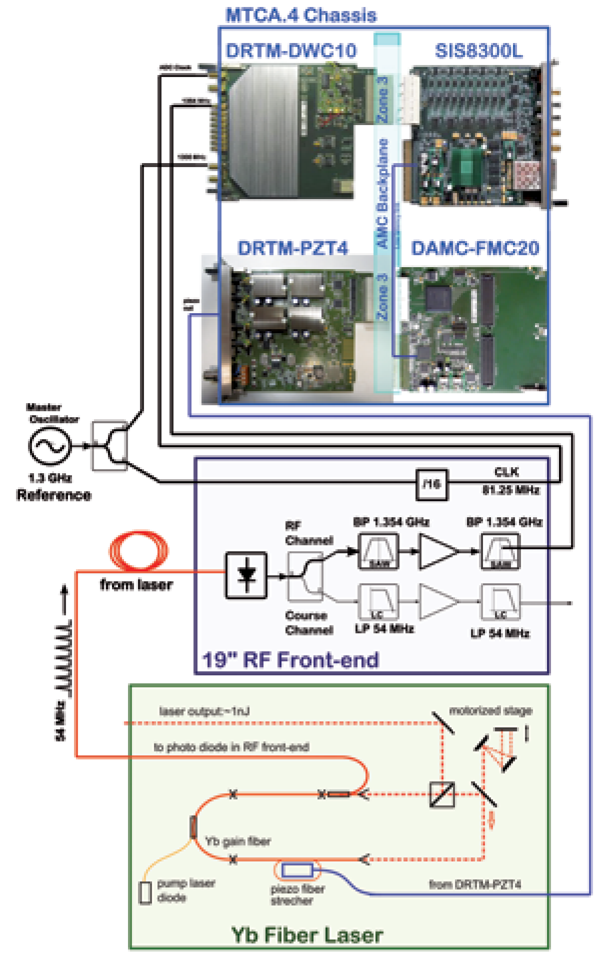

Figure 1

The prototype synchronization system consists of the MTCA.4 chassis with AMC and RTM boards, the RF front end and the Yb fibre laser.

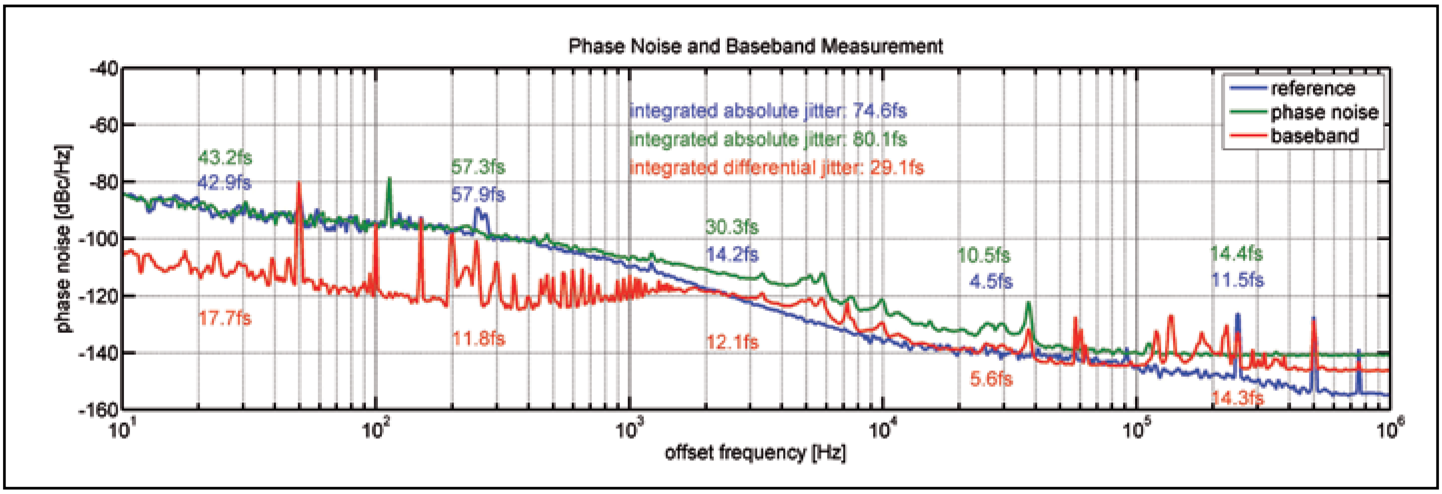

Figure 2

Phase noise spectrum of the 25th harmonic (1354 MHz) of the laser fundamental (54.2 MHz) (green curve), phase noise spectrum of the local oscillator (reference @ 1300 MHz) (blue curve) and baseband noise of the 24th harmonic (1300 MHz) of the laser mixed with local oscillator (red curve). The jitter per decade is indicated with coloured numbers. The 50 Hz lines in the baseband noise contribute considerably to the jitter per decade.

FPGA mezzanine card (FMC) carrier board that consists of two FPGAs. One FPGA is used for backplane interconnects (PCIe, multigigabit transceivers etc.), and the second FPGA is used for interconnecting with the RTM over the Zone 3 connector. The RTM is a MTCA.4-compliant piezo driver called DRTM-PZT4. The board is equipped with four power amplifiers supplied from internal DC/DC converters (0V÷100V or -100V÷100V). Software-programmable span DACs (500 kSPS) have been applied to provide all requested control signal ranges. Each power amplifier gain has been fixed to 10 V/V. The RTM can drive up to four parallel piezos with capacitances of up to 10 µF. The output of the piezo driver is directly connected to the piezo of the laser.

The RF front-end 19'' chassis converts the photodiode signal generated from the laser pulses into an RF 1.354 GHz signal, which is the 25th harmonic of the laser repetition rate. Instead of generating an extra local oscillator (LO) signal (RF + IF), we use the 1.3 GHz reference as the LO input. The clock (CLK) signal of 81 MHz for the SIS8300L ADCs is generated from the 1.3 GHz reference to avoid trigger jitter.

The ytterbium fibre laser is housed in a 19'' chassis with 6 HU. It delivers 1 nJ pulses at a wavelength of 1030 nm with a repetition rate of 54 MHz. The laser consists of a ring oscillator with a fibre and a free-space part. Amplification and pumping are done in fibre, the free-space part is necessary for dispersion compensation and the mode-locking mechanism. A piezo stretcher changes the resonator length and thereby the laser pulse repetition rate.

First results

The performance of the laser synchronization is given by the phase noise of the locked laser at the locking frequency (1354 MHz) and the resulting integrated jitter. Figure 2 shows the in-loop phase noise of the laser RF (green curve) and the local oscillator (LO, blue curve). It is clearly visible that the locking to the LO has a strong influence on the laser from 10 Hz up to 1.5 kHz offset frequency, i.e. the phase noise curve of the laser RF follows the phase noise curve of the LO. Amplified noise and resonances in the locking loop prevent setting a higher locking bandwidth. Several peaks can be identified in the red curve in Fig. 2. The most prominent is located at 37 kHz and corresponds to the piezo crystal resonance. The plateau at higher offset frequencies (> 50 kHz) is caused by the limited performance (noise) of the photo receiver.

The baseband noise depicted in Fig. 2 (red curve) shows the differential timing jitter between the laser and the RF reference measured independently (out-of-loop) with a 1300 MHz double-balanced mixer at baseband. The spurious peaks at multiples of 50 Hz result from ground loops in the measurement setup.

The total integrated jitter of the laser was determined to be 80 fs with the jitter of the LO being 75 fs. The differential jitter of laser and LO (baseband) was 29 fs. The analysis of the jitter per decade (coloured numbers in Fig. 2) reveals room for improvement of the locking setup in the range of 1–10 kHz.

Summary and future plans

Synchronization of a laser to an external RF source was demonstrated for an ultracompact system based on commercially available MTCA.4 components and prototypes. All system components, i.e. laser, RF front end and MTCA.4 crate, were placed in one 19'' rack. Valuable input was gained for the further developments of the prototype components, such as piezo driver card (DRTM-PZT4) and RF front end (to be included in a dedicated downconverter board). The optimized system will be used to synchronize various lasers to the reference RF at the European XFEL.

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Femtosecond-precision laser-to-RF phase detection for FLASH and European XFEL.

