ACCELERATORS 2012.

Highlights and Annual Report

Accelerators | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

Cover

Since February 2012, DESY has taken over the responsibility for the European XFEL tunnel construction and installation.

The photograph shows the tunnel and part of the general infrastructure. (Photo: Dirk Nölle)

ACCELERATORS 2012.

Highlights and Annual Report

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Chairman's foreword

The discovery of the long-sought Higgs particle at the Large Hadron Collider (LHC) at CERN near Geneva in July 2012 is certainly one of the top scientific highlights of the last years. While celebrating this success, we should also remember that one hundred years ago, in 1912, two other discoveries dramatically influenced the scientific world: the observation of cosmic rays by Victor Hess and the discovery of X-ray diffraction by Max von Laue. Both physicists were pioneers in their respective field. While the study of cosmic radiation stimulated many developments in particle and astroparticle physics, X-ray diffraction opened a new gateway into the world of molecules and atoms.

DESY´s light sources PETRA III and FLASH as well as the European XFEL X-ray laser are the most advanced X-ray facilities built on Max von Laue´s legacy. These modern research facilities enable leading-edge research ranging from physics, chemistry and biology to materials and life sciences, and support application-driven research for our society's needs, for instance in the fields of energy, environment, key technologies and health.

The European XFEL is DESY´s priority project. DESY contributes significant resources to this international prestige project on German ground. As major cooperation partner, we are responsible for the superconducting accelerator, which, in a 2 km long tunnel, supplies the tailored 17,5 GeV electron bunches for the X-ray lasing process. The construction of the European XFEL accelerator is well under way and will be finished in the second half of 2015. This is a huge effort for our laboratory, in particular for the machine division, the administration and the DESY infrastructure. Together with our partners, we are currently working out the best conditions and appropriate governance frame for the future operation of the European XFEL.

In October 2012, we ended synchrotron user operation at the DORIS III storage ring. The remaining weeks of DORIS operation were dedicated to the OLYMPUS experiment, which was set up to shed light on the startling discrepancy, discovered at Jefferson Lab in the USA, in the ratio of the electric to magnetic elastic form factors for electron scattering off protons. As far as we can see today, the experiment – thanks also to the fantastic

European XFEL tunnel completion ceremony on 14 June 2012

Shutdown of the DORIS III storage ring on 2 January 2013

On 19 September 2012, German Federal Chancellor Angela Merkel visited DESY and the unique nano–bio research campus that is being established on the DESY site in Hamburg. Merkel, Hamburg's First Mayor Olaf Scholz, Nobel Prize laureate in chemistry Ada Yonath and DESY Director Helmut Dosch symbolically christened the experimental hall of PETRA III, the world's most brilliant X-ray source, after the physics pioneer Max von Laue. One hundred years ago, von Laue discovered X-ray diffraction by crystals, which opened the door to the exploration of the nanocosm. The interdisciplinary nano–bio research campus that is being erected around PETRA III will take this field of research into the 21st century.

DORIS machine crew – ran extremely well and produced unique data to solve this form factor puzzle. Over its entire life span, DORIS was a most successful research infrastructure, serving as a world-leading collider for particle physics and a European workhorse for synchrotron radiation. During almost four decades of scientific productivity, DORIS generated an immense output in research. Today, demonstrating the impact that research infrastructures have on science, economy and society to policy-makers and funding agencies has become ever more important. We have therefore launched a socio-economic study covering the complete lifetime of DORIS.

DESY is striving to further enhance its collaboration with German universities. DESY is the national hub for two Helmholtz alliances in particle and astroparticle physics, thereby establishing an interactive network between all major German universities and Helmholtz research centres that are active in these fields. DESY´s role herein has been further strengthened. The two key projects, the LHC at CERN and the IceCube neutrino telescope at the South Pole, are producing inspiring scientific results, which are boosting such research. DESY´s future weight at the LHC will critically hinge on its role in the LHC detector upgrade programme. DESY is currently organizing the necessary resources for its contribution to the ATLAS and CMS upgrades at the LHC.

The new partnership with the University of Hamburg, PIER, is gathering momentum. The new PIER Helmholtz Graduate School was launched at the end of October, with strong support by the Helmholtz Association and the Joachim Herz Foundation.

To ensure that DESY research remains at the forefront of science, it is mandatory to promote young talents and offer equal opportunities at DESY. Ten young investigator groups are currently carrying out research at DESY in close collaboration with our partner universities.

I would like to thank all collaborators and colleagues for their fruitful work. ●

Helmut Dosch
Chairman of the DESY Board of Directors

Accelerators at DESY.

Introduction

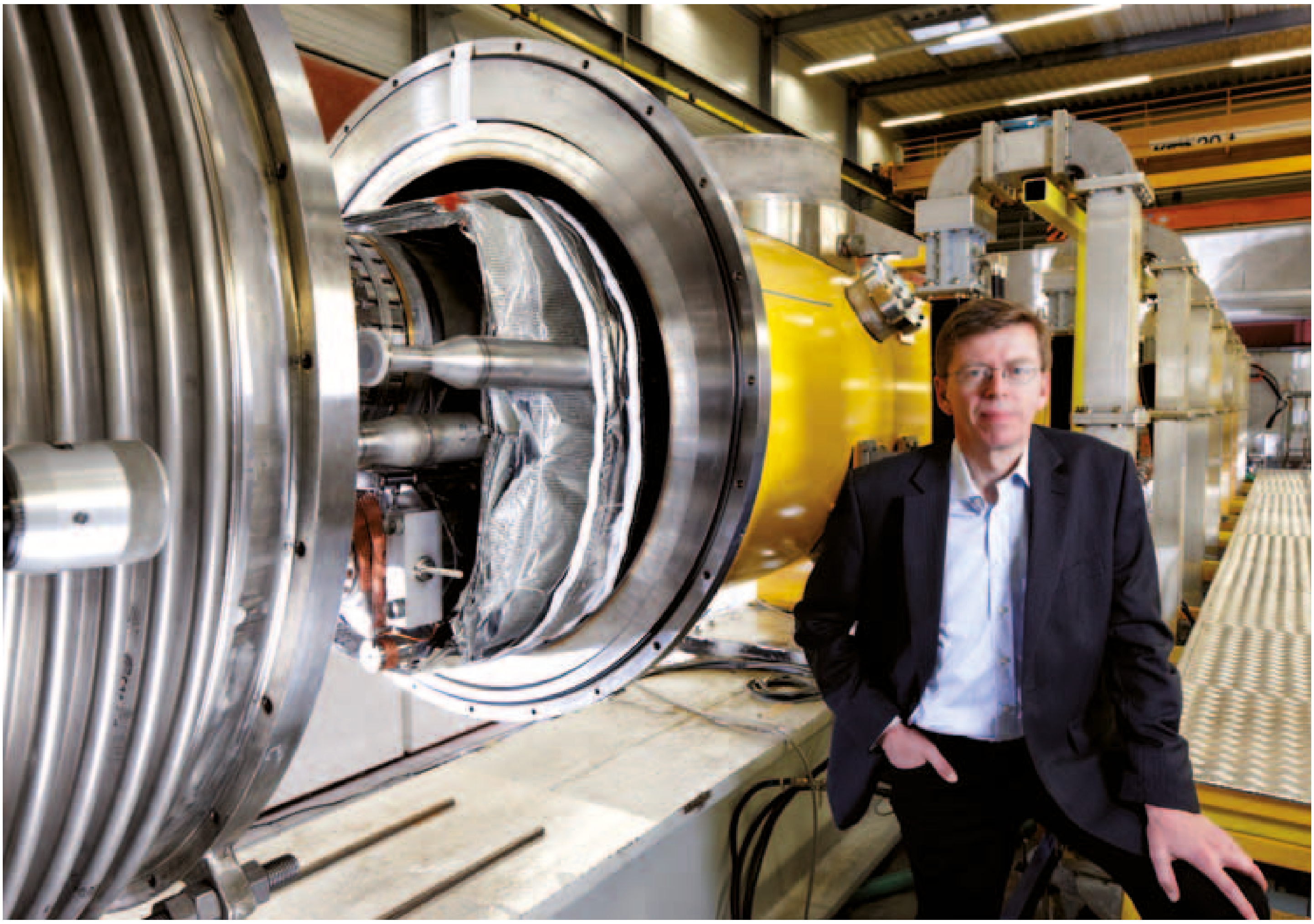
The DESY accelerator division has experienced a very busy and successful year 2012. The DORIS III storage ring finished its many years of operation as a synchrotron light source in October and went into retirement by the end of 2012 – but not before setting a final highlight with an extremely efficient two-month operation phase for the OLYMPUS experiment in November/December. The PETRA III synchrotron radiation run went well, and the FLASH free-electron laser (FEL) facility achieved new records in some of its user operation parameters. The large accelerator construction project of the European XFEL X-ray laser, where technical installations in the tunnel are ongoing and production of linear accelerator components has started, is approaching full speed. The new "Accelerator Research and Development" (ARD) programme of the Helmholtz Association is gathering way and new ideas for exiting future activities emerge. Our team of accelerator physicists received a strong enforcement in August, when Ralph Aßmann (formerly at CERN near Geneva, Switzerland) joined DESY as a new leading scientist in the accelerator division.

The DORIS and pre-accelerator teams had prepared very well for the final performance of the 40-year-old DORIS storage ring: returning for a short period of 10 weeks to its original purpose as a facility for particle physics experiments. Efficient operation for OLYMPUS, which measures the difference in scattering rate of electrons and positrons off protons in a gas target, required running in a quasi top-up mode with small variations in beam intensity and only short interruptions for polarity changes. These requests were met extremely well and, together with almost failure-free operation, provided very smooth conditions for OLYMPUS. The highly motivated operation crew also managed to find volunteers for keeping up a continuous 24h/7 days per week run even over the Christmas and New Year holidays. Furthermore, the teams were able to keep the unavoidable perturbations of PETRA III operation during this run period well within limits.

PETRA III continued regular user operation in top-up mode with peak-to-peak beam current fluctuations of only 1% throughout most of the year. Operation efficiency was enhanced by an increased mean time between failures, but a small number of events caused a few unexpectedly long breaks, so that on average the machine availability was comparable to the previous year, i.e. very slightly below the design goal of 95%. During the last two months of operation, when DORIS III frequently required changing from positrons to electrons, a compromise for topping-up PETRA III was established, which kept beam current variations in a much smaller range than what was originally anticipated (and promised to the users). The preparation work for the extension with new beamlines continued, and an improved concept for the modifications of the accelerator tunnel in these sections of the ring was worked out, which is beneficial for the installation of both accelerator and photon beamline components.

FLASH was operated again with a satisfactory availability well above 90% during user runs, although the excellent figure of the previous year could not quite be reached. Highlights of the 2012 user operation were runs at small wavelengths (about 4.2 nm) in the so-called water window for the first time, more frequent runs with long trains of many bunches and the systematic and reproducible setup of very short photon pulses. Regarding femtosecond technology, further progress was made with extremely accurate synchronization systems and an active feedback stabilization of beam arrival time at a level of only 12 fs. In April, the sFLASH experiment, conducted in close collaboration with the University of Hamburg, could for the first time demonstrate a seeded FEL photon beam at 38 nm wavelength. Unfortunately, at the beginning of June, the FLASH user run had to be terminated about two weeks prematurely because of RF breakdowns in the RF gun. The gun was exchanged with the one that had been operated very successfully at the PITZ photoinjector test facility at DESY in Zeuthen, and FLASH was able to resume operation without further serious problems. The civil construction work for the FLASH II extension has made good progress, and installation of the new electron and undulator beamline will take place in 2013.

The construction work for the European XFEL accelerator complex entered a new phase with the start of installation work in the linear accelerator tunnel. During 2012, a major fraction of the infrastructure installations, such as cable trays, water pipes, pulse cables etc., was completed. For the superconducting cavities, a large part of the niobium material was delivered and checked



for appropriate quality at DESY. The infrastructure for the series production of cavities was built up at the two manufacturers, and the qualification of the different production steps took place. Test results for the first reference cavities were very encouraging. The infrastructure for module assembly at CEA in Saclay, France, was commissioned using the European XFEL prototype accelerator modules, with experts from DESY continuously present on site and supporting our French colleagues in establishing the assembly procedures. The production of many other components for the European XFEL linear accelerator was launched and is proceeding on schedule and within budget. PITZ in Zeuthen contributed to the European XFEL (and FLASH) programme through the processing of RF guns and studies of their operational stability.

At the REGAE electron diffraction experiment, our youngest accelerator family member, which DESY operates in cooperation with the Max Planck group of Prof. Dwayne Miller at CFEL in Hamburg, first diffraction patterns could be recorded in 2012. Further work is focusing on improving the RF and beam stability. REGAE will also be used for one of our new activities in close cooperation with Prof. Florian Grüner at the University of Hamburg within the ARD accelerator research programme, namely tests of laser-driven plasma wakefield acceleration (LPWA). A building next to REGAE has been refurbished to accommodate a 200 TW laser (to be installed in 2013). The REGAE beam will then be injected into the plasma wave excited by this laser. Preparations for a second LPWA experiment using the same laser have also started, in which an undulator beamline will be set up in a nearby unused beam transfer tunnel to test the generation of FEL radiation from plasma-accelerated electron bunches. Further plans are being worked out to test beam-driven plasma acceleration using part of the FLASH electron beam and a plasma cell setup in the new FLASH II tunnel. Related to another subtopic of ARD, continuous-wave and long-pulse RF excitation of a European XFEL prototype accelerator module were tested, with the longer-term goal of developing concepts and technology for a possible future upgrade of FLASH and/or the European XFEL. Last but not least, we had again very lively and inspiring discussions on accelerator physics and technology topics at the fourth round of the DESY accelerator ideas market in September 2012.

You will find much more information on the topics I only briefly mentioned here on the following pages. Enjoy the reading!

R. Brinkmann

Reinhard Brinkmann
Director of the Accelerator Division

News and events.

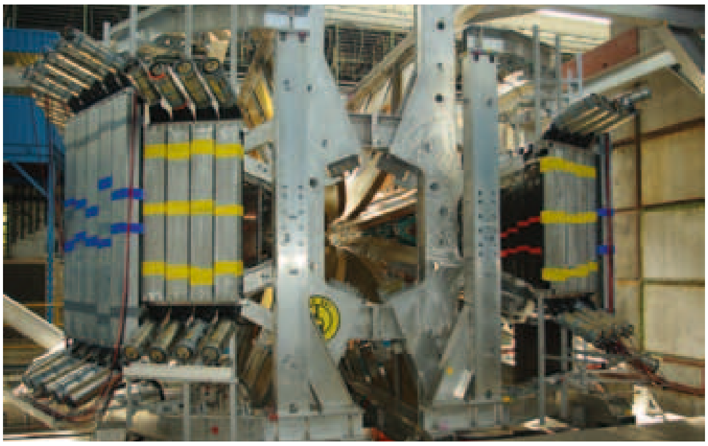
News and events.

A busy year 2012

February

OLYMPUS starts research programme

At the DORIS III storage ring, the new particle physics experiment OLYMPUS, which aims to investigate the interaction of electrons and protons with high precision, started the first of two data-taking runs in February 2012.



The OLYMPUS detector prior to installation at DORIS III

The international OLYMPUS collaboration, which comprises 13 institutes, installed the detector at DORIS III to deliver the most precise measurements of the electric charge and magnetic momentum distributions in the proton. To this end, electrons or positrons are accelerated inside DORIS III to an energy of 2 GeV and shot at a hydrogen gas target inside the detector, inducing the electrons and positrons to scatter off the protons of the gas.

One of the most important features for the experiment is the alternating collisions of protons with electrons and positrons provided by DORIS III. Through the comparison of reaction rates for both particle types, the OLYMPUS team will be able to calculate how often the collision involves the exchange of two photons instead of one. Experiments at Jefferson Lab in the USA had suggested the existence of so far undiscovered higher-order contributions, which could be measured thanks to the regular switching between electrons and positrons at high beam intensity that was only possible at DORIS III.

The second, two-month measuring period of OLYMPUS took place from October to December 2012.

Hamburg mayor visits DESY

Olaf Scholz, First Mayor of the Free and Hanseatic City of Hamburg, visited DESY on 15 February to learn more about the current plans and projects of Hamburg's largest research centre.

In DESY's school lab physik.begreifen, Hamburg's Mayor Olaf Scholz conducted some vacuum experiments together with Karen Ong, the head of the school lab.

After discussions with the DESY Board of Directors, Scholz visited the DESY school laboratory "physik.begreifen", where he witnessed the good atmosphere and the commitment and concentration of fourth-graders doing vacuum experiments, and of upper secondary school pupils carrying out electron experiments.

Scholz was then shown around the 300 m long experimental hall of the PETRA III X-ray source. In his discussions with scientists, he showed himself impressed by the sophisticated technology and the wide range of research that is possible at these modern synchrotron light sources. Scholz also emphasized his appreciation that DESY's top-level research is not carried out in an ivory tower but takes place in a process of lively communication with the city of Hamburg, its citizens and local companies.

Accelerator tunnel for the European XFEL completed

Construction of the more than 2 km long accelerator tunnel for the European XFEL X-ray laser facility was completed. At the end of February, the construction company ARGE Tunnel XFEL officially handed over the tunnel to DESY.

In March, the Accelerator Consortium led by DESY started to equip the tunnel with infrastructure and security equipment. The last accelerator module is scheduled to be installed in May 2015, after which the accelerator will be tested for the first time.

Work on the accelerator tunnel started in January 2011, when the boring machine TULA began to dig its way from Osdorfer Born to DESY-Bahrenfeld. Right behind the machine's cutting wheel, more than 8000 precast concrete segments were inserted to construct the tunnel wall. In July 2011, TULA reached its destination and was dismantled and removed from the construction site. The tunnel was then equipped with a flat concrete floor, which cover parts of the infrastructure.

The accelerator tunnel runs from the future injector building in DESY-Bahrenfeld to a shaft in Osdorfer Born. Further towards Schenefeld, the tunnel branches into two and then eventually five tunnels. These photon tunnels, which lead to the future experimental hall on the Schenefeld site, were constructed using a second tunnel boring machine, AMELI. DESY is the main shareholder of the European XFEL company.

The accelerator tunnel for the European XFEL

March

Hamburg and Dresden accelerator physicists cooperate

DESY and Helmholtz-Zentrum Dresden-Rossendorf (HZDR) intend to closely cooperate in a range of fields, including accelerator physics and technology, detector technologies and systems, the use of synchrotron radiation and the development and application of free-electron and high-power lasers. The two research centres, which already bundle their competence in accelerator physics with other Helmholtz centres and university and non-university institutes within the Helmholtz portfolio initiative "Accelerator Research and Development" (ARD), signed a bilateral cooperation agreement in March.

HZDR staff member working on a mirror of the FELBE free-electron laser

In their cooperation, DESY and HZDR will focus on the design and application of accelerator-based light sources in the terahertz and X-ray range, which are operated at both centres: experiments with terahertz radiation have been possible at the FELBE free-electron laser in Dresden since 2004 and at FLASH in Hamburg since 2008.

The two research centres also intend to cooperate on the underlying superconducting accelerator technologies. Already today, the facilities at DESY and HZDR allow the acceleration of ultrashort electron bunches with a quality that enables significantly more experiments to be carried out in less time than at comparable, normally conducting linear accelerators. DESY and HZDR aim to further optimize electron beam diagnostics methods in order to improve the properties of the centres' light sources even further. The cooperation includes the exchange of personnel, technical solutions and research equipment, as well as joint experiments and measuring times at FLASH and FELBE.

May

First seeding at FLASH

On 28–29 April, one possible seeding method using a high-harmonic generation (HHG) pulse was successfully demonstrated at DESY's FLASH free-electron laser by a team from DESY and the University of Hamburg.

The sFLASH undulators in the FLASH accelerator tunnel

Institutes around the world are searching for methods to initiate the production of laser light in free-electron lasers (FEL) with a well-defined radiation pulse generated by an external laser source and superimposed onto the electron bunch at the entrance of the FEL undulator – a process called seeding. Seeding promises an FEL pulse that is more stable and better reproducible in both pulse duration and frequency spectrum. Moreover, the achievable time resolution of pump–probe experiments is improved when the seeding laser is simultaneously used to initiate a dynamic process in the sample under investigation.

In the sFLASH experiment, the researchers superimposed the high-order harmonic of a laser synchronized with the accelerator onto the bunches of the FLASH electron beam in an undulator line. The electron bunches, excited by the seeding pulses, generated an intense FEL flash with a wavelength of 38 nm. This is the shortest wavelength ever obtained with this “direct seeding” method – a new world record for FLASH and an important milestone on the way to FLASH II, which will be equipped with variable-gap undulators, such as those used in the sFLASH experiment, and with a seeding option.

European free-electron laser collaboration established

On 31 May, ten European research centres, including DESY and European XFEL, agreed on a long-term close collaboration in the field of free-electron lasers and accelerator-based short-pulse radiation sources. In a joint effort, the technologies and methods for the operation and use of these novel research facilities will be further developed and implemented, creating a unique top-level research infrastructure for science in Europe that will offer optimal experimental conditions for a wide range of applications.

Representatives of ten research organizations sign a cooperation agreement.

With more than 200 publications to date, the experiments at the first X-ray free-electron lasers, FLASH in Hamburg and LCLS in California, USA, impressively demonstrated the scientific potential of the new facilities. However, many technical and methodical developments are still necessary to exploit this potential to its full extent. By signing the collaboration agreement, the ten research institutions from Germany, France, Italy, Poland, Sweden, Switzerland and the UK expressed their interest to promote research with free-electron lasers.

The partners in the new collaboration are:
- Deutsches Elektronen-Synchrotron DESY, Germany
- European XFEL GmbH, Germany
- Istituto Nazionale di Fisica Nucleare (INFN), Italy
- Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (HZB), Germany
- MAX IV Laboratory, Sweden
- National Centre for Nuclear Research (NCBJ), Poland
- Paul Scherrer Institut (PSI), Switzerland
- Science and Technology Facilities Council (STFC), UK
- Sincrotrone Trieste S.C.p.A. (Elettra), Italy
- SOLEIL, France

June

European XFEL tunnel construction completed

The European XFEL reached an important milestone: the construction of the network of tunnels – which has a total length of nearly 5.8 km and extends 3.4 km from the DESY site to Schenefeld in Schleswig-Holstein – was finished according to plan. The tunnel completion was celebrated on 14 June with more than 400 participants, including guests from politics and science as well as staff from collaborating companies.

With an investment volume of more than one billion euro, including 240 million euro for the construction of the tunnels and other underground buildings, the new international research facility is one of the largest scientific projects on German territory. Starting in 2015, it will generate laser-like X-ray flashes that will enable completely new insights into the nanoworld.

The tunnel boring crew in front of the cutting wheel of AMELI

Tunnel construction began in July 2010 with the accelerator tunnel using the tunnel boring machine TULA. In January 2011, the second machine, AMELI, started to excavate the five photon tunnels leading into the experimental hall. This was a difficult mission: given the special layout of the tunnel, the 160-tonne colossus had to be repeatedly relocated and prepared for the next section. Tunnelling with TULA was concluded in August 2011. With the completion of the last tunnel section, the mission of AMELI came to an end in June 2012.

