ACCELERATORS 2010.

Highlights and Annual Report

Accelerators | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

Cover

A superconducting nine-cell resonator manufactured from high-purity large-grain niobium (Photo: Volker Breitkopf)

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Highlights and Annual Report

Contents.

The year 2010 at DESY.

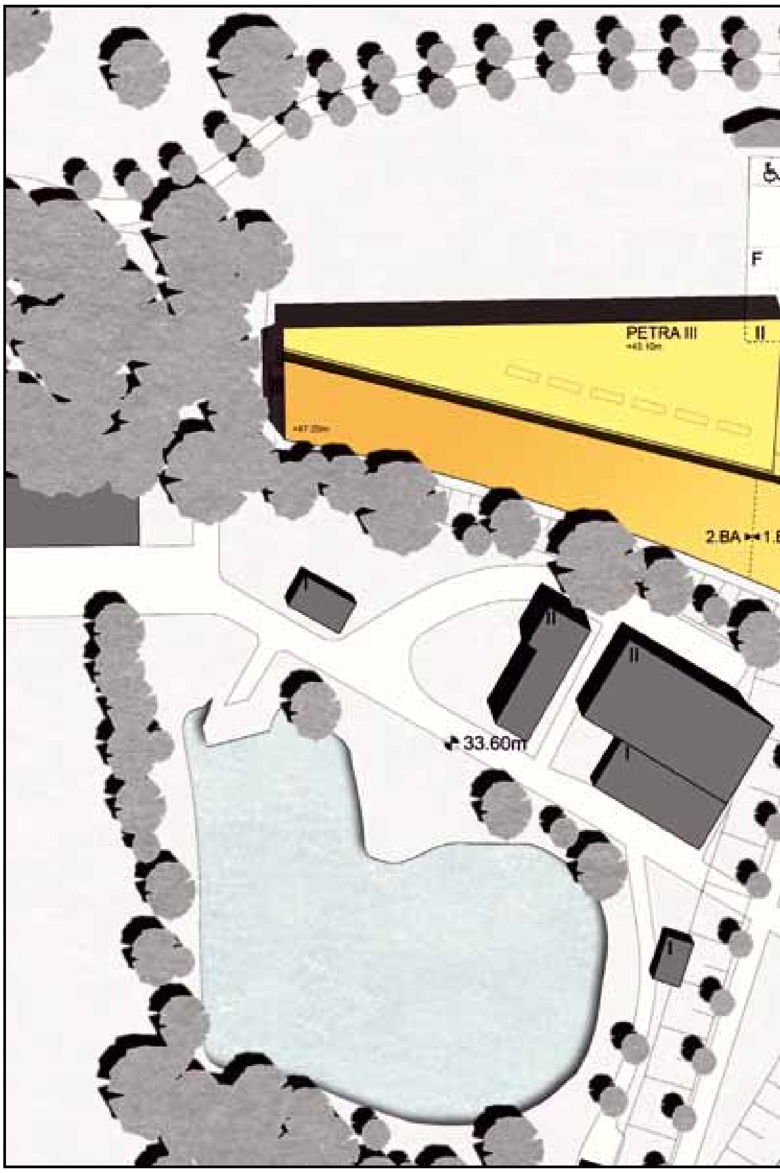
Chairman's foreword

It is now more than 50 years ago that Theodore H. Maiman announced a breakthrough – the construction of the first optical laser to produce red light at 694 nm. Since then, lasers have revolutionized our world, providing many unique solutions that make our life safer and better. With the advent of free-electron lasers (FEL) in the soft and hard X-ray regime, we are witnessing another bold leap into the future. Early pioneering work carried out by DESY sparked a worldwide boom of FEL research. With the worldwide FEL race in full swing, we achieved another milestone in 2010 by operating our FLASH free-electron laser facility at a wavelength of 4.12 nm. This will allow exciting science on ultrafast phenomena in the magical "water window".

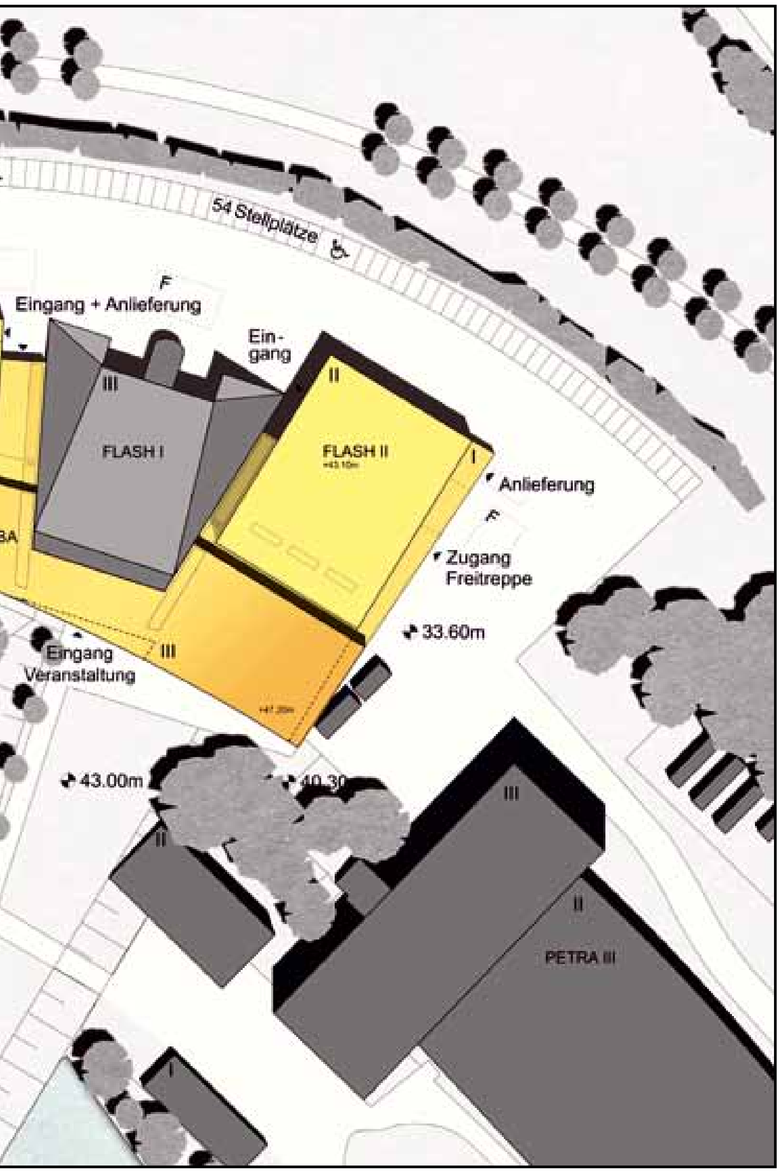
However, key technologies need continuous improvements and developments. Starting in 2011, the FLASH facility will be expanded with a second tunnel section and another experimental hall. This will not only double the user capacity to satisfy the great demand, but also offer substantial technical improvements to increase the beam quality and optimize the experimental conditions.

The European XFEL X-ray free-electron laser is now in its second year of construction. An important milestone in 2010 was the start of the industrial production of the superconducting accelerator structures. Given the success of the LCLS X-ray free-electron laser at SLAC National Accelerator Laboratory in Stanford, the message is clear: FEL technology is a moving target that continuously expands its parameter space. To ensure that the European XFEL is the world's best X-ray FEL when it is switched on, we thus cannot afford to make any compromises about technical scope, performance and schedule. We must push for the ultimate technology – even if it is costly – to deliver the world's best facility without any delays in construction and commissioning.

Architects' conception of the building complex for the PETRA III extension (hall North) and FLASH II (courtesy Architekturbüro Renner Hainke Wirth)



Helmut Dosch at the first tunnel and borer christening ceremony on the European XFEL construction site Schenefeld on 30 June 2010



In November 2010, we reached the design beam current of 100 mA in our PETRA III storage ring in a normal user operation mode. With this achievement, this brilliant synchrotron radiation source has finally attained all the sophisticated beam design parameters of emittance, beam current and beam position stability simultaneously. Top-up operation keeps the beam current on a very constant level, now uninterrupted for more than 70 hours. By the end of 2010, 12 out of 14 beamlines had been successfully put into operation. Starting in March 2011, around 50 user groups will have the opportunity to perform experiments at PETRA III.

I warmly thank all the colleagues of the accelerator division and their collaborators for their impressive work in 2010.

Yours,
Helmut Dosch

Chairman of the DESY Board of Directors

Accelerators at DESY.

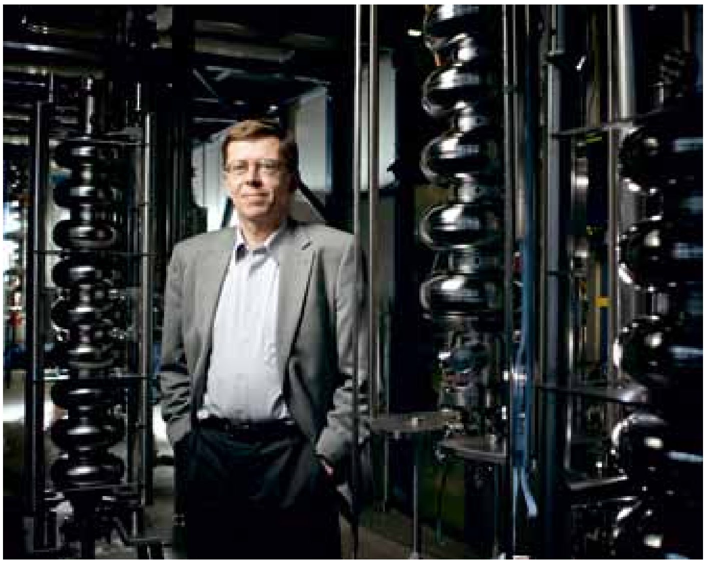
Introduction

The year 2010 has been a very busy and very successful one for accelerator operation, construction and research at DESY – one may well say that our activities in this field are truly accelerating! The refurbished PETRA III storage ring entered its first regular synchrotron radiation user operation period. The FLASH free-electron laser facility went into operation again with spectacular performance after a major upgrade programme. The construction work for the accelerator complex of the European XFEL X-ray free-electron laser is picking up speed on a large scale. And new exciting activities have been launched which underline DESY's broad range of competence and creativity in accelerator research and development.

PETRA III stored beam for the first time in spring 2009. In 2010, it demonstrated its full potential for the users of the world's most brilliant synchrotron light in the hard X-ray regime. The facility reached its full design specifications, including beam current, emittance and sub-micrometer orbit stability. The availability of the machine was already well in excess of 90%, an excellent achievement for a new facility at a very early stage of routine operation. Smooth and reliable operation of the pre-accelerators has been essential in this context. The planning and design work for the extension of PETRA III with more photon beamlines, scheduled for 2013, is ongoing. In parallel with PETRA III, the DORIS III storage ring continued to operate smoothly as a "work horse" for a large number of synchrotron radiation users. First preparations started in 2010 to accommodate the OLYMPUS electron-(positron-)proton scattering experiment into the DORIS III ring.

During a shutdown of several months in late 2009 and early 2010, FLASH was significantly upgraded. A seventh accelerator module with eight superconducting cavities was added to the linear accelerator (linac), boosting its design energy to 1.2 GeV. A superconducting third-harmonic accelerator module, built at Fermilab in collaboration with DESY, was added to the machine to improve the beam dynamics and the performance of the bunch compression process. The injector photocathode radio frequency (RF) gun was exchanged with the one that had previously been successfully tested at the PITZ photoinjector test facility in Zeuthen, showing a much-reduced level of undesirable dark current. In addition to these major (and many other smaller) machine improvements, the FEL seeding section sFLASH was installed, a collaborative project led by Hamburg University.

After the technical restart in spring 2010, FLASH quickly benefited from the accelerator upgrades: In May 2010, measurements of the electron bunch properties clearly revealed that the new third-harmonic system was working perfectly. In June, a beam energy of 1.207 GeV was reached, which even slightly surpassed the design goal. This limit could be pushed even further to 1.25 GeV in September, thus reaching an FEL radiation wavelength of 4.12 nm within the "water window" – a wavelength range that is particularly important for the study of biological systems. Besides these new record parameters achieved at FLASH, the stability and reliability of the machine was excellent and user operation in 2010 was remarkably successful. The design work for the new FLASH II beamline has continued. Construction will begin in 2011.



Reinhard Brinkmann surrounded by superconducting nine-cell cavities

The work on the European XFEL project has by now become the largest activity in DESY's accelerator division. DESY's large-scale contributions to the accelerator complex are taking shape more and more. The orders for the industrial production of the superconducting cavities were placed and several other procurement procedures for long-lead items were launched. The large hall for the cavity and accelerator module test facility (AMTF) was completed, and fabrication and installation of technical equipment is ongoing. The coordination of the international consortium of partner institutes contributing to the European XFEL accelerator is a major task for DESY. Much work in 2010 was put into specifying the technical details of these contributions and working out the contracts for the delivery of the in-kind contributions together with the partner institutes and the European XFEL GmbH.

In July 2010, in connection with his appointment as leading scientist in the machine division, Hans Weise took over the responsibility as European XFEL project leader at DESY and coordinator of the accelerator consortium. At DESY in Zeuthen, after having demonstrated an injector beam quality more than sufficient for the European XFEL specifications, the PITZ photoinjector test facility has been upgraded, and experimental work is continuing to further improve the performance of this crucial subsystem for the future operation of the European XFEL.

In addition to our large accelerator projects, smaller-scale new activities were also started in 2010. In collaboration with the Max Planck group of the CFEL Center for Free-Electron Laser Science, the REGAE electron diffraction experiment is under construction in the building which, many years ago, accommodated DESY's first electron linac. REGAE will deliver electron bunches of a few MeV energy with ultralow emittance and femtosecond bunch length for performing time-resolved structure investigations with atomic resolution.