Development of femtosecond synchronization techniques

Optical reference distributions have become an indispensable asset for femtosecond-precise synchronization of free-electron lasers. At FLASH and the European XFEL, laser pulses are distributed over large distances in round-trip time-stabilized fibres to all time-critical accelerator subsystems. Novel laser-to-RF phase detectors will be used to provide ultra phase-stable and long-term drift-free microwave reference signals for the accelerator RF controls using this optical reference. Laboratory measurements have proven an unrivalled performance.

Introduction

To achieve femtosecond clocking of large-scale accelerators, optical synchronization techniques are used. The optical synchronization system at FLASH and the future European XFEL comprises a passively mode-locked master laser oscillator emitting laser pulses with a repetition rate of 216.7 MHz. The laser pulses are distributed through optical fibre links to various end stations within the accelerator facility. To overcome environmental propagation time variations in the fibre link, active corrections are applied in order to achieve short-term and long-term synchronized laser pulses at the fibre link output. By using an optical reference module (REFM-OPT), RF reference signals can be locally drift-stabilized by locking them with femtosecond precision to the laser pulses at the fibre link output.

In the accelerators, 1.3 GHz RF reference signals are distributed through coaxial cables providing an excellent phase noise performance, but these RF signals will be subject to cable drifts in the 100 fs range. In the future, laser-to-RF (L2RF) phase detectors will be used within the REFM-OPT to remove low-offset phase noise and phase drifts. The L2RF detectors measure the RF phase drifts with respect to the optical reference laser pulses and actively correct these RF phase variations.

The heart of the L2RF setup is a commercially available Mach–Zehnder amplitude modulator (MZI) in which the ultrashort, sub-picosecond duration laser pulses sample the RF wave. If the optical pulses hit the zero crossing of the RF wave, no laser pulse modulation will be observed. To distinguish MZI bias offset drifts or laser power variations from phase changes of the RF, the laser pulses are split and recombined in a free-space setup, such that the laser pulses sample both the positive and negative zero crossings of the RF wave. Using this arrangement, phase errors now impose a (sub-)harmonic amplitude modulation onto the recombined laser pulse train, which is filtered, strongly amplified and read out by a synchronous detection circuit with high precision.

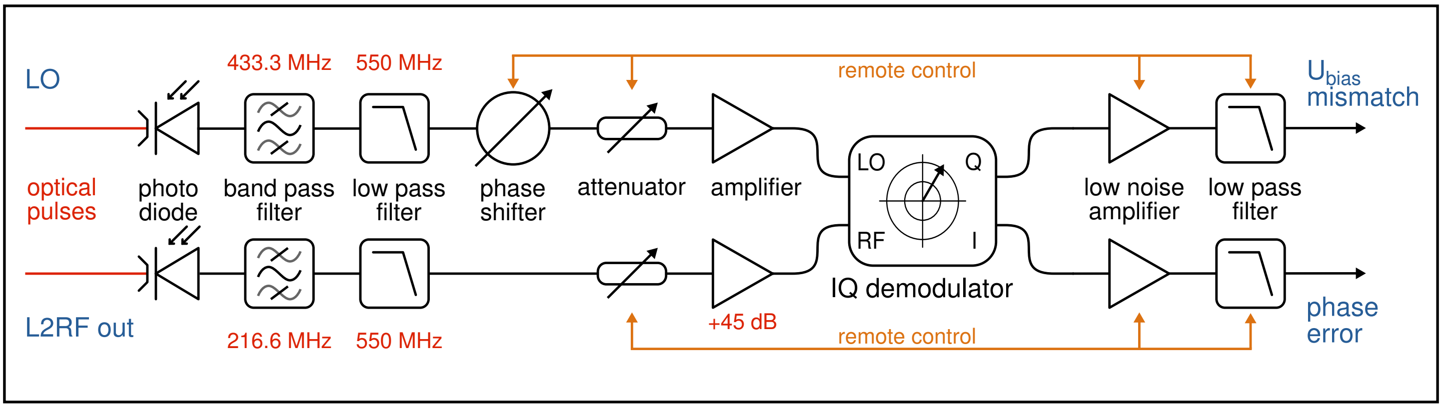

Figure 1

Simplified block diagram of the L2RF readout PCB

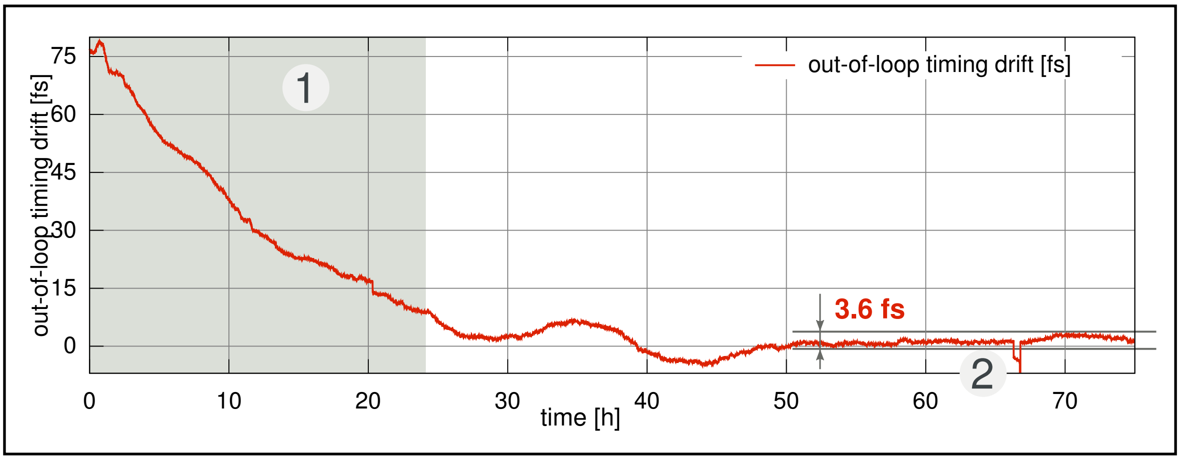

Figure 3

Out-of-loop timing of the L2RF drift measurement. (1) 22 h burn-in phase. (2) Glitch due to server restart of the control system.

Engineered detector electronics

The synchronous detection circuit was integrated into a single printed circuit board (PCB) within a custom housing in order to meet the space constraints of the REFM-OPT 19'' chassis. The whole setup is already suited for installation in an accelerator environment.

To adjust the ideal operation point of the L2RF converter, the RF gains and the local oscillator (LO) phase at the input stage as well as the gain and bandwidth of the low-noise output amplifiers can be remotely controlled and diagnosed with the on-board electronics (Fig. 1). The board has three main output signals, which can all be used to set up feedback loops on dedicated parameters of the setup. The most important output signal is the phase signal, which drives the actual phase-locked loop (PLL) within the REFM-OPT. Additionally, bias drifts of the MZI are detected, and the bias voltage of the MZI is continuously stabilized.

The digital interface for remote control is connected to a general-purpose FPGA-based controller board, used in various low-level RF (LLRF) units for the European XFEL. Additionally, the board will take care of the actual PLL within the REFM-OPT and the bias feedback for the MZI. Because this will be the only digital controller involved, it is very easy to integrate the whole L2RF setup for accelerator usage.

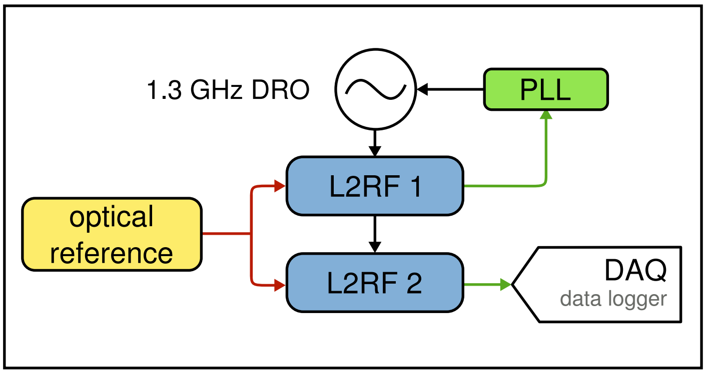

Figure 2

Long-term drift measurement setup

Performance measurements

To evaluate the long-term performance, two L2RF phase detectors were built. L2RF 1 was used to synchronize a low-phase-noise dielectric resonator oscillator (DRO). The RF output of L2RF 1 was connected to the RF input of L2RF 2 to allow for an out-of-loop measurement for performance evaluation (Fig. 2). The phase sensitivity K_φ of the in-loop detector was 1.41 V/ps during this measurement, while the out-of-loop detector showed a lower K_φ of about 0.73 V/ps. The long-term measurement was recorded using an Agilent 34970A data acquisition unit, with a sampling rate of 0.1 Hz. The measurement result is shown in Fig. 3.