The tunnels were then to be equipped with the necessary infrastructure and safety devices, after which the main components of the facility will be installed: the superconducting electron linear accelerator, whose development, installation and operation is conducted by DESY, and the photon tunnels, undulator beamlines and experimental hall, whose equipment and instrument installation is led by European XFEL.

Helmholtz Association funds commercialization of new electronics industry standard

Controlling modern accelerators demands extremely precise and fast technology that can process numerous data sets in parallel. To this end, DESY developed a new generation of control electronics for FLASH and the European XFEL. After implementation of this low-level radio frequency (RF) system, which is based on the electronic standard MTCA.4, the new standard proved to be so multifunctional that it is being prepared for commercialization and application in industrial enterprises and large-scale research projects. The costs of about 4 million euro for the two-year project are borne by the Helmholtz Association through the Helmholtz Validation Fund, DESY and partners from industry.

DESY's fast control electronics has great potential for applications in industry.

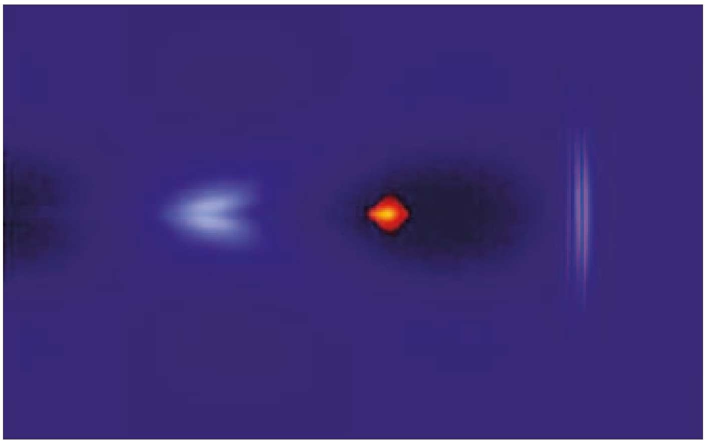
With linear accelerators, it is not possible – as with storage rings – to measure a parameter in one particle round and regulate it in the next. Instead, the data from a particle bunch already traversing the accelerator must be used to determine the starting values for the next bunches. To this end, DESY developed a control hardware that acts on subsequent particle bunches within the same bunch train. Such a system must be able to very quickly process a wide range of data in parallel. To control the RF for the linear accelerator of the European XFEL, developers used the new electronics standard MTCA.4, which was elaborated within the PCI Industrial Computers Manufacturers Group (PICMG) with significant participation of DESY and adopted in October 2011.

Together with seven industrial companies, DESY is now further developing the modules, which will be made available on a license basis, and optimizing them for industrial application. In addition, the product line will be completed and extended for special industrial requirements. DESY and the involved companies will also offer extensive counselling to promote the implementation of the new industrial process control standard.

June

New virtual institute for plasma acceleration

The Helmholtz Association is funding a new “virtual institute” at DESY that will advance a novel accelerator technology. Plasma wakefields have the potential to accelerate particles over very short distances, thus offering a promising technology for future accelerator applications. The newly established virtual institute “Plasma wakefield acceleration of highly relativistic electrons with FLASH” will do basic research to explore the possibilities of using the extremely high electric fields created in a plasma to reliably accelerate high-energy electrons. The Helmholtz Association will fund the virtual institute for a period of five years.



Simulation of an electron bunch in a laser-driven plasma wave

A plasma is a highly excited state of ionized matter, with electrons moving freely between the atomic nuclei. It is, for example, generated by an intense laser beam or by a particle beam in a gas. Initial experiments at other institutes to use such fields for particle acceleration produced very promising results.

One of the major challenges is to inject a particle bunch into the plasma at exactly the right time for it to be accelerated – an experiment that has not been carried out so far. This is one of the topics of the new virtual institute, which involves DESY, the University of Hamburg, the Max Planck Institute for Physics in Munich, the John Adams Institute (UK) and the accelerator centres SLAC, LBNL (both USA) and CERN. The scientists will inject the electron beam of the FLASH II accelerator into a plasma cell, thereby accelerating it using the plasma. At one of the experimental setups, the plasma will be created by the particle bunch itself; in another approach, it will be produced by an extremely intense laser. Further experiments are also planned at the Relativistic Electron Gun for Atomic Exploration (REGAE) at DESY in Hamburg and at the PITZ photoinjector test facility at DESY in Zeuthen.

August

Ralph Aßmann new leading scientist

In August, Ralph Aßmann took up office as leading scientist in the DESY accelerator division. Aßmann came to DESY from CERN, where he built the collimator system for the Large Hadron Collider (LHC), among other things, and served as machine coordinator. Aßmann has worked in both particle and accelerator physics, including participating in one of the very first plasma accelerator experiments at SLAC in California.

At DESY, Aßmann will concentrate on plasma acceleration and assume tasks within the “Accelerator Research and Development” (ARD) portfolio programme of the Helmholtz Association. Moreover, he will represent DESY in European accelerator physics programmes and networks, such as the European Network on Novel Accelerators (EuroNNAc) and the European Coordination for Accelerator Research and Development (EuCARD).

First and foremost, however, Aßmann wants to continue to design and build accelerators. “I think that within the coming ten years we should be able to build a reasonable plasma wakefield accelerator,” he says. To this end, he will build up his own team. He thinks that the conditions at DESY for such a project are perfect: “Excellent research is done here at DESY, and the existing accelerators and know-how are a big advantage.”

Ralph Aßmann

Self-seeding for better pictures of the nanoworld

In 2010, Gianluca Geloni (European XFEL), Vitali Kocharyan (DESY) and Evgeni Saldin (DESY) invented a self-seeding method designed to improve the features of X-ray free-electron lasers. In 2012, researchers from SLAC and LBNL in California, ANL in Illinois, and the Technical Institute for Superhard and Novel Carbon Materials in Russia successfully implemented the scheme at the LCLS X-ray laser at SLAC and confirmed the predicted outcome. The results were published in *Nature Photonics* in August.

The chamber containing the diamond crystal used for self-seeding at SLAC

The breakthrough was obtained through a relatively simple modification of LCLS, improving the longitudinal coherence of the X-ray beam while maintaining a very high intensity.

X-ray generation in FELs usually starts from electron beam shot noise, resulting in radiation that is not very coherent and consists of slightly different wavelengths. To improve the X-ray flashes, a special crystal was inserted between the undulators. When the light generated in the first part of the undulator hits the crystal at a certain angle, most of the light passes through the crystal, keeping the same properties as the incoming beam. However, because of the specific properties of the crystal, the first pulse is followed by a second one, slightly delayed and monochromatic. If the electron beam that generates the light is also delayed using a magnetic chicane, and then set on top of the second light pulse, the electron beam will amplify this second pulse. Thus, only the high-quality, monochromatic X-rays seed the light generation in the second part of the undulator, resulting in very intense and coherent single-wavelength flashes, which might be used to obtain even more sophisticated pictures of the nanoworld than expected.

Start of construction work for FLASH II main tunnel

Construction of the main tunnel section of the FLASH II extension started in August. In 2013, a second undulator line will be installed in the 110 m long tunnel to serve a second experimental hall, allowing DESY to double the research capacities of its FLASH user facility.

Construction site of the FLASH II main tunnel

Using the soft X-ray laser beam of FLASH, scientists can take snapshots of the world of molecules and photograph ultrafast processes in the nanocosm. The existing FLASH measuring stations are completely overbooked, however. With FLASH II, DESY will not only extend the number of measuring stations, the facility will also become more flexible. FLASH II will allow operators to change the wavelength of the emitted radiation during operation, which is not possible at the existing beamline.

In order not to disturb research operation at FLASH and PETRA III, the construction of the extension tunnel was divided into three sections. The front section – the connection to the existing FLASH accelerator tunnel – and the rear section with the connection to the future experimental hall were already completed. In August, construction started on the main section of the tunnel, including two new buildings for technical installations for operation and research. Planners have already provided for a possible further expansion in the future: the 15 m wide and 9 m high tunnel offers enough space for an optional third undulator line.

September

German Federal Chancellor Merkel visits DESY

On 19 September, German Federal Chancellor Andrea Merkel visited DESY. Together with Hamburg's First Mayor Olaf Scholz, Nobel Prize laureate in chemistry Ada Yonath and DESY Director Helmut Dosch, she symbolically christened the experimental hall of PETRA III, the world's most brilliant X-ray source, after the physics pioneer Max von Laue.

German Federal Chancellor Angela Merkel, DESY Director Helmut Dosch, Nobel laureate Ada Yonath and Hamburg's First Mayor Olaf Scholz unveil the name "Max von Laue" on the wall of the PETRA III experimental hall.

PETRA III is "in the truest sense of the word a brilliant example" for the further development of Laue's method, Angela Merkel emphasized in her address. "PETRA III extends, in a remarkable way, the world of research and knowledge for which Max von Laue laid the foundation stone one hundred years ago." DESY possesses the outstanding ability to employ its large-scale facilities to address important questions of humanity, and thus enhance the benefit of the individual, Merkel said. "Germany needs top-level research like what is done here. Germany needs your knowledge and ideas for tomorrow's technologies and markets."

Chancellor Merkel also underlined the importance of progress in basic research as breeding ground for the technologies and innovations of tomorrow. "Progress in basic research paves the way for economic and social progress. This is, of course, extremely important for a nation lacking in raw materials like Germany. This is why basic research is crucial for us. It is the key for Germany's future prosperity." According to Merkel, DESY offers the best conditions for global research cooperation. "In the field of basic research in the natural sciences, DESY plays a leading role in the world. And it is an attractive location for state-of-the-art large-scale facilities," Chancellor Merkel said.

October

PhD thesis award 2012

The PhD thesis award 2012 of the Association of the Friends and Sponsors of DESY (VFFD) was shared by Katarzyna Anna Rejzner and Arik Willner.

Katarzyna Anna Rejzner

Arik Willner

Katarzyna Anna Rejzner from Poland studied in Cracow, and then started her doctoral studies on gauge theories at the II Institute of Theoretical Physics at the University of Hamburg. Despite their high predictive value, gauge theories present a series of unsolved problems related to the auxiliary parameters that are required for their formulation. An important question is whether the theories' predictions depend on the rather arbitrary choice of these auxiliary parameters. Rejzner developed a mathematically precise version of a formalism devised by Soviet physicists Batalin and Vilkovisky, showing that the choice of the auxiliary parameters does not play a decisive role. As a consequence of her work, a consistent quantification of gravity – one of today's major unsolved problems in physics – now seems to be within reach.

Arik Willner studied in Kassel and Hamburg, where he obtained his doctoral degree working on the possibilities of seeding free-electron lasers. These novel research facilities emit extremely intense ultrashort X-ray flashes. However, the beam pulse quality is subject to statistical fluctuations if nothing is done to specifically prevent the effect. One possible countermeasure is seeding, which consists in inducing the laser process with a weak beam pulse of the required wavelength. Producing such seeding pulses in the wavelength range from 10 to 100 nm is very difficult, however, especially when thousands of these pulses are needed every second, as is the case at FLASH. Arik Willner was able to solve this problem in his PhD thesis, thereby significantly advancing the technology.

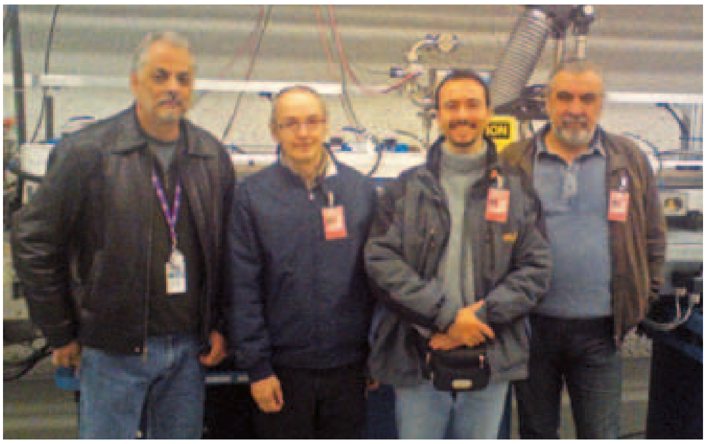
The PhD thesis award of the Association of the Friends and Sponsors of DESY includes a prize money of 3000 euro. The association presents the prize every year for one or two outstanding PhD theses.

December

DESY and European XFEL scientists win Innovation Award

Gianluca Geloni (European XFEL), Vitali Kocharyan (DESY) and Evgeni Saldin (DESY) received the Innovation Award on Synchrotron Radiation 2012 from the Association of Friends of Helmholtz-Zentrum Berlin. Together with Paul Emma (LBNL), the physicists from DESY and European XFEL were honoured for their invention of a self-seeding method that significantly improves X-ray free-electron lasers (see August).

The Innovation Award is conferred annually by the Association of Friends of Helmholtz-Zentrum Berlin to scientists at European research institutions. The 2012 award was presented at the HZB users' meeting on 13 December.



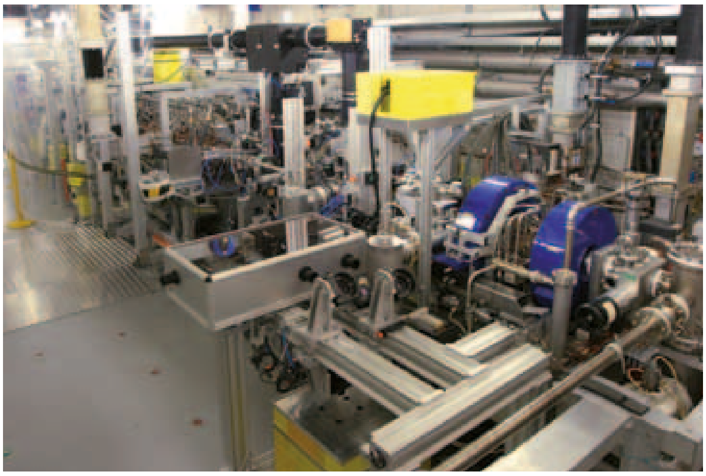
From left: Paul Emma, Evgeni Saldin, Gianluca Geloni and Vitali Kocharyan

New Helmholtz–Russia Joint Research Group approved at PITZ

The Helmholtz Association approved a Helmholtz–Russia Joint Research Group, which will be headed by Mikhail Krasilnikov (DESY) and Efim Khazanov (Institute for Applied Physics in Nizhny Novgorod, Russia). The group will optimize the generation of high-charge electron bunches at the PITZ photoinjector test facility at DESY in Zeuthen. The Helmholtz Association will fund the group over a period of three years with a total of 390 000 euro, with Russia contributing another 3.6 million rouble. The German–Russian cooperation is part of a longer-term project at DESY approved by the German research ministry in 2010, aiming to develop the ideal electron sources for the radiation sources of the future.

The quality of the electron bunches generated by the photoinjectors of X-ray free-electron lasers decisively influences the quality of the resulting X-ray radiation. To test such electron sources, DESY started the construction of the PITZ facility in 1999. Since then, PITZ has served to improve numerous technologies and methods for photoinjectors.

Using a photocathode laser system developed by Max Born Institute (MBI) in Berlin, scientists at PITZ today provide electron bunches with the world's best emittance at very high stability. However, simulations suggest a possible emittance improvement of up to 30% if the laser pulses have an egg-shaped profile in space and time rather than a uniform intensity over the whole pulse duration (a so-called beer can profile). The new Helmholtz–Russia Joint Research Group will fathom the feasibility of this further improvement and test whether the technology can be used to produce ultrashort electron bunches that would allow even shorter X-ray laser flashes.



The PITZ photoinjector test facility in Zeuthen

Accelerator operation and construction.

DORIS III.

Exciting finish

At the end of 2012, after 38 years, the exciting story of DESY's first storage ring came to an end. DORIS took up operation as an electron–positron collider ring in 1974 to extend our knowledge of the world of elementary particles. From the first year on, other research groups seized the opportunity to use the hard and intense X-rays produced in the storage ring for experiments. The scientists at DORIS were among the pioneers who investigated and developed the potentials of the new radiation. The success of their work formed the basis for the conversion of DORIS into a dedicated synchrotron radiation source in 1993, when the high-energy physics programme came to an end.
After several modernizations, it was decided to finally shut down DORIS III at the end of 2012, as the new high-brilliance source PETRA III had successfully started routine operation. As a last challenge, DORIS III became home to the new nuclear-physics experiment OLYMPUS, which aims to investigate fundamental properties of electron–proton scattering. After installation of OLYMPUS during the last years, data taking started in January 2012 for one month and was completed during 10 weeks of dedicated beam time at the end of the year.

Reliable synchrotron radiation source

Until its final year of operation, DORIS III was in great demand as a facility for research with photons. The number of beam time proposals from national and international groups increased once more, attesting the excellent research environment offered by the storage ring in combination with the infrastructure and instruments at the various beamlines. Photon science at DORIS III in 2011 was documented in 600 publications, and a similar number is expected for 2012.

In 2012, DORIS III reliably provided the experimental stations of HASYLAB, EMBL and Helmholtz-Zentrum Geesthacht with hard and intense X-rays. The effective beam time from March to October was 4640 hours, which corresponds to 95% of the scheduled beam time. There was not a single event that caused a longer interruption of the beam operation. On 22 October 2012, the final synchrotron radiation run ended after 38 years of photon science at DORIS.

Successful finish for OLYMPUS

In June 2007, a proposal was presented to move the BLAST detector from the Bates Linear Accelerator Center near Boston to Hamburg and rebuild it at DORIS III as the OLYMPUS experiment. The motivation behind the proposal was new results in electron–proton scattering experiments, which were in contradiction with theories so far. To solve this discrepancy, a new type of setup was chosen, which needed beams of electrons and positrons of about 2 GeV energy. The protons came from an internal hydrogen gas target. As DORIS was originally designed for this type of large detectors, with a diameter of about 10 m, the space and infrastructure in the experimental hall were still available. After approval, a short and intense planning phase followed, with contributions from the OLYMPUS collaboration and the participating DESY groups. The visible work began in 2010 with the removal of the ARGUS detector, which was still in its parking position in the experimental hall and is now exhibited in a prominent place near the DESY entrance.

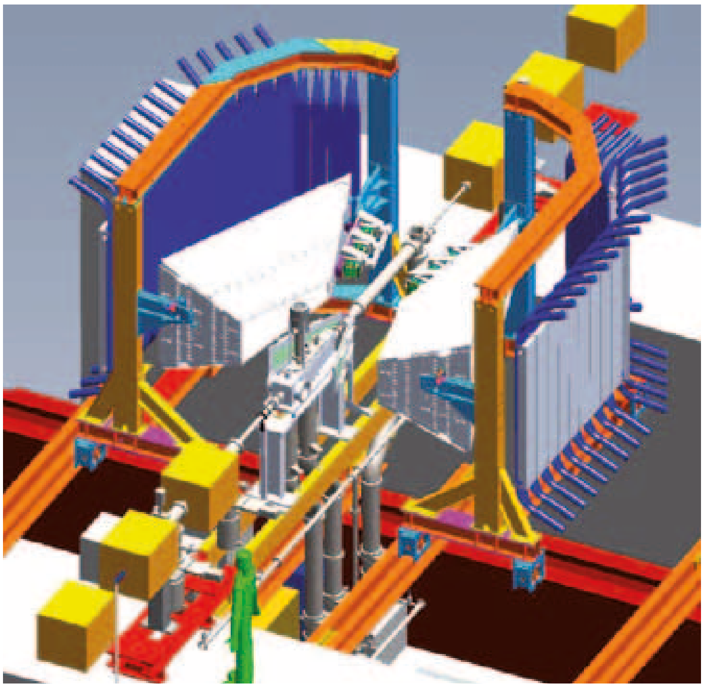


Figure 1

The OLYMPUS detector with the gas target chamber in the centre, the trapezoidal wire chambers and the time-of-flight counters on the outside

The modifications of the DORIS III storage ring for its new task followed in the winter 2010/11, including installation of a new vacuum system. All the work was carried out under the precondition that synchrotron radiation operation must not be compromised. During the summer of 2011, the OLYMPUS detector was completed and eventually rolled into its final position. On 20 January 2012, beam operation started after the winter shutdown with preparations for the frequent switching between the particle types at 2 GeV, which was crucial for the success of the experiment.

Figure 2

View along the beamline onto the OLYMPUS target chamber in the DORIS III tunnel. The detector is in a half-open position. The four coils of the toroidal magnet on each side produce a magnetic field that is part of the particle detection system.

The first measuring period of OLYMPUS extended over the complete month of February 2012. Concerns that conditions with the electron beam might be worse than with the positron beam came up beforehand, because of experiences from former times when positively charged microparticles had been trapped by the beam. However, it turned out that this happened only very rarely and did not affect the performance. After optimization of all relevant parameters, the detector efficiently took data independently of the particle type.

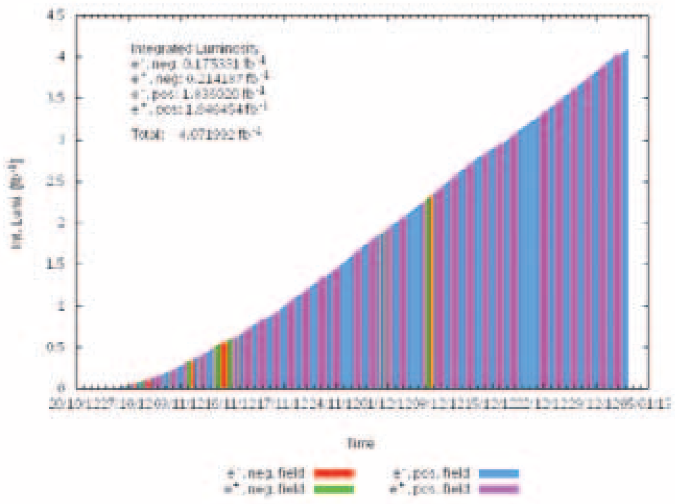


Figure 3

Development of OLYMPUS integrated luminosity with electrons and positrons for positive and negative magnetic detector field from 22 October 2012 to 2 January 2013

The time for switching the polarity could be minimized so that the beam was stored over 90% of the time – the overall efficiency of data taking was about 75%. Nevertheless, the total amount of data was significantly too low, because the density of the hydrogen target was reduced due to a failure in the gas supply system. This defect was repaired by autumn, and the second and main measuring period started on 22 October 2012 with a fully operational and optimized detector.

Because of the higher target density, the lifetime of the beam in DORIS III was reduced to about 15 min, which was compensated for by frequent fillings on top of the stored beam every 2 min. This was possible since all the components of the detector stayed active during injection. The frequent fillings significantly increased the efficiency of the data collection.