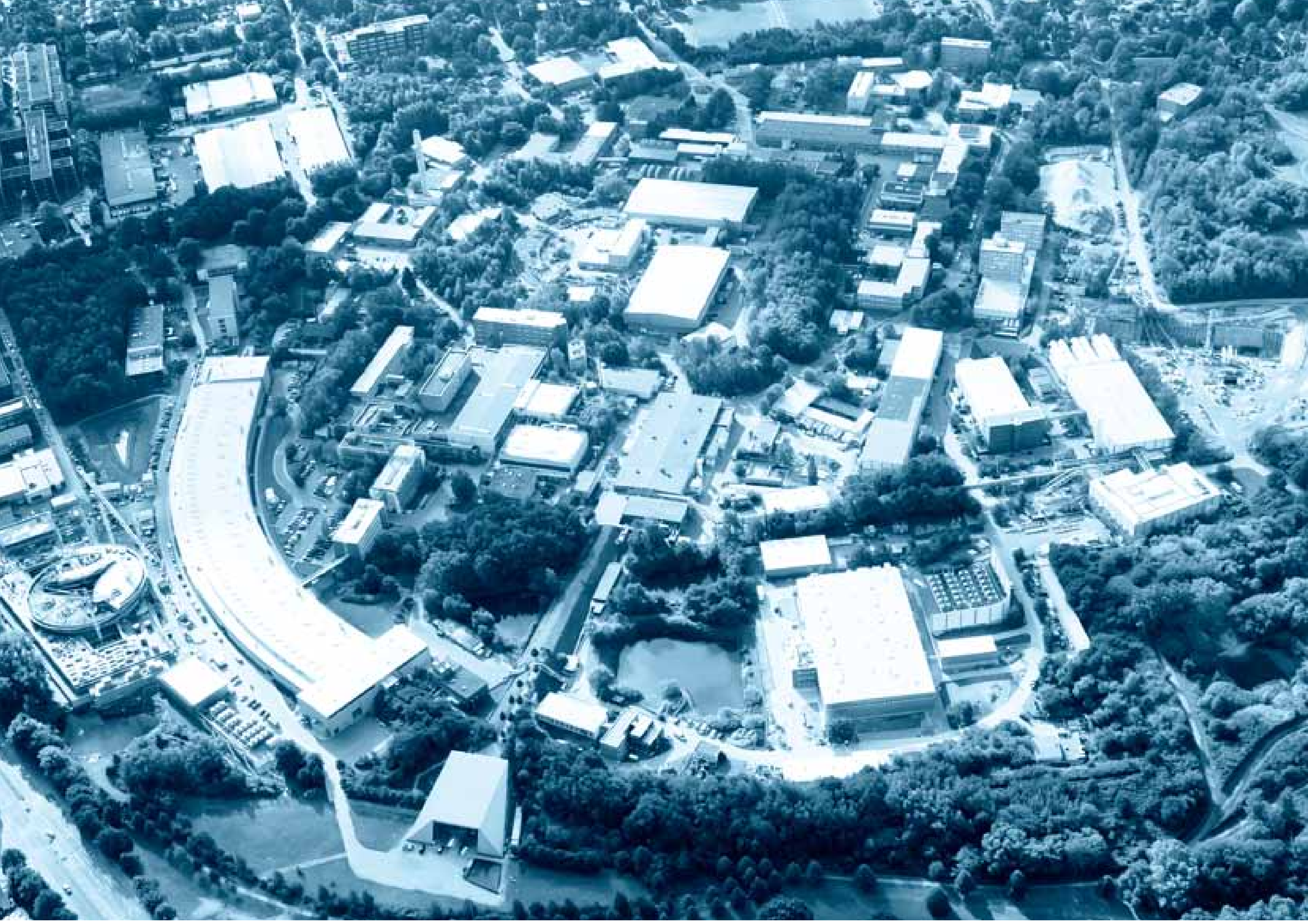
In June 2010, about 80 colleagues from DESY's FH, FS and M divisions and collaborating universities came together for the first DESY accelerator ideas market – a very open, informal and somewhat unconventional approach designed to stimulate the development and exchange of ideas related to accelerators in a broad sense. Close to 40 proposals ranging from small technical improvements to large-scale new facilities were presented and discussed. This new forum at DESY was extremely well received and everybody agreed that this activity should be continued. A follow-up ideas market took place in November, with equally strong attendance and number and quality of presentations. The next ideas market is scheduled for September 2011.

In parallel to this in-house activity, DESY took a leading role in the initiative of six Helmholtz Centres for the implementation of an independent Accelerator Research and Development (ARD) programme within the Helmholtz Association's research area Structure of Matter. A proposal for this joint research programme and an application for funding were submitted in December. Approval of the ARD programme is expected by spring 2011.

The following pages will give you more insight into the topics which I could only briefly touch in this introduction.
Enjoy the reading! ●

R. Brinkmann

Reinhard Brinkmann
Director of the Accelerator Division



News and events.

News and events.

A busy year 2010

February

Tate Medal for Gustav-Adolf Voss

The American Institute of Physics (AIP) awarded the Tate Medal for International Leadership in Physics to Prof. Gustav-Adolf Voss.

He received the renowned medal on 14 February at a meeting of the American Physical Society in Washington in recognition of his outstanding success in promoting international physics for many years, especially for his effective support of Soviet and Eastern European physicists after the breakup of the Soviet Union, his stimulation of the development of accelerator technology throughout Europe and his leadership in the construction of the synchrotron radiation source SESAME in Jordan, which is to be used as a collaborative facility by nine countries in the Middle East.

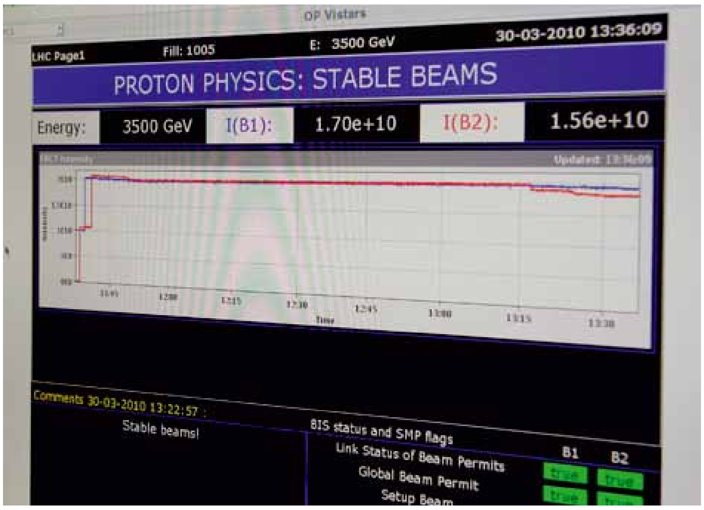
Gustav-Adolf Voss is remembered at DESY particularly for his successes as project leader for the PETRA and HERA storage rings. Voss was a member of the DESY Board of Directors and head of the accelerator division from 1973 to 1994. With unorthodox, internationally oriented and very effective methods, he shaped the complete research centre. He always brought together the best experts from all over the world. For his lifetime achievements in accelerator physics, Gustav-Adolf Voss was the first to be awarded the golden DESY pin in September 2009.

Professor Gustav-Adolf Voss

March

Particles collide inside the LHC

On 30 March at 13:06, the proton beams circulating in opposite directions inside the Large Hadron Collider (LHC) at the CERN research centre near Geneva were brought to collision. With an energy of 3.5 TeV each, the beams produced particle collisions in the four LHC experiments at the highest energies ever reached in an accelerator.



LHC operation on 30 March 2010. The particle beams are stable and first collisions at 7 TeV are produced in all four experiments.

"Congratulations to the colleagues at CERN," said Joachim Mnich, DESY director in charge of particle physics. "Today's start of the LHC physics programme is the culmination of years of work of many scientists and at the same time the start into a completely new era of particle physics".

The LHC will run for 18 to 24 months at a collision energy of 7 TeV, providing sufficient data for the four experiments ALICE, ATLAS, CMS and LHCb to make substantial progress in particle physics. After that, the LHC will be shut down for a longer maintenance period and prepared for operation at the full collision energy of 14 TeV.

April

Brandenburg Research Minister Martina Münch visits DESY

On 9 April, Martina Münch, Research Minister of the German federal state of Brandenburg, visited DESY in Zeuthen. In a conversation with Helmut Dosch, chairman of the DESY Board of Directors, and Ulrich Gensch, representative of the DESY directorate in Zeuthen, she was introduced to the DESY research programme and the role of DESY in Zeuthen, which is firmly established in the core programme of DESY accelerator physics as well as DESY's effort in the field of astroparticle physics.

On a tour around the Zeuthen campus, the minister then had the opportunity to learn more about the scientific projects. DESY staff members ranging from senior scientists to doctoral students explained the particular aspects of their research projects. The wide range of projects, including the PITZ photoinjector test facility, the planned Cherenkov Telescope Array (CTA) and the new ATLAS control room, demonstrated the collaborative work of both DESY locations, the centre's substantial participation in international research and its role in future large projects. The minister was impressed by the results and proud that important contributions to international large-scale projects are made in Brandenburg.

Sakhorn Rimjaem shows Research Minister Martina Münch the PITZ photoinjector test facility.

Röntgen Medal for Helmut Dosch

The chairman of the DESY Board of Directors, Prof. Helmut Dosch, was awarded the Röntgen Medal 2010 of the city of Remscheid on 24 April. He received the medal for his ground-breaking work in the field of surface-sensitive X-ray scattering. It is thanks to his efforts in particular that X-ray scattering is also used in surface science today.

"I accept this very honourable distinction with pride," said Helmut Dosch. "Wilhelm Conrad Röntgen played a dominant role in my scientific career, and Röntgen would hopefully have been delighted by the novel X-ray sources that are currently operated at DESY."

Helmut Dosch (centre) was awarded the Röntgen Medal 2010.

Every year, the city of Remscheid, the birthplace of Wilhelm Conrad Röntgen, awards the Röntgen Medal to persons who have rendered outstanding services to the promotion and dissemination, in science and in practice, of Röntgen's discoveries.

May

Strong partners for future research

On 19 May, the day of DESY's official 50th anniversary ceremony, the course was also set for the future. Four high-ranking research organizations – DESY, Stanford University with the SLAC National Accelerator Laboratory, the University of Hamburg and the Max Planck Society – signed a Memorandum of Understanding on the collaboration in two promising research areas: X-ray science and free-electron laser research.

The participating partners have vast experience in these fields. DESY and SLAC are operating the first free-electron lasers in the X-ray range in the world, thereby creating completely new experimental possibilities. All four institutions are centres of excellence that fathom the potential of research with extremely intense, ultrashort pulsed X-ray laser flashes. These have many applications. Even the scientists' dream to make films of chemical reactions or of the motion of biomolecules at the atomic level is already within reach.

The goal of the agreed collaboration is to bundle and mutually strengthen this competence in the best possible way. The four centres aim to achieve more together in both the requisite training of scientists and the planning and development of research programmes.

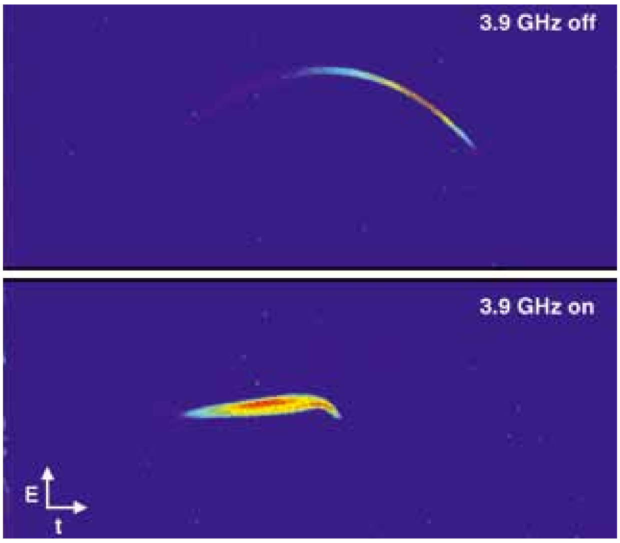
Close collaboration (from left): Persis S. Drell (SLAC), Helmut Dosch (DESY), Dieter Lenzen (University of Hamburg), Martin Stratmann (MPG)

Flat FLASH – 3.9 GHz system acting on beam

For the first time, one of the key components of the recent FLASH upgrade, the newly installed superconducting 3.9 GHz RF system, demonstrated its ability to flatten the energy distribution of the electrons in a bunch – a process called phase space linearization. This will significantly improve the performance of FLASH by optimizing the creation of ultrashort bunches with high peak current and of bunches with uniform intensity and adjustable length.

In the FLASH accelerator, ultrashort bunches are obtained using a two-stage bunch compression scheme based on the acceleration of the beam off the RF field crest. This means that the accelerating gradient of each electron in a bunch depends on the position of the particle in the bunch. The superconducting accelerator modules of FLASH are operating at 1.3 GHz. The deviation of the 1.3 GHz RF field's sine shape from a straight line is visible as a crescent moon in the bunch distribution, leading to long bunch tails and reducing the peak current. The effect is eliminated by the superconducting third-harmonic system, which operates at 3.9 GHz and linearizes the RF field. The 3.9 GHz system also allows for the creation of uniform-intensity bunches of adjustable length that are needed for seeded operation – another main objective of the FLASH upgrade during the winter shutdown 2009/2010.

The FLASH 3.9 GHz RF system is a joint international effort grouped around the two research centres DESY and Fermilab. A major part of the work was performed by the staff of the accelerator and technical divisions at Fermilab, who constructed the superconducting 3.9 GHz accelerator module ACC39. Other US members of the TESLA Technology Collaboration like the Thomas Jefferson National Laboratory, the Argonne National



The 3.9 GHz system acting on the FLASH beam

Laboratory and Cornell University contributed to the development of the 3.9 GHz module by giving advice and performing production steps. Colleagues from INFN Milano also provided technical advice. DESY contributed to the effort by providing substantial subcomponents like the RF power, RF control and other electronics, as well as by getting the RF system into operation.

The module was transported from Fermilab to DESY in April 2009. The first complete system test at DESY's cryomodule test bench in autumn 2009 already showed a very promising performance. Installation in the FLASH facility followed during the winter shutdown 2009/2010. Starting in April 2010, the system was then commissioned together with the other new components installed in FLASH during the shutdown.

The commissioning of FLASH and its new components enabled a first examination of the longitudinal phase space distribution, comparing the situation with the 3.9 GHz RF system switched on or off. This demonstration of the influence of the 3.9 GHz system on the beam was a significant milestone in the ongoing commissioning effort at FLASH.

June

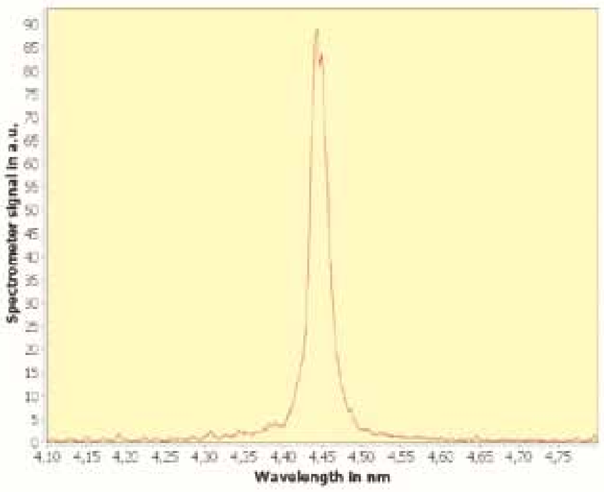
Record wavelength at FLASH – first lasing below 4.5 nm

FLASH, the world's first X-ray free-electron laser, has been available to the photon science user community for experiments since 2005. For the first time, on 15 June, the facility produced laser light with a wavelength of 4.45 nm, considerably beating its previous record of 6.5 nm. In addition, the peak intensity of single light pulses nearly doubled by reaching 0.3 mJ.