The measurement that was taken before the one presented in Fig. 3 was interrupted by a power cut after only a few hours. The power cut affected the climate control system and all the auxiliary electronics in the lab. After a burn-in phase of roughly 24 h, the environmental conditions in the laboratory had stabilized again. The feature at 66.5 h measurement time was caused by an accidentally restarted server in the control system. The glitch demonstrates the robustness of the system, since it recovered to exactly the same operation value as before the incident. The peak-to-peak stability finally amounted to only 12 fs for the last 48 h, while the last 24 h showed a 3.6 fs peak-to-peak stability.

The engineering and full integration of the L2RF phase detectors into the optical reference module are nearly complete, and prototypes will be installed at FLASH in 2014. The installation will provide a dramatic improvement in RF phase stability for the LLRF system. This will substantially enhance the short- and long-term stability of the free-electron laser operation. To our knowledge, the demonstrated performance for a 1.3 GHz laser-to-RF phase-locked loop is unmatched.

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High-power RF distribution.

New RF waveguide distribution for the European XFEL RF gun

The RF gun of the European XFEL will be operated at an accelerating gradient of 60 MV/m. An RF power of 6.5 MW at 1.3 GHz RF frequency, 650 µs pulse duration and 10 Hz repetition rate is required to achieve the gradient. A new type of RF waveguide distribution has been developed to transmit up to 10 MW RF power at long pulse duration in air-filled WR650 waveguides from the high-power, long-pulse multibeam klystron to the RF gun.

Introduction

The European XFEL requires an L-Band RF gun operated at 1.3 GHz with an accelerating gradient of 60 MV/m. In order to generate the gradient, an RF input power of 6.5 MW at 650 µs pulse length and 10 Hz repetition rate is required. The RF power is generated by a multibeam klystron and then transmitted through WR650 waveguides to the RF gun. The system is designed for a maximum klystron output power of 10 MW. The RF gun is installed in the European XFEL injector seven floors underground, whereas the multibeam klystron is located four floors above on the third underground floor.

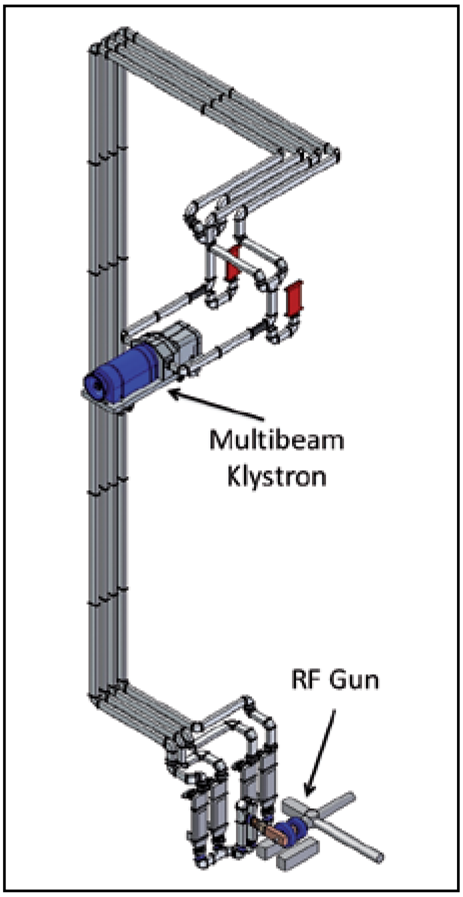

Figure 1

Layout of the European XFEL RF waveguide distribution

European XFEL RF gun waveguide distribution

Figure 1 shows the layout of the RF waveguide distribution for the European XFEL RF gun. The two output waveguides of the klystron can be connected either to two RF loads for testing or commissioning purposes, or to the waveguides leading to the injector. The two waveguides are split before being guided from the third underground floor into the shaft of the European XFEL injector building. Figure 2 shows the first series multibeam klystron, which was tested at the DESY test stand and installed in the European XFEL injector, with connected waveguides.

Figure 2

Toshiba E3736H multibeam klystron and connected waveguides

Four waveguides transmit the RF power in the shafts from the third to the seventh underground floor (Fig. 3). The maximum power per waveguide is 2.5 MW. Isolators are installed at the end of each of the four waveguides to protect the klystron from reflected power from the RF gun. RF windows in front of each isolator separate the isolators from the upstream wave-

Figure 3

Waveguides in the European XFEL injector shaft

guide distribution. Behind the isolators, the four waveguides are combined by two asymmetric shunt tees into two and finally by one shunt tee into one waveguide, which is connected to the input window of the RF gun (Fig. 4).

Since the height in the isolators is reduced, the RF power must be limited to 2.5 MW in each isolator. The RF power in the waveguide elements behind the isolators can reach between 5 MW and 10 MW. To guarantee the RF breakdown strength in the isolators and waveguide elements, the air pressure must be increased to 1.3 bar in total. The improved electrical breakdown strength allows operation without sulfur hexafluoride SF_6, which is usually used as a dielectric medium to increase the breakdown strength.

Since the total power is split in four waveguides and finally combined to one, proper phasing of the waveguides is mandatory. This is achieved by two measures. Coarse adjustment of less than 25° phase difference between the segments was achieved by proper adjustment of the geometrical length of the four long waveguide segments and installation of fixed phase shifters in some of the segments. Fine adjustment can be accomplished using an air pressure regulation system for each waveguide pass. By applying a small overpressure between 1.3 and 1.5 bar in total, the dimensions of the waveguides change minimally and thus the phase advance in each waveguide changes. As a side effect, the breakdown strength in each waveguide segment improves.

Figure 4

Four isolators with RF power waveguide combination (rear) and RF gun (front)

The system was tested at the end of 2013 in the European XFEL injector. An RF power of 6.5 MW at 400 μs and about 5 MW at 650 μs was already applied to the RF gun. A further test is planned for mid-2014.

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High-resolution scintillating screen monitors.

Transverse electron beam profile diagnostics for the European XFEL

Transverse beam profile diagnostics in modern electron linear accelerators, such as free-electron lasers or injector linacs, is mainly based on optical transition radiation (OTR) as the standard technique. OTR is emitted in backward direction when a charged particle beam crosses the boundary between two media with different dielectric properties. Experience at modern linac-based fourth-generation light sources shows that OTR diagnostics might fail because of coherence effects in the OTR emission process. As a consequence, at the European XFEL and FLASH2, transverse beam profile measurements are based on scintillating screen monitors. The LYSO:Ce screens are oriented such that coherent OTR generated at the screen boundaries is geometrically suppressed. An additional feature is that the imaging optics operates in Scheimpflug condition, adjusting the plane of sharp focus with respect to the CCD chip and significantly increasing the apparent depth of field. A first profile monitor was successfully installed and commissioned at FLASH, and the batch production is under way for both accelerator projects.

Introduction

OTR monitors are standard tools for measuring transverse beam profiles in electron linacs. Unfortunately, microbunching instabilities in high-brightness electron beams of modern linac-driven free-electron lasers can lead to coherence effects in the emission of OTR. Beam profile imaging dominated by coherent OTR leads to an incorrect representation of the transverse charge distribution and makes electron beam diagnostics with standard imaging screens impossible. Therefore, it was decided to use scintillating screens for transverse beam profile measurements at the European XFEL. For a detailed discussion, see e.g. C. Behrens et al., Phys. Rev. ST Accel. Beams 15, 062801 (2012).

The required resolution is 10 µm over the entire field of view. A series of experiments was carried out to study the performance of different types of scintillators as a function of material property, thickness and observation geometry. Based on these results, it was decided to use 200 µm thick LYSO:Ce and to observe the scintillator under an angle of 45° with respect to the beam axis. In order to minimize depth-of-focus effects, the Scheimpflug principle was applied to the optical layout of the monitor. In the following, the monitor setup will be described together with test measurements performed in the laboratory and at FLASH.