To be sure to reach the goal of 3.6 fb^{-1}, operation continued without interruption until 2 January 2013. The total integrated luminosity at the end of the measuring period was 4.07 fb^{-1}. The OLYMPUS collaboration will now analyse these data, and we are looking forward with great interest to getting the first results in the course of 2013.

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PETRA III.

User operation and facility extension

The year 2012 at PETRA III was fully devoted to user operation. In total, 4944 hours of synchrotron radiation beam time were delivered to users at 14 beamlines. A continuous effort was made to improve the reliability of the facility and increase the key performance indicators, availability and mean time between failures. In addition, studies and experiments were carried out to improve the insight into the behaviour of the machine. In parallel, the design of the future extension of the facility has been promoted to its final stage and will be issued for construction early in 2013. As a social highlight, the PETRA III experimental hall was symbolically christened after Nobel laureate Max von Laue.

User operation

After a winter shutdown and an intense period of machine development, user operation resumed in March 2012 and ended on 18 December 2012. The somewhat late start of user operation was more than balanced by dispensing with a summer shutdown. The necessary maintenance work was carried out in five service weeks distributed over the year, dividing the full user period into six 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 2012 is shown in Fig. 1.

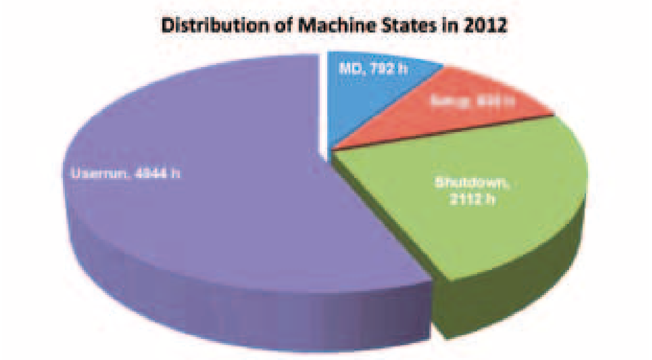


Figure 1

Contribution of different machine states to the total available time in 2012

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 240 evenly spaced bunches or, for the first time during regular user operation, in 320 bunches. In 2011 and before, operation with more than 240 bunches was strongly affected by a blow-up of the vertical beam size. This blow-up was attributed to the so-called electron cloud effect. Increasing the number of bunches was possible thanks to a successful application of scrubbing runs during the machine setup period in February/March 2012. The success of the scrubbing procedure can be regarded as strong evidence that the minimum bunch spacing is limited by electron cloud effects. Increasing the number of bunches further was not successful. Even after a second period of scrubbing, 480 bunches could not be filled without compromising the vertical beam size.

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 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. In 2012, a large part of those bellows have been replaced with a new design, but this work will only be finished in 2013. Fig. 2 shows the distribution of different user modes in 2012.

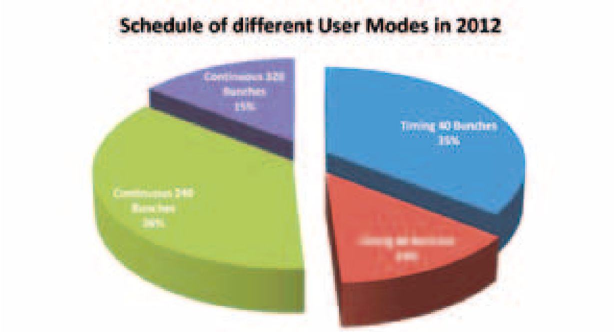
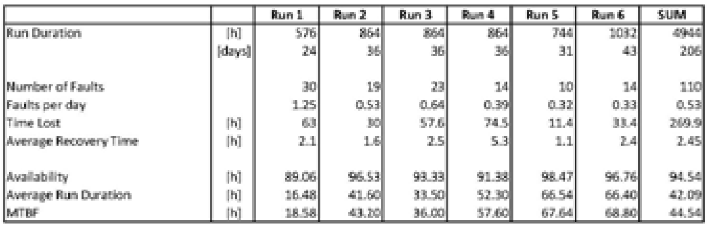


Figure 2

Contribution of different operation modes to the user run in 2012. The total available time for user runs is almost equally divided into timing mode and continuous mode.

Timing mode and continuous mode each take up approximately half of the available time for user runs. Both modes were routinely operated in top-up mode with 0.3–1% current fluctuation.

High reliability is one of the key requirements of a synchrotron radiation facility. The key performance indicators, availability and mean time between failures (MTBF), are summarized in Fig. 3. After a cumbersome start mainly caused by problems with the RF systems, the availability was above the targeted 95% over long periods of the year, and the increased stability of operation can be read off from the increasing MTBF.



		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	SUM
Run Duration	[h]	576	864	864	864	744	1032	4944
	[days]	24	36	36	36	31	43	206
Number of Faults		30	19	23	14	10	14	110
Faults per day		1.25	0.53	0.64	0.39	0.32	0.33	0.53
Time Lost	[h]	63	30	57.6	74.5	11.4	33.4	269.9
Average Recovery Time	[h]	2.1	1.6	2.5	5.3	1.1	2.4	2.45
Availability	[h]	89.06	96.53	93.33	91.38	98.47	96.76	94.54
Average Run Duration	[h]	16.48	41.60	33.50	52.30	66.54	66.40	42.09
MTBF	[h]	18.58	43.20	36.00	57.60	67.64	68.80	44.54

Figure 3

Key performance indicators, availability and mean time between failures (MTBF), in 2012. The table shows the six run periods and the average values. After a somewhat cumbersome start, operation stabilized, as indicated in particular by the rising MTBF.

However, run periods 3 and 4 suffered from a few single events causing comparatively long downtimes. In particular, in early August a vacuum incident in the cavity section led to an interruption of machine operation for a few days and resulted in a dominant dip in the weakly availability, as can be seen in Fig. 4. The figure also shows the development of the average availability over the year. Although the target of 95% was just missed, the evolution of the availability and MTBF confirms the progress in reaching high reliability.

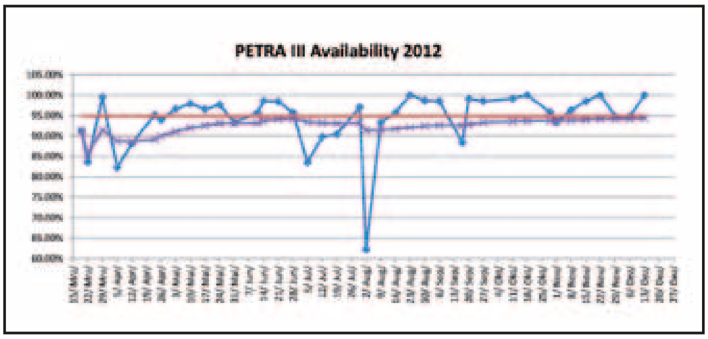


Figure 4

Availability in 2012. The blue curve shows the weekly average, the magenta curve the yearly average. The solid red line indicates the target availability of 95%.

After the end of DORIS III operation as a synchrotron radiation source in October 2012, PETRA III was operated in parallel to the OLYMPUS experiment installed in the DORIS III ring. OLYMPUS operation required a daily switch between positrons and electrons delivered by the pre-accelerators. Thus, standard top-up operation with current fluctuations as low as 0.3% could not be maintained during the last two months of user operation at PETRA III. A major effort in minimizing the time needed for switching the polarity of the pre-accelerators made it possible to limit the current variation to less than 5% for most of the time, even in periods of very short refill cycles for the OLYMPUS experiment. This ensured minimal disturbance of the beam stability, which was routinely beyond the specifications as established in 2011.

A social highlight in 2012 regarding PETRA III was the visit of German Federal Chancellor Angela Merkel in September. Together with Hamburg's First Major Olaf Scholz, chemistry Nobel laureate Ada Yonath and DESY Director Helmut Dosch, she symbolically christened the experimental hall after Nobel laureate Max von Laue.

Figure 5

German Federal Chancellor Angela Merkel, DESY Director Helmut Dosch, Nobel laureate Ada Yonath and Hamburg's First Major Olaf Scholz unveil the name “Max von Laue” on the wall of the experimental hall.

PETRA III extension

The preparation and design work for the extension of PETRA III was continued in 2012. The lattice changes were already fixed in 2011 with the notable exception of adding a canting option to beamline P21 in the modified straight section east. This will allow simultaneous operation of an additional standard undulator serving the side station while the inline beamline is operated either using an in-vacuum undulator or a short wiggler.

On the construction planning side, a new concept for the machine and front-end areas in the experimental halls has been adopted. The existing tunnel will be dismantled and machine and experimental areas will share the same floor slab, as is the case in the existing “Max von Laue” hall. In combination with active measures like air conditioning and orbit feedback, this will guarantee a high level of stability of the photon beam. In view of these additional measures to ensure the performance of the machine, the already very tight schedule had to be shifted and civil construction is foreseen to start in September 2013. User operation will then resume in mid-2014, serving “friendly users” after a short period of commissioning.

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Figure 6

View of the PETRA III storage ring showing the planned additional halls North and East. Each extension hall will house five beamlines. Overall options for additional extensions are marked with shaded ovals.

FLASH.

Consolidating operation with remarkable stability

After the successful completion of the first phase of the construction work for the second undulator beamline FLASH2, more than 3500 hours of user beam time divided in six blocks were scheduled for the fourth user period in 2012. A failure of the RF gun exacted an unscheduled shutdown of 2.5 weeks plus one week of commissioning time. User block 3 was shifted from June 2012 to January/February 2013 to compensate the lost beam time. Highlights of the 2012 runs were a remarkable stability of beam parameters, especially the arrival time, together with successful operation with long bunch trains. Short photon pulses below 50 fs duration are now set up routinely for users. This year also saw remarkable experiments using THz radiation. The sFLASH team achieved their first seeding at 38 nm in April 2012, at that time the shortest externally seeded wavelength worldwide. Compared to the second and third user periods, the uptime of the accelerator could not be improved. The uptime of 89.4% during user runs in 2012 fell well below the uptimes of 93.1% for the second and 94.4% for the third period. This was mainly due to continuing problems with the operation of the RF gun, but also to infrastructure-related failures. Construction work for the new FLASH2 beamline continued. FLASH2 will be connected to the FLASH accelerator in spring 2013.

Fourth user period March 2012 – Feb. 2013

After the 2011 shutdown, FLASH quickly and successfully restarted in January 2012. SASE radiation is now produced with the best performance ever: 500 µJ at 13 nm and 450 µJ at 7 nm wavelength, to give two examples.

The fourth user period started as scheduled on 26 March 2012. It was divided into six blocks with a total of 3912 hours of scheduled beam time. 3528 hours were allocated to user experiments, including 9% contingency and 7% dedicated setup time for difficult experiments. In addition, 6% of the beam time was used for developments to further automatize setup procedures, and 4% was scheduled maintenance. Twenty-six experiments were scheduled with an average of 115 hours of beam time each. As for the previous periods, beam time was also reserved for machine studies and maintenance. Most of the machine study time was devoted to improving the free-electron laser (FEL) performance and to setting up and advancing photon beamlines and diagnostics. Part of the study time (20%) was reserved for general accelerator physics studies and developments related to future projects, in particular the European XFEL and the International Linear Collider (ILC).

In 2012, a total of 2181 hours of FEL radiation was delivered to users (Fig. 1). This corresponds to 75% of the overall time dedicated to user runs – the same fraction as for the third user period. Due to the vast range of requested parameters, many of them changing from day to day, such as wavelength, pulse duration and pulse pattern, 15% of the beam time was required for setup and tuning of the machine. This is a nice improvement compared to the third user period, where 19% was spent on tuning and setup. New in 2012 was the parallel tuning of THz and X-ray radiation for the same experiment.

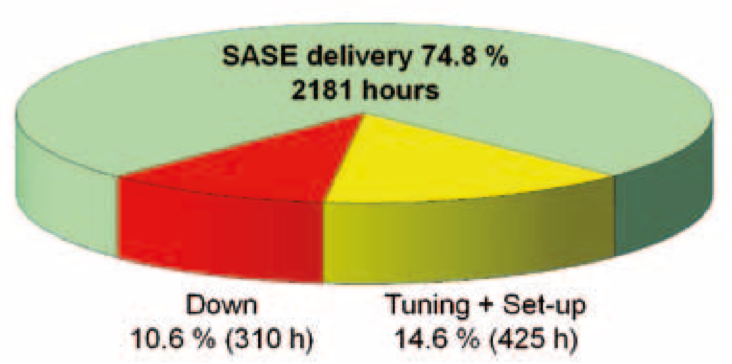

Figure 1

SASE delivery, tuning and setup, and downtime during the 2012 user period (User blocks 1–2, 4–6)

However, the failure of the RF gun during User block 2 and the increased downtime ate up the quicker tuning and setup time. Thanks to scheduled contingency and also by partially cancelling study times, the lost beam time could mostly be compensated, with the result that 90% of the time originally scheduled for experiments could be realized.

The uptime of the third user period, which was considerably improved compared to earlier periods, could not be maintained. The total downtime during user blocks increased from 5.5%

in 2011 to 10.6% in 2012. Failures were related predominantly to the RF gun, but infrastructure and photon beamline vacuum issues also contributed to the increase in downtime. After two years of operation, the RF gun suddenly exhibited a very high trip rate, accompanied by dark current, and could not be processed any more to operate at high gradients. It was found that damage had occurred in the cathode area, probably caused by an exceptionally strong RF spark. Thanks to the immediate effort of DESY staff in Hamburg and Zeuthen, the gun could be replaced by the one in operation at PITZ within only 2.5 weeks, followed by only one week of commissioning.

The continuous improvement of beam-based feedbacks stabilizing beam energy, pulse compression and arrival time allows operation of FLASH with long bunch trains and at the beam energy limit of 1.25 GeV with remarkable stability (Fig. 3). In 2012, two experiments used radiation in the water window (4.2 and 4.3 nm). A new record was achieved by exceeding 400 mW of average power in SASE radiation.

Efforts to set up and measure short electron and photon pulses continued. Tuning procedures were developed that now allow the operators to reliably set up the beam with short photon pulse duration below 50 fs. In several experiments, long trains of up to 5000 soft X-ray pulses per second with short durations were delivered successfully. Figure 2 shows an example of a longitudinal profile of the electron bunch measured with the transverse deflecting cavity LOLA. The measured bunch length is 30 fs (rms), yielding an estimated photon pulse duration below 30 fs FWHM. Operators now routinely use the LOLA cavity and the CRISP4 spectrometer to set up and monitor short photon pulses.

Again, considerable efforts were made to directly measure the photon pulse duration. A promising technique uses THz radiation as a “streak” field for photoelectrons. It has already been shown that the radiation of the THz undulator can be used for this purpose with resolutions below 10 fs. A new method uses an optical laser to generate THz radiation in special crystals. Another method is based on the generation of coherent optical radiation in the THz undulator (“afterburner”). Although all methods now give consistent results, they are not yet mature enough for routine operation.

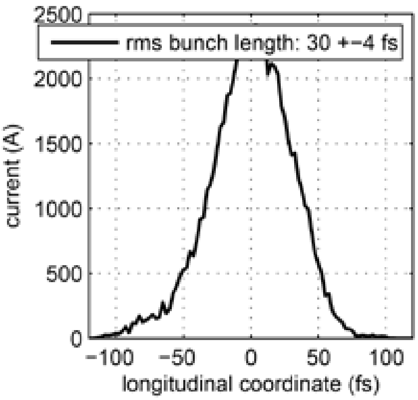

Figure 2

Longitudinal shape of an electron bunch measured with the deflecting cavity LOLA

Experiments with THz radiation

After first pioneering experiments during previous beam time periods, the THz/BL3 beamline has now been extended so that it can also be used for experiments requiring their own specialized end stations. In addition, a solid hutch was built with optical tables to facilitate THz diagnostics and the use of optical laser radiation. The combination of THz and XUV radiation is attractive for various applications. For example, the strong electromagnetic field of the THz pulses can be used to excite electrons. The wavelength can also be tuned to excite specific phonons or magnons and then probe the excited system with the XUV FEL pulses.

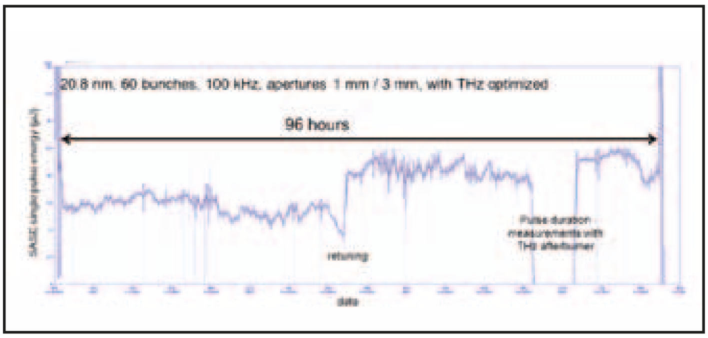

Figure 3

Example of SASE energy during a run in November 2012 optimized for THz radiation. The data show a remarkable stability for the whole run duration of 96 hours.

FLASH2 – progress with the new undulator line

Construction of the infrastructure for the new undulator line FLASH2 continued (Fig. 4). In combination with a new experimental hall to be finished in 2013, the new beamline will double the capacity for experimental stations. It aims for a wavelength range from 4 to 60 nm.

In February 2013, right after the construction of the tunnel building, the connection of the new beamline to the FLASH accelerator will be realized. This requires a four-month shutdown. Restart of beam operation at FLASH1 is planned for late summer 2013, shortly followed by the fifth user period. The FLASH2 beamline will be commissioned in parallel.

Figure 4

Construction work along the FLASH tunnel for the new FLASH2 undulator beamline

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European XFEL.

Constructing the accelerator complex – a collaborative effort

The accelerator complex of the European XFEL X-ray free-electron laser is being constructed by an international consortium under the leadership of DESY. Seventeen European institutes are contributing to the complex, both to the construction of the superconducting accelerator and subsequent transport systems for the 17.5 GeV electron beam and to the comprehensive infrastructure. DESY also provides the technical building equipment with its associated general infrastructure. The consortium already delivered first components. The production of series components is due to start in early 2013. Following the handing over of the accelerator tunnel to DESY in February 2012, the installation phase is well under way.

Figure 1

Attendees of the spring meeting of the European XFEL Accelerator Consortium

Close collaboration

Work in an international consortium requires close collaboration. With the support of the work package leaders, the DESY project team is coordinating all activities related to the accelerator complex. At the same time, it acts as a link to the European XFEL project management. Additional coordinators take care of selected general issues, like accelerator cavities or modules. The preparation of the accelerator installation phase also requires special attention.

To foster the team spirit required for such a complex international undertaking, the DESY project team organized a general meeting of all consortium members in spring 2012 (Fig. 1). In addition, well-established regular meetings of the various work package groups and the Accelerator Consortium Board ensure information exchange and coordination between work packages and management. The daily work in teams with members from different institutes in different countries guarantees that local expertise is spread and knowledge transferred to the benefit of the European XFEL project.

Regular project status presentations help to update the project plan with its sophisticated interconnections. Corrections are made whenever and wherever required in order to ensure the overall project goal of starting the accelerator commissioning in 2015.

First components

Many accomplishments of the work package groups and consortium institutes are directly visible through the delivery of first components. Prototypes and first series components are available for assembly checks. Regular visits to manufacturers and the exchange of knowledge and information in the context of work meetings determine the daily life of many partners. Virtually all major contracts for manufacturing the accelerator components have been awarded.

More than 70% of the niobium – including tubes – required to build the superconducting accelerator cavities was delivered to the cavity producers after inspection at DESY. First pre-series cavities have already been produced. The mechanical fabrication process has been qualified, and the surface treatment is currently being qualified in a multistep procedure with intermediate cavity tests at DESY carried out by a team from IFJ-PAN in Kraków, Poland. The actual work at the cavity producers is supervised by a team from DESY and INFN in Milano, Italy.

At the end of 2012, first cavities that were completely produced and surface-treated in industry were delivered to DESY (Fig. 2). After full qualification of those first cavities, a final delivery rate of up to eight cavities per week is anticipated, yielding 50 tested cavities available by spring 2013. This will allow the start of accelerator module assembly at IRFU of CEA in Saclay, France.

Figure 2

First accelerator cavities for the European XFEL

In the production of high-power RF couplers, brazing and copper plating remain challenging, but some progress has been achieved. Production of a first set of eight couplers, with relaxed specifications, was accepted by the coordinating institute, LAL in Orsay, France. Further couplers will be used to improve the process. The start of the series production is still on a critical path, and DESY continues to support the efforts of the consortium partner, LAL Orsay.

The assembly of the accelerator modules requires not only cavities and high-power couplers, but also the cryostats themselves as well as superconducting quadrupole packages. Here, DESY is collaborating with INFN Milano and CIEMAT in Madrid, Spain. One third of the beam position monitors are provided by CEA Saclay, higher-order mode absorbers by the NCBJ in Świerk, Poland, and cold vacuum components by BINP in Novosibirsk, Russia.

The accelerator of the European XFEL consists of many technically challenging components, such as beam diagnostics elements, with their associated complicated vacuum chambers, and beam transport magnets (Fig. 3). All the work package groups have made a lot of progress. Procurement, including tendering and contracting, is realized in close cooperations that sometimes last several months. As long manufacturing times are not uncommon in large-series orders, the following contract supervision may, in some cases, extend until the commissioning of the accelerator. By the end of 2012, virtually all prototype components had been delivered for final quality inspection. The production of series components is due to start at the beginning of 2013.

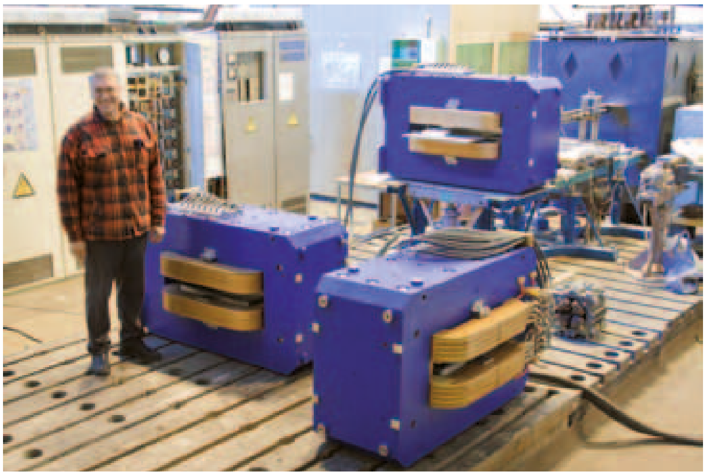

Figure 3

Many beam transport magnets are produced by NIIEFA in St. Petersburg, Russia.

An essential milestone for the European XFEL was reached when the boring of the linear accelerator tunnel was completed in the summer of 2011. Construction of the tunnel entry and floor followed. DESY took over the responsibility for further tunnel construction at the end of February 2012 and, together with subcontractors, immediately started to install the general infrastructure, such as tunnel lighting, safety equipment, general energy supply, etc. The pulse cables for the supply of the RF transmitter tubes followed a short time later. Installation of the accelerator itself will begin in 2013. First preparations started with some steel work for support structures and welding of accelerator module suspensions. The prerequisite was a precise survey of the overall tunnel geometry.