This excellent FLASH performance was achieved following a five-month upgrade in which the linear accelerator in particular was significantly improved. It was equipped with a seventh superconducting accelerator module to increase the maximum electron energy to 1.2 GeV. Moreover, a special 3.9 GHz module was installed to improve the quality of the accelerated electron bunches. The first tests during commissioning showed excellent results: the linear accelerator was operated at 1.207 GeV and the 3.9 GHz module shaped the electron bunches in such a way that the intensity of the laser radiation was higher than ever before. In addition, a seeding experiment was installed together with the University of Hamburg.

"The fast and promising operation of FLASH after such a substantial upgrade is absolutely impressive. My compliments to the FLASH accelerator team," said Reinhard Brinkmann, director of the DESY accelerator division. With the now obtainable lowest laser wavelength, experiments with carbon in organic molecules come within reach, and magneto-dynamics experiments with the third-harmonic wavelength benefit from substantially increased intensities.

This success is also an important milestone for the European XFEL. The accelerator module recently installed at FLASH is a prototype for the European XFEL accelerator, and the properties of the 3.9 GHz module are also decisive for operating the European XFEL injector.



Spectral distribution of the first FLASH radiation at a wavelength of 4.45 nm

July

Faraday Cup 2010

Kirsten Hacker (DESY) and Florian Löhl (formerly DESY, now at Cornell University) were awarded the Faraday Cup 2010 on 14 July at the Beam Instrumentation Workshop BIW10.

Both laureates received the Faraday Cup award for a newly developed diagnostic technology. The technique tested at FLASH uses short light pulses to determine the arrival time of a particle bunch in the accelerator with a precision of 6 fs. It also enables the determination of the beam position with an accuracy of 3 µm.

Kirsten Hacker and Florian Löhl were awarded the Faraday Cup 2010.

Hans Weise appointed leading scientist at DESY

DESY's Administrative Council agreed in its July session to give Hans Weise the status of leading scientist in the accelerator division at DESY. Weise will lead the work on superconducting accelerators and on the European XFEL project at DESY. He will also take over the coordination of the accelerator consortium for the European XFEL. Besides DESY, the members of this consortium are institutes from the European XFEL member states which provide in-kind contributions to the construction of the European XFEL.

Topping-out ceremony for CFEL

Vis-à-vis the PETRA III experimental hall at DESY, a new building celebrated its topping-out ceremony on 20 July: the Center for Free-Electron Laser Science (CFEL) – a centre of excellence for photon science at next-generation light sources that is unique in Europe. Even though the construction of the real roof structure was delayed by the hard winter, CFEL already boasts an excellently developed "scientific roof structure", as Hamburg's State Minister of Science and Research Dr. Herlind Gundelach underlined in her address. By winning the world's best scientists for its working groups, CFEL already turned into a scientific success story, the State Minister said.

CFEL topping-out ceremony (from left): Prof. H. Siegfried Stiehl (University of Hamburg), Prof. Helmut Dosch (DESY), Hamburg's Science Minister Dr. Herlind Gundelach, Prof. Martin Stratmann (MPG), Prof. Joachim H. Ullrich (CFEL). (Photo: UHH, RRZ/MCC, Arvid Mentz/CLASSE)

CFEL is a novel cooperation between DESY, the Max Planck Society (MPG) and the University of Hamburg, aimed at further intensifying the collaboration between universities and non-university institutions. Across all borders of scientific disciplines and institutions, the CFEL members strive to fathom the full potential of the new free-electron lasers. Thanks to their temporal resolution of a few femtoseconds and their extreme intensities, these new light sources enable scientists to observe and analyse dynamical processes and structural changes of atoms, molecules, solids, plasmas or biological systems in real time. As DESY director Helmut Dosch emphasized, CFEL sets new standards in particular for research in the field of bio- and nanomaterials.

The costs for the construction of the new building amount to almost 49 million euro, the main part of which is borne by the City of Hamburg. Because of the outstanding scientific concept of CFEL, the German federal government contributes around 14 million euro.

September

First 480 m of European XFEL tunnel system completed

On 3 September, after less than two months, the tunnel boring machine TULA broke through the wall of its reception shaft and reached the first milestone – 480 m of the tunnel system for the European XFEL were completed.

When TULA set out for its “maiden trip” at the beginning of July 2010, it was not at all sure that it would reach its goal on schedule eight weeks later. How long the tunnel boring machine will actually take depends on the composition of the soil and on the presence of unknown potential obstacles underground; and, of course, on the skill of the tunnel builders in guiding the colossus through the earth, compensating for a little unevenness or “sensing” possible changes in soil composition in time. To achieve this, they sometimes even have to slip in diving suits into the slurry in front of the machine to check the tools fixed on the cutterhead.

During the following weeks, TULA was dismantled, the various parts were transported back to the construction site Schenefeld and then reassembled again to start building the next 594 m long tunnel section in early November.

The tunnel builders with the two patronesses (left: Imke Gembalies, right: Hamburg State Minister Dr. Herlind Gundelach) in front of the cutterhead of TULA. The rest of the borer is still inside the newly completed tunnel section. (Photo: European XFEL GmbH)

European XFEL accelerator components go into production

An important milestone was reached on the way to the European XFEL superconducting linear accelerator: the start of industrial production of the superconducting accelerator structures. On 6 and 7 September, kick-off workshops took place to coordinate DESY’s future collaboration with two industrial companies. The superconducting accelerator structures for the European XFEL are a joint contribution of DESY and INFN Milano, coordinated by DESY.

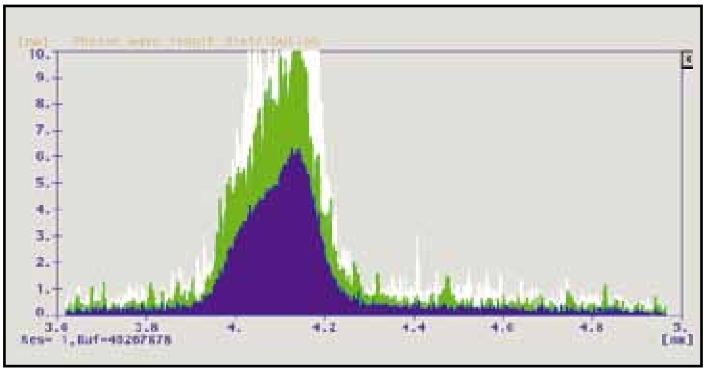
DESY commissioned both companies – Research Instruments (Bergisch-Gladbach, Germany) and Zanon (Schio, Italy) – to produce 300 accelerator cavities each, for a total of about 50 million euro. Each company will first deliver eight preproduction units to test the newly installed infrastructure at the firms. The preproduction will be followed by another 280 serial cavities and 12 accelerator structures manufactured within the framework of the EU ILC-HiGrade project. The aim of the project is to increase the accelerating gradient for the International Linear Collider (ILC). The cavities are submitted to an extensive quality control and undergo a special surface treatment, if necessary.

Representatives of the firms and DESY met at the kick-off workshops to discuss their technical and business collaboration. In this context, DESY is not only acting as ordering party for the cavities. It also provides the superconducting niobium, its own machines and know-how for quality control. The delivery of the preproduction will start in 2011. The delivery of the serial cavities is to begin in early 2012 and to be finished within two years. After successful testing at DESY, the cavities will be transferred to CEA Saclay, Paris, for the assembly into the European XFEL accelerator modules.

Representatives of Research Instruments and DESY at the kick-off meeting for the European XFEL cavity production

FLASH opens view through water window

On 26 September, FLASH set a new record: the accelerator team operated the free-electron laser at an electron energy of 1.25 GeV, thus reaching a wavelength of 4.12 nm. For the first time, FLASH generated laser light with the fundamental wavelength in the water window – so far this was only reached with the higher harmonics. The shortwave laser flashes had an average energy of 70 µJ and a peak energy of 130 µJ.



Spectral distribution of a FLASH pulse with a wavelength of 4.12 nm

"Congratulations to the FLASH team for their outstanding work," said Reinhard Brinkmann, director of the DESY accelerator division. "By optimizing the accelerator, they increased the electron energy by another 50 MeV and – reaching the water window – created brilliant conditions for FLASH scientists."

The water window is the wavelength region between approximately 2.3 and 4.4 nm. In this wavelength range, water is transparent to light, i.e. it does not absorb the FEL radiation. This opens up the possibility to investigate samples in an aqueous solution. This option is especially important for biological samples, because the carbon atoms contained in such samples are highly opaque to the X-ray radiation, while the surrounding water is transparent and therefore does not disturb the measurement.

Additional measurements with extremely short wavelengths are scheduled for November 2010. Starting in April 2011, the FLASH radiation will give the users the opportunity to peer through the water window.

October

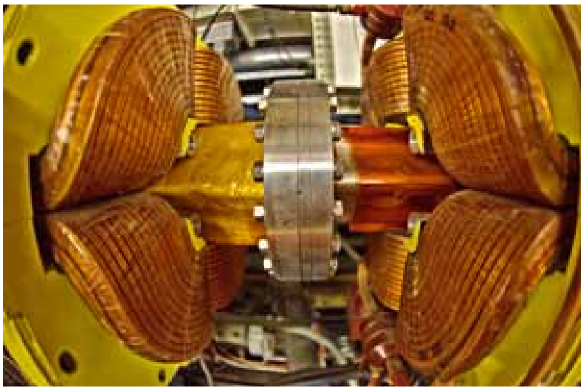
DESY triumphs in international particle physics photo competition

An international jury and a public vote confirmed it: the best particle physics photographers come from around Hamburg. The winners of the Global Particle Physics Photowalk were announced on 3 October – and four out of the six winning pictures where taken during DESY's photowalk. The winners were determined by an international jury and a public internet vote.

The winning portrait of a wire chamber

The portrait of a wire chamber, a part of a particle detector, immediately catches the eye. Its photographer is Hans-Peter Hildebrandt from Pinneberg, normally an amateur nature photographer. "To take these technical pictures was a great challenge for me. I had visited DESY before but thanks to the photowalk I had enough time to concentrate on each subject. And now I really like taking technical pictures," said Hildebrandt. His picture had already won the local competition. It also won the public vote with a large margin and was awarded the second prize by the international jury.

A picture of two quadrupole magnets in the HERA tunnel – which the jury called the "kissing lips" – won the third prize. This picture was taken by retiree and amateur photographer Heiko Römisch. Matthias Teschkes' picture of the HERA tunnel won the third prize in the public vote.



The "Kissing lips"

November

PETRA III runs at full speed

During the first week of November, the PETRA III storage ring reached a beam current of 100 mA during user operation for the first time, thereby achieving its last design value. “The PETRA III positron beam now simultaneously reaches all the ambitious beam parameters of emittance, beam current and beam position stability,” said Klaus Balewski from the DESY accelerator division.

A total of 240 positron bunches, combined into groups of four, now fly through the 2.3 km long storage ring, 130 000 times per second. The top-up operation mode keeps the beam current constant within 1% between 99 and 100 mA for more than 70 hours on end. The upgrade of two additional PETRA III beamlines has been concluded, bringing the number of operational beamlines to 9 out of 14. Currently, three beamlines are available for regular user operation.

The evaluation of the applications for the next user run was also concluded. Starting in March 2011, after a planned winter shutdown, about 50 user groups will have the opportunity to experiment at five PETRA III beamlines.

PETRA Energy: 6.084 GeV Lifetime: 5.48 h Current: 99.39 mA

Und.	Gap	Status
PU02	202.00	▨
PU03	11.23	🟩
PU04	147.04	▨
PU05	217.00	🟩
PU06	217.00	🟩
PU07	11.31	🟩
PU08	20.85	🟩
PU09	17.95	🟩
PU10	16.23	🟩
PU11	211.00	▨
PU12	217.00	🟩
PU14	215.72	🟩

Number of Bunches: 240

Mean Vacuum Pressure: 1.434E-08 mbar

Orbit Control: On

Top-Up Operation: 0.23 mA (RMS)

User Operations->Experiments

User Run

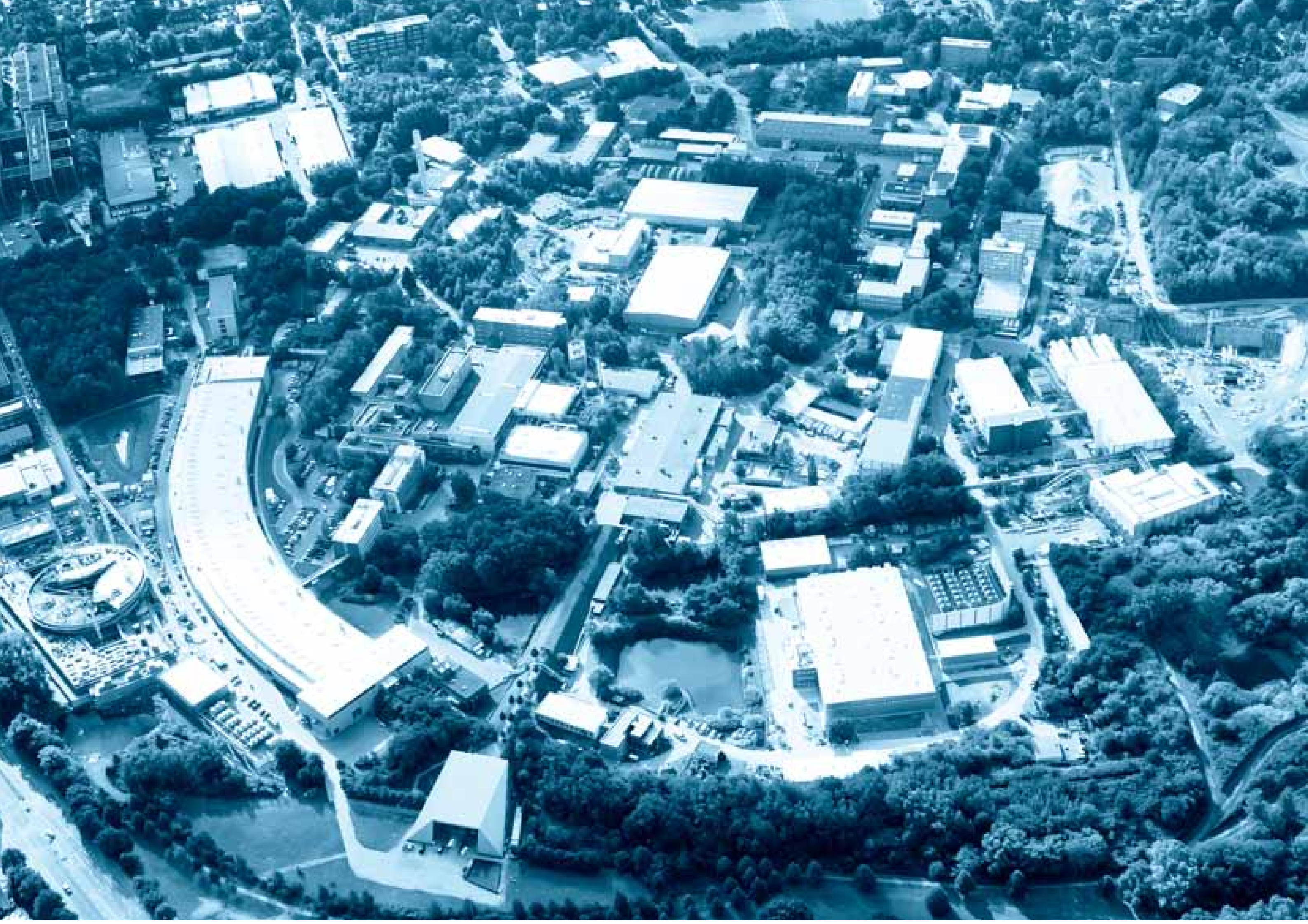
Thanks to the top-up mode of operation, the PETRA III beam current can be kept constant within 1%.