Monitor layout

The monitor consists of three basic components (Fig. 1): the vacuum chamber, the mover and the optic box. The stepper motor driven mover serves to precisely position the target, which consists of a scintillating screen and a test chart for calibration purposes. Observation of the screen is performed under an angle of 45°. The imaging optics consists of a tilted mirror, an objective lens and a CCD camera. The camera with

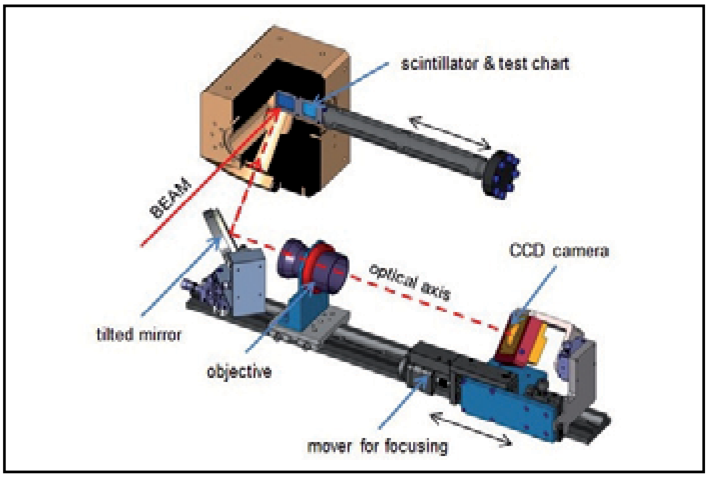

Figure 1

Monitor layout for transverse electron beam profile diagnostics

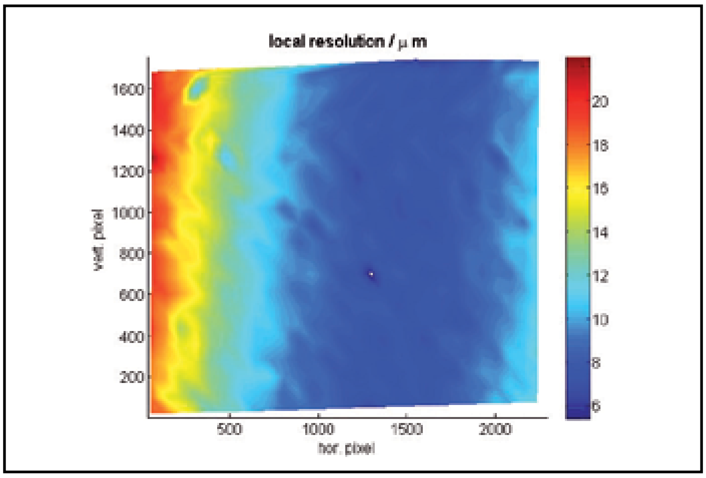

Figure 2

Local resolution along the CCD chip as measured in the screen monitor chamber using a dot grid pattern (colour code in µm) a pixel size of 5.5 µm x 5.5 µm is mounted onto a motorized mover to optimize the imaging distance. An important prerequisite for the CCD selection was the requirement of a large chip size of 1 inch, allowing the observation of electron bunches moving a certain distance away from the nominal beam axis without the additional need to use different optical magnifications. To correct perspective distortion caused by the 45° observation geometry over the whole CCD chip, the Scheimpflug principle is applied. This principle states that a planar object (scintillating screen) that is not parallel to the image plane (CCD chip) will be completely in focus if the extended object-, lens- and image planes intersect in one line. Two monitor versions with different optical magnifications of 1:1 and 1:2 are being designed for the European XFEL.

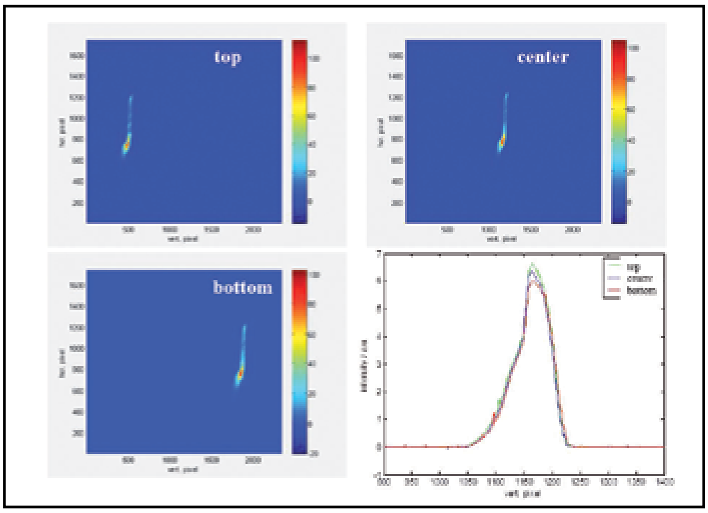

Figure 3

Beam spots recorded at three different electron beam positions at the scintillating screen (images rotated by 90°) and comparison of the vertical beam projections

Test measurements

A series of test measurements was carried out to verify that the 10 µm resolution could be achieved. In a laboratory measurement, a dot grid pattern was installed inside the monitor chamber and imaged onto the CCD oriented in Scheimpflug geometry. To determine the local resolution along the CCD chip, the steepness of each bright/dark transition was analysed for all dots. Figure 2 shows the local resolution, resulting in a mean resolution of 10.5 µm, which is in very good agreement with the required resolution.

Finally, a prototype of the complete monitor setup was tested under realistic conditions at FLASH. The monitor was installed in the test dump section for single-bunch operation, and beam profiles were recorded at 685 MeV and bunch charges from 50 pC up to 1 nC. For a test of the quality of the Scheimpflug geometry, the vertical electron beam position was varied at the location of the LYSO:Ce screen by changing the settings of an upstream corrector dipole magnet.

Figure 3 shows examples of measured beam spots for different electron beam positions together with a comparison of the vertical projections. As can be seen from this comparison, no beam profile broadening or distortion was observed, thus demonstrating the applicability of the Scheimpflug imaging in the monitor setup.

Finally, an upper limit for the achievable monitor resolution was deduced with the electron beam. To this end, a cut was made through a recorded beam image (Fig. 4). As can be seen, a beam structure of about 22 µm is clearly visible. Therefore, beam sizes on the order of 50 µm as expected for the European XFEL can easily be measured.

Summary and conclusion

A screen monitor has been designed for the European XFEL with a resolution of 10 µm over a large field of view. A series of test measurements was carried out to verify the design goals and to study the influence of design decisions on the resolution. Measurements carried out in the laboratory to study the optical resolution under Scheimpflug geometry with an observation angle of 45° indicate that the monitor concept meets the resolution requirements.

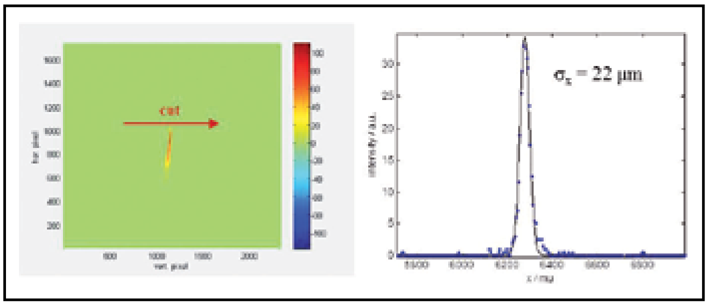

Figure 4

Left: Structure of the beam spot as measured at a bunch charge of 100 pC together with the slice for resolution analysis. Right: Evaluation of the slice profile.

A prototype test was performed at FLASH under realistic beam conditions to study the imaging properties. According to these investigations, the images recorded for different beam positions at the scintillating screen show no beam distortion. These measurements imply that the effective resolution of the monitor including the scintillating screen is better than 22 µm, thus making it possible to resolve transverse electron beam profiles as expected for the European XFEL.

According to the screen and observation geometry, coherent OTR that might be produced at the screen boundary will not be observed by the CCD camera, allowing beam profiles to be measured in situations where standard OTR monitors would suffer from coherent effects with a comparable resolution.

The final design, construction and serial production of the screen stations for the European XFEL are presently under way, and FLASH2 will also be equipped with this new generation of transverse beam profile monitors.

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DaMon at REGAE.