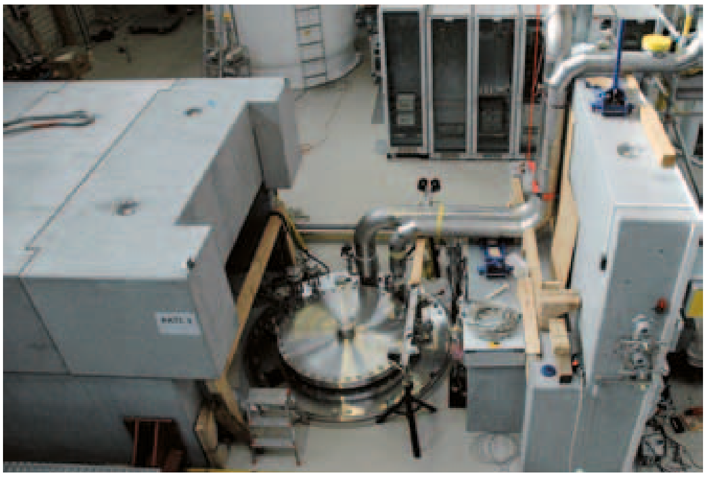

Figure 4

Vertical test cryostats in the Accelerator Module Test Facility (AMTF) are used to test all 800 superconducting cavities of the European XFEL.

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REGAE.

First electron diffraction images recorded

Relativistic electron diffraction at DESY's smallest accelerator – REGAE, the Relativistic Electron Gun for Atomic Exploration – requires electron bunches of extreme quality and sophisticated diagnostics for machine operation.

Electron and X-ray diffraction are complementary tools for exploring the structural dynamics of matter. While in X-ray diffraction a very large number of photons traverse the probe material with a small scattering probability, the scattering cross section is some 10^6 orders of magnitude higher for electrons, so that only a small number of electrons are required to achieve comparable results. However, the required electron beam quality is extraordinary. To study proteins, for example, a coherence length of 30 nm is required, which translates into a transverse emittance of 5 nm at a spot size of 0.4 mm. In addition, short bunch lengths down to 10 fs and a temporal stability of the same order are required to study chemical reactions or phase transitions in pump–probe experiments. These are challenging parameters for an electron source, which demand improvements at many frontiers.

A first electron diffraction image was recorded at REGAE in June 2012 (Fig. 1). The detector developed by the machine group provides a high spatial resolution of 15 µm over the full detection area of 15 x 15 mm^2. Single-electron detection at MeV energies is enabled by the combination of two technologies: light generation in a fibre-optic scintillator (FOS) and light detection with an electron-multiplying CCD (EMCCD) camera. The FOS (originally developed for X-ray imaging) is based on needle-like prismatic crystals, which act at the same time as light-producing scintillators and as light-guiding fibres. In this way, light can be produced in a thick scintillator without losing spatial resolution, as would be the case in a standard scintillator.

The scintillator is grown directly on a thin fibre optics plate, which further improves the image quality by filtering stray light. The light generated in the FOS is imaged onto the chip of the EMCCD camera. Because of the on-chip multiplication, a photon quantum efficiency of 95% is achieved. At this high sensitivity, an effective suppression of background signals is mandatory. Three sources contribute to the background: electronic noise, background light and background electrons from dark current or scattered electrons. To reduce electronic noise, the chip is thermo-electrically cooled to -95°C, which reduces the noise level down to below one signal electron per pixel. To avoid contamination by background light, the FOS and the camera are connected by a light-tight enclosure. The electron beam enters the enclosure through a thin layer of aluminium that is deposited directly onto the FOS, traverses the scintillator and leaves the enclosure again through a thin silicon wafer, which is also coated with a thin layer of aluminium acting as a mirror for visible light (Fig. 2). While being light-tight, the enclosure should not be air-tight, because it is placed into the vacuum of the beamline. Without connection between inside and outside, the thin FOS would break due to the pressure difference.

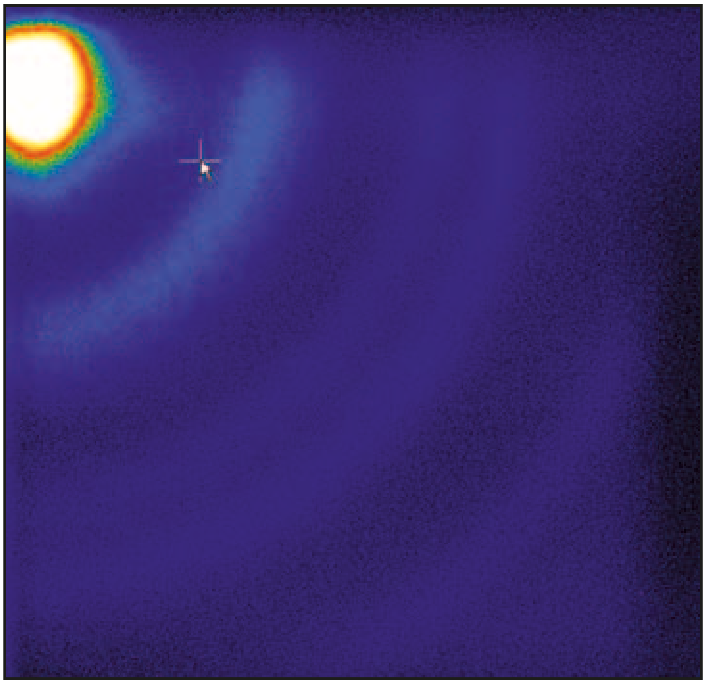

Figure 1

Electron diffraction image from a polycrystalline gold foil

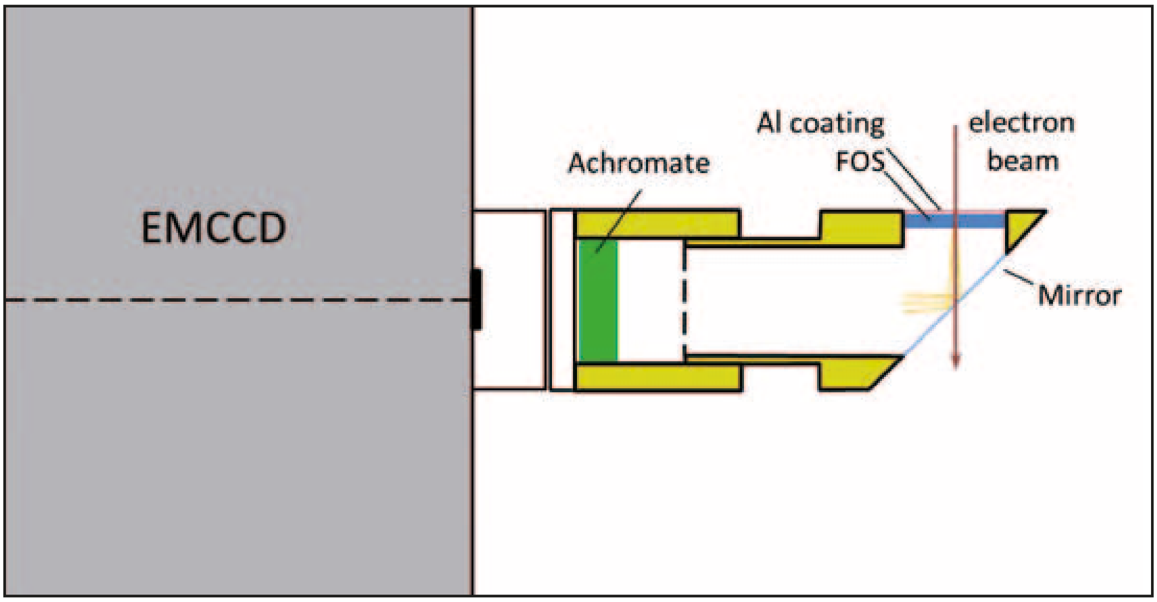

Figure 2

Schematic layout
of the detector

The primary source of background electrons is dark current, which is produced in the high electric field of the RF gun. Dark-current electrons are emitted due to the field enhancement caused by tiny geometrical irregularities, such as microscopic dust particles. Removing particles and mounting in a cleanroom minimize dark-current generation. At REGAE, a dry-ice cleaning technique – proven at FLASH – has been employed for the preparation of the cavities. Furthermore, transverse collimators are installed to scrape off dark-current electrons on the way to the detector. A second source of background electrons is electrons that scatter off supporting material of the target holder rather than off the target material itself. A careful design of the target holder including a local collimator is required to minimize this contribution.

Imaging of the electron beam is not only required at the detector, but is a standard diagnostics tool. To this end, several screen stations are installed along the REGAE beamline. To cope with local requirements, a different, more cost-effective technology is chosen here. Standard CCD cameras are combined with image intensifiers and scintillators made of LYSO, a cerium-doped scintillator based on lutetium. LYSO offers efficient light generation and a fast decay time of about 50 ns. Image intensifiers improve the sensitivity, but can also be gated on a nanosecond time scale, i.e. much faster than any CCD. Since the dark-current signal is produced over a large fraction of the RF pulse, i.e. 1–2 µs at REGAE, gating in combination with a fast scintillator can be used to cut out the beam signal in time and thus improve the signal-to-noise ratio. The suppression of the background signal is equal to the ratio of dark-current pulse length to decay time of the scintillator, thus about a factor of ~40 at REGAE. As a result, down to 10 signal electrons per pixel could be detected with a signal-to-noise ratio of about 10, even at the first screen station directly behind the gun where the dark-current contribution is maximal.

In 2012, detailed studies of the machine stability revealed important insights. Time-varying magnetic fields generated by the nearby DESY II synchrotron were identified as dominant source for the transverse beam position jitter at REGAE. Presently, REGAE operates at 12.5 Hz synchronously to the synchrotron to mitigate this effect. Compensation coils will be installed in the next shutdown period of DESY II in summer 2013.

Measurements of the temporal jitter yield a stability of below 50 fs short-term and of about 60 fs over 46 hours of machine operation. The long-term measurement determines the jitter of RF to master clock, while the short-term measurement is based on a charge measurement at an RF phase where the charge depends strongly on the RF phase. It thus determines the relative jitter of laser to RF. Since intensity fluctuations of the laser and noise of the charge monitor also influence this result, this should be understood as upper limit. Further improvements of both the temporal stability and the measurement capabilities are in preparation.

In parallel to the technical commissioning of REGAE, training of operators and students is ongoing. Since REGAE will be operated to a large extent by the experimenters themselves – often PhD students or postdocs – detailed documentation of important machine components is mandatory. As an information platform a wiki page has been set up, which contains not only descriptions of machine components but also safety instructions, operational procedures, archived calibration measurements, data sheets, manuals, etc. The wiki page thus presents a versatile tool for machine operation and for the training of students.

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PITZ.

Preparing an electron source for the European XFEL

Through 2012, the operation modes and installation changes at the PITZ photoinjector test facility at DESY in Zeuthen were specifically chosen in view of the upcoming injector commissioning for the European XFEL. In early summer, the electron source (gun) operating at PITZ was delivered to Hamburg to replace the broken FLASH gun. Consequently, a new gun was prepared and put into operation at PITZ. The gun setup was modified according to the injector installation planned for the European XFEL. It is now in the commissioning phase.

Facility operation and beam studies in 2012

In the last weeks of 2011, the PITZ facility went back into operation after a long shutdown period, which led to the realization of the PITZ2 diagnostics beamline setup. After the necessary conditioning of the RF cavities (gun and booster), facility operation was mainly devoted to the following electron beam studies:

- Standard emittance measurements at different charges using the emittance measurement system,
- Tomographic measurements with the phase space tomography module,
- Commissioning of the new high-energy dispersive section HEDA2, installed in autumn 2011 (Fig. 1).

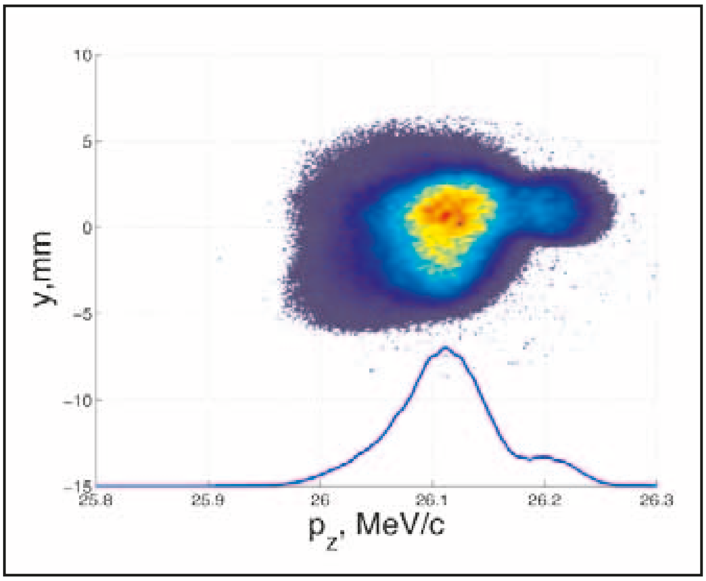

Figure 1

One of the first measurement results from the commissioning of the HEDA2 high-energy dispersive section: the *y*-axis shows the beam extension in the non-dispersive plane; the *x*-axis displays the beam size after dispersion, thus representing the momentum distribution.

During the conditioning of the booster cavity, sparks appeared in the circulator and waveguide system. After exchanging the circulator, it turned out that some waveguide pieces had to be carefully cleaned and partially replaced, which took more than three months.

Since the booster system could not be operated from February to April 2012, the time was used to investigate several aspects of the gun system: gun stability, multipacting studies, thermal emittance measurements, studies of beam-based alignment (BBA) procedures with a solenoid polarity changer, long-term tests of gun operation with long pulse trains, photoemission studies, and tests of a new device in the photocathode laser system, the acousto-optical modulator (AOM), which is used to select individual pulse patterns from the laser pulse train. Most of these topics are essential for the startup and operation of the injector system at the European XFEL.

The first half of 2012 was also used to analyse data from 2011, leading to a publication in *Physical Review Special Topics – Accelerators and Beams* [1].

The booster RF system went back into operation at the beginning of May 2012, thus allowing us to continue the electron beam characterization started in January.

PITZ delivers fast replacement gun for FLASH

In early June, it became clear that the gun installed at FLASH (Gun 4.2) could not be operated anymore due to a problem in the cathode region. A gun exchange was therefore necessary. Since the available spare gun did not allow a continuation of FLASH operation with its current parameters, it was decided that the operating PITZ gun (Gun 4.1) should be used in order to minimize downtime of the FLASH user facility. Gun 4.1 was therefore dismounted from PITZ and shipped to Hamburg (Fig. 2), where it arrived on 14 June and was smoothly put into operation.

Figure 2

Transport of the PITZ gun to FLASH: loading the gun setup into the truck

Preparations for the European XFEL injector

As a replacement gun for the PITZ facility, Gun 3.1 – an old cavity characterized at PITZ in 2006 – was dry-ice cleaned in Hamburg and sent to Zeuthen in August, together with all the other parts needed to build up a gun system. In Zeuthen, these parts were modified according to the latest design, and mounted together with a new type of RF window, the so-called Thales window. This kind of RF window is a new production specially designed for operation in the European XFEL injector system.

The setup of the complete configuration corresponds to a large extent to the installation that will be used at the European XFEL (Fig. 3). In order to install it at PITZ, the waveguide tracing in the PITZ tunnel had to be changed completely.

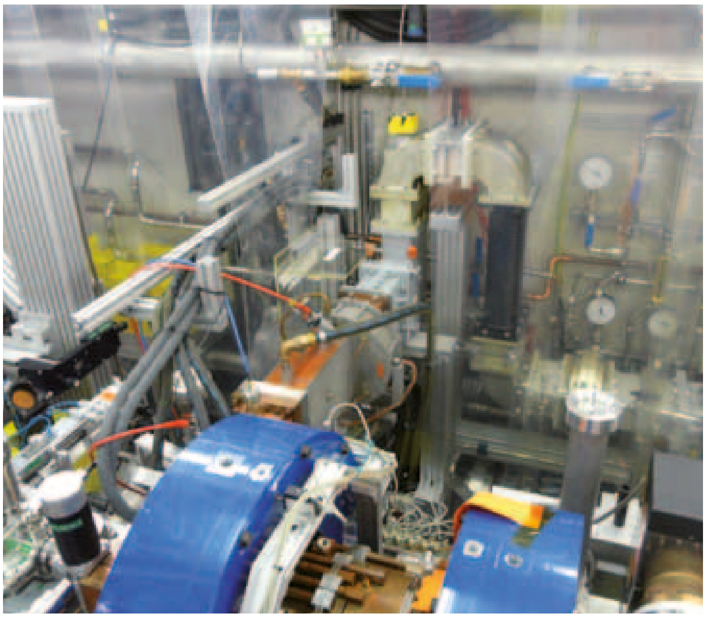

Figure 3

The gun system with Thales window, as it is planned to be used at the European XFEL, in the PITZ tunnel. Part of the new waveguide installation can be seen in the background, at the tunnel wall.

The gun system was brought into the PITZ tunnel in October. Baking of the gun and Thales window, integrating the new gun system into the PITZ beamline and connecting the new waveguide pieces to the old waveguide took a few weeks. On 11 November, conditioning of the system (Gun 3.1 + Thales window) started. Due to the special requirements of the Thales window, conditioning has to be done with extreme caution, and is therefore progressing slowly (Fig. 4). However, the lessons learned from this process are extremely important for the European XFEL.

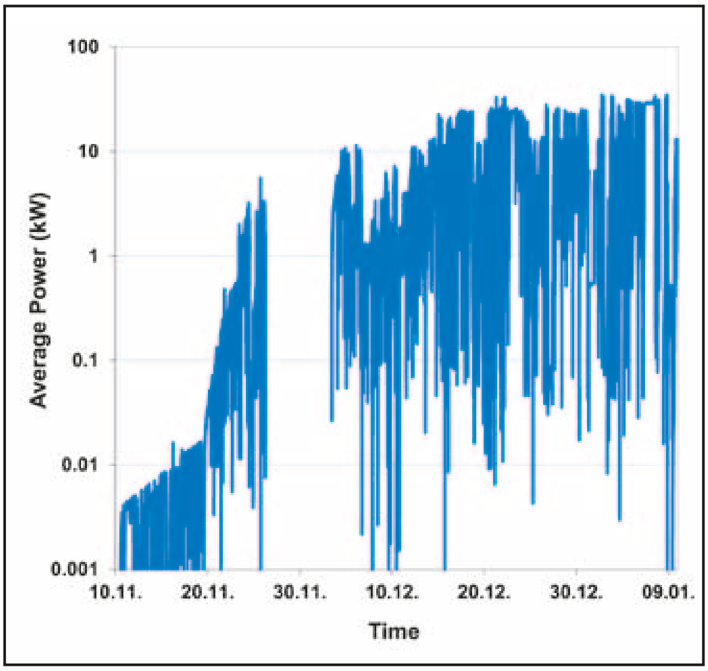

Figure 4

Conditioning progress in terms of average power in the system gun + Thales window from November 2012 to January 2013

It is planned to operate the system with an electron beam in January 2013, while waiting for the European XFEL startup gun to be delivered to Zeuthen. This gun, together with a second Thales window that is currently being conditioned at an RF test stand in Hamburg, will then be prepared at PITZ for subsequent operation in the injector of the European XFEL.

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Highlights · New technology · Developments.

Accelerator research and development programme.

A new research topic of the Helmholtz Association

In 2011, the Helmholtz Association established a new research topic on "Accelerator Research and Development" (ARD) in its research area "Structure of Matter". Alongside DESY as the coordinating laboratory, the five Helmholtz centres FZJ, GSI, HZB, HZDR and KIT are participating in these activities. Traditionally, accelerator R&D was defined and financed mainly as part of big science projects. The ARD programme establishes accelerator R&D for the first time as a project-independent research topic with a significant and long-term secure funding. This paradigm change aims at strengthening the traditionally leading role of German laboratories and Helmholtz centres in accelerator science and technology. The ARD programme will foster German-wide coordination of accelerator R&D in the Helmholtz centres. Significant synergetic effects and collaborative efforts between the centres are expected and are already being realizing.

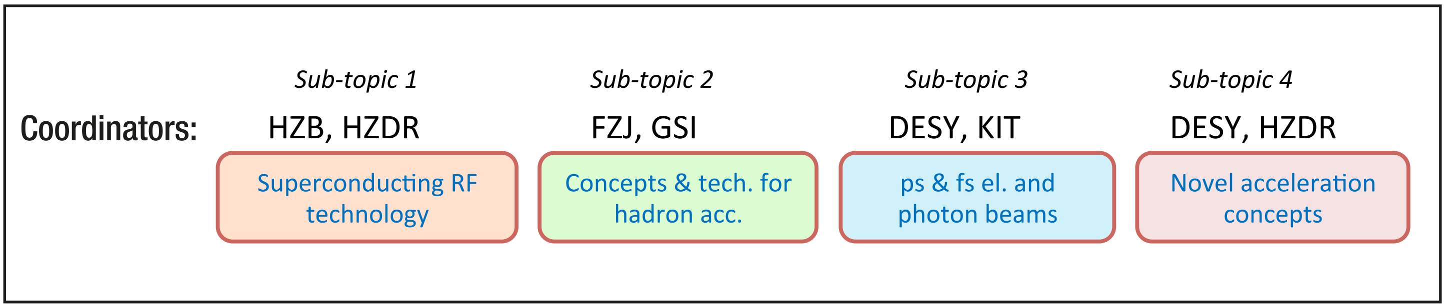

Figure 1

The Helmholtz ARD programme is structured in four subtopics (ST). DESY is participating in ST 1, 3 and 4 and co-coordinating ST 3 and 4.

Networking and cooperation

One important aspect within the ongoing ARD implementation phase is the improvement of networking and cooperation between the participating Helmholtz centres as well as with German universities and international institutes.

First successful outcomes in this respect were clearly visible in 2012. Several workshops and smaller-scale meetings were organized, at which new ideas for cooperation and joint activities emerged. The University of Hamburg is a particularly close and strategic partner of DESY for conducting research in the fields of superconducting RF, short bunches and novel acceleration concepts.

Superconducting RF technology

In the area of superconducting RF technology (ST1), the research focus is on the development of high-duty-cycle up to continuous-wave (CW) operation. Together with HZB, HZDR and international partners, DESY participates in the activities of the Helmholtz "SRF Gun Cluster" towards the development of high-brightness CW beam sources. On the DESY site, tests were performed with a CW inductive output tube (IOT) RF source powering an eight-cavity European XFEL prototype accelerator module. By switching the RF source on and off on a slow scale (on the order of hundreds of ms), the duty cycle and cryogenic load were varied over a large range and an accelerating gradient above 8 MV/m was achieved (Fig. 2). The main long-term DESY objective of this research is the development of possible future options for high-duty-cycle operation of FLASH and the European XFEL.