Helmut Dosch receives honorary doctorate from the Kurchatov institute

The chairman of the DESY Board of Directors, Prof. Helmut Dosch, received an honorary doctorate from the Kurchatov Institute on 25 November.

In a ceremony at the Russian institute, Dosch was honoured for his outstanding contribution to the development of X-ray techniques of condensed-matter investigation including phase transitions, and for strengthening the German-Russian collaboration in the field of utilization of synchrotron radiation for a wide range of scientific problems. Dosch is the first foreigner to become an honorary doctor of the Kurchatov Institute.

Professor Helmut Dosch



Accelerator operation and construction.

25 years of DESY II beam operation.

A pre-accelerator running at the highest duty cycle ever

The first electron beam circulated in the DESY II synchrotron more than 25 years ago, on 22 March 1985. Since then, DESY II has been the central machine within the accelerator complex at DESY for delivering electron or positron beams of up to 7 GeV with high stability and reliability to the user facilities.

History

DESY's first accelerator, DESY I, started operation in 1964. It was first used for high-energy experiments, which took place directly at the synchrotron (until 1979), and then also for delivering beam to the new electron-positron storage rings DORIS (1974) and PETRA (1977). With the HERA electron-proton storage ring coming up as a new project, it became clear 30 years ago that electron beams would be needed at DESY for decades to come. Because DESY I featured a combined-function lattice resulting in a horizontally anti-damped beam with a correspondingly large emittance, it was decided to split the upcoming needs for electron and proton pre-acceleration.

A new separated-function synchrotron – DESY II – for electron beams of up to 10 GeV was thus constructed in the same tunnel (Fig. 1, 2), using much of the existing DESY I infrastructure. In parallel to the DESY I routine operation in 1985, first beam tests with provisional power connection were performed. With the end of the PETRA collider programme at the end of 1986, DESY I was irrevocably switched off and converted into the proton synchrotron DESY III. After the final connection of all transport lines and magnet circuits, from spring 1987 on, DESY II delivered beam to DORIS, PETRA and detector test areas.

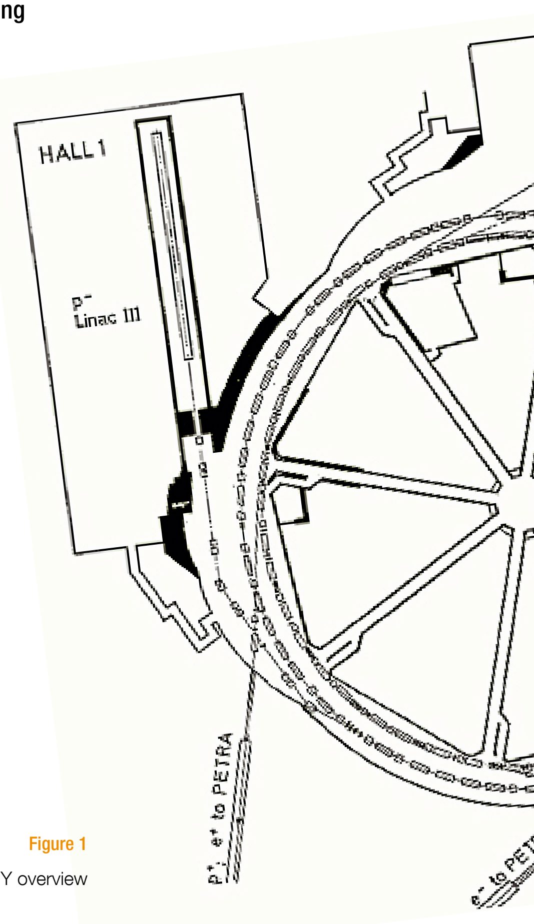


Figure 1

DESY overview

DESY II

The magnet system of DESY II consists of five circuits: one dipole, two quadrupole and two sextupole circuits, all synchronously oscillating with 12.5 Hz. 24 horizontal and 24 vertical DC corrector coils allow some orbit manipulation at lower beam energies. The optical lattice is formed by 8 x 3 FODO cells. Eight 7-cell PETRA-type cavities are supplied by one 1 MW HF station. One bunch of about 10^{10} electrons or positrons is injected (on axis) at 450 MeV, shortly after the time of minimal fields, and accelerated to usually 6.3 GeV, maximum 7 GeV. For DORIS and PETRA, the beam is extracted during acceleration at 4.5 GeV or 6.0 GeV, respectively. Three thin internal targets generate bremsstrahlung photons which are converted back into charged particles for test beam purposes.

Figure 2

View of the DESY tunnel, DESY II is on the right.

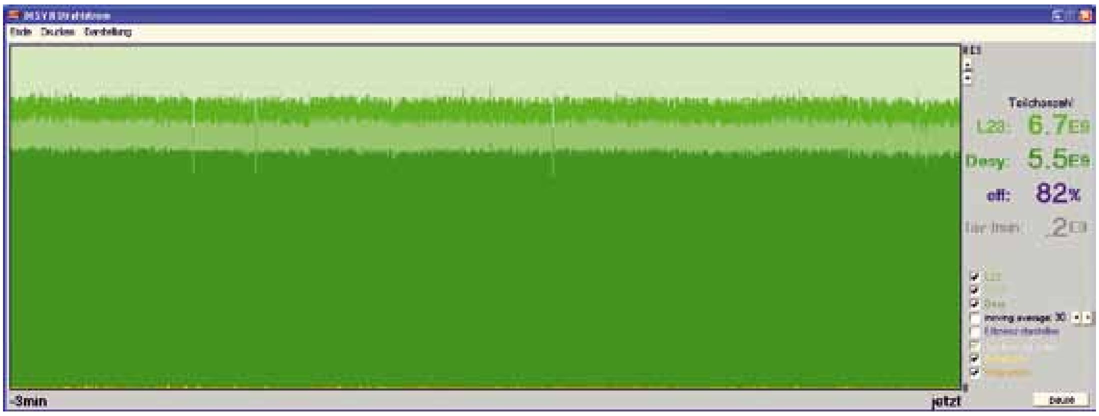
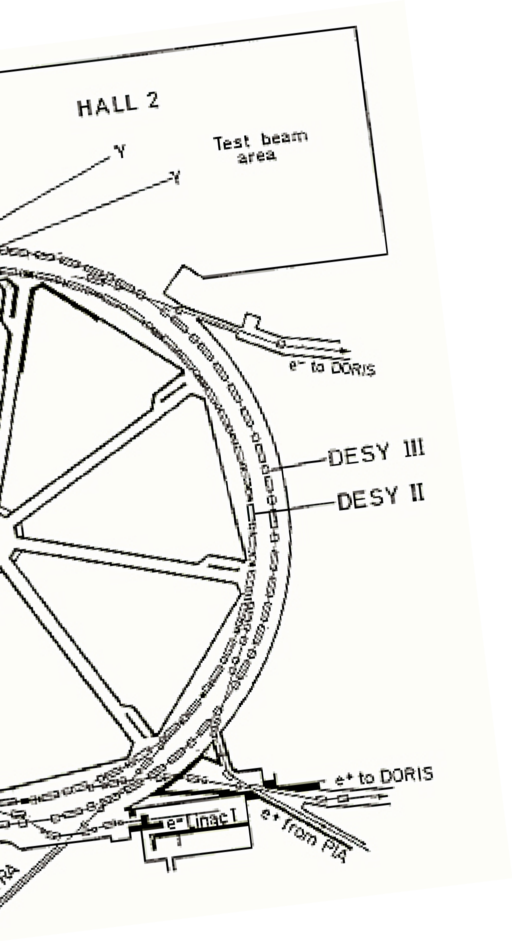


Figure 4

Beam intensity versus time for a typical situation today. The beam intensity in DESY II (dark green) follows the delivered intensity from LINAC II (light green) without breakdowns.



Status 2010/2011

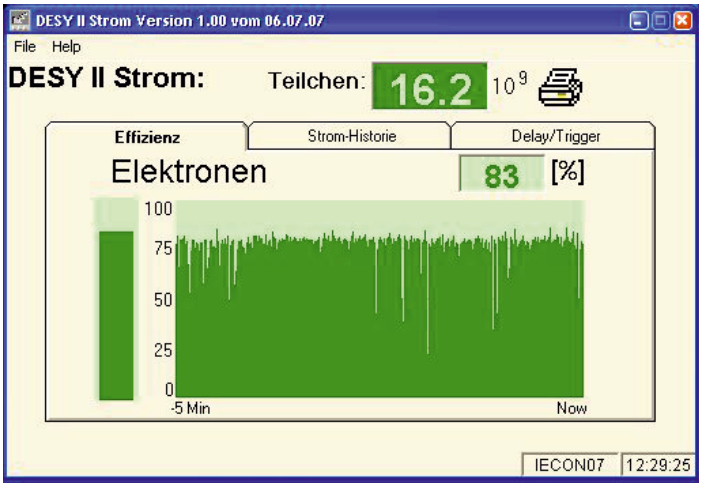
With the constant-current (“top-up”) operation mode of PETRA III, DESY II must deliver beam every few minutes. As a consequence DESY II has to run continuously. Maintenance periods are rather limited. At the same time, the reliability and operation stability must be very high.

As an important measure of infrastructure renovation, all six main power supplies (dipole DC, dipole AC, QD, QF, SD and SF) including the regulation concept were renewed during the past few years. The beam intensity variation could thus be significantly reduced, an overall efficiency of about 85-90% is typical (Fig. 3, 4). The availability usually reaches 99%.

For the last several years, DESY II has been running in a completely automated operation mode without manual actions by the operators. Beam requests from all users (DORIS, PETRA and test beams) are identified to set all necessary parameters for the requested operation mode.

DESY II is assigned to deliver beam quietly, without fanfare. This challenge has been completely and continuously fulfilled. To further reduce possible downtime, a second independent HF station is currently under construction. It will come into routine operation in summer 2011.

As a completely new activity at DESY, first tests for a dedicated beam dump experiment, HIPS (Hidden Particle Search), have recently been performed. For this experiment, the DESY II beam is extracted and directed onto a target inside the DESY II tunnel, parasitically to the pre-accelerator operation. The detector too will be located inside the tunnel. With this experiment, accelerator-based particle physics at DESY has returned home to the synchrotron.


DESY II Strom Version 1.00 vom 06.07.07

DESY II Strom: Teilchen: 16.2 10^9

Elektronen 83 [%]

IECON07 12:29:25

Figure 3

Snapshot of the beam intensity versus time in 2007 under optimal conditions, nevertheless with unavoidable intensity breakdowns

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Contact: Heiko Ehrlichmann, heiko.ehrlichmann@desy.de

DORIS III.

An old machine is preparing for an exciting particle physics experiment

The year 2010 was another year of exciting and successful research using the DORIS III storage ring as a dedicated synchrotron radiation source. In addition, DORIS III is preparing for another experiment that will be carried out during three months in 2012: OLYMPUS, a particle physics experiment designed to investigate a riddle concerning the elastic scattering of electrons on protons.

Synchrotron radiation run 2010

In 2010, DORIS III delivered a total beam time of 4600 hours with an availability of 84.1% and a mean time between failures of 44.5 hours. The operation was disturbed by several breaks of the beam pipe vacuum, starting with a disrupted window at startup in March 2010. These failures could be repaired quickly, but required several days each to improve the vacuum and the correlated beam lifetime to the values necessary for high-class experiments.

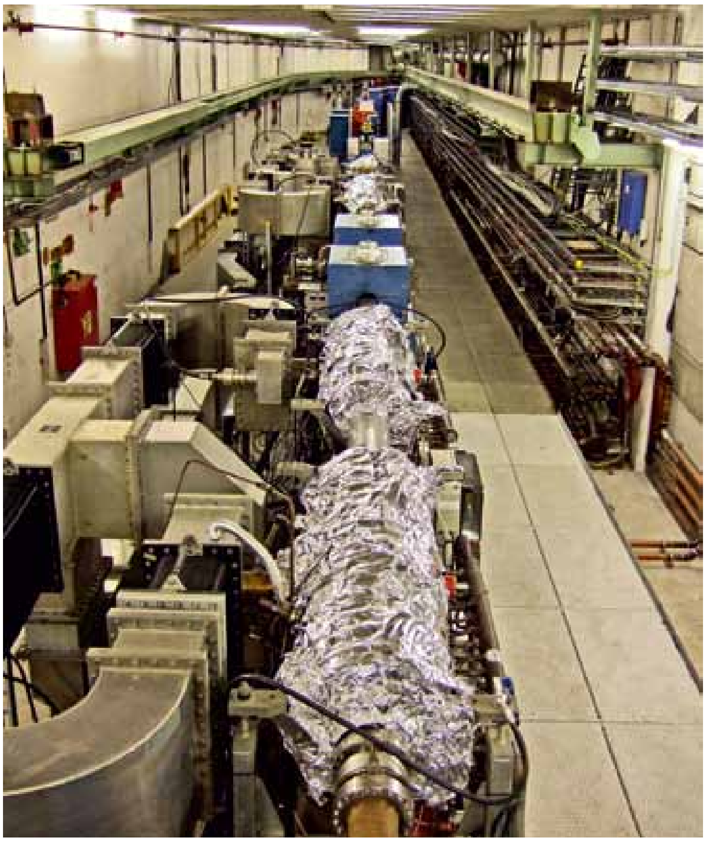


Figure 1

View of the long straight section of DORIS III before the winter shutdown 2010/11. The position of the former ARGUS detector was occupied by two accelerating cavities, which were moved 25 m upstream during the shutdown to make room for the OLYMPUS experiment.

OLYMPUS at DORIS III

In June 2007, an experiment was proposed for a precision measurement at DORIS III of the cross section ratio of electrons versus positrons scattered off protons using the BLAST detector from MIT, Boston, with an internal hydrogen gas target. After intense investigations, it was decided to implement this experiment, which is feasible since the total time needed to obtain the desired results is only three months. DORIS III will thus nevertheless operate most of the time as a dedicated synchrotron radiation source.