A resonator to measure beam charges with fC resolution

A resonator-type beam charge monitor has been developed to measure dark current and charge at the European XFEL, FLASH and PITZ. The first monopole mode TM_{01} at 1.3 GHz is used to detect the dark current and charge with high resolution. At REGAE, this type of monitor has been installed to non-destructively detect regular bunch charges well below pC level. The same electronics as for the dark-current and charge measurement is used, and the best resolution is measured to be 2.3 fC at 200 fC.

Measuring the beam properties during operation is essential for accelerator control. Non-destructive measurements are preferred because the running beam can be used afterwards for experiments. One of the most important beam properties to be measured is the beam intensity, resp. the bunch charge.

Here, a (re-entrant type) cavity is used in which the beam induces electromagnetic fields at certain resonance modes. The cavity resonates on the TM_{01} mode at 1.3 GHz without tuners; this mode is picked up by antennas inside the resonator. The signal is then guided to electronics via low-loss UHV-HF feed-throughs and HF cables. The amplitude of the signal is proportional to the charge of the beam. Such a device will be installed at the European XFEL, where it is not only intended to measure the beam charge. Its second task is to detect the much smaller dark current produced by field emission in the accelerator, because the dark-current rate induced by the 1.3 GHz accelerating fields have the same frequency. Superimposing the signals of the small dark-current bunches at their high repetition rate amplifies the signal to a measurable level. Such monitors are already being tested at FLASH and PITZ, where the name Dark current Monitor (DaMon) was coined.

The typical bunch charge at REGAE is expected to be much smaller compared to the accelerators mentioned above. In experiments, the DaMon has shown that its resolution might be good enough to resolve even the low charges at REGAE. Therefore, this type of monitor including its readout electronics has been installed at REGAE.

Two antennas are used to increase the dynamic range of the monitor: One antenna has a 10 dB attenuator in its signal path to work in a higher charge range regime. The second antenna is connected directly to the input in order to be sensitive to low charges. Each signal of the two antennas is processed individually by the readout electronics, which consists of a circulator, band-pass filter, limiter, downconverter to an intermediate frequency, logarithmic detector, and offset and gain control. Due to the logarithmic detector, the signal processing range is 80 dB. The processed signals are digitized by a high-resolution 16 bit, 200 MS/s ADC.

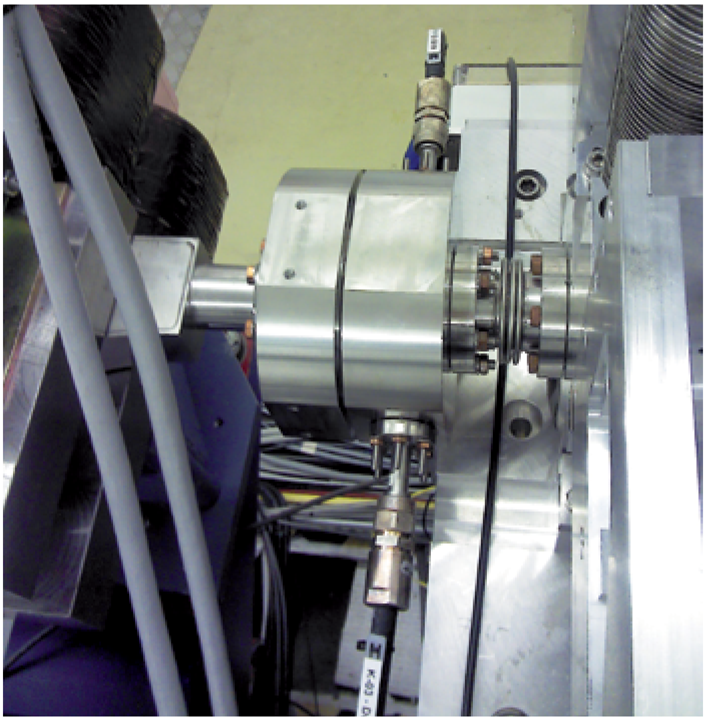
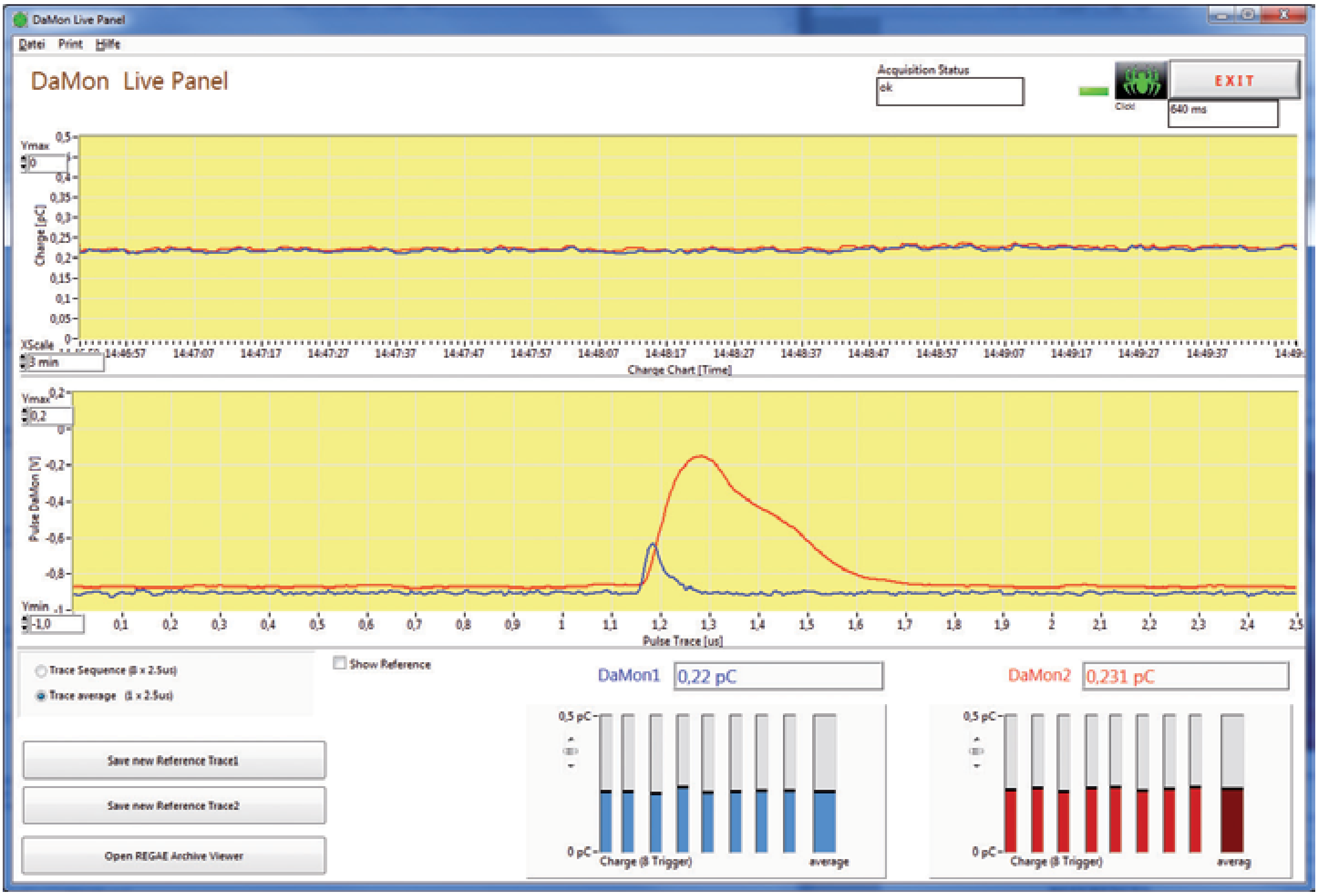


Figure 1

DaMon installed at REGAE

To calibrate the measured signals in terms of absolute charge, all the properties of the resonator, the cable attenuation and the electronics respond function were carefully analysed in advance. These calibration values were taken into account to convert the measured voltage amplitude into a charge value.