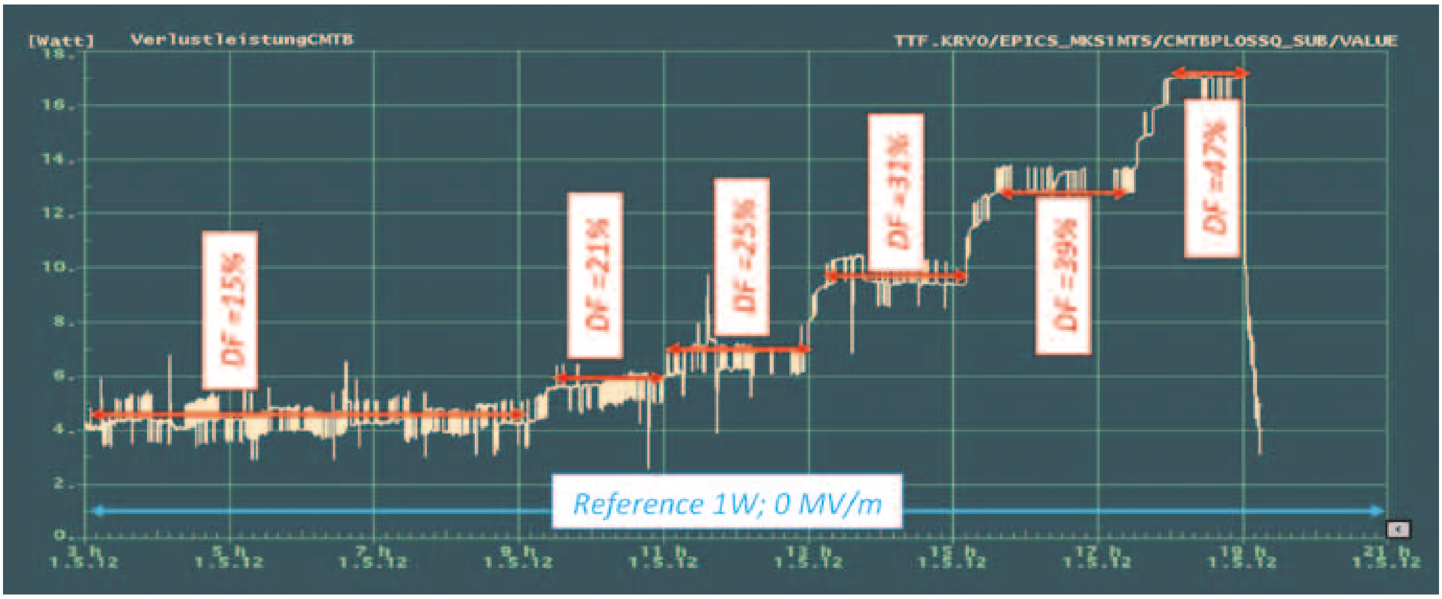

Figure 2

Measured cryogenic load at 2 K (in watts) versus time when varying the duty cycle of superconducting European XFEL prototype cavities from 15% to 47%. The measurement covers a period of 18 h and power loads reached up to 17 W. The accelerating gradient could be maintained at above 8 MV/m without quenches for all working points shown.

Plasma wakefield acceleration

Plasma wakefield acceleration (PWFA) is a new R&D activity at DESY, jointly pursued within the LAOLA collaboration by the DESY Accelerator and DESY Particle and Astroparticle Physics divisions, including the PITZ group at DESY in Zeuthen and the Hamburg University groups of Florian Grüner and Brian Foster.

The LAOLA@REGAE experiment aims at demonstrating the injection and acceleration of femtosecond bunches from DESY's REGAE accelerator into a plasma wave driven by a 200 TW laser pulse. The same laser will also be used to drive a PWFA experiment for the demonstration of X-ray (possibly free-electron laser) photon beam generation in an undulator beamline ("LUX beamline") to be set up in an unused beam transfer tunnel (Fig. 3). Much of the infrastructure work necessary for the laser and beamline installations was done in 2012, and first experiments will start in late 2013.

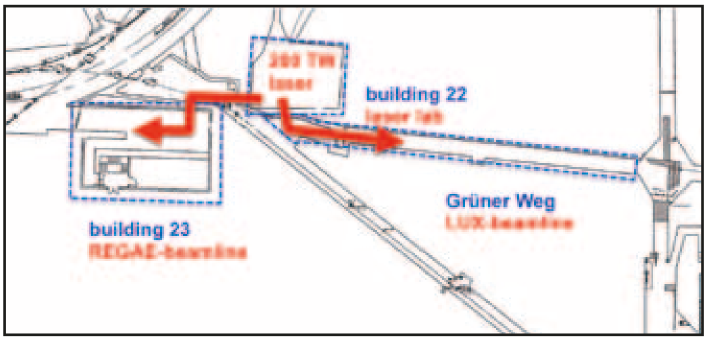

Figure 3

Layout of the first DESY experiment on laser-driven plasma acceleration, LAOLA@REGAE, which is presently being installed. The heart of the experiment is a 200 TW laser that can send high-intensity, short laser pulses either into the REGAE beamline for external-injection experiments or into the LUX beamline for tests on very compact X-ray/FEL schemes, based on plasma acceleration.

The LAOLA@FLASH experiment ("FLASHforward") foresees an additional beam extraction line in the new FLASH II tunnel with the goal to use high-brightness electron bunches from the FLASH linear accelerator to drive a plasma wakefield. This beam-driven plasma accelerator could then accelerate a probe bunch from around 1 GeV to several GeV in energy. First experiments could start in 2016. International participation in this project is supported by additional funding from a Helmholtz virtual institute that was approved in 2012.

DESY accelerator ideas market

In the context of the ARD programme, it should be mentioned that the fourth DESY accelerator ideas market took place in September 2012. The ideas market was launched in 2010 to promote the development of novel concepts for future accelerators. During the fourth ideas market, we had again very lively and inspiring discussions on accelerator physics and technology topics. Topics presented spanned from new accelerator concepts like plasma acceleration, a gamma–gamma Higgs factory in the HERA tunnel and new tools for the control and maintenance of accelerators to new ideas in accelerator diagnostics. All in all, the DESY accelerator ideas market has proven to be very valuable for collecting and discussing new ideas, which are of particular importance for the future of the laboratory. The next ideas market is scheduled for late summer 2013.

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Harmonic lasing in X-ray free-electron lasers.

An effective option to extend user capabilities

Recent studies [1] have shown that harmonic lasing is much more robust than usually thought, and holds great potential for producing intense, stable and narrow-band radiation. It can be easily implemented in the existing or planned X-ray free-electron laser (FEL) facilities. After minor modification, LCLS at SLAC in California can lase at the third harmonic up to a photon energy of 25–30 keV, providing multi-gigawatt power level. At the European XFEL, harmonic lasing would allow an extension of the operating range ultimately up to 100 keV. Harmonic lasing opens up new opportunities for X-ray FELs using low-energy electron beams, among them a continuous-wave option for the European XFEL.

Radiation of an electron beam moving in a planar undulator contains strong contributions of the odd harmonics. Harmonic lasing in a single-pass high-gain FEL (i.e. the radiative instability at an odd harmonic of the planar undulator developing independently from lasing at the fundamental wavelength) might have significant advantages over nonlinear harmonic generation. Harmonic lasing in a high-gain FEL provides an intense, stable and narrow-band FEL beam, which is easier to handle if the fundamental is suppressed. A thorough revision of the parameter space for harmonic lasing has been performed recently within the framework of three-dimensional FEL theory and taking into account all essential effects. In particular, it was found that harmonic lasing has an advantage over wavelength tuning by means of opening the undulator gap (which is the current baseline option at the European XFEL). The complete spectrum of prospective applications of harmonic lasing covers the following fields:

- Extension of wavelength ranges of existing and planned X-ray FEL facilities beyond the baseline
- More flexible operation of facilities with several undulator beamlines
- Reduction of the bandwidth at saturation (mild monochromatization) and increase in brilliance
- Simultaneous production of two colours for pump–probe experiments with easy control of the intensity ratio
- Fast switching between two or more colours for different user experiments
- Possibility of using more simple and robust undulator technology with larger periods and gaps at low-energy X-ray FEL facilities.

Realization of a harmonic lasing option is technically simple and just requires a clever tuning of phase shifters between undulator modules. The use of radiation attenuators can additionally improve the scheme. With an appropriate tuning of phase shifters, the fundamental harmonic is disrupted, opening the way for a strong growth of higher harmonics. Selective suppression of the fundamental harmonic is also possible in the X-ray range using the strong dependence of absorption coefficients on the wavelength.

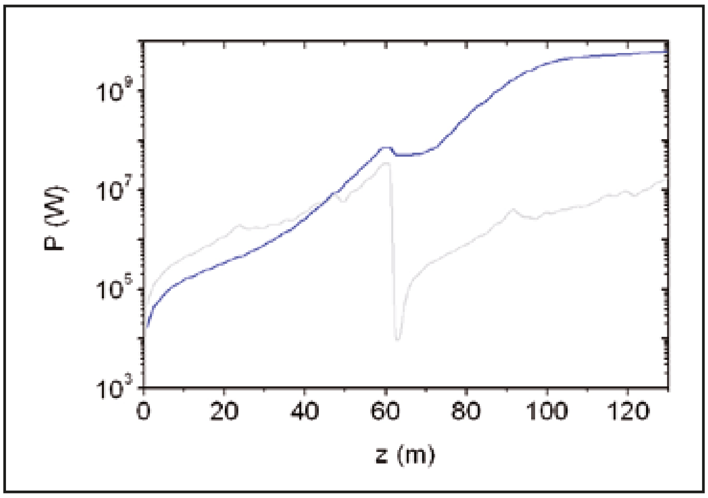

Figure 1

Example for LCLS: Averaged peak power for the fundamental harmonic (grey line) and the third harmonic (blue line) versus geometrical length of the LCLS undulator (including breaks). The wavelength of the third harmonic is 0.05 nm (photon energy 25 keV). The fundamental is disrupted with the help of a spectral filter and phase shifters. The spectral filter is placed in the existing self-seeding chicane.

Harmonic lasing can be easily implemented in the existing and planned X-ray FEL facilities. After minor modification, LCLS can lase at the third harmonic up to a photon energy of 25–30 keV, providing multi-gigawatt power level. At the European XFEL, harmonic lasing would allow for an extended operating range

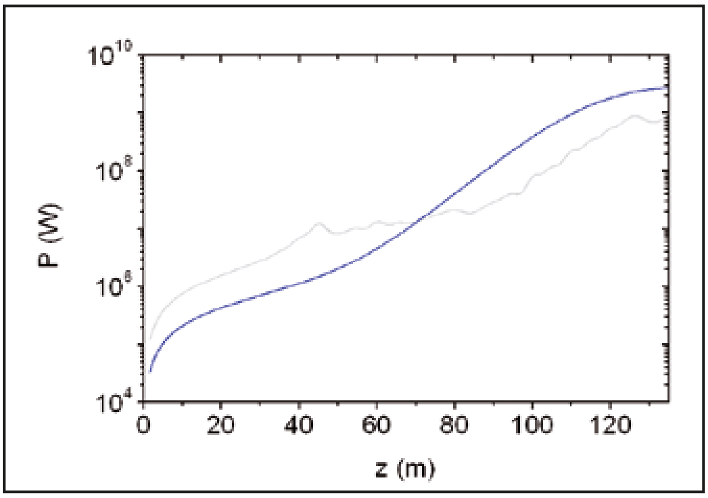

Figure 2

Example for the European XFEL: Averaged peak power for the fundamental harmonic (grey line) and the third harmonic (blue line) versus magnetic length of the SASE1 undulator. The wavelength of the third harmonic is 0.02 nm (photon energy 62 keV). The fundamental is disrupted with the help of phase shifters installed between the 5 m long undulator segments.

(ultimately up to 100 keV), increased brilliance, two-colour operation for pump–probe experiments and more flexible operation at different electron energies.

An attractive option that can be considered for the European XFEL is a reduction of the bandwidth by using harmonic lasing instead of lasing in the fundamental mode. In a gap-tunable undulator, one can combine a high power and a narrow bandwidth. A possible trick is to use harmonic lasing in the exponential gain regime in the first part of the undulator, making sure that the fundamental frequency is well below saturation (two options can be considered: with and without disruption of the fundamental by phase shifters, depending on the ratio of gain lengths). In the second part of the undulator, the value of *K* is reduced so that now the fundamental mode is resonant with the wavelength previously amplified as the third harmonic. The amplification process proceeds in the fundamental mode up to saturation. In this case, the bandwidth is defined by the harmonic lasing, i.e. it is reduced by a significant factor depending on the harmonic number. But the saturation power is still as high as in the reference case of lasing at the fundamental, i.e. brilliance increases.

Although this increase in brilliance is essentially smaller than when applying seeding and self-seeding schemes, the method of combined lasing does not require extra undulator length, is not restricted by a finite wavelength interval, and is completely based on the baseline design. For many experiments, such a mild reduction of the bandwidth is sufficient. Relative intensities of the fundamental and the third harmonic can be easily controlled by changing the phase shifters. Simultaneous lasing at the fundamental and the third harmonic with comparable intensities for jitter-free pump–probe experiments can be realized in a wide range of wavelengths and radiation intensities.

In conclusion, we note that the application of harmonic lasing can stimulate further developments of X-ray FEL projects using low-energy electron beams. In particular, it will be possible to operate the European XFEL in a continuous-wave (CW) mode and cover a wavelength range below 0.1 nm.

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1. E.A. Schneidmiller and M.V. Yurkov, Harmonic lasing in x-ray free electron lasers, Phys. Rev. ST AB 15 080702 (2012)

Longitudinal space charge amplifier.

From unwanted effect to generation of attosecond X-ray pulses

Longitudinal space charge (LSC) instability effectively develops in electron beam transport systems consisting of drift and dispersion sections. It is well known as an unwanted effect in the beam formation systems of X-ray free-electron lasers (FELs), causing modulation of the electron beam at optical frequencies, which significantly complicate electron beam diagnostics with optical methods. However, when LSC instability develops in a controlled way, it can be used to generate powerful radiation in the X-ray range. An LSC amplifier (LSCA) setup consists of a few amplification cascades (focusing channel and chicane) and a short radiator undulator at the end. The broadband nature of LSC instability supports the generation of few-cycle pulses with durations on a 100 attosecond scale. Realization of this scheme at FLASH would allow the generation of 60 attosecond (FWHM) long X-ray pulses with a peak power at the 100 MW level.

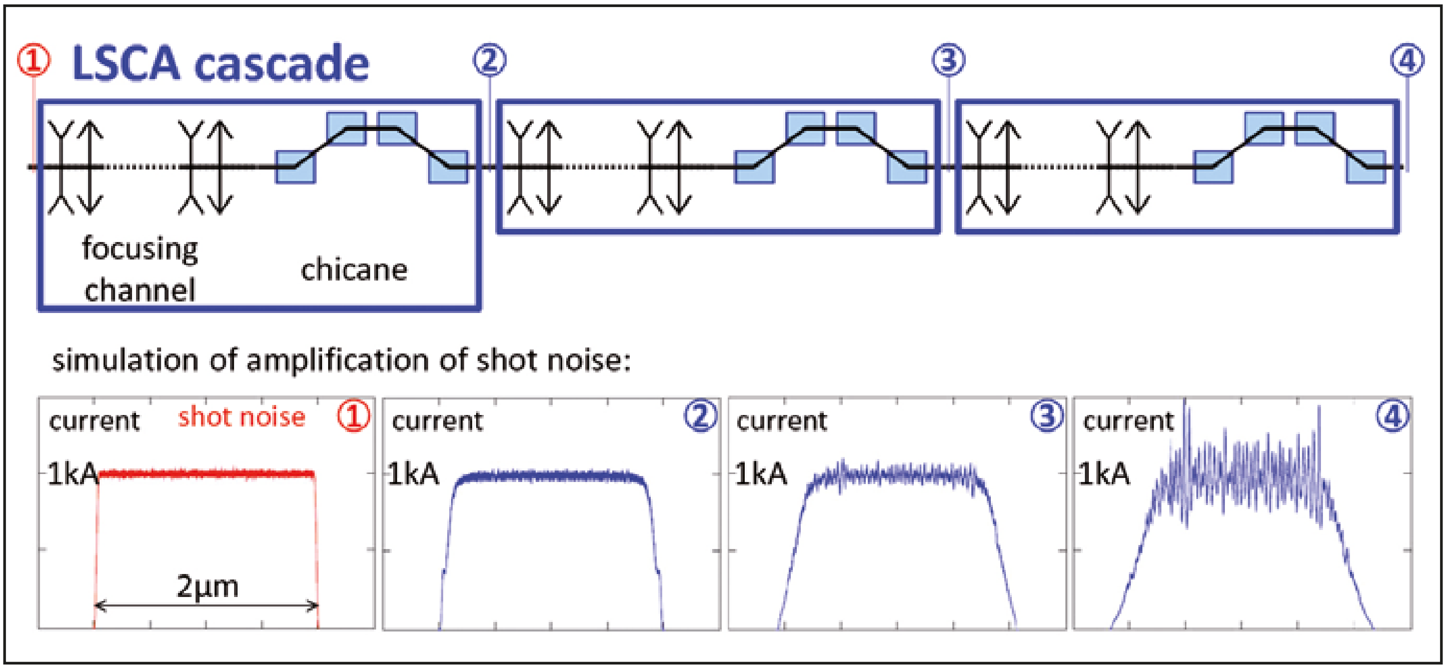
Description of the scheme

The LSCA scheme (Fig. 1) is simple, both conceptually and technically. Density fluctuations of the particle beam (due to shot noise) are amplified in a sequence of LSCA cascades. Each amplification cascade consists of a focusing channel (some FODO periods) and a dispersive element (usually a chicane) with an optimized longitudinal dispersion. In the channel, energy modulations are accumulated that are proportional to the density modulations and space charge impedance. In the chicane, these energy modulations are converted into induced density modulations, which are much larger than the initial ones. The number of cascades is defined by the condition that the total amplification be sufficient for saturation (density modulation of the order of unity).

The amplified density modulation has a large relative bandwidth, typically in the range of 50–100%. A radiator undulator behind the last cascade (Fig. 2) produces powerful radiation with a relatively narrow line (inverse to the number of undulator periods) within the central cone. This radiation is transversely coherent, and the longitudinal coherence length is given by the product of the number of undulator periods and the radiation wavelength. When the LSCA saturates in the last cascade, a typical enhancement of the radiation power over that of spontaneous emission is given by the number of electrons per wavelength.

Figure 1

Scheme of the LSCA (top) and current profiles before and after the amplification stages (bottom)



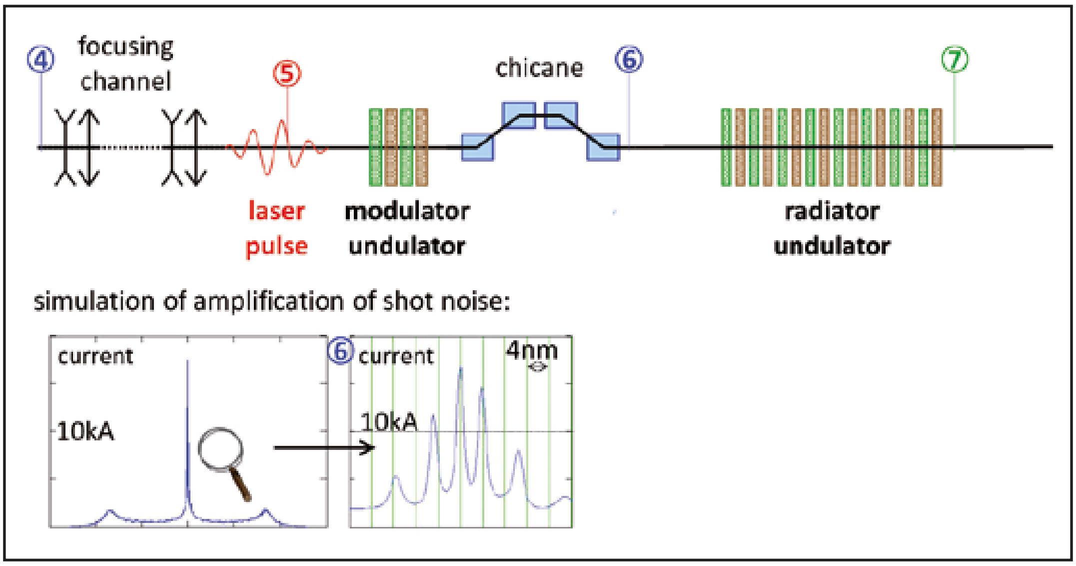


Figure 2
Scheme of the modified last amplification stage followed by the radiator undulator (top) and current profile before the undulator (bottom)

The last cascade is modified: a short modulator undulator is installed in front of the last chicane. In this undulator, the electron beam is modulated in energy by a powerful few-cycle laser pulse. The modulation wavelength is large compared to the microbunching wavelength, so that a short slice in the electron bunch gets the strongest energy chirp and is strongly compressed in the following chicane. At the same time, the wavelength is shrunk and the peak current increased. The dispersion of this chicane and the chirp are adjusted such that a required wavelength compression within that slice is achieved and the amplification of the microbunching through the last chicane is optimal. (The parameters of the whole amplification chain are adjusted such that saturation is reached in the last chicane.) Other parts of the electron bunch are either uncompressed or have much weaker compression.

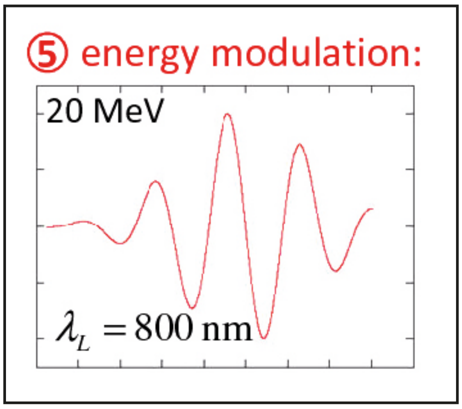


Figure 3
Energy modulation by a few-cycle laser pulse

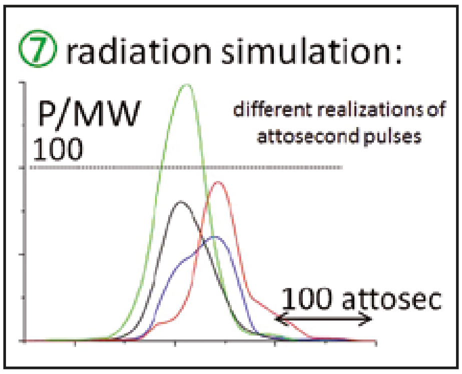


Figure 4
Some realizations of 100 MW attosecond pulses after the radiator undulator

FLASH with LCSA

Operation of the attosecond scheme is exemplified with beam parameters as can be reached at FLASH. A 100 pC bunch is compressed to 1 kA and accelerated to 1.2 GeV. Beam dynamics simulations expect a slice energy spread of 150 keV and a normalized emittance of 0.4 μm. For these parameters, the optimal wavelength for amplification in the LSCA is around 40 nm. Each cascade in Fig. 1 has a drift of 2.8 m (or two FODO periods) and a total length (with chicane) of 3.5 m. A last special cascade (Fig. 2) is required, so that the total length is about 14 m. A short part of the beam is compressed 8 to 10 times, so that the final wavelength is 4–5 nm. For this purpose, a two-period modulator undulator is installed in front of the last chicane. In this undulator, the electron beam is modulated in energy by a powerful few-cycle laser pulse (Fig. 3). A short slice of the electron bunch gets the strongest energy chirp and is compressed (by a factor of about 10) in the following chicane. The dispersion of the chicane and the maximal slope of the laser pulse are adjusted such that a required wavelength compression (in a short slice) is achieved and, at the same time, the amplification of the microbunching is optimal (Fig. 2, bottom).