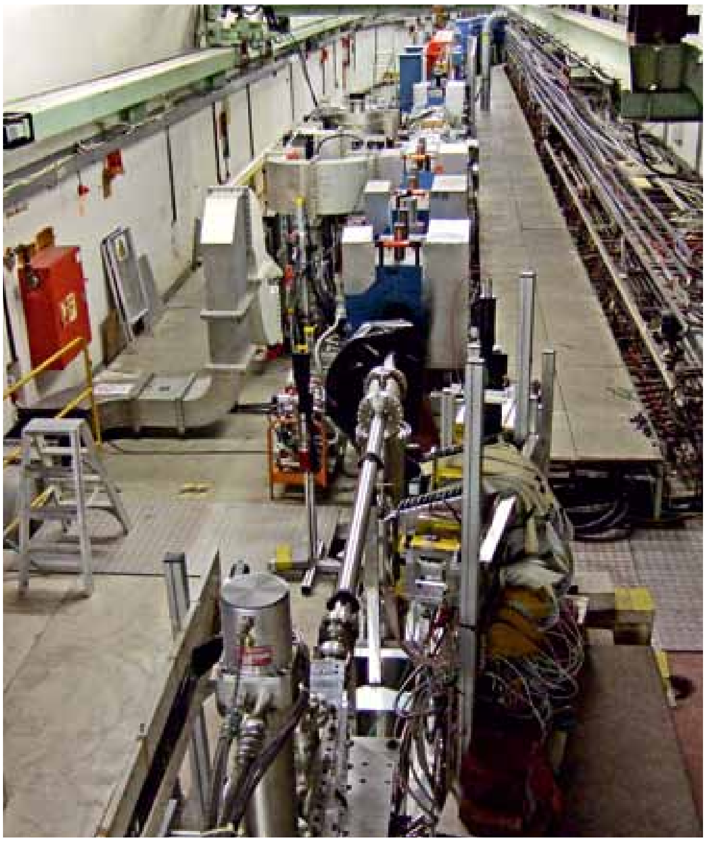


Figure 2

The OLYMPUS target chamber can be seen in the foreground. It is followed by a test detector setup adjacent to the beamline. In the summer of 2011, the main frame equipped with detectors and the toroid magnet will be installed in this region.

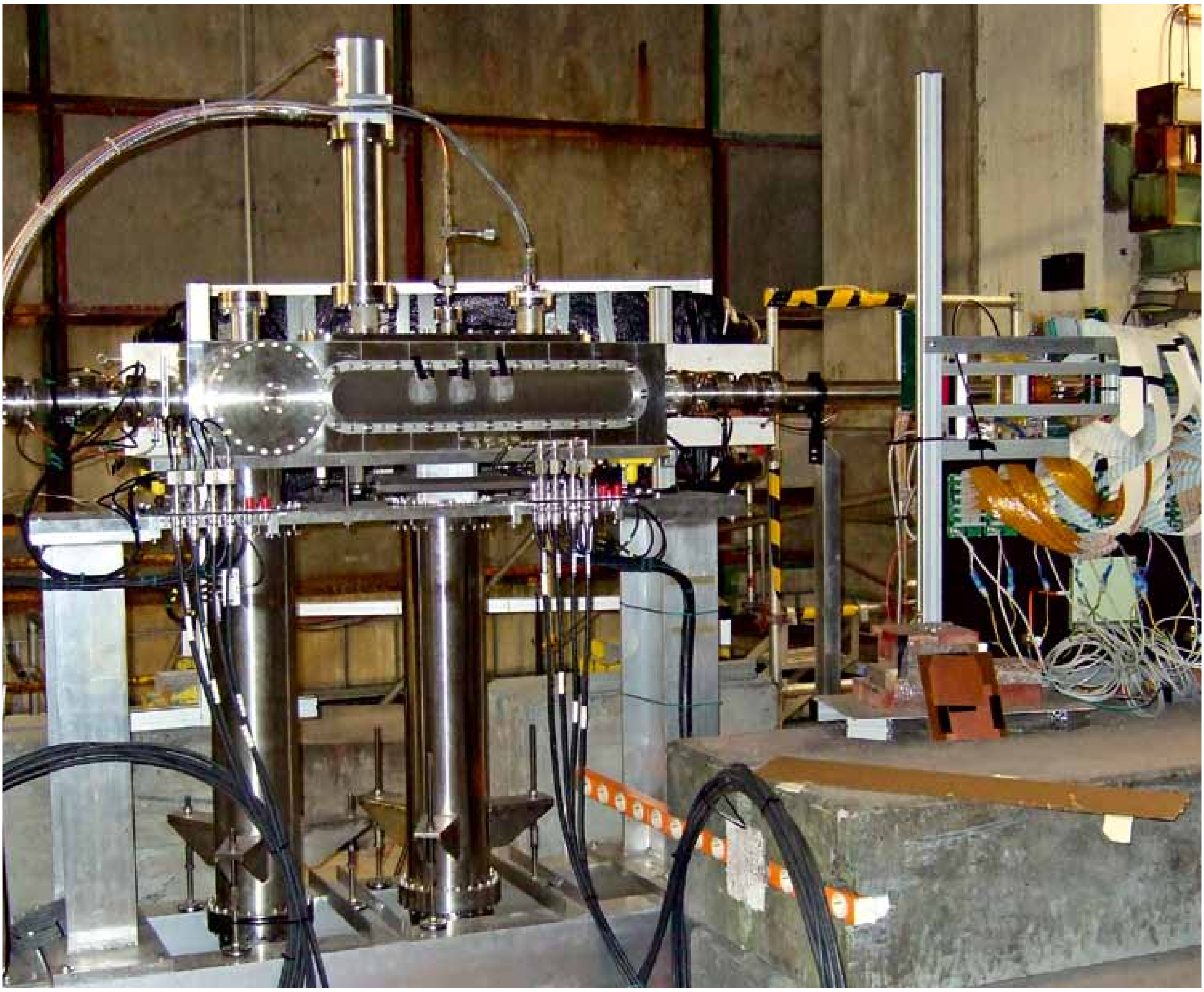


Figure 2

The OLYMPUS gas target scattering chamber in its place in the DORIS III storage ring. The hydrogen gas is fed in from the top and evacuated through the large pipes on the bottom of the chamber.

Since the DORIS III storage ring was originally built as an electron-positron collider ring, the infrastructure for a large detector – such as the experimental hall, the opening in the shielding walls and the pit with rails to house the detector – already exists. It turned out that the BLAST detector just fits into the existing environment, but not without major modifications. The space in the new interaction region was occupied by accelerating structures which had to be moved to a new position. A new pair of quadrupole lenses was required to focus the particle beam down to the size of the target cell. The complete shielding walls had to be removed and rebuilt. All magnet power supplies were equipped with switches for rapid changing from electron to positron operation. Modifications of beam diagnostics, interlocks etc. completed the work.

After two years of preparations, the interaction region was rebuilt within two months in the winter of 2010/11. This work also included the installation of the complete OLYMPUS vacuum system with the scattering chamber and a setup of test detectors. This enables the measurement of all relevant parameters and the preparation of the dedicated measuring time scheduled in 2012. The main detector will be finished in the DORIS III experimental hall by summer 2011, when it will be installed during a three-week shutdown.

All these modifications had to be designed with the requirement not to compromise the quality of DORIS III as a synchrotron radiation source. Beam operation is due to begin in February 2011 with commissioning and machine studies, followed by the start of the synchrotron radiation run on 1 March 2011.

Contact: Frank Brinker, frank.brinker@desy.de

PETRA III.

Commissioning and operation

The two main goals for the commissioning and operation of the PETRA III storage ring in 2010 were first to push all key parameters of the machine as close to design as possible (Table 1), and then to offer reliable operation for the first regular users in the second half of the year.

Pushing PETRA III towards design

The machine was operated at an energy of 6 GeV right from the beginning. The design emittance in the horizontal plane was achieved already last year, but it remained to be demonstrated that all the other parameters could be achieved as well.

In 2009 already, it was observed that the vertical emittance blew up to unacceptably large values for currents above 50 mA. This blow-up was found to have two reasons: In case of a small distance between bunches (≤ 32 ns, i.e. 240 or more evenly filled bunches), the blow-up is most likely caused by the so-called e-cloud effect. In case of a large distance between bunches (≥ 64 ns, i.e. 120 or less evenly filled bunches), the blow-up is probably caused by an interaction of higher-order head-tail modes of the bunches with the feedback system.

This problem and the potential explanations are still under investigation. However, operational modes have been found which avoid the blow-up. In case of a high number of bunches, special filling patterns have been set up which allow to run the machine at the design current without any blow-up. Although operation with 960 bunches is still not possible, the machine has been successfully operated with up to 240 bunches. In case of a small number of bunches, increasing the vertical chromaticity and in addition optimizing the gain and phase of the vertical multibunch feedback avoids the vertical blow-up. This allowed to run the machine with 40 bunches with currents of a bit more than 90 mA.

The current in the 40-bunch mode is also limited by a technical problem caused by insufficient thermal contact of RF fingers in particular bellows. Once the problem had been figured out, measures were taken to ensure a sufficiently large spring constant of these RF fingers so that in 2011, operation with 40 bunches and 100 mA should be no problem.

Table 1: Design parameters of PETRA III

Parameter	
Energy (GeV)	6
Current (mA)	100
Number of bunches	40 / 960
Horizontal emittance (nm rad)	1
Vertical emittance (pm rad)	10
Pointing stability at ID horizontal vertical	10 µm 0.5 µm
Number of insertion devices (ID)	14

As previously mentioned, it was proven in 2009 that the horizontal emittance is as small as 1 nm rad, which is the smallest horizontal emittance of all synchrotron radiation sources. Observations of the synchrotron radiation users and measurements of accelerator parameters such as coupling, spurious vertical dispersion and Touschek lifetime suggest that the value of the vertical emittance is close to design or at most less or equal to 20 pm rad.

The pointing stability of the particle beam is very import to fully exploit the excellent beam quality. Extensive passive measures have been taken to guarantee the required orbit stability. Based on past experience, however, it was clear that an orbit feedback would be necessary to realize the demanding stability goal. Figure 1 shows the vertical stability at a canted undulator section (PU 8 & 9) and a non-canted undulator section (PU 10). The picture clearly shows that the required orbit stability can be guaranteed even over more than 50 h, which significantly exceeds the anticipated period of 20 h.

By the end of 2010, all straight sections were equipped with an undulator so that all beamlines have been commissioned. The impact of the undulators on the beam is as expected. It mainly causes an orbit distortion if the undulators are closed or the gaps are changed. For all devices, feed-forward tables were set up to correct the effect on the orbit. In addition, the APPLE II undulator has a strong influence on the optics depending on the mode of polarization. This influence was measured and found

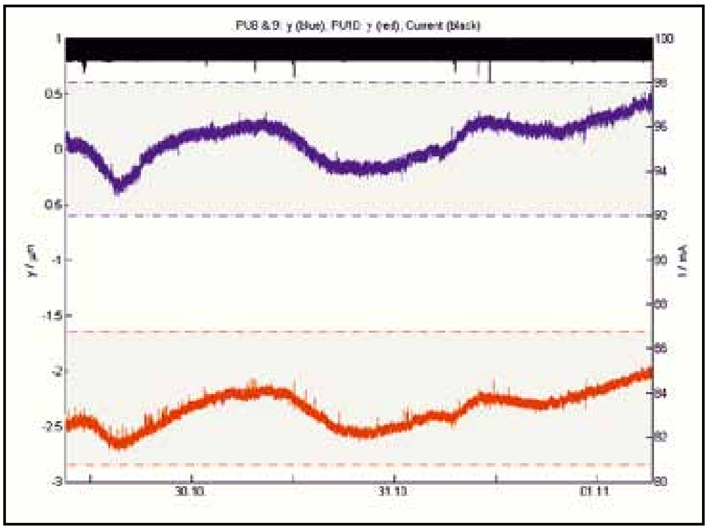


Figure 1

Vertical orbit stability at two different ID positions over more than 50 h. The dashed bands indicate the acceptable deviations of ± 0.5 µm.

to agree quite well with theoretical predictions. Presently work is ongoing to minimize the effect on the optics using special shims to modify the magnetic field. In addition, a feed-forward strategy is being worked out to compensate the distortions of the optics locally with the quadrupoles adjacent to the undulator.

In summary, PETRA III is now essentially running close to design, even if there are still some questions and problems that need clarification.

First user run

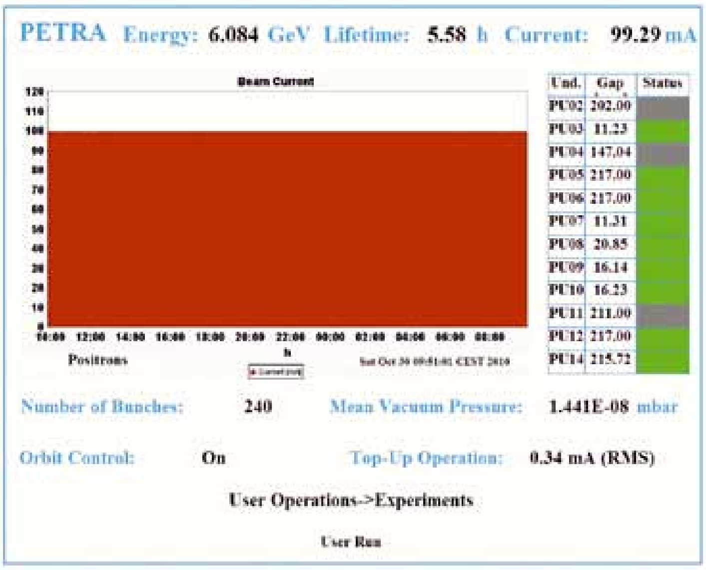
During the second half of 2010, PETRA III was operated for the first time in regular user mode. Beam time was allocated based on a peer review for the undulators PU 8, PU 9 and PU 10. One import aspect of routine operation is to run the machine in top-up operation mode to ensure high beam stability. Top-up operation means frequent injections into the machine (for example every three minutes) to keep the current constant at the percent level. This ensures an almost constant heat load to the machine as well as to beamline components, which improves stability. The hard- and software involved in the top-up process were approved over the first half of 2010 so that reliable operation was ensured during the second half of the year. Figure 2 shows a typical run during the second half of the year at a beam current of 100 mA.

The horizontal beta function in the straights of the DBA cells can be either large (i.e. 20 m, so-called high-beta mode) or small (i.e. 1 m, so-called low-beta mode). The magnetic lattice was designed such that each cell can be operated in high- or low-beta mode, respectively. In the first half of 2010, it was demonstrated that such an optics change can be made successfully within a reasonable time.

One important requirement for user operation is a high availability of the machine, which means that all components of the accelerator and the pre-accelerators have to work very reliably. At the beginning of the run in August 2010, the reliability was relatively low, but it could be increased to a sufficient level of about 95% at the end of the year.