Figure 2 shows the graphical user interface (GUI) of the measurement. The lower diagram displays the measured signal. The



Acquisition Status ok

640 ms

Ymax 0

XScale 3 min

Ymax 0,2

Ymin -1,0

○ Trace Sequence (8 x 2.5us)

● Trace average (1 x 2.5us)

☐ Show Reference

DaMon1 0,22 pC

DaMon2 0,231 pC

Figure 2

Graphical user interface of DaMon output. Top diagram: History of charge values over a few minutes. Lower diagram: Recent voltage of both channels as a function of time, with attenuated (blue) and sensitive (red) channel. Below: Recent calculated charges for last eight bunches of both channels, with the same colour definition including an average.

amplitude of the two channels is different because of their different sensitivity. The first channel with 10 dB attenuation is foreseen for higher charges between 2 and 50 pC. The second channel can be used for charges between 10 fC and 2 pC, with a corresponding improved resolution at lower charges. In addition, the charges of the last eight bunches are shown in the bar charts at the bottom of the GUI together with the average charge of the bunches. A history of the bunch charges in REGAE is shown in the upper part of the figure.

Assuming that both channels are identically (except for the attenuation), the resolution of the system can be determined by subtracting the charge values of both channels and calculating the residuals. The standard deviation of the residuals gives an overall resolution of both channels. The 10 dB attenuation of Channel 1 is included for the calculation of the resolution of the individual channel. In Figure 3, the resolution of both channels is presented for different charges in REGAE during the operation period between March and August 2013. The resolution depends logarithmically on the charge due to the logarithmic detection. The best resolution is measured with Channel 2 to be 2.3 fC at 200 fC. This shows that the DaMon system can measure and resolve low charges with high resolution in a non-destructive manner.

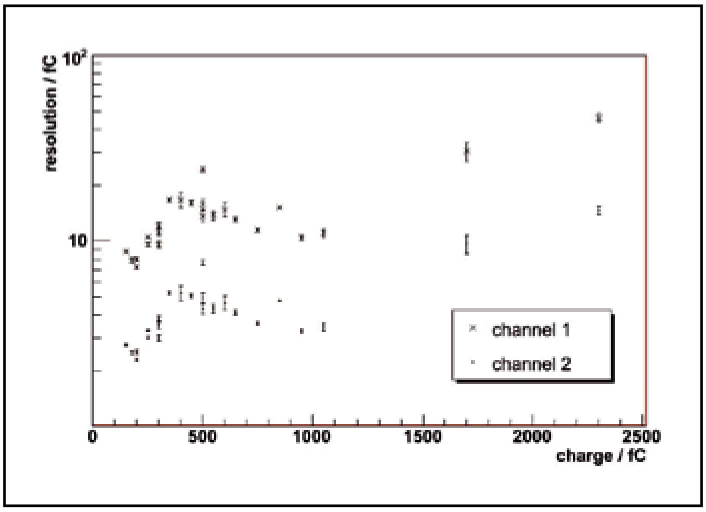


Figure 3

Resolution for both channels as a function of charge in REGAE. The 10 dB attenuation of Channel 1 is included.

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Putting the pieces together.

Parts management at the European XFEL

A particle accelerator consists of hundreds of thousands of parts and components. Developing and manufacturing all those parts is one challenge, making sure they are available on time is another. DESY has introduced a parts management solution for the European XFEL that offers reliable methods and tools to support an efficient fabrication of high-quality accelerator components.

What's in an accelerator?

Besides the technical complexity, building an accelerator like the European XFEL is also a logistical challenge. Hundreds of thousands of parts, many of them designed in leading-edge technologies, have to be developed, produced and delivered on time. They include small components and higher-level assemblies, and they can be of very different nature: parts of the vacuum system or parts that operate at -271°C; parts of the accelerator or parts of the cabling, piping or support infrastructure; mechanical devices or electronic boards for the control system. All these parts have to be of outstanding high quality to ensure that the accelerator reaches optimum performance.

Contributors and suppliers

Accelerator facilities are developed by collaborations of research laboratories from several countries. The labs contribute different parts to the project – usually "in kind", i.e. they deliver parts that are ready for installation in the facility. In the case of the European XFEL, twenty labs from ten countries are contributing in kind to the project. While the labs are able to develop prototype components in leading-edge technology, they usually do not have the capabilities for producing large series of parts. The series production is therefore subcontracted to industrial suppliers, who have the necessary infrastructure and capacities for producing hundreds of components in short periods of time. However, they need to learn the specifics of each part first, often with additional technology transfer from the research lab to the suppliers.

Understanding the logistical complexity

The logistical complexity can be well understood by following parts through their life cycles, from first ideas until they are installed and ready for operation in the accelerator. In a typical scenario, parts are designed and developed in the research labs. The designs are often based on similar parts from a previous project, which are updated and optimized for next-generation projects. The labs build and evaluate prototypes and iterate the design, until satisfactory quality and performance are reached.

A tendering process is started to find one or more suppliers who can produce and deliver the parts. For high-tech parts, the suppliers may need to be qualified first. In such cases, suppliers first produce a small amount of parts in collaboration with the research lab, where they can learn the technology and prove that they are able to deliver the parts as specified. Then, the contracts for the series production are awarded, and the suppliers produce and deliver the parts to the labs.

The labs conduct quality checks and performance tests to ensure that the parts fulfill all quality requirements. Once accepted, the labs forward the parts to the accelerator site, where they get double-checked once more before being installed in the facility.

Real scenarios are much more complex, as they include several labs and suppliers. For example, the European XFEL accelerator modules rely on parts from more than a dozen different sources. It has to be ensured that the different parts arrive on time in order not to delay the production and the completion of the project. Shipments need to be monitored, and buffers need to be provided. In addition, to achieve optimum performance, some parts that are assembled into a module need to be handpicked to ensure they have best-matching properties. To this end, the status, whereabouts and performance test results of every individual part have to be known.

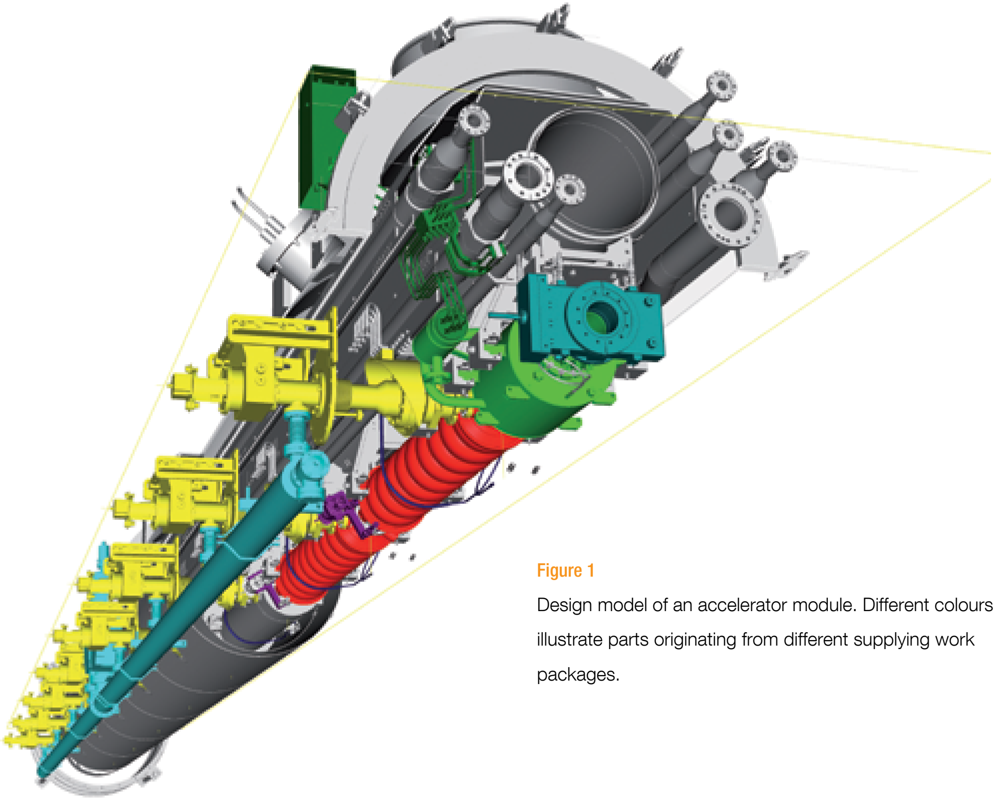

Figure 1

Design model of an accelerator module. Different colours illustrate parts originating from different supplying work packages.