Self-interaction of electrons in the beam due to space charge fields in the focusing channels is simulated with a 3D version of the space charge tracking code Astra. The macroparticles of the simulation correspond to real electrons and produce physical shot noise. Only a 2 μm piece of the 100 pC bunch is tracked (see current profiles in Fig. 1 and 2). The radiation process is computed with the code FAST. Several realizations of attosecond pulses are shown in Fig. 4. The typical duration of these pulses is 50 to 70 attoseconds, the peak power is at the 100 MW level, and the bandwidth is about 20%. The ensemble-averaged pulse energy is 5 nJ with pulse-to-pulse rms fluctuations of about 35%.

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Multibeam klystrons for the European XFEL.

Testing 10 MW multibeam klystrons at the klystron test stand at DESY

For the European XFEL, multibeam klystrons, which can produce 10 MW of RF power at 1.3 GHz RF frequency, 1.5 ms pulse length and 10 Hz repetition rate, were chosen as RF power sources. Twenty-seven horizontal multibeam klystrons (MBKs) together with connection modules (CMs) will be installed in the European XFEL underground tunnel. The CM connects the MBK to the pulse transformer with only one high-voltage (HV) cable, because the CM has a filament transformer inside as well as all the diagnostics for klystron HV and cathode current measurements. MBK prototypes together with CM prototypes have been tested a long time at a test stand at DESY, with about 4600 hours of operation for each horizontal MBK at full RF output power, full pulse length and a repetition rate of 10 Hz. Testing of first series production MBKs has started.

Introduction

For the European XFEL project, horizontal MBKs made by two companies have been chosen as RF power sources for the 27 RF stations: MBK TH1802 from Thales and MBK E3736H from Toshiba. The main parameters of the MBKs are given in Table 1.

Parameter	Design	Measured
Peak output power (MW)	10	10.3
RF pulse length (ms)	1.5	1.5
Efficiency (%)	> 63	64
Repetition rate (Hz)	10	10
Average RF power (kW)	150	155
Average power in collector (kW)	300	270
Max. drive power (W)	< 200	< 150
Bandwidth (MHz)	3	> 3

Table 1

Design and measured main MBK parameters

Figure 1

Toshiba E3736H with connection module and HV cable

Because the klystrons of the RF stations will be located in the underground tunnel, it is very important to avoid handling of transformer oil during installation of the MBKs. Therefore, a connection module (CM) and HV cable were proposed and tested as connection between the MBK and the HV pulse transformer (Fig. 1). Several types of HV cables and connectors as well as CM prototypes were tested. Another big advantage of using a CM is the integration of a HV high-frequency filament transformer and monitors for measurement of klystron voltage and cathode current in the CM.

MBK test stand

Since the DESY test stand has two test chambers, two klystrons can be tested in parallel. Figure 2 shows a top view of the test stand.

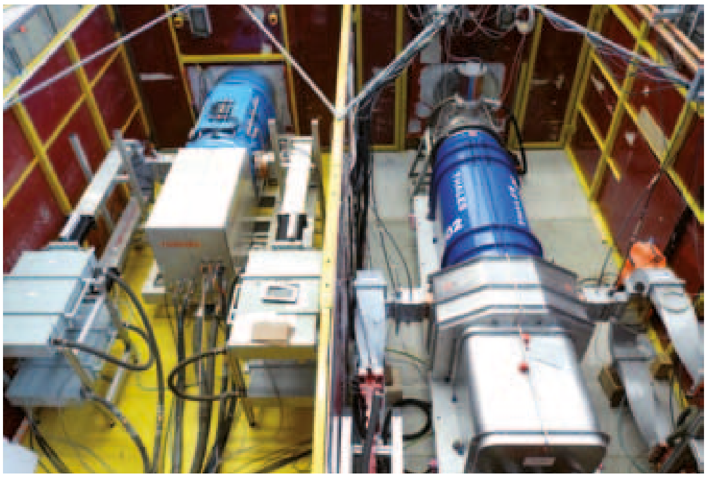

Figure 2

Toshiba E3736H and Thales TH1802 in the chambers of the DESY MBK test stand

Each of the output waveguides of the klystron is connected via WR650 directional couplers and RF power dividers to two RF loads. This allows testing up to full power for both peak power (10 MV) and average power (150 kW). The waveguide system is pressurized by dry air up to 1.35 bar absolute. The pressurized waveguide and air flow up to 10 l/min allow operation without breakdown at a pulse power level of 5 MW in one klystron output arm, with a pulse length of 1.5 ms and a repetition rate of 10 Hz. During the prototype tests, several klystron parameters are checked and recorded, such as RF power, voltage, current, bandwidth, gain, phase response and efficiency.

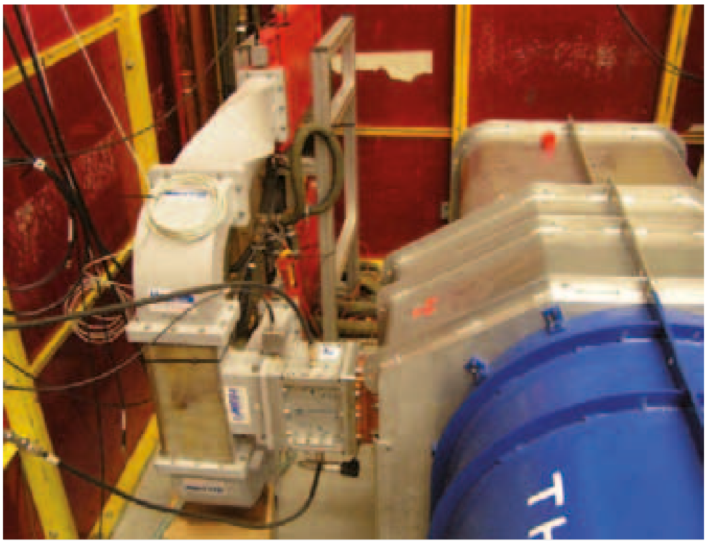

Figure 3

Thales TH1802 with directional coupler, power divider and two RF loads

The horizontal MBKs for the European XFEL make use of M-type dispenser cathodes. For this type of cathode, we can expect an average klystron lifetime of up to 145 000 hours. Under real operation conditions, however, the lifetime of the klystron can be reduced by serious fault conditions, such as klystron gun arcing, RF breakdown, klystron beam loss inside the tube or operation of the klystron under bad vacuum conditions. To minimize the influence of severe conditions on klystron lifetime, a special fast protection system (klystron lifetime management, KLM) was developed and tested. The main tasks of the KLM are: fast detection of all events that can destroy or damage the klystron, stop of input power to the tube, stop of HV pulse and finally initiation of a recovery procedure.

The klystron recovery procedure depends on the type of event that has happened. In order to make a decision which type of recovery procedure should be used, the KLM accumulates signals from different types of sensors. The klystron input and both outputs have a directional coupler. These couplers are used to detect reflected RF power from the input and outputs and to analyse the difference of the expected and actual pulse shape. Fast light sensors are used to detect a breakdown on the air side of the output window of the klystron or in the waveguide section between the window and the direction coupler. Gun arcs in the klystrons are detected by a HV breakdown sensor. Additional measurements, e.g. of the vacuum level inside the tube, the level of partial discharge in the HV system and information from sound detectors on the waveguides, help to understand the reason for the interruption and to determine the right automatic recovery procedure.

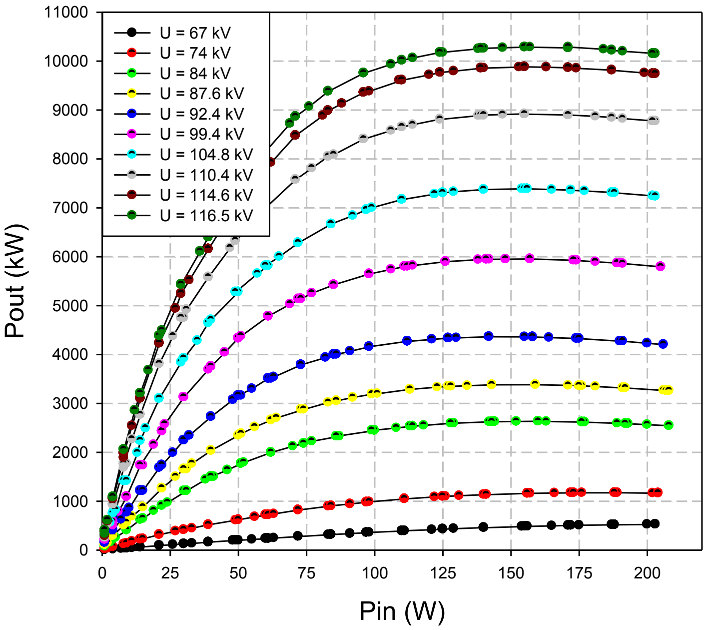

Figure 4

Thales TH1802 RF output power as function of RF input power for various cathode voltages

Since February 2008, we have been developing and continuously improving our test facilities and carrying out comprehensive tests of prototype MBKs. In September 2012, the testing time for both MBK prototypes reached about 4600 hours of operation at 10 MW output power, 1.5 ms RF pulse duration and 10 Hz repetition rate. The HV pulse level was about 117 kV at a HV pulse duration of 1.7 ms. The average time between two gun arcs is about 230 hours for E3736H and about 460 hours for TH1802. The klystrons were tested together with CMs and different types of HV cables. During the testing time, we did not observe any signs of degradation of klystron and CM parameters. The installed equipment works without any problems, and testing of the series MBKs for the European XFEL started in August 2012.

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RF power measurement at AMTF.

A joint development of a commercial company and DESY

More than 100 accelerator modules for the European XFEL have to be conditioned and tested in the Accelerator Module Test Facility (AMTF) at DESY. Besides a large high- and low-power RF, vacuum and cryogenic infrastructure, complex RF testing equipment is necessary to accomplish this task. To ensure simple measurement procedures and reliable results in a cost-conscious way, optimized power measurement devices have been developed by the company D.A.R.E!! Instruments together with DESY. When the test facility will start operating in spring 2013, about 150 of these devices will be in use for the next two to three years.

Major components of the European XFEL are the superconducting accelerator cavities working at 1.3 GHz. Eight such cavities are assembled together with RF high-power couplers, tuners and other accessories in one module. Prior to their installation in the linear accelerator of the European XFEL, all modules are subject to a performance test on a module test stand. For these tests, DESY has built a new test facility, the AMTF.

To reach the highest possible accelerating fields in the cavities, RF components such as the RF power couplers have to be conditioned accordingly. This conditioning is done through a slow increase of the RF power and pulse length over time, which “cleans” the RF vacuum components to later ensure a stable operation. A well-proven conditioning procedure that has been used at DESY for many years is as follows: The RF power starts with a pulse length of 20 µs and a power rise up to a maximum power of 1 MW. Then the pulse length is successively increased (50 µs, 100 µs … 1.3 ms), and again a power rise is performed. The repetition rate is 2 Hz to allow a sufficient recovery of the vacuum in the RF components.

The whole conditioning procedure is controlled by sophisticated software, and many different signals are monitored to ensure that the components are not harmed or destroyed. The most important signals during this conditioning are the different RF power values. The power measurements have to deliver actual power values at any time – wrong values can lead to unexpectedly high RF power on the components and bear the risk of performance degradation or damage of the components.

After the RF components have been conditioned, the transmitted power of the cavity has to be calibrated to the accelerating field of the cavity. For every cavity, five different power values are measured during the test (*P* forward, *P* reflected, *P* transmitted, PHOM1, PHOM2). Every module contains eight cavities, and there are three module test stands at the AMTF. For the whole test facility, we thus have to be able to measure 120 calibrated RF power values simultaneously (Fig. 1).

The process described above entails the following RF power measurement requirements:

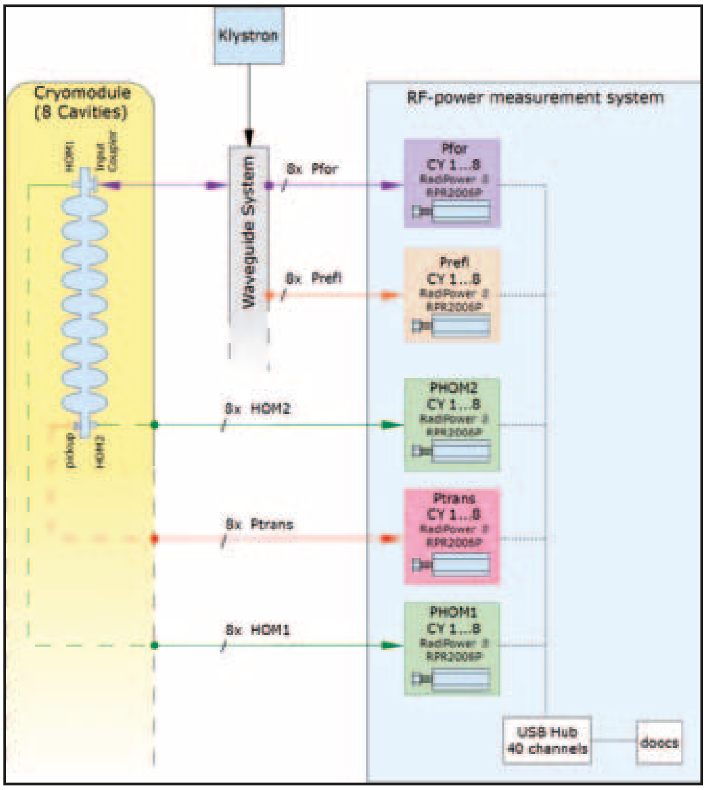

Figure 1

Block diagram of the power measurement at the module test stands at AMTF

- Peak RF power measurement for short pulses: 2 µs to 2 ms
- Repetition rates of 100 ms to 1 s
- High dynamic (> 55 dB): calibration at *P* forward ≤ 1 kW and conditioning up to ≥ 1 MW
- Very high reliability (no dependency on external trigger signals)
- No new adjustment for different operating modes to ensure error-free measurements
- Open interface for the data acquisition system
- Because of the high channel density: low cost

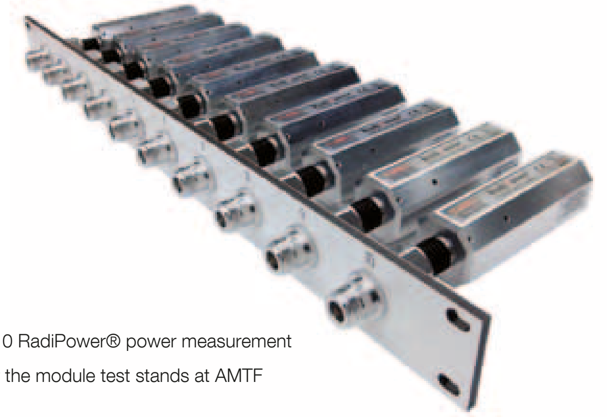

Figure 2

Array of 10 RadiPower® power measurement heads for the module test stands at AMTF

A continuous market analysis proved that many good products were available. But it also showed that, in many cases, the power measuring devices were too complicated, too special (hand adjustment necessary) or too costly.

Three years ago, the company emv GmbH in Taufkirchen, Germany, called our attention to the RadiPower® power measurement devices (with USB interface) from D.A.R.E!! Instruments in Woerden, the Netherlands (Fig. 2). We asked them for a simple and safe measurement procedure: permanent RF power measurement with a high detection rate of the maximum value. By readout of the peak value from the measurement device, the held value will be reset and a new maximum value can be measured and held. A server reads the value and stores the maximum power as a history.

D.A.R.E!! Instruments adapted the RF power measuring heads hardware and the firmware to our requirements, and we tested the devices in a module test stand and in the accelerator environment at FLASH.

The devices are also able to measure a calibrated power curve of the RF pulse with a dynamic > 65 dB. This allows us to simplify the complex and costly power trace measurement (down-converter and ADCs) and use only one device for both functions (Fig. 3).

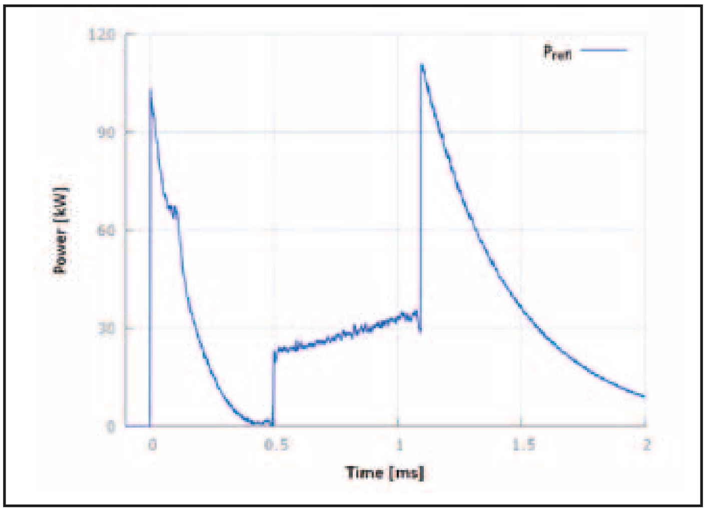

Figure 3

Trace of the reflected power at a FLASH cavity during operation

In addition to the safe and simple peak power measurement, the server now also uses the trace measurement. Usually the repetition rate during the conditioning of the cavities and couplers is ≥ 1 Hz, therefore the peak power searching time has a minimum of 1 s. After this, the device automatically measures a new power trace.

For one module test stand, 40 devices are connected to one USB hub (6*7-channel USB hub with three power supplies), which provides the LINUX server with the data. The power meter is now integrated into the DOOCS control system and the measurement software can access the power values and traces.

After some iterations of the hard- and software as well as many tests at DESY, we have ordered and received 150 RadiPower® RF power measurement devices (RPR2006P) for all the DESY module test stands.

We would like to thank the company D.A.R.E!! Instruments and all their personnel for the fruitful and professional collaboration.

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Start of cryogenic operation at AMTF.

Cold helium reaches Accelerator Module Test Facility

Before the final assembly of the European XFEL accelerator modules, the performance of all 800 superconducting RF cavities has to be verified. In addition, all 100 complete accelerator modules will be tested in the Accelerator Module Test Facility (AMTF) at DESY after assembly and prior to installation in the European XFEL accelerator tunnel.
The tests can only be performed under the final operating conditions of the superconducting components in a liquid-helium bath at a temperature of 2 K. For this purpose, two large helium cryostats and three module test benches have to be supplied with liquid helium. Major components of the helium distribution system, helium pumps and the first test cryostat were installed and operated for the first time.

Cryogenics at AMTF

A cryogenic safety instruction is required for access to the AMTF. After erection of the building, installation of the infrastructure and setup of the main RF systems, cryogenic components were still missing, however, and questions came up why this cryogenic instruction was needed at the AMTF at all. By the end of 2012, it has become clear why: the AMTF is now supplied with cold helium by means of a 167 m long helium transfer line (XATL1), which connects one of the former HERA helium refrigerators (now “FLASH refrigerator”) to the AMTF. Together with two vertical cryostats, the transfer line is part of the in-kind contribution of Poland to the European XFEL. It consists of four helium process tubes for the 5/4.5 K and 40/80 K supply and return circuits, respectively. The process tubes are surrounded by a thermal shield cooled to 80 K and a vacuum shell to prevent heat from entering from the environment. The transfer line was installed in the first half of 2012 and ready for cold commissioning in August.

Despite the excellent thermal insulation, the helium is warmed up on its way from the refrigerator to the AMTF and needs re-cooling. As a consequence, the 5 K / 3 bar helium supply is directed to a heat exchanger located in a liquid-helium bath at about 4.5 K and sub-cooled to 4.5 K. In addition, all helium circuits are distributed to the different user devices. A large sub-cooler box (XASB) takes over these functions. This box, an additional valve box (XAVB) and a 100 000 l liquid-helium storage dewar (XAST) were designed and manufactured in industry and installed ahead of the XATL1 line.

Installation of the cryogenic components means, among other things: mechanical mounting, manufacture of helium leak-tight welding connections in line with pressure vessel regulations, X-ray examination of welds, pressure tests and setup of vacuum and cryogenic control systems.

In August, the XATL1 transfer line and the XASB sub-cooler box were cooled down for the first time. The commissioning went smoothly without any significant problems, and the stage was prepared for the next step.

All 800 superconducting cavities have to be cooled in a liquid-helium bath at 2 K to verify their RF performance. Four cavities will be cooled and tested simultaneously in one vertical cryostat. The cryostat consists of a vacuum-insulated liquid-helium vessel of about 2 m^3 volume inside a thermal shield. In addition, the cryostat is equipped with magnetic shields outside and inside the helium vessel to protect the cavities from the Earth’s magnetic field.

Figure 1

Top plate of the first vertical cryostat

Two cryostats are needed for the tests to line up with the production rate of the cavities. The first cryostat (XATC1) was delivered in July 2012 and the second (XATC2) in November. Installation of the first cryostat started immediately after delivery. A transfer line connection to the XASB sub-cooler box had to be established, as well as a sub-atmospheric process connection for the 2 K return, helium safety exhaust tubes and warm gas supply (Fig. 1).

In parallel, the XAST liquid-helium storage dewar was connected to the sub-cooler box. This liquid-helium reservoir will buffer the liquid-helium peak demand of the vertical cryostats during operation.

The 4.5 K helium supply to the helium vessel is expanded from atmospheric pressure to 31 mbar through a Joule-Thomson valve, resulting in a mixture of helium vapour and liquid helium at 2 K. The cold helium vapour passes heat exchangers, is warmed up and returned to warm helium pumps, which discharge the helium back to the refrigerator at 300 K / 1 bar. The helium pumps were already installed and commissioned separately.

Figure 2

The insert with four RF cavities is mounted into the cryostat.

In December 2012, the first vertical cryostat was filled with liquid helium for the first time and pumped down to 31 mbar, corresponding to liquid helium at 2 K. On the way down, about 2 m^3 of liquid passed the Lambda transition to helium II – truly a “macroscopic” quantum state transition. This first cryogenic operation of the vertical cryostat was already combined with the cool-down of four cavities and the subsequent commissioning of the related RF equipment including the interlock system for radiation and RF safety. As a result, a complete system test for the unique cryostat insert frame could be conducted and the complicated mechanical design of the insert frame validated together with the operation vacuum and RF systems (Fig. 2).