PETRA III extension

In 2007 already, scenarios were studied on how to extend the number of experimental stations at PETRA III. This has become even more important given that DORIS III is to be shut down at the end of 2012. To accommodate some of the DORIS III experimental stations and offer additional beamlines, the lattice of the PETRA III storage ring will be modified in the two arcs north and east left. The first hundred metres of the two arcs will be remodelled and the existing FODO lattice replaced by two DBA cells and matching sections. Two undulators of 2 m length canted by 20 mrad will be installed in the straights of the cells. Furthermore, the hard X-ray beam of the damping wigglers in the north will serve as a source, and in the east, a combination of an undulator and a wiggler will be installed. In total, the two sections will offer five additional beamlines.


PETRA Energy: 6.084 GeV Lifetime: 5.58 h Current: 99.29 mA

Und.	Gap	Status
PU02	202.00	▨
PU03	11.23	🟩
PU04	147.04	▨
PU05	217.00	🟩
PU06	217.00	🟩
PU07	11.31	🟩
PU08	20.85	🟩
PU09	16.14	🟩
PU10	16.23	🟩
PU11	211.00	▨
PU12	217.00	🟩
PU14	215.72	🟩

Number of Bunches: 240 Mean Vacuum Pressure: 1.441E-08 mbar

Orbit Control: On Top-Up Operation: 0.34 mA (RMS)

User Operations->Experiments

User Run

Figure 2

Top-up operation at 100 mA and 240 bunches in October 2010

In 2010, the basic layout process and the specification of the accelerator components began. In view of the short time available for the preparation of the extension, use of known components is foreseen to ease the design work. The new experimental stations will be housed in two new experimental halls, which will be built on either side of the existing PETRA III experimental hall. The time line for the extension is as follows. Civil construction is due to start in autumn 2012. The modification of the PETRA magnet lattice will be carried out in parallel. The necessary shutdown is to be as short as possible, and the restart of the machine is envisioned during the first half of 2013.

Contact: Klaus Balewski, klaus.balewski@desy.de

FLASH.

Lasing in the water window

On 15 February 2010, the most recent upgrade of FLASH was completed on schedule. During a five-month shutdown several important upgrades were accomplished. A seventh accelerating module was added to the accelerator to further increase the beam energy. The module was built as the first prototype for the European XFEL. Fermilab contributed a 3.9 GHz module attached to the first accelerator module of the injector. It contains four superconducting cavities that linearize the longitudinal phase space to allow for a more efficient compression of the electron bunches. A seeding experiment, sFLASH, was integrated in the facility to test future seeding options for FLASH and the European XFEL. All RF stations were brought up to date and three new stations added. The repetition rate of the RF pulses was increased from 5 Hz to 10 Hz. A new electron gun cleaned with dry-ice technology induces a reduction of dark current by a factor of 10, making 10 Hz operation with long RF pulses possible. The photon beamline was upgraded as well, new photon diagnostics and beamline components were installed, and many other changes were made.

At the end of May 2010, electrons were accelerated to 1.2 GeV for the first time, and a week later free-electron laser (FEL) radiation at 4.5 nm wavelength, just outside the so-called water window, was produced with pulse energies of around 75 µJ. Further optimization of the accelerator finally made it possible in September to increase the beam energy to 1.25 GeV and generate intense FEL pulses at a wavelength of 4.1 nm. Figure 1 shows the first-ever recorded spectrum of self-amplified spontaneous emission (SASE) radiation reaching the water window. The water window is the spectral range between the carbon and oxygen K-edges. It is particularly interesting for the investigation of organic material due to the high sensitivity for carbon and the rather low absorption of the radiation in water.

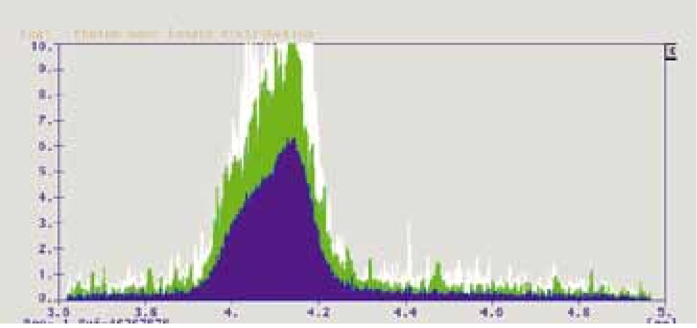


Figure 1

New wavelength record at FLASH. The first recorded spectrum of SASE FEL radiation in the water window at 4.1 nm wavelength. The low-resolution spectrum shows a single pulse (blue) and an average over several pulses.

Soon after commissioning of the new 3.9 GHz module, significantly higher numbers of photons per pulse could be produced. Energies of up to 300 µJ per photon pulse with more than 10^{13} photons were recorded. The main reason for the increased pulse energy is the improved compression of the electron bunches due to the compensation of the curvature in the longitudinal phase space. Figure 2 shows a measurement of the longitudinal phase space with the transverse deflecting cavity LOLA. The beam is streaked by LOLA to measure the time coordinate and sent through a dipole magnet to measure the energy distribution at the same time. With the 3.9 GHz cavities switched on with proper voltage and phase, the initially curved distribution in phase space is linearized. A larger fraction of electrons in the bunch now contributes to the FEL process. In general, higher pulse energies go along with higher bunch charge and longer pulses, up to about 200 fs (rms). This is indicated by the large number of spikes observed in high-resolution spectra (Fig. 3). Long and homogeneous electron bunches with a high number of photons per pulse are important for many experiments. Long bunches are also mandatory for seeding experiments like sFLASH.

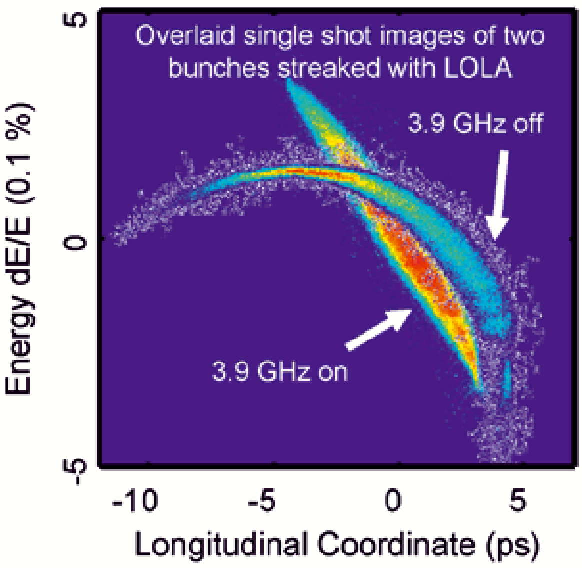


Figure 2

Phase space distribution of the electrons of two bunches measured with LOLA, with the 3.9 GHz cavities turned on and off. The linear distribution leads to a more homogeneous bunch compression.

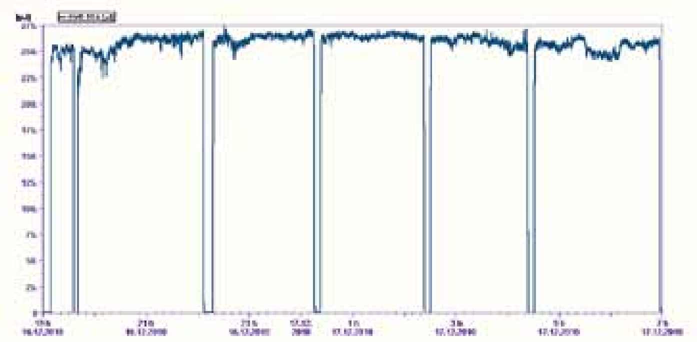


Figure 5

Example of stable FEL beam delivery during the user run. In this case, 500 bunches per second with a wavelength of 15.8 nm were delivered with a single pulse energy of 250 µJ. The occasional interruptions are intentionally.

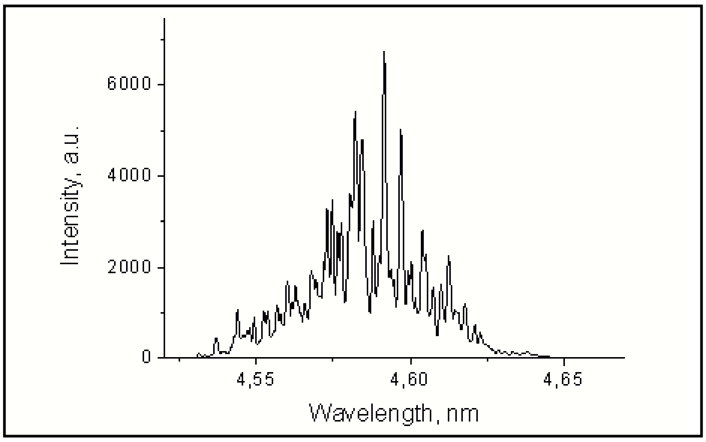


Figure 3

Spectral distribution of a single FEL pulse at 4.6 nm wavelength measured with high resolution

Other experiments, however, especially those dealing with nonlinear excitation processes or ultrafast phenomena, need extremely short pulses in the 10 fs range or shorter. Fine adjustment of the compression process with reduced beam charge is required to provide adjustable ultrashort pulse lengths. So far, electron pulses below 50 fs have been produced and delivered to experiments. Further experiments are planned to realize and measure FEL pulses approaching 10 fs.

Already during the first three beam time blocks in 2010, the users benefited from the improved stability of the machine and the higher average photon pulse energies. The downtime was only 4%, compared to 8% the year before (Fig. 4). In addition, improved feedback systems require less interference of the machine operators, allowing stable operation for a whole shift without readjustment (Fig. 5).

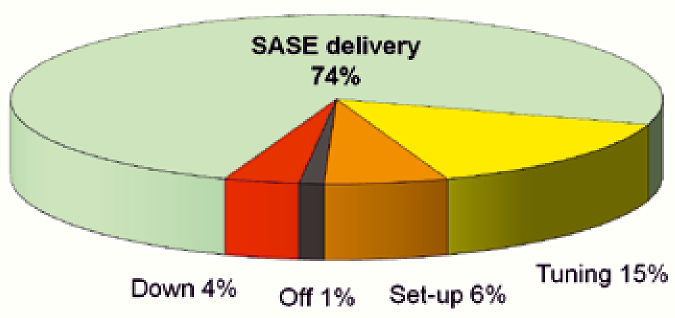


Figure 4

FEL beam delivery during the three user beam time blocks in 2010

21 different wavelengths between 4.8 nm and 44 nm have been provided to experiments.

The low-level RF system to drive and stabilize the amplitude and phase of the accelerating gradient of the gun and all superconducting modules was completely refurbished. Now all five RF stations have the same FPGA-based modern controller hardware and common software. This greatly improves the reliability and also facilitates and streamlines the development effort. Besides the usual feedback, learning feed-forward has been successfully implemented. Many sources of distortions on the RF amplitude and phase are repetitive from pulse to pulse. The algorithm is able to recognize this and adapt the feed-forward signal appropriately. Figure 6 shows an example where the pulse train was flattened using learning feed-forward.

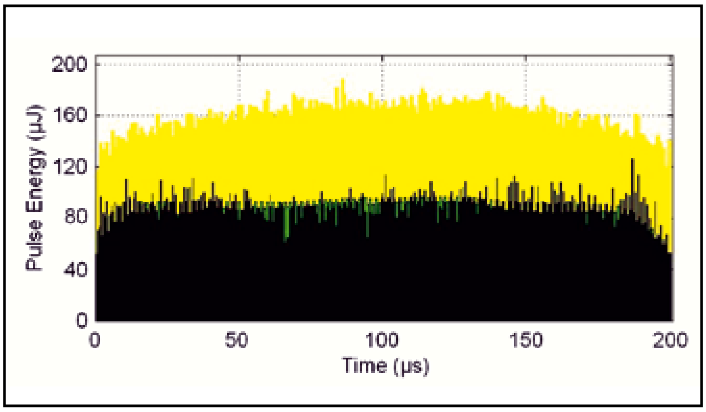


Figure 6

Example of a stable and flat FEL pulse train. 200 bunches at 1 MHz in a pulse train are produced with a wavelength of 4.8 nm. The black pulses show the single-shot train measured at the moment when the picture was taken. The green trace is the average, the yellow one is the maximum obtained.

The synchronization system made further progress. The goal is to provide arrival time stability of the order of or smaller than the radiation pulses, i.e. at the 10 fs level. This is only possible using a beam-based feedback system. A fast pick-up signal from the beam is compared to an ultrastable fibre laser. The resolution of the system is 5 fs. So far, the arrival time has been stabilized after a couple of bunches in a train close to 20 fs (rms). Soon, this system will be available for users.

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

FLASH II.

An extension of the FLASH facility

The next major extension of the FLASH facility, also referred to as FLASH II, was jointly proposed by DESY and the Helmholtz-Zentrum Berlin (HZB). It was approved in 2010 by the Helmholtz Association and the funding bodies.

FLASH II includes a new experimental hall to double the number of user stations, and an additional variable-gap undulator in a separate tunnel to be able to deliver two largely independent wavelengths to two different user stations simultaneously. The electron beam is switched between the present fixed-gap undulator line of FLASH (here referred to as FLASH I) and the new variable-gap undulator FLASH II (Fig. 1).

The necessary modification of the present facility is minor. In the new experimental hall, space for at least five experimental stations is foreseen. To avoid damage and allow the reflection of the 3rd and 5th harmonic down to 0.8 nm wavelength with high efficiency, the first deflecting mirrors for FLASH II will be set at 1° grazing incidence.