Getting organized

DESY has developed a parts management solution for the series production of accelerator components for the European XFEL. This solution is based on DESY's Engineering Data Management Systems (EDMS), which provides the entire fabrication documentation, records all inspection and performance test results, and tracks the assembly progress of all major accelerator components. It offers procedures for quality inspections and for managing changes, it tracks the current whereabouts and the entire history of each part, and it ensures that the documentation is compliant with legal documentation requirements. The solution integrates the contributing labs and suppliers, ensuring that all partners can exchange information seamlessly and that they always possess the same level of information.

Cultural changes and challenges

Parts management is a proven approach for managing the complexity of large-scale projects, which is well known in major industries. But research labs are very different environments: while industrial companies often have decades of experience in series production, research labs usually work on unique and often large infrastructures in leading-edge technologies. While industrial companies can establish and evolve their production management solution over many years, benefitting from previous reference projects, DESY had to develop and establish the entire parts management solution during the European XFEL project. In this sense, introducing a parts management solution for part fabrication was a challenge comparable to developing the parts in the first place.

Contact: Lars Hagge, lars.hagge@desy.de

Physical Part : D000000010010669,A,1,1 : Item Info : Summary

Related Items

Is In Team Folder : 1 object

Name

Supplier

Is Member Of : 2 objects

Name

Packaging list from Supplier

Packaging list to Manufacturer

Based On : 1 object

Name

E4NT-36 Ingot,A,1,1

Has Description : 2 objects

Name

DT201105-1 Inspection Certificate,A,1,1

N00521 – Eddy Current Scan,A,1,1

Is Instance of : 1 object

Name

Properties

Description

Serial Number N00521

Figure 2

Example of a niobium sheet that was used in the production of a superconducting RF cavity: the sheet has a tracking number (left), the EDMS contains all supplier, shipment and inspection records, and tracks where and when the sheet has been used (right).

Safety underground.

Access control and tracking at the European XFEL

The European XFEL facility is located between 6 m and 38 m below ground, which increases the risk potential during construction and operation of the facility. Various stipulations are defined within the plan approval process to take this risk into account. This article describes the measures to meet these stipulations and reports on first experiences.

Legal requirements of plan approval order

The central demands of the plan approval order can be summarized as follows:

- An access control and singling system is requested as a general requirement to meet safety and fire protection demands within the tunnel buildings.
- A safety instruction covering all relevant hazards is mandatory for everybody working in the underground areas.
- A real-time visualization of the positions of people in underground areas must be available to improve intervention time in case of an emergency.

Figure 1

Turnstile in front of the elevator and the access to the stairs with materials lock (on the left)

Technical realization

The European XFEL Work Package 36, “General Safety”, is in charge of the technical implementation of these demands. It launched a collaboration with the DACHS team, which represents several DESY groups from different divisions.

As a first measure, turnstiles were installed at all access points. The DESY access control system DACHS checks the authorization and the validity of the safety instruction at every access. The DACHS system, which is in use at both DESY sites (Hamburg and Zeuthen), was described in the DESY ACCELERATORS 2011 annual report.

The tracking of personnel is a novelty for DESY, so a second system besides DACHS was established. Besides the functionality, the daily handling has a large impact on the design of the tracking system, since persons carrying out rough work underground should not be affected by the tracking system. The early construction phase and the installation period in particular have to be considered. For this reason, only systems based on transponders working in the far-field region have been taken into account. The signals of the transponders can be detected by antennas without requiring any active actions by the people who should be tracked. The chosen system has been tested and proven at other construction areas situated underground, such as the Gotthard tunnel in Switzerland. It is characterized by its robust and modular design, which is underlined by its application in industry.

Therefore, at each turnstile, the validity of the access authorization is verified by reading the DACHS card, and it is also checked that the person who wants to go underground is carrying a single transponder. To this end, a reading device for the DACHS cards and an antenna to receive the transponder signal were installed. In the current configuration, the transponders are anonymous, in contrast to the cards.

Technical design of the tracking system

The range of the internal antenna of the far-field receivers can vary from 1 cm to 10 m and may be extended without any difficulties by adding external frame antennas. At the turnstiles, the range is reduced to near field to assure that only the entrance area is covered.

During the early installation phase of the accelerator, the area below ground was equipped with antennas working in the far-distance range to cover the whole region. First the shafts that allow access to underground areas were taken care of. The expansion of the system to the inner sections was gradually carried out and will be finished during the first quarter of 2014.

The reliability of the system was a crucial point and had a large impact on the design. The tracking system, as well as the DACHS access control system, profit from using the same protected data cabling as the other safety systems, such as the tunnel radio, being part of the communication systems in case of an emergency. The optical-fibre backbone of these data connections between the European XFEL sites in Bahrenfeld and Schenefeld is under a full fire prevention function and has therefore a guaranteed lifetime of 90 min in case of fire. Furthermore, the network distributors are installed in rooms that are highly protected against fire. These devices are equipped with their own uninterruptible power supplies to prevent power failures. Also, an individual multiserver solution guarantees an extremely high and fail-proof availability of the position data of people in the monitored area to the emergency services.

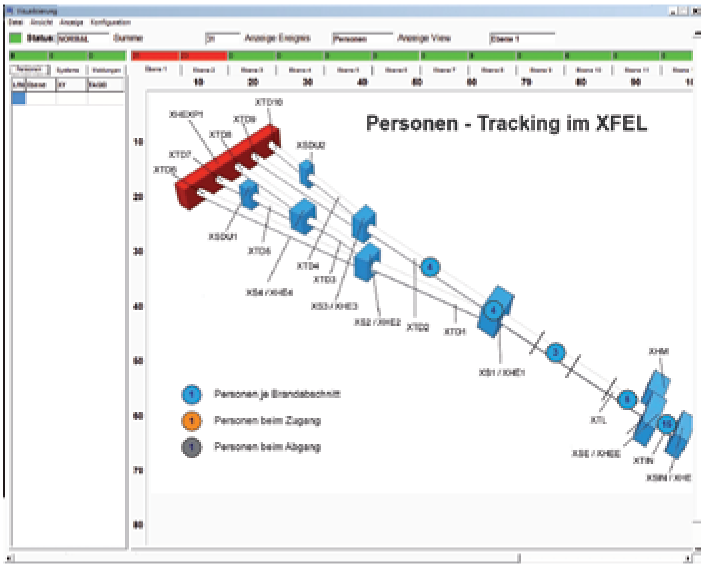

Figure 2

Visualization of transponder movement data

The main accelerator tunnel splits into several smaller tunnels leading to the experimental hall in Schenefeld, which is also located below ground. These tunnels serve as emergency exits for the experimental hall. Since they belong to the monitored underground area, everybody entering the experimental hall has to carry a transponder.

No active check-out is necessary when leaving the monitored area. As a consequence, all zones that can be used to leave the tunnel system, such as media shafts, were equipped with antennas. By this means, the emergency services can register all persons leaving the monitored area.

Tracking visualization and experience

The visualization of the position data will be provided at different locations, primarily at DESY's technical emergency service (SAVE) to coordinate the external and internal emergency forces, and additionally at the control room to operate the accelerator. In later phases, more visualization clients can be made available, for example at the European XFEL site in Schenefeld.

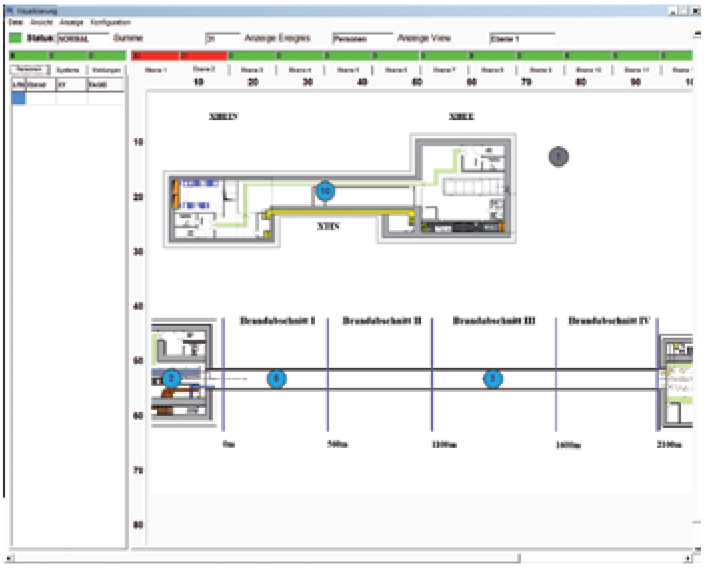

Figure 3

Top view of the 16-channel piezo driver prototype for the European XFEL

The system was commissioned in September 2012. More than 1000 people are presently allowed to enter the tunnel. On average, between 40 and 60 persons are staying underground simultaneously every day. A higher number of daily accesses is expected in the near future, when the accelerator itself will be installed. Up to now, no significant blackouts or other disturbances have occurred, even during first tests of the electron source. The combination of tracking system and DACHS access control system has proven itself in everyday use.