Since the turn of the year, the first vertical cryostat has been available for the serial tests for the European XFEL. The installation and commissioning of the second dewar and three module test benches will be completed by mid-2013.

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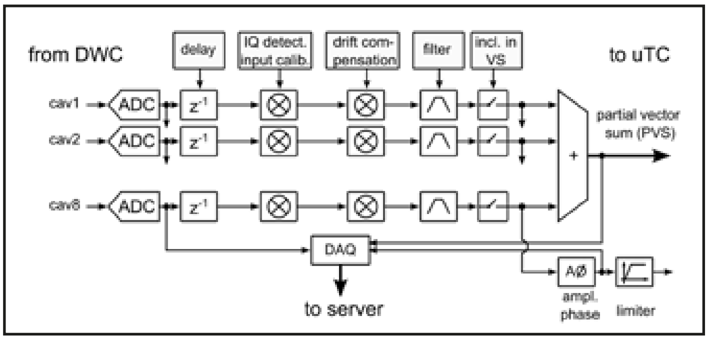
Precision regulation of superconducting cavities.

Developing a new LLRF regulation infrastructure

The European XFEL requires a high-precision control of the electron beam to generate femtosecond-pulsed laser light for user experiments. The low-level radio frequency (LLRF) control system is one of the key subsystems affecting 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, which is currently being tested at DESY. First experimental results showed excellent system performance capabilities. Investigation of regulation-limiting factors evidenced the need to control fundamental cavity modes, which is done using complex controller structures and filter techniques. The improvement in measurement accuracy and detection bandwidth increased the regulation performance and contributed to the integration of further control subsystems.

LLRF control system for superconducting cavities

The LLRF system of the European XFEL superconducting (SC) linear accelerator is a semi-distributed system, controlling up to 32 cavities within one RF station. For each RF station, a single 10 MW klystron provides the necessary RF power for particle acceleration in four TESLA-type cryogenic modules. This requires the LLRF system to collect and process a large number of RF signals in real time, using most recent FPGA-based techniques. To regulate the sum of all acceleration voltages from each cavity – the field vector sum – special processing techniques of the RF signals inside the system are required. For instance, the differences in frequency response among individual cavities need to be filtered to optimize the vector sum control. Cross-coupling between measurement channels is another contribution that reduces the overall system performance. Therefore, techniques have to be developed to condition the detected RF cavity probe signals such that they reflect the RF field encountered by the electron beam. This requires both a very sophisticated hardware design and substantial signal processing within the controller. In the current controller design, the data processing is shared between the LLRF ADC front end and the main controller. The focus of this report is on the first part, where data pre-processing is performed. The ADC board can be used as a stand-alone front end for general applications requiring monitoring and processing of a large variety of signals. For this purpose, its firmware follows a highly generic design. A schematic overview is shown in Fig. 1.



The signal flow reads as follows. Analogue signals arrive from the down-conversion stage and are sampled by high-speed 16-bit ADCs. A variable delay shifts the signals from individual channels to correct for possible transmission differences. Real and imaginary parts are then computed and signals calibrated in amplitude and phase. Compensation of temperature-induced amplitude and phase drifts introduced by the down-converters is then applied based on calibration measurements performed by an external module. Next, a multipurpose second-order infinite impulse response filter (IIR) is used to suppress unwanted signal contributions from individual channels. Finally, signals are summed up and transmitted to the main controller.

Identifying fundamental modes of SC cavities

By design, SC TESLA-type cavities host additional fundamental modes besides the main acceleration mode. Broadband excitation due to amplifier noise, beam loading and the RF drive itself contribute to exciting these modes. Their contributions to the measured RF signals have a negative impact on regulation performance and should be suppressed within the feedback loop design. For the controller bandwidth, special care should be taken to suppress the 8π/9 and the 7π/9 modes in particular. The exact resonance frequency of these modes depends on the geometry of each cavity and can be spread over a certain frequency band for one RF station. For example, the 8π/9 modes are typically spread over the 700–900 kHz frequency range, as shown in Fig. 2. For the measured cryomodule, the 8π/9 mode frequencies were found to be spread over 50 kHz, while three cavities have their resonance frequencies nearly aligned. This example illustrates the typical frequency spread to be expected depending on the production and assembly process of the European XFEL cryomodules.

Figure 1

The RF system front-end board is designed as a generic, multipurpose data acquisition and pre-processing device. Inside the LLRF system, it is used to pre-process all cavity signals for monitoring and further use inside the main controller.

These uncorrelated effects will be suppressed by $1/\sqrt{N}$, where N is the number of cavities. However, knowing the frequency of these secondary cavity modes is essential to predict their impact on the control loop. Furthermore, the ability to independently filter individual cavities to suppress their unwanted modes is a design requirement.

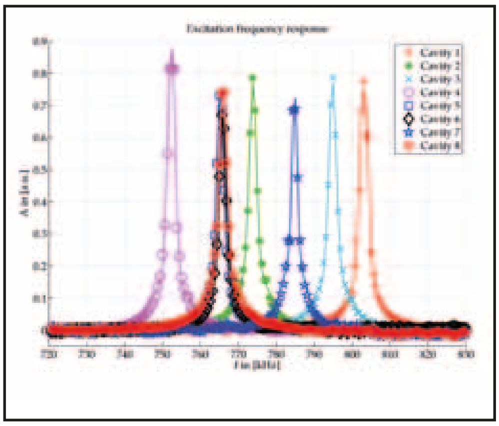


Figure 2

Response of individual cavities to a sweeping sinusoidal excitation modulating the drive signal

One possible method to identify these cavity modes is to explicitly excite the resonance modes by superimposing high-frequency signals to the regular RF drive. This method yields a good signal-to-noise ratio and does not require closed-loop operation, a potential source of instabilities due to self-excitation.

Influence on the RF feedback loop

According to control theory, the processing delay within digital control loops introduces phase lags reducing the phase margin of the closed-loop system. Having additional resonance peaks in the system leads to instability regions as a function of loop delay. To study this effect, an additional delay was introduced into the regular feedback loop. The result of this delay scan is shown in Fig. 3.

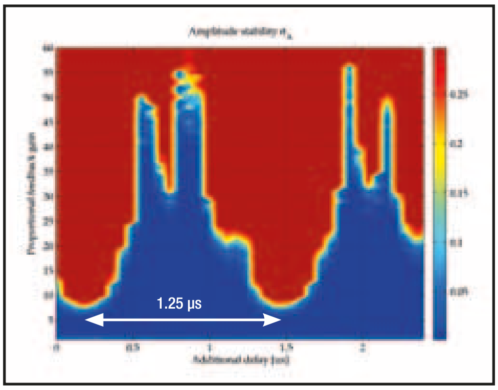


Figure 3

Measurement of the vector sum amplitude variation (red: instable areas; blue: stable areas) as a function of feedback gain and applied additional loop delay. Frequent stability patterns can be observed, with a period of about 1.25 µs.

The unstable areas recur with a periodicity corresponding to the resonance frequency of the 8π/9 mode. In the current firmware implementation, individual notch filters are applied to suppress the 8π/9 frequency content from individual cavity probe signals. The bandwidth of the notch should be narrow enough to optimize the filtering, while maintaining sufficient regulation bandwidth for the controller. In Fig. 4, the previous measurement is repeated with tuned filters. While the maximum proportional gain inside the feedback loop is increased, a second instability pattern can now be observed.

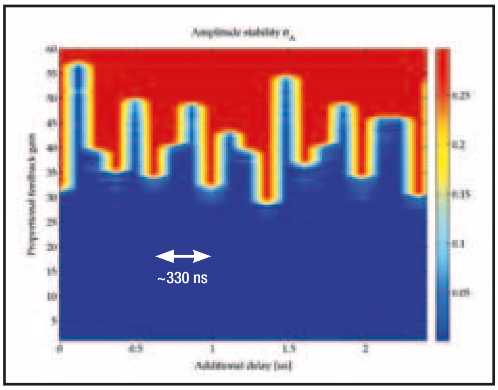


Figure 4

Measurement of the vector sum amplitude variation as a function of feedback gain and applied additional loop delay, after filtering contributions from the 8π/9 mode. Compared to Fig. 3, the frequent pattern visible here is an effect of the next fundamental mode.

The periodicity of these stability regions is now induced by the 7π/9 modes. Whereas individual notch filters are used for the 8π/9 mode, the 7π/9 mode contribution is suppressed by a single broadband notch filter located inside the main feedback controller and designed such that the closed-loop bandwidth rolls off at high frequencies for additional noise suppression. This feedback controller is implemented on the main controller board, which collects all signals and generates the driving signal to the klystron. As a result of the extensive pre-processing steps performed on the front-end ADC board, the controller workload is largely reduced, leaving space for additional applications and signal processing. Sharing of signal detection, data collecting and processing are key elements of this distributed design. Its implementation is enabled by the MTCA.4-based hardware topology and will be installed at the European XFEL.

Summary and future plans

The next steps are to equip FLASH with MTCA.4-based LLRF systems for all RF stations and to gain operational experience for the European XFEL. Especially, operation in a radiation area has to be guaranteed, and potential single-event upsets have to be accounted for. It is essential to have a highly reliable system as the tunnel installation allows only remote access to the systems. The firmware has to be mitigated to the most recent hardware currently produced. Improvements in communication bandwidth and higher processing power broaden the horizon for future projects and applications based on this generic data processing setup. This first application example illustrates ideas for possible signal processing tasks the MTCA.4 platform design is capable of.

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Industrial production of European XFEL cavities.

Launching the series production of 800 superconducting niobium cavities

In 2012, the main effort in the production of superconducting 1.3 GHz cavities for the European XFEL was dedicated to transferring experience in superconducting technology to industry. Technology transfer to industry and monitoring of the manufacturers' work is assured by DESY and INFN/LASA. 560 serial cavities are contracted to two companies, RI Research Instruments and E. Zanon, and the allocation of an additional 240 cavities is foreseen for the end of 2012 / beginning of 2013. DESY provides the cavity manufacturers with semi-finished products of high-purity niobium for the superconducting cavities, and has meanwhile delivered the complete cavity material to the companies. Both cavity manufacturers established new or upgraded infrastructure for the series production. A strategy for infrastructure debugging and qualification on the basis of dummy or reference cavities was developed, and both companies successfully implemented the infrastructure qualification. E. Zanon produced first pre-series cavities and shipped them to DESY. Most of the cavities immediately fulfilled the European XFEL specifications. Both companies are now ramping up the cavity production in order to start delivering a total of eight cavities per week in 2013.

Production of superconducting cavities for the European XFEL includes mechanical fabrication using material provided by DESY, prior electropolishing (EP) treatment, ethanol rinsing, outside etching, 800°C annealing, tuning to resonant frequency, final surface treatment by buffered chemical polishing (BCP) or EP, high-pressure water rinsing (HPR), 120°C baking, integration of the cavity into the helium tank (HT), assembly of higher-order mode (HOM) pickup and high-Q antennas and finally shipment to DESY for the vertical RF test.

Production of 560 of the required 800 serial cavities is currently contracted to two companies (RI Research Instruments in Germany and E. Zanon in Italy) on the principle "build to print". To stimulate competition between the companies, a separate allocation of the remaining 240 cavities is foreseen. A part of these cavities was allocated at the end of 2012.

Work in 2012 was mostly dedicated to setting up, debugging and qualifying a new infrastructure for cavity treatment at both companies. The infrastructure comprises electron beam welding (EBW) equipment, ISO 7 and ISO 4 cleanrooms with cleaning, rinsing and etching facility, ultrapure water (UPW) production systems, HPR, 800˚C annealing furnaces, tools for cavity integration in HT, 120˚C final baking oven, slow pumping slow venting (SPSV) vacuum system and systems for visual inspection of the cavities' internal surface (Fig. 1).

DESY provided both companies with a sophisticated machine for cavity tuning at room temperature (CTM) developed in-house and with equipment for the RF measurement of dumb bells and end groups (HAZEMEMA). DESY has taken over the responsibility for stable working of the equipment.

Several DESY groups (MPL, MKS3, MHF-SL, IPP, MVS) and colleagues from INFN/LASA accompany and monitor the production process. The main principle of production supervision means that the cavities must be built strictly according to European XFEL specifications, but a performance guarantee is not required. The supervision consists of: quality control plan, also for pressure equipment directive (PED), see below; internal quality assurance (QA) and quality management (QM) system of the companies; nonconformity reports; and regular visits of DESY expert teams to the companies. In addition, regular project meetings take place at the company locations approximately every month, depending on the production progress and quality.

The information flow from the companies to DESY and INFN is organized in the following way: all documents are deposited

Figure 1

Work in the ISO 4 cleanroom at RI Research Instruments in the DESY engineering data management system (EDMS); the transfer of documents/data from the data system to EDMS is fully automated; for statistical analysis, relevant data are picked up from EDMS and transferred to the European XFEL data bank; the data has to be received “in time” by EDMS; cavity manufacturers have access to documents and data (relevant to them only); documentation is paperless.

The debugging and qualification of the new infrastructure was a challenging task, for which the following strategy was developed. Each company produced eight special cavities (four dummy cavities (DCVs) and four reference (RCVs) cavities, respectively). The objectives of the DCVs are: mechanical check and optical inspection, but no treatment. The DCVs are used at the company for operator training, mechanical test of devices, infrastructure set-up and ramp-up, plant verification, final treatments test, tuning test etc. The DCVs remain at the company all the time up to the end of series production, and are used for infrastructure checks if necessary (e.g. after repair). At least one DCV has to be integrated into the HT for infrastructure ramp-up (handling of cavity with HT).

The objectives of the RCVs are: mechanical check, optical inspection, treatment at DESY including the final treatment (final EP for RI, flash BCP for E. Zanon) and RF test at DESY. After treatment at DESY, the RCVs of both companies reached an RF accelerating gradient E_{acc} of 30–35 MV/m, exceeding the European XFEL specifications. The RCVs were then used for the stepwise qualification of the surface treatment infrastructure (after the infrastructure set-up using the DCVs had been done).

Five steps for qualification of the treatment infrastructure have been determined: 1) transportation between DESY and company; 2) SPSV including leak check and residual-gas analysis (RGA); 3) disassembly of beam tube flange (short side), HPR cycle, drying and reassembly of tube flange; 4) disassembly of all flanges, assembly of flanges, full HPR cycle, leak check with RGA; 5) final 40 μm EP (RI) / final 10 μm BCP (E. Zanon), full HPR cycles, ethanol rinse, assembly of field measurement system, 120°C bake. After each step, the RCV is sent to DESY for cold RF test. Each qualification step has to be repeated in case of failure. Both companies successfully finished the qualification based on the rules described above.

After the test procedure, the RCVs remain at the company all the time up to the end of series production for infrastructure requalification (e.g. after repair). If any RCVs survive, they will be integrated into the HT and shipped to DESY.

Another important issue in 2012 was the implementation of the pressure equipment directive (PED). The cavity with HT has to be built as a component according to European Directive PED/97/23/EC. To avoid a pressure test on the complete cryomodule, a two-step procedure has been developed. The first step is a detailed examination (EC-type examination) that includes: examination of design; FEM calculations; qualification of welding processes; qualification of further PED-relevant processes (annealing, deep drawing, forming); production and destructive examination of test pieces; supervising the production qualification on the first eight series cavities; finding PED-relevant testing methods for the series production of the cavities. An important stage of this activity was the qualification of test pieces. The test piece is composed of two cells with helium vessel, without end groups, representing all pressure-bearing parts and welds. It is built using exactly the same manufacturing methods and welding parameters that will later be used in the series production. Two test pieces per company were produced and successfully qualified through destructive examinations.

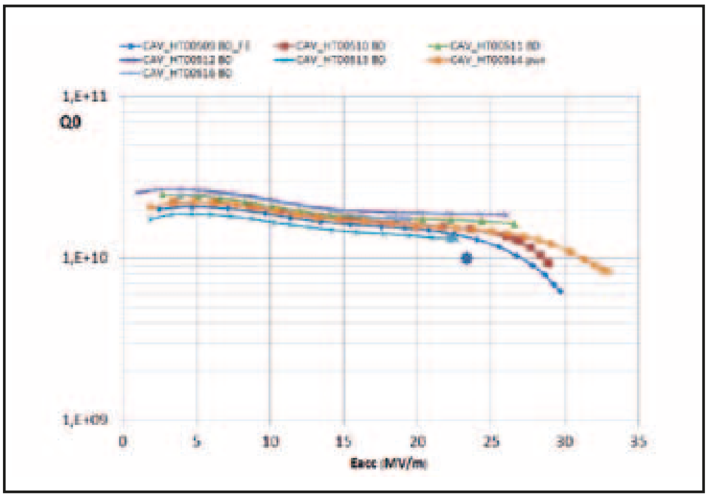

Figure 2

Unloaded quality factor Q_o versus accelerating gradient E_{acc} of first cavities produced at E. Zanon. The star indicates the European XFEL specification.

After passing the detailed test, a simplified procedure could be applied to the series production (product verification), which includes mainly visual inspections, control of documents and a pressure test for each cavity. The contracted “notified body” (TUEV NORD) advises and tracks the process.

As mentioned above, DESY provides the cavity manufacturers with cavity material (semi-finished products). Semi-finished products for pressure-bearing subcomponents of cavities and helium tanks are also qualified and purchased according to PED 97/23/EC.

Meanwhile, the first seven pre-series cavities were produced, treated using the new, qualified infrastructure and shipped to DESY by the E. Zanon. Most cavities immediately fulfilled the European XFEL specifications (Fig. 2). One of the cavities demonstrated an unacceptably high level of field emission, however. After retreatment at DESY, this cavity also passed the acceptance test. These results are very encouraging, especially when taking into consideration that these are the first cavities that were completely produced by industry. Both companies are now ramping up the cavity production in order to deliver a total of eight cavities per week starting in April 2013.

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Successful seeding at sFLASH at 38 nm.

Shortest wavelength ever obtained with HHG seeding

The gain process in free-electron lasers (FELs) operating in self-amplified spontaneous emission (SASE) mode starts from noise. This startup from noise has an impact on the properties of the emitted photon pulses. To name but a few, spectrum and energy of the pulses vary on a shot-to-shot basis. Moreover, the SASE radiation consists of multiple uncorrelated longitudinal modes, leading to reduced temporal coherence. One way to address these issues is to operate the FEL as an amplifier of externally generated radiation fields. A promising source for the external radiation field is a laser-driven higher-harmonic generation (HHG) process. The HHG pulse is longitudinally coherent, with stable spectrum and pulse energy. When correctly brought into overlap with the electron bunch in the first undulator, the HHG pulse can be amplified to GW power level. To some extent, the timing of the FEL output signal is insensitive to the arrival time jitter of the electron bunch, since it is intrinsically synchronized with the HHG drive laser. This makes the HHG-seeded FEL an ideal source for pump–probe experiments. To study the scheme, the HHG seeding experiment sFLASH was installed at FLASH. In 2012, sFLASH demonstrated the world's first successful seeding at a wavelength as short as 38.2 nm. This is the shortest wavelength ever obtained with this "direct seeding" method.

Introduction

DESY's FLASH user facility delivers SASE radiation pulses with wavelengths down to 4.1 nm. The sFLASH project was installed in a 40 m long part of the FLASH beamline upstream of the SASE undulators (Fig. 1) to study the concept of direct HHG seeding. The injection chamber, where the extreme ultraviolet (XUV) seed pulses arriving from the laser laboratory adjacent to the tunnel are sent into the electron beamline, was installed upstream of the last dipole magnet of the FLASH energy collimator. The longitudinal overlap setup is located at the exit of the first ORS undulator (for the optical-replica synthesizer experiment). The FEL light pulses generated by the sFLASH undulators are extracted upstream of the SASE undulators. The photon pulses can be sent either to the experimental hutch next to the tunnel or to the in-tunnel diagnostic devices. This diagnostic assembly features a high-resolution XUV spectrometer and several microchannel plates (MCPs) used to measure the pulse energy. A dedicated beamline provides the infrastructure for experiments using the XUV photons with an expected time resolution on the order of 10 fs. For pump–probe experiments, a near-infrared (NIR) beamline will be commissioned to transport light from the HHG drive laser to the experimental station.

sFLASH aims at sub-40 nm seeded operation without disturbing parallel FLASH SASE delivery to the already existing user stations. Successful seeding requires accurate six-dimensional overlap in space, time and frequency between seed and electrons. Particularly challenging are the tolerances for the transverse overlap, which are in the sub-50 μm, sub-50 μrad range. Even more demanding is the synchronization between the electron bunch and the XUV seed, which has to be controlled with a precision on the order of 100 fs. These challenging tolerances have been taken into account not only in the hardware design, but also by developing experimental procedures for machine setup and preparation.

A prerequisite for spectral overlap is that the sFLASH variable-gap undulators are operated in SASE mode. For the spectral overlap, the undulator gaps are tuned by comparing the central wavelength of the measured SASE spectrum with a reference HHG spectrum using the undulator calibration curves. In addition, it must be verified that the first undulator, where the seed–electron interaction takes place, is tuned to the correct wavelength and has sufficient FEL gain.

To establish the transverse overlap of the XUV seed and the electron bunch, the compact electron and photon diagnostic units located at both ends of the first sFLASH undulator are used. They provide transverse position information for both electrons and photons. Thus, one can compare the transverse positions of the two beams and apply the necessary corrections with the mirrors in the HHG injection beamline. A software tool for reliably establishing transverse overlap has been developed to speed up this procedure.

After achieving overlap in the wavelength and transverse degrees of freedom, temporal overlap has to be established. For this purpose, the first electromagnetic ORS undulator is tuned to emit spontaneous undulator radiation at a central wavelength of 800 nm. A magnetic chicane located downstream of the ORS undulator permits extraction of the undulator radiation together with light pulses from the NIR laser driving the HHG process. Due to the wide span of relative arrival times that have to be measured, multiple detection methods are used one after the other. For the coarsest timing down to a few nanoseconds, a photomultiplier connected to an oscilloscope located outside the tunnel is used. Once a timing difference of about 1 ns between the two light pulses has been achieved, a streak camera is used to further reduce the timing difference to about 10 ps. Then the longitudinal overlap is scanned in steps of typically 100 fs.