In addition to the self-amplified spontaneous emission (SASE) mode that has been used in FLASH I, high-harmonic generation (HHG) and possibly, in a later stage, cascaded high-gain harmonic generation (HGHG) seeding is foreseen for FLASH II. The cascaded HGHG uses a Ti:Sa laser at a repetition rate of 100 kHz, which is currently under development at DESY in collaboration with the Helmholtz-Institut Jena. After frequency up-conversion, the seeding radiation enters the beam tube at the beginning of the undulator vacuum pipe, as indicated in Fig. 1. Direct seeding with an HHG source, which delivers high harmonics of an intense optical laser pulse focused on a gas target, is foreseen for wavelengths between 10 nm and 40 nm. This scheme makes use of the same laser than the HGHG scheme. The SASE mode will be used for long wave-

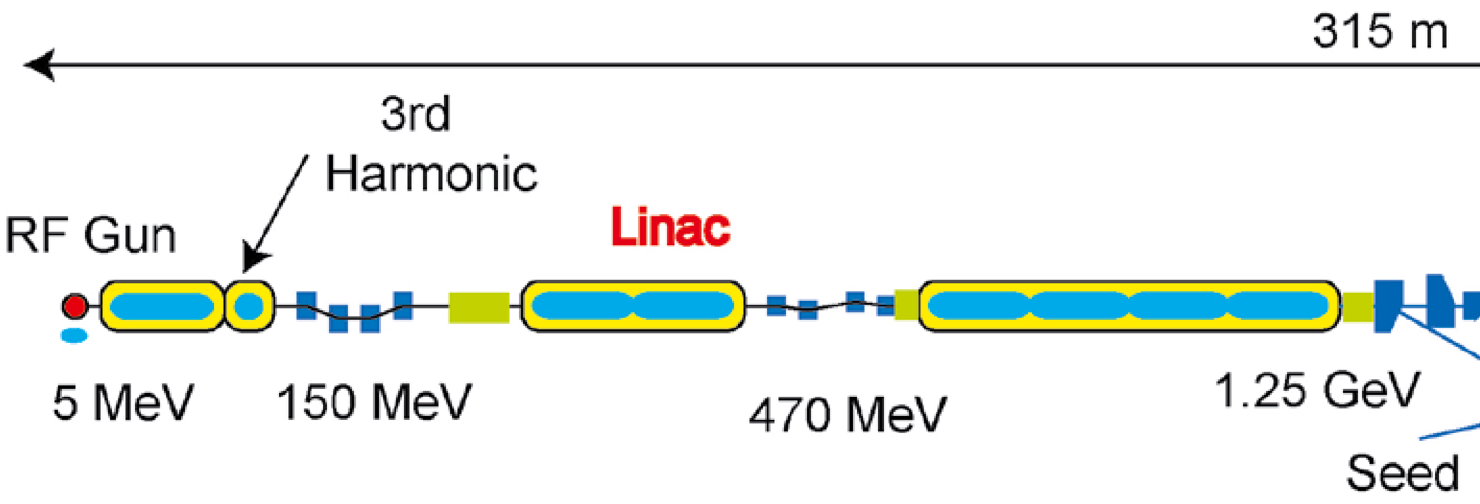


Figure 1

Schematic layout of the FLASH facility. The electron gun is on the left, the experimental hall on the right. Behind the last accelerating module, the beam is switched between the present undulator line (FLASH I) and the new line (FLASH II). Behind the extraction point, space is reserved for an additional laser system for seeding.

Table 1: Expected output parameters for FLASH II

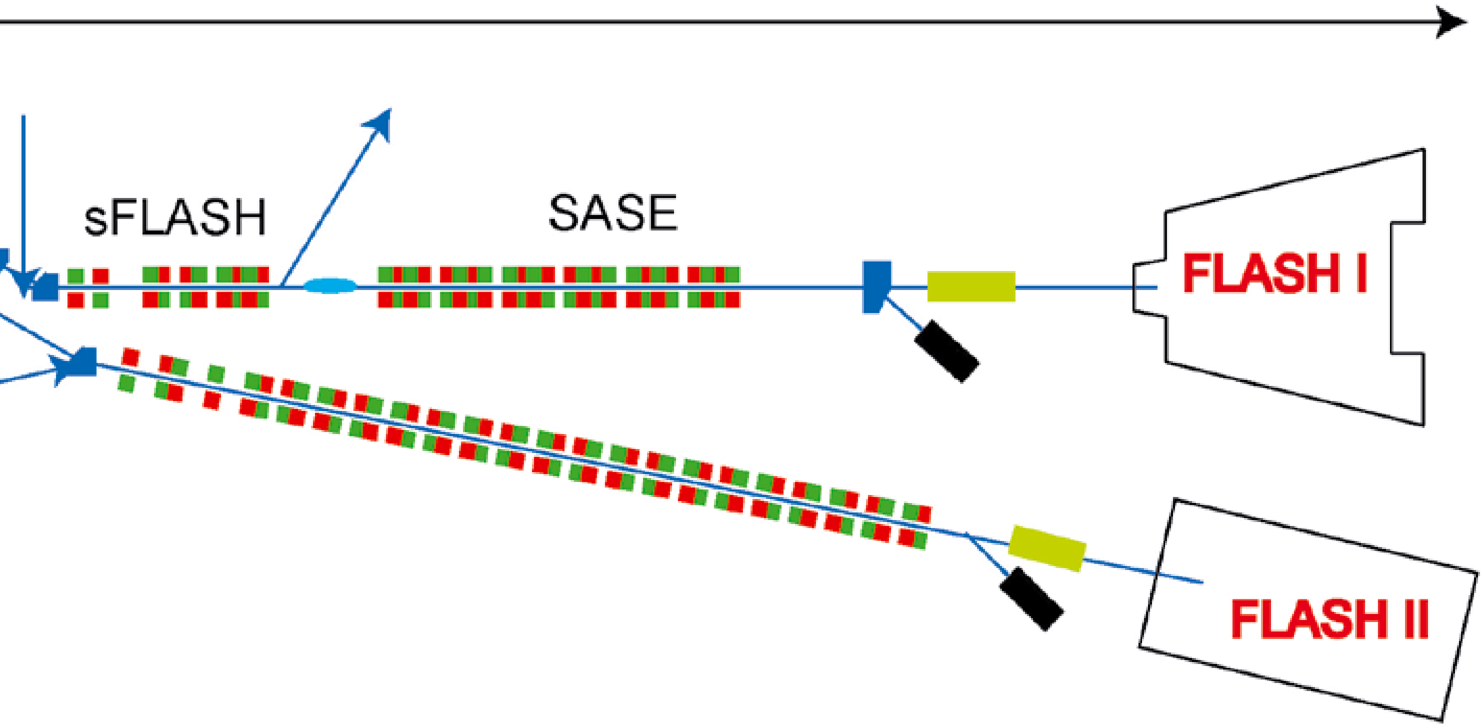
Photon beam	HHG	HGHG	SASE
Wavelength range (fundamental)	10 – 40 nm	4 – 30 nm	4 – 80 nm
Average single pulse energy	1 – 50 µJ	30 – 200 µJ	1 – 1000 µJ
Pulse duration (FWHM)	<15 fs	15 – 80 fs	10 – 200 fs
Peak power (from av.)	1 – 5 GW	1 – 6 GW	1 – 5 GW
Spectral width (FWHM)	0.1 – 1%	0.1 – 1%	0.1 – 1%
Peak brilliance*	10^{28} – 10^{31}	10^{28} – 10^{31}	10^{28} – 10^{31}

* B=photons/(s mrad^2 mm^2 0.1% bw)

lengths and for wavelengths shorter than ~10 nm, where the power of the HHG source will not be sufficient for seeding. The parameters expected for FLASH II are shown in Table 1. The SASE parameters are similar to those for FLASH I.

Studies to extend the wavelength range down to 2 nm and provide circularly polarized radiation are in progress. One idea is to use a short afterburner optimized for the short wavelength together with the maximum available electron beam energy of 1.25 GeV. To allow for a variable polarization, this afterburner would be an APPLE III undulator.

Contact: Bart Faatz, bart.faatz@desy.de



European XFEL.

Preparing the accelerator complex of the European XFEL

The European XFEL is based on the superconducting accelerator technology that was developed by the TESLA collaboration in the 1990s. It uses the self-amplified stimulated emission (SASE) free-electron laser principle for the production of highly brilliant photon beams in the 0.1 nm wavelength region. Both the superconducting technology and the SASE principle were successfully demonstrated at lower electron beam energy and longer wavelengths at DESY's FLASH facility.

New accelerator parameters

The scenario originally described in the European XFEL technical design report (TDR) is based on an electron beam energy of 17.5 GeV and relatively conservative beam quality parameters: an electron beam emittance of 1.4 mm mrad was assumed at a bunch charge of 1 nC. Start-to-end simulations have demonstrated that lasing at 0.1 nm is achievable with a sufficient safety margin at these electron beam parameters. Both the achievement of much smaller emittances well below 1 mm mrad at DESY in Zeuthen and the very successful commissioning of the Linac Coherent Light Source (LCLS) at SLAC (demonstrating the reliability of simulation codes) allow for a more aggressive strategy. Improved beam quality makes it possible to reach the TDR parameters at reduced electron energies (and thus to save money by shortening the linac) or to extend the performance beyond the shortest wavelength originally foreseen.

Extensive simulations support a new parameter set that features a reduced electron energy of 14 GeV. However, shortening the linac reduces the safety margin and makes a later conversion to continuous wave (CW) operation more expensive: because of reduced acceleration gradients (limited by cryogenics), the conversion would require lengthening the linac at a later date. Although the new parameter set enables lasing down to a wavelength of 0.05 nm, higher electron beam energies would allow for even shorter photon wavelengths.

The project team proposed the shortening of the linac by 20 accelerator modules to the European XFEL Council and received the go-ahead for ordering the linac components required for 14 GeV. The council also stipulated that options for a later extension be included in all discussions and, as far as applicable, in calls for tender. The replacement of the 20 accelerator modules by temporary electron beamlines was initiated. In parallel, efforts continue to acquire the funding necessary to build the full 17.5 GeV linac as planned.

Accelerator Consortium

The accelerator complex of the European XFEL is to be built by an Accelerator Consortium led by DESY, in which a small coordination team interacts with all European XFEL work package leaders and institutes.

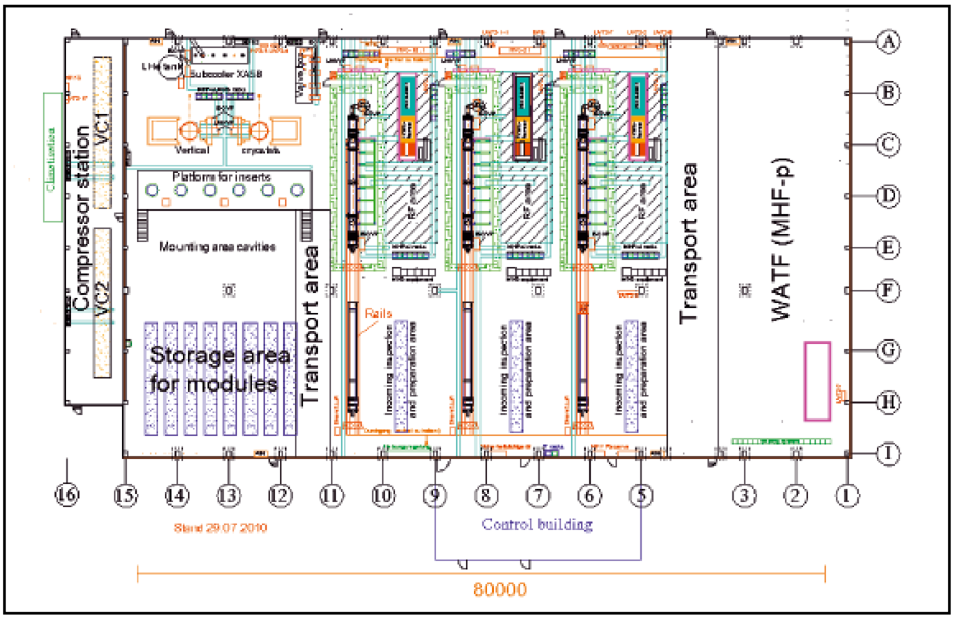
The accelerator of the European XFEL will be assembled from a large number of superconducting accelerator modules. These modules are contributed by DESY, CEA Saclay, LAL Orsay, INFN Milano, IPJ Świerk, CIEMAT Madrid and BINP Novosibirsk. The other institutes contribute to the roughly 3000 m of electron beamlines remaining. Some examples of the ongoing activities are provided below.

Figure 1

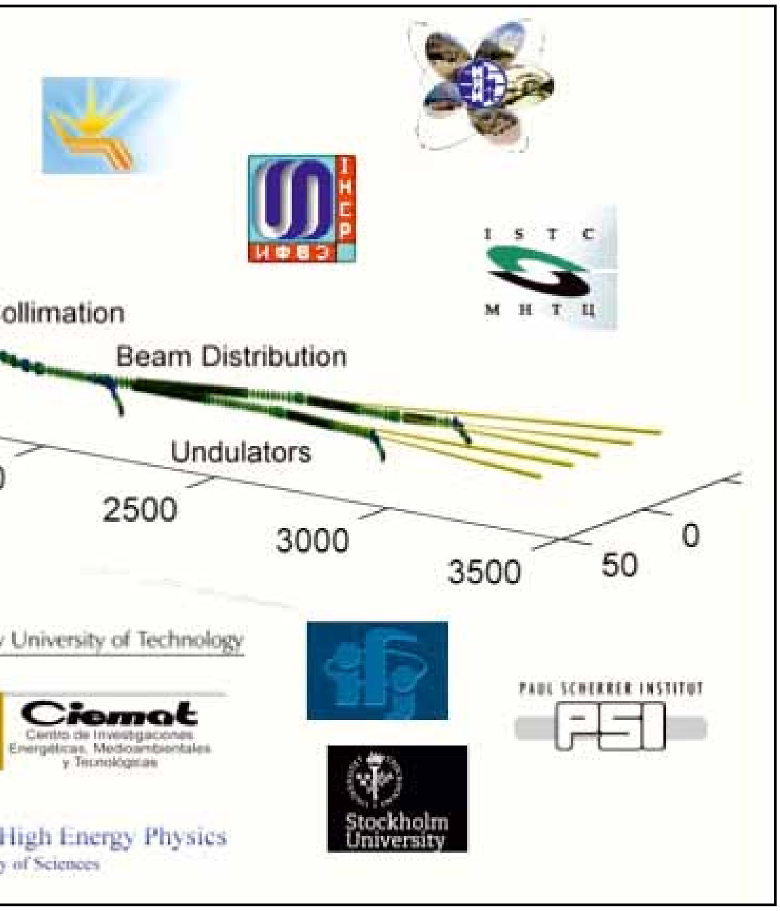
Sixteen institutes contribute to the accelerator complex of the European XFEL.

Figure 2

Layout of the new Accelerator Module Test Facility at DESY



At CEA Saclay, a new clean room infrastructure is available for accelerator string and module assembly. LAL Orsay is responsible for the procurement and conditioning of the RF power coupler attached to each accelerator cavity. The contract for the production of 640 power couplers was placed in late summer 2010. At DESY, a new test area for accelerator cavities and completed accelerator modules is under construction. This Accelerator Module Test Facility (AMTF) includes two vertical cryostats for cavity testing and three test stands for module testing, as well as a waveguide assembly and test area. The relatively large hall was finished in May 2010. The first infrastructure is now in place. Commissioning of the AMTF is scheduled for the end of 2011.



Two contracts for the production and surface treatment of 300 superconducting niobium cavities each were placed by DESY. The first series cavities will arrive in early 2012. The total production time is two years. Material procurement was taken over by DESY. Here, contracts were placed in January 2011. A receiving inspection process, various quality checks and a procedure for unmistakable numbering in accordance with the pressure vessel regulations – which have to be applied to the final cavity – were established for approximately 22 000 semi-finished niobium parts. The new infrastructure to perform this very important task was set up at DESY, and is already used for the semi-finished products of first reference cavities.
The procurement of cryostats, i.e. the cryogenic part and outer shell of the accelerator module, was started in autumn 2010.