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European Advanced Accelerator Concepts Workshop (EAAC2015)
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ESS Annual Review
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European Strategy Group for Accelerator R&D (ESGARD)
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FAIR Machine Advisory Committee
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FLAC, Machine Advisory Committee SwissFEL
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Helmholtz Virtual Institute 2012
"Plasma Wakefield Acceleration of Highly Relativistic Electrons
with FLASH"
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High Lumi LHC Collaboration Board
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ICFA Beam Dynamics Panel
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ICFA Workshop Electromagnetic Wake Fields, International Advisory Committee
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ILC Accelerator Advisory Panel (AAP) and International Detector Advisory Group (IDAG)
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International Conference on RF Superconductivity (SRF2013) International Program Committee
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Joint ICFA/ICUIL Task Force "High power laser technology for accelerators"
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Physical Review Special Topics - Accelerator and Beams - Editor
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TTC Executive Committee
Hans Weise

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Wolf-Dietrich Möller, Detlef Reschke

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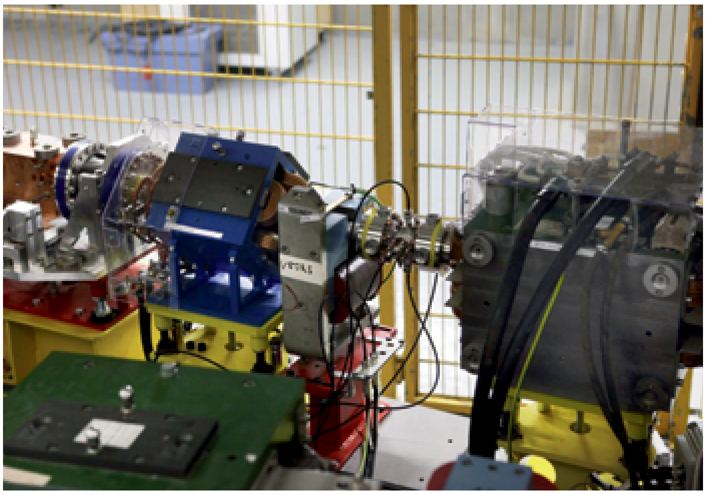
European XFEL, FLASH and PETRA III.

Superconducting accelerator modules for the European XFEL X-ray laser are being measured on test benches in DESY's Accelerator Module Test Facility (AMTF).

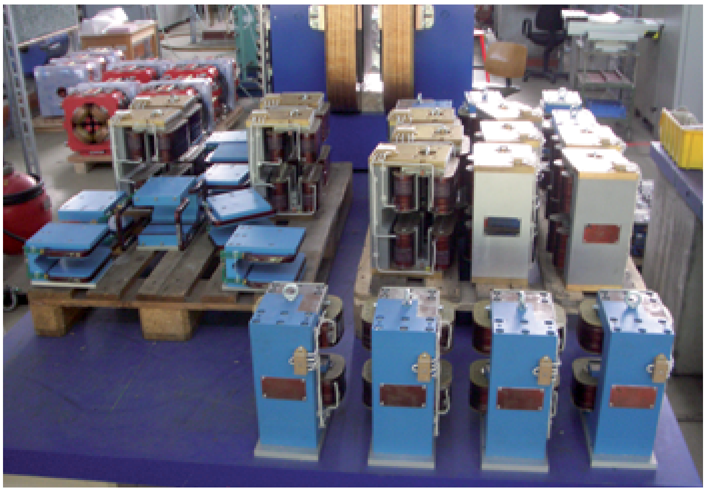
Undulators for the European XFEL X-ray laser



Beam position monitor for the FLASH free-electron laser, with four signal pickups in the middle between a quadrupole magnet (left, blue) and a dipole magnet (right)

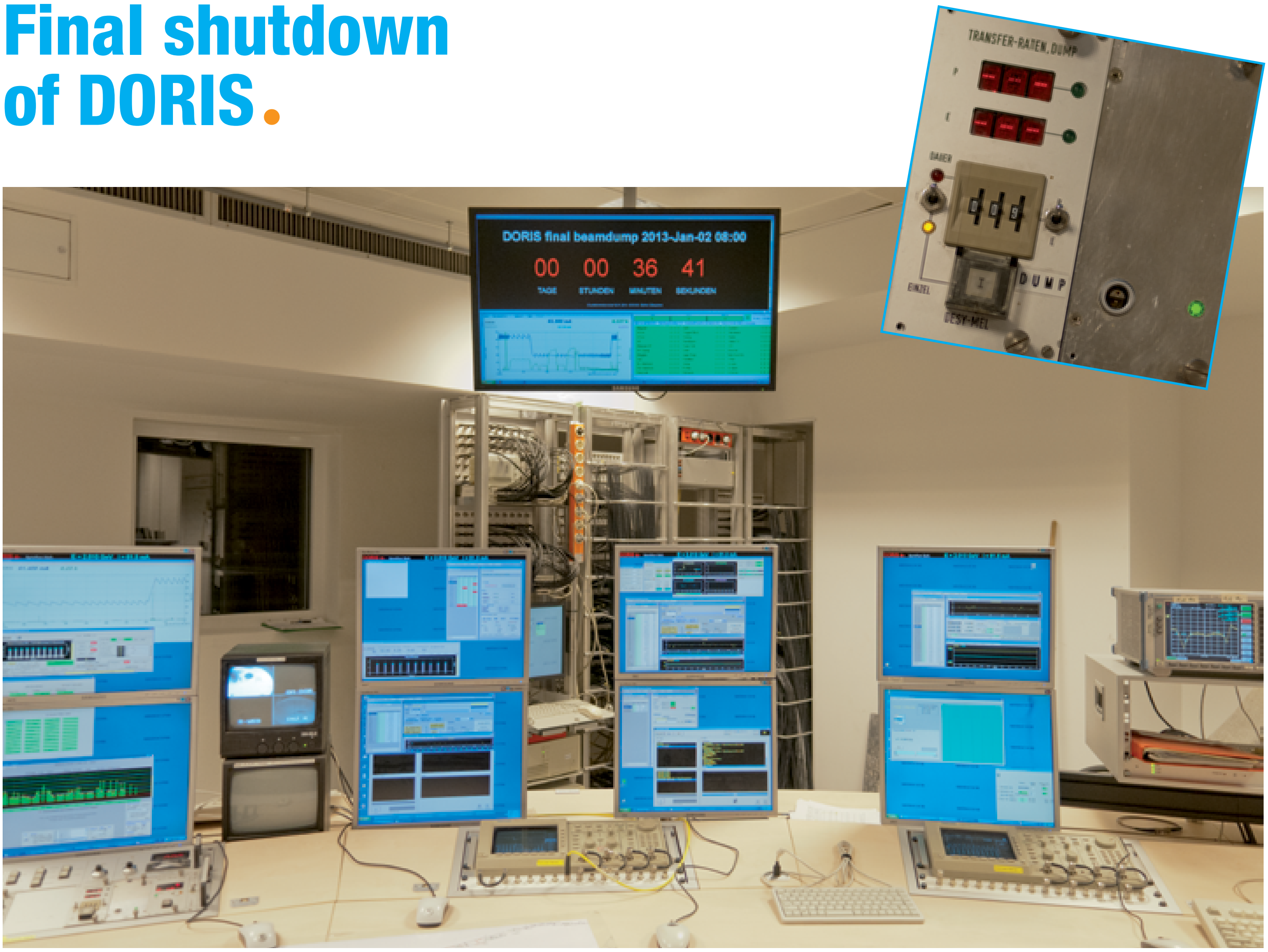
Tunnel of the FLASH free-electron laser

Quadrupole magnets for the extension of the PETRA III synchrotron radiation facility



Corrector magnets for the PETRA III extension

Final shutdown of DORIS.



Final shutdown of the DORIS storage ring on 2 January 2013, after nearly 40 years of operation for particle physics, accelerator development and research with synchrotron radiation

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