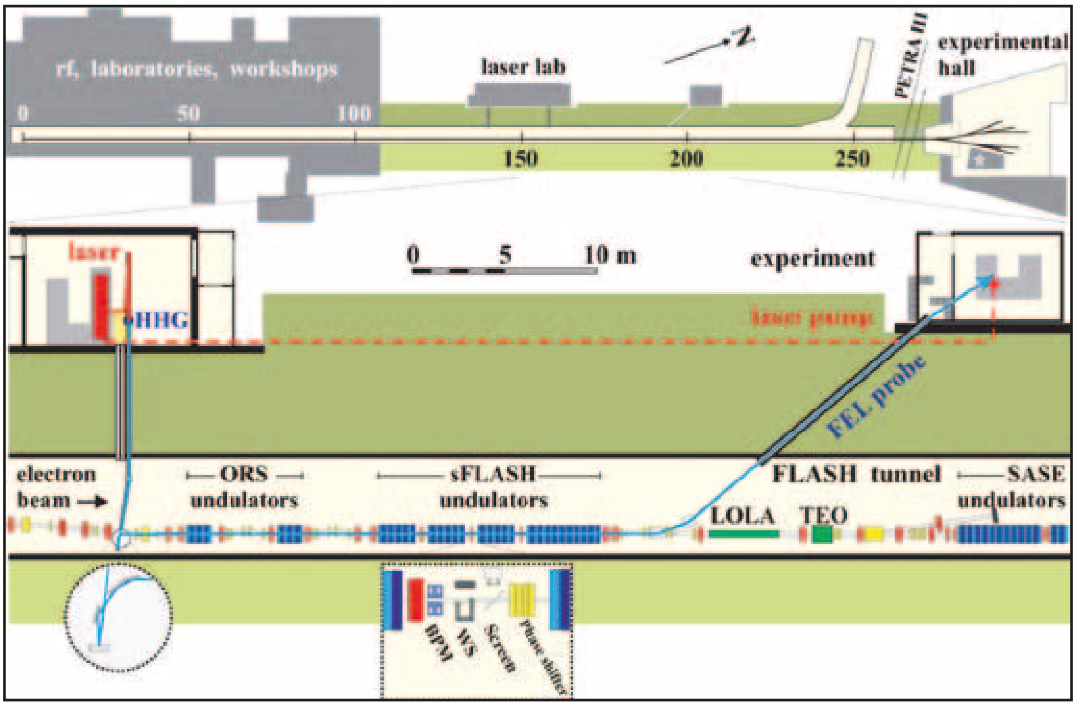

Figure 1

Schematic of the sFLASH experiment as part of the FLASH facility. FLASH has an overall tunnel length of 260 m, out of which 40 m are dedicated to the XUV seeding experiment. sFLASH is located in the section upstream of the SASE undulators. Seed pulses from the HHG source in the building adjacent to the FLASH tunnel are injected into the electron beam pipe downstream of the last dipole of the energy collimator (left). By means of an IR beamline (dashed red line), a fraction of the optical drive laser energy can be used for pump–probe experiments. The dashed bordered boxes show detailed views of the XUV injection and the undulator intersections.

Seeding results at 38 nm

The seeding results presented here were achieved in 2012, shortly after the upgrade of the sFLASH HHG seed source. The measurements demonstrate the dependency of the seeded FEL output energy on the time delay between the electron bunch and the HHG seed pulse. In case the temporal overlap is achieved, one expects an increase of the FEL pulse energy. Moreover, there should be a clear correlation between the XUV seed pulse energy and the FEL energy, i.e. an FEL pulse energy difference when the seed source is switched on and off.

Such a measurement is shown in Fig. 2. It represents a time scan over a range of 4 ps with steps of 0.1 ps. The number of data points acquired for each time step was 100 with HHG source switched on and 100 with HHG source switched off. While scanning the time range, the analysis software calculated for every scan step the correlation of the seed pulse energy and the FEL pulse energy arriving at the energy detector. In the region between $t = 2.1$ ps and $t = 2.6$ ps, a strong positive correlation was observed, which can be attributed to the seeding.

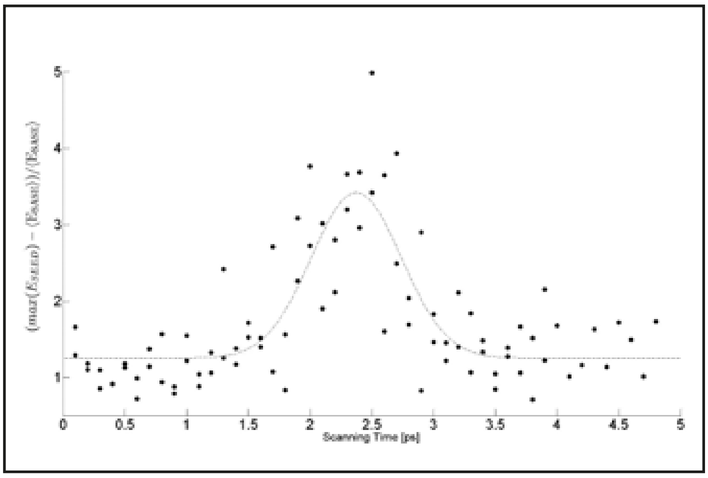

Figure 2

Contrast of the maximum pulse energy and the averaged pulse energy of SASE for each time delay

So far, an energy contrast of the seeded and unseeded FEL pulses of 5 has been observed. The effect of the seeding has been reproduced and studied as a function of various parameters, e.g. relative timing of electron bunches and seed pulses, wavelength de-tuning and transverse scans. A clear correlation between FEL pulse energy and XUV seed pulse energy has been observed within a time range of a few hundred femtoseconds, and no indication of seeding was observed outside this time window.

The rather large overlap range compared to the duration of seed and electron pulses discloses the critical role of the stability of the longitudinal overlap. So far, the relative arrival time fluctuation of the electron bunches and the seed laser pulses limit the fraction of effectively seeded bunches. This will be solved in the future by applying the intra-train longitudinal feedback system. A further important step will be the realization of two-colour cross-correlation experiments providing information on both the spectral amplitude and the phase of the amplified light wave. These experiments will reveal to what extent the FEL process preserves the favourable pulse properties of HHG-generated XUV pulses.

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Extraction arc for FLASH II.

Beamline design and start-to-end simulations for the FLASH extension

FLASH II is an extension of FLASH, DESY's free-electron laser (FEL) in the VUV and soft X-ray range, using the same linear accelerator as the existing machine. FLASH II will provide five additional experimental stations for users in a new experimental hall. Fast kickers and a septum will be installed behind the last superconducting module of the FLASH linear accelerator, providing the possibility to distribute the beam to the existing FLASH undulator beamline and through the new extraction arc. Variable-gap undulators in the new beamline allow the photon wavelength to be adjusted independently from the beam energy and therefore independently from the existing FEL. The new beamline is being prepared for self-amplified spontaneous emission (SASE) and high-harmonic generation (HHG) seeding.

Beamline layout

Finding a suitable beamline layout for the FLASH II extraction was challenging because it had to fulfil several boundary conditions set by the building environment and by demands on the beam optics.

The FLASH II photon beamline has to cross PETRA III, a brilliant storage-ring-based X-ray radiation source, at a certain position to reach the experimental hall located on the other side of the ring. Furthermore, the extraction position behind the last accelerator module is fixed. This leads to a total extraction angle of 12° between the new beamline and the existing FLASH beamline.

To mitigate coherent synchrotron radiation effects (CSR), it is necessary to have small horizontal beta functions in the strong bending magnets. Additional requirements on the beam optics are a closed dispersion in both planes and zero momentum compaction at the end of the arc.

Special care has been taken in the beamline layout to have the possibility to include a proposed third beamline later on, which would begin at the end of the FLASH II arc.

The final solution for the extraction is now realized with deflection angles of 6.5°, -0.9°, 3.2° and 3.2°. Three fast vertical kickers and a DC Lambertson septum enable distribution of the beam either to FLASH or to the extraction arc with a repetition rate of 10 Hz. A set of quadrupole and sextupole magnets establishes a beam optics that fulfils the given requirements.

All magnet positions in the extraction arc are depicted in Fig. 1, which shows the existing FLASH beamline, the extraction arc for FLASH II and a suggestion for the proposed third beamline. The plot shows the section between the last accelerator module and the beginning of the seeding section in the new tunnel.

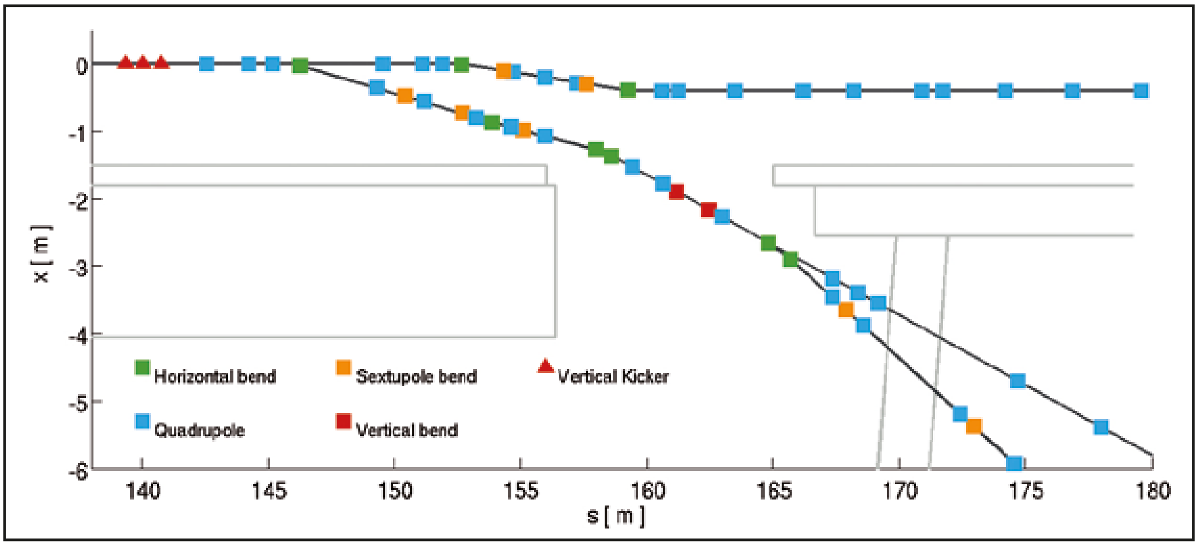

Figure 1

Magnet positions in the new extraction arc for FLASH II

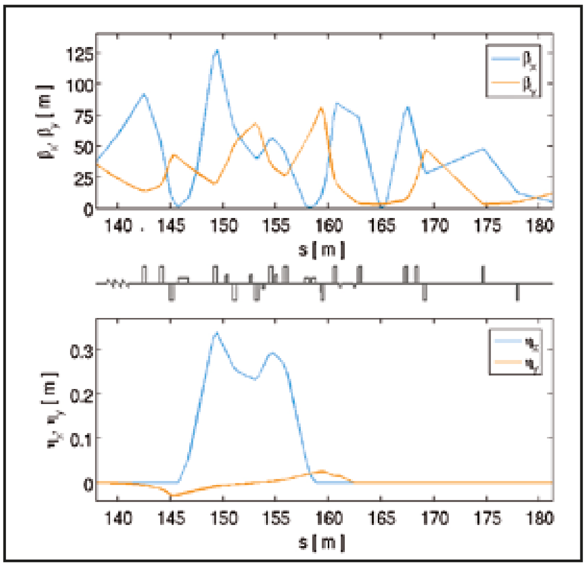

Figure 2

Top: Horizontal and vertical beta functions

Bottom: Horizontal and vertical dispersion

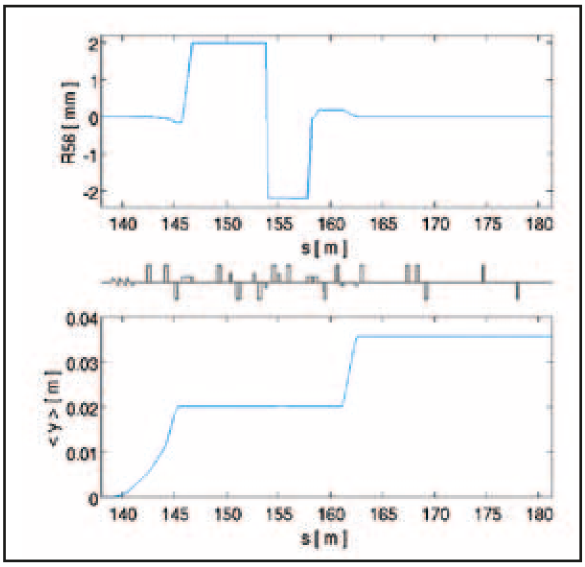

Figure 3

Top: Momentum compaction in the FLASH II arc

Bottom: Vertical beam centre position

FLASH II optics

The new beam optics design exhibits small beam waists in all strong horizontal bending magnets as required to mitigate CSR effects. The beta functions are shown in Fig. 2 (top). At the end of the arc, the Twiss functions are matched into the FODO structure of the new beamline's seeding section. Figure 2 (bottom) shows the dispersion functions in both planes, which are closed at the end of the extraction arc.

The course of the dispersion functions and the strength of the dipole magnets were chosen such that the momentum compaction is zero, thus there will be no change of the bunch compression. This function is presented in Fig. 3 (top).

The required vertical beam offset of 2 cm for the Lambertson septum can be achieved with three kickers and the dipole field of two quadrupole magnets, which are passed with an offset. A third quadrupole magnet between the kickers and the septum deflects the beam back to the straight trajectory. These quadrupole magnets also provide the beam waist in the septum for CSR mitigation. A plot showing the course of the vertical beam centre position is shown in Fig. 3 (bottom).

FEL simulations

Start-to-end simulations were carried out using the new FLASH II beamline and particle distributions from former start-to-end simulations for FLASH. The first results for different bunch charges are presented in Fig. 4. Theses simulations are important to demonstrate the suitability of the arc for FEL operation. The results obtained are in line with expectations for single-bunch simulations. Further simulations with bunches optimized for FLASH II and including SASE statistics will be carried out soon to get more results for the extraction arc.

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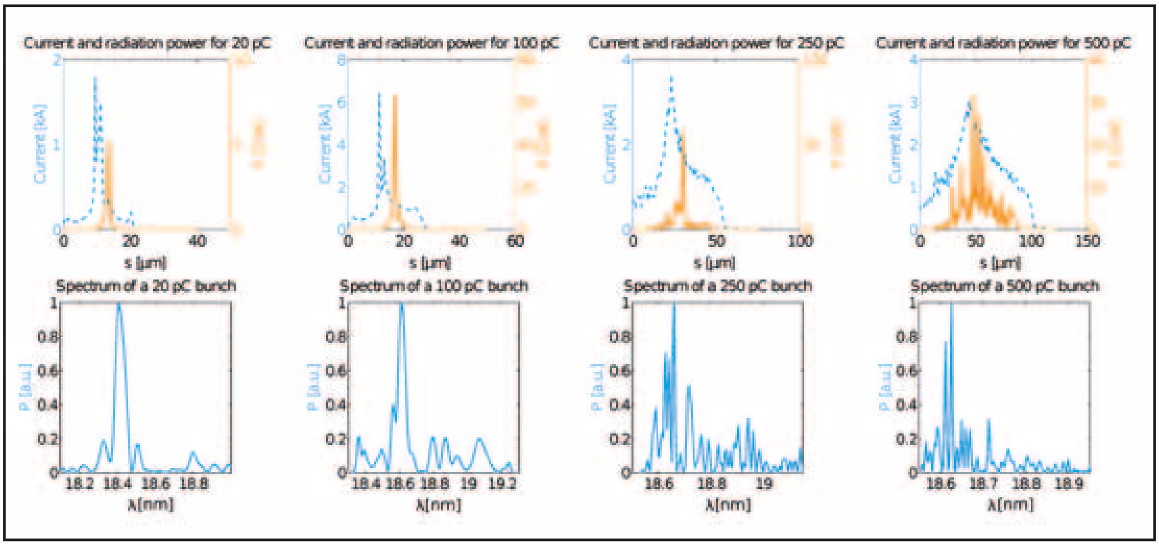

Figure 4

Results from FEL simulations for different bunch charges

MicroTCA for industry and research.

A broad alliance to foster a new electronic standard

MicroTCA^{TM} (Micro Telecommunications Computing Architecture), also known as MTCA^{TM} or µTCA^{TM}, has rapidly evolved to 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^{TM}, or ATCA^{TM}, the MicroTCA standard has gained popularity as a compact, versatile and cost-efficient alternative wherever ultrahigh-speed analogue and digital signal processing is required. In FLASH, complete MicroTCA systems controlling the accelerator could be demonstrated.
DESY gained a leading position in designing such high-performance systems. With the help of funding from the Helmholtz Association, a 4 million euro project was started to foster the MicroTCA standard in further applications and license DESY property.

MicroTCA is a standard defined by the PCI Industrial Computer Manufacturers Group (PICMG, www.picmg.org). MTCA.4 is a MicroTCA enhancement for rear I/O and precision timing, which was developed by several institutes and industry with the European XFEL project as a main driver. The PICMG published this standard in October 2011, with DESY contributing as an executive PICMG member. In parallel to the work on the MTCA.4 specifications, first prototypes were developed and tested at FLASH.

Since it turned out that the new system exceeded expectations in performance, it was time to promote MTCA.4 in further applications in industry and research. The Helmholtz Association, which created the Validation Fund to support industrialization of products developed in research, approved the maximal allowed budget of of 4 million euro per project for the proposal “MicroTCA for industry and research”. The project started in mid-2012 for a duration of two years. Industry companies contribute 17%, DESY bears 33% and the Helmholtz Association 50%.

The goals of the project are:

- Commercializing modules developed at DESY with industrial partners to allow other projects to buy them and DESY to gain license fees
- Adding new modules by industry that are missing on the market
- Providing support for new projects to ease their startup with the new technology
- Further improving the performance of the systems, including qualifying products (electromagnetic interference, EMI)

So far, 14 modules are in preparation to be licensed by DESY. The spectrum is wide and ranges from different RF up- and down-converter modules for field detection and regulation on to powerful digital controllers (Fig. 1). Extending these modules in the frequency range to support further applications is planned as well. All the modules are designed with a high degree of modularization. Building highly complex systems requires huge investments. A modular system design allows improvement of single modules without re-doing major parts.

Figure 2

MicroTCA workshop in December 2012 in the DESY auditorium

The benefit of an old standard is the availability of many modules. Introducing a new standard initially requires the creation of a set of common modules. With the help of industrial part-

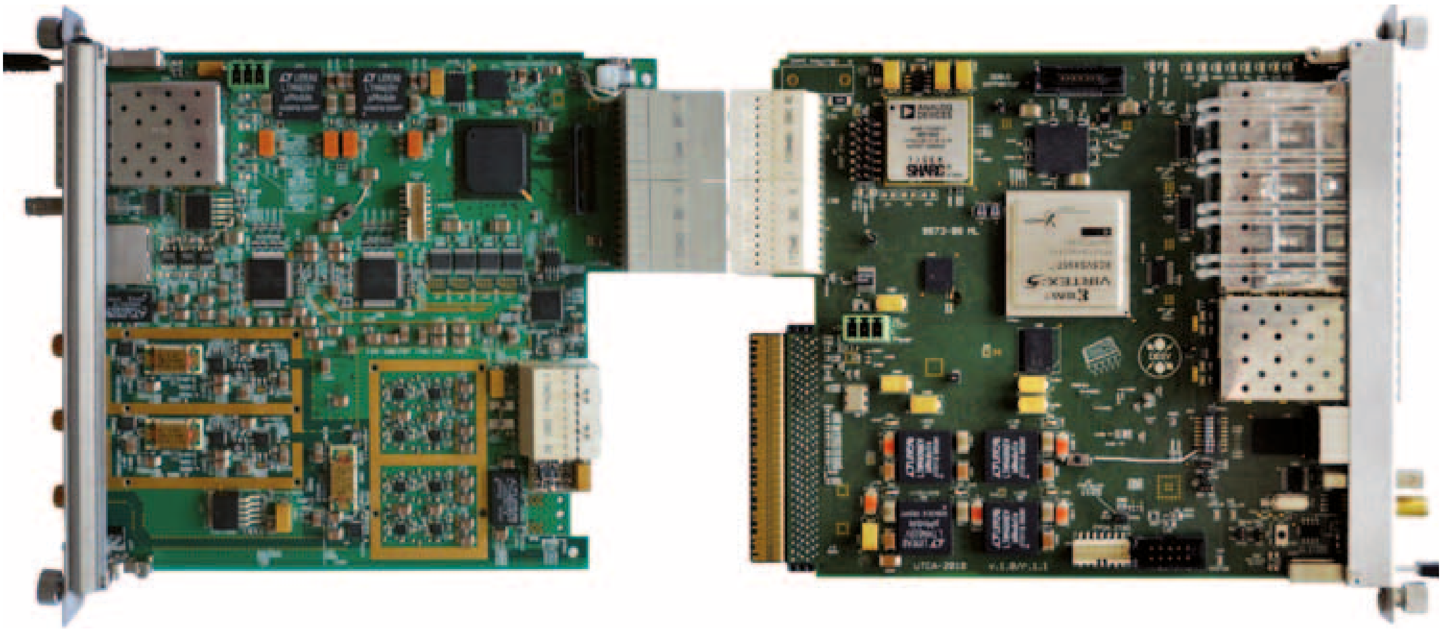

Figure 1

MicroTCA AMC and RTM module to control 32 cavities, developed for the European XFEL

ners, new products are being developed within the funding to complete the portfolio. Analogue-to-digital converters with different features in resolution and frequency are good examples. Improving the quality and management of power supplies is a further step to widen the application fields of MicroTCA beyond the initial telecom usage. Since typical applications in research projects require sensitive analogue data conditioning, EMI qualification of modules is a further ingredient of the project.

Together with its industrial partners, DESY will advertise the developed products at workshops and fairs. A first two-day MicroTCA workshop was held at DESY in December 2012 (Fig. 2 and 3). With 180 registered participants from 26 institutes and 29 companies, attendance was much higher than expected.

The workshop started with a half-day tutorial to introduce the vast capabilities of MTCA.4. In the following reports from large facilities, the growing number of big projects evaluating or using MicroTCA was remarkable. To underline the strong contribution of industry to the development of the standard, a significant number of presentations came from product manufacturers and vendors. The second day featured many talks from smaller projects. Information about the workshop is available at mtcaws.desy.de. The excellent feedback from the participants motivates a second event in December 2013.

In addition, to provide a communication platform for the growing MicroTCA community, support for users is organized within the Helmholtz project. An introduction for beginners in form of a booklet, seminars at different places and a helpdesk to answer support requests will be organized. This should support starters and professionals from industry and institutes and help them to successfully apply the new technology. Furthermore, a website (mtca.desy.de) with information about available modules and all kind of information relevant to the project was established.

Figure 3

180 people attended the MicroTCA workshop at DESY.

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Photographs and graphics
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DESY
Helmholtz-Zentrum Dresden-Rossendorf (HZDR)
Marta Mayer, DESY
Heiner Müller-Elsner, Hamburg
Dirk Nölle, DESY
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RI Research Instruments, Bergisch Gladbach
SLAC, Menlo Park, California, USA
E. Zanon, Schio, Italy

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Acknowledgement

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

Imprint

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www.desy.de
ISBN 978-3-935702-81-2

Editing
Klaus Balewski
Ilka Flegel, Jena

Layout
Britta Liebaug

Printing
Heigener Europrint, Hamburg

Editorial deadline
1 March 2013

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