A total of 22 RF power stations – consisting of a modulator, pulse transformer and klystron – are needed. The procurement of klystrons has begun. Contracts will be placed in March 2011.
In the undulator, the electron beam trajectory must be measured with an accuracy of 1 µm. This is achieved using cavity beam position monitors (BPMs), which have been developed in collaboration between DESY and PSI Villigen. Three BPM prototypes have been installed in FLASH. Recent measurements with a first version of the readout electronics demonstrate that the ambitious resolution goal can be reached.
The work on the cryogenic system is proceeding. DESY will soon contract the refurbishing and adaptation of the existing refrigerator to the needs of the European XFEL project.
During 2010, emphasis was placed on defining the technical infrastructure for all accelerator sections, i.e. tunnels, shafts and above-ground buildings. The European XFEL technical coordination group interacted with all work packages involved in the different accelerator systems. Responsibilities for infrastructure setup and component installation, as well as installation procedures, were defined.

Contact: Hans Weise, hans.weise@desy.de
Winfried Decking, winfried.decking@desy.de

REGAE – Relativistic Electron Gun for Atomic Explorations.

A new small accelerator on the DESY site

REGAE is an electron gun for time-resolved electron diffraction experiments presently under construction at DESY within the framework of the Center for Free-Electron Laser Science (CFEL), i.e. in a collaboration of the Max Planck Society, the University of Hamburg and DESY.

In electron diffraction experiments, electrons are shot onto a target and the scattering image is analysed to deduce the inner structure of the target material. This is comparable to transmission electron microscopy where – instead of a mathematical evaluation – an optical system is used to reconstruct the image of the material structure. Time-resolved experiments are performed as pump-probe experiments: the target is excited for example with a photon pulse from a laser, and diffraction images are taken at defined time intervals after the arrival of the pump pulse. For this type of experiments, the electron bunches have to be short compared to the required temporal resolution, i.e. of the order of 10 – 100 fs.

Depending on the energy, the scattering cross section for electrons is some four to six orders of magnitude higher than the one for short-wavelength photons. In the case of electrons, the scattering process involves not only the more polarizable valence electron cloud, as in the case of photons, but is dominated by the higher charge density of the nucleus and the core electrons. Electrons are therefore excellent probes to study samples involving few scattering centres. Key examples include the investigation of materials on the nanoscale and of isolated molecules in the gas phase. These systems are difficult to study with X-ray-based structural probes because of the very small scattering volume. In these cases, REGAE provides a complementary tool for exploring structural dynamics. The other important consideration is the damage induced by the probe. With respect to the total scattered flux, electron pulses with 10^7 electrons per bunch are comparable to photon pulses with 10^{11} to 10^{12} X-ray photons. In the X-ray case, the sample is destroyed by the photon pulse for typical focusing conditions and sample constraints. In the electron case, the damage mechanism is different and the sample is essentially unaffected. In this sense, electrons provide a nonperturbative probe even at full intensity.

One of the biggest challenges in developing REGAE for structural studies is the coherence of the source. The transverse coherence needs to be at least three times larger than the length scale of the object to be resolved. Thus, in the case of typical solid-state samples the coherence length must be about 3 nm, while for the study of proteins a coherence length of 30 nm is required. The latter corresponds to emittance values of about $5 \cdot 10^{-3}$ μm at a spot size of 0.4 mm. The required emittance is hence a factor of 200 lower than typical design parameters for FELs. Fortunately the charge density required in diffraction experiments allows operation at much lower charges (below 1 pC) compared to standard FEL parameters (~1 nC). Generating a beam with the required small emittance together with the short bunch length and ensuring the stability required for pump-probe experiments are thus the great challenges of the project.

In Fig. 1, the 1½-cell S-band RF gun cavity is located right after the cathode exchange system. The beam is transversely focused by solenoids, which are followed by a buncher cavity. The bunch passes this cavity off-crest, so that it is longitudinally compressed in the subsequent drift section due to its velocity spread. A target chamber and a detector system follow further downstream (not shown).

A simulated example for the bunch length development in this configuration is shown in Fig. 2. Here $5 \cdot 10^5$ electrons were started, yielding a calculated coherence length in the vicinity of the longitudinal focus of ~30 nm.

The machine will be set up in the old LINAC I building in the direct vicinity of the DESY synchrotron. After the dismantling of LINAC I in the 1990s, the building has been in use only partially as a storage place. Meanwhile, the rooms have been completely refurbished and the infrastructure, such as electrical distribution, air conditioning etc., has been renewed. Installation of machine components, including controls, interlock systems and RF system, is well advanced and the photo cathode laser is already in operation. After the installation of the cavities in February 2011, conditioning and commissioning can start. First beam is expected within the first half of 2011.

Contact: Klaus Flöttmann, klaus.floettmann@desy.de
Dwayne Miller, dwayne.miller@desy.de

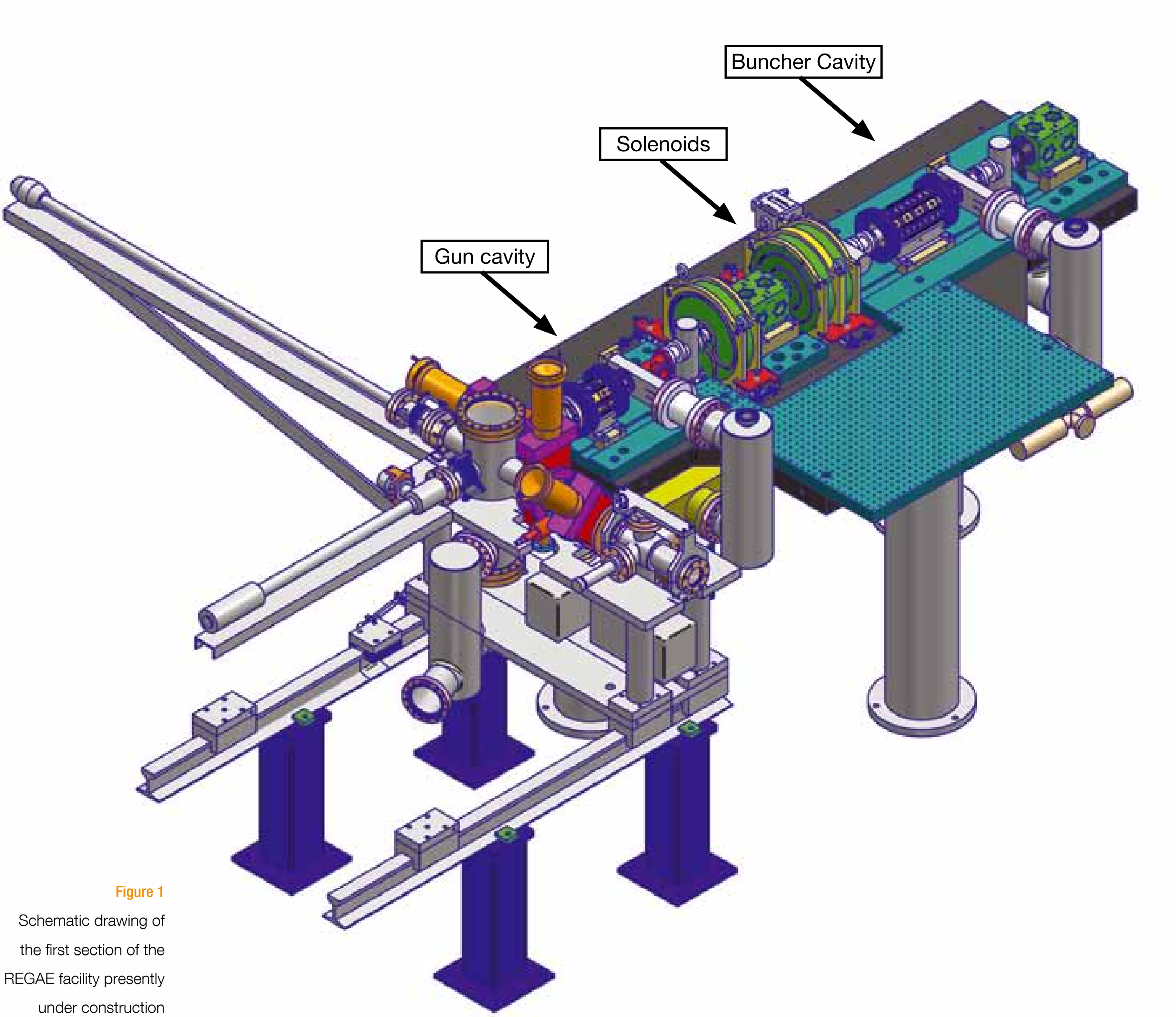


Figure 1

Schematic drawing of the first section of the REGAE facility presently under construction

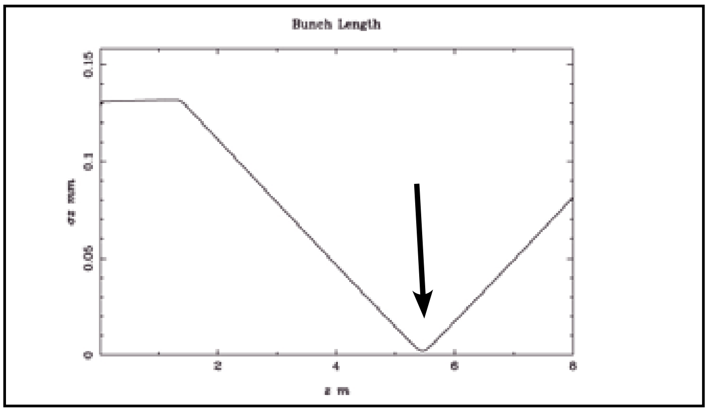


Figure 2

In the drift section behind the buncher cavity – at about 1.5 m – the bunch length shrinks to a minimum of about 7 fs before increasing again. The target chamber will be located in the longitudinal focus.

Towards better beam quality.

PITZ commissions new hardware

At the Photo Injector Test facility at DESY in Zeuthen (PITZ), the year 2010 was marked by the end of a shutdown period used for the installation of new beamline components, and, in the second half of the year, the commissioning of the new hardware with emphasis on the operation of the extended facility.

At the end of 2009, the PITZ gun was shipped to Hamburg to replace the aged gun of FLASH. The improved performance of this PITZ gun, especially the significantly lower dark-current emission, will greatly facilitate the operation of FLASH in the coming run periods. A new gun – a copy of the formerly used model – was hence installed at PITZ in spring 2010. In addition, the booster was replaced and further beamline components were installed, bringing the facility another step closer to completion and full functionality (stage PITZ 2).

The gun generates electron beams at the Cs2Te photo cathode via the photo effect and accelerates the beams to more than 6 MeV. The gun cavity was conditioned up to the maximum available klystron output power of 6.25 MW, for RF pulse lengths of 700 µs and a repetition rate of 10 Hz. It is now regularly used at this power level. A new in-vacuum directional coupler was used for the low-level RF regulation, allowing for an improved measurement of the power level at the gun and the use of a feedback algorithm. Applying these improvements, phase stability studies have been undertaken at different power levels and are to be continued. The first promising results showed an improvement of the phase stability of the gun, yielding 0.4 deg (rms).

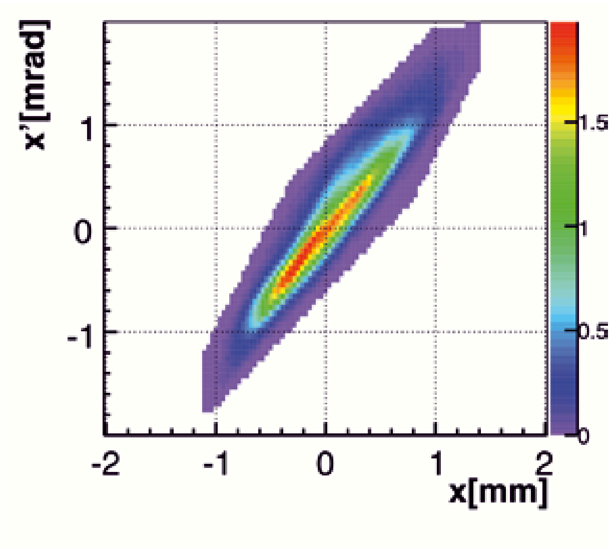
The new booster cavity (Fig. 1), a normal-conducting cut-disk structure (CDS), enables post-acceleration of the electron beam delivered by the gun to about 25 MeV. At these energies, the beam quality (emittance) is almost preserved when the beam propagates further through the beamline. Furthermore, for the first time, the new booster allows the acceleration of long bunch trains. Studies for optimizing the emittance conservation process have started and will continue in 2011. In addition to

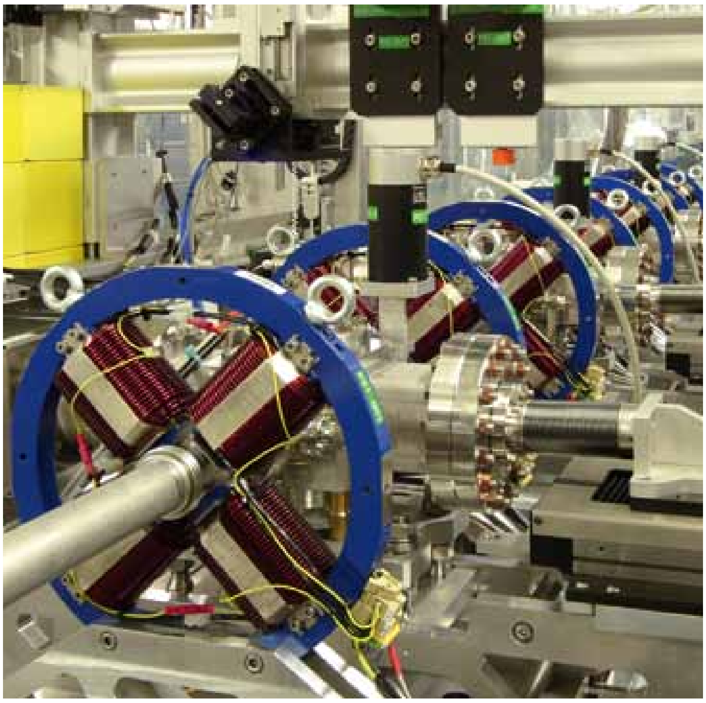
Figure 1

The CDS booster cavity on its support frame before its installation in the beamline

Figure 2

Right: View of the tomography module setup.
Left: Example of a reconstructed phase space as measured with the phase space tomography module.





the measurements of the projected emittance of the complete bunch, the evolution of the transverse emittance along the electron bunch extension has been studied using off-crest acceleration in the booster cavity. These beam slice emittance measurements were done at different charge levels and gave encouraging results.

Another big task during the shutdown was the installation of the phase space tomography module. This tool, which consists of a sequence of quadrupole magnets and view screens, enables the simultaneous measurement of the x-x' and y-y' planes of the electron beam phase space – also at low charges – and thus acts as an independent additional emittance measurement device. Its commissioning took place in autumn 2010 and the first measurements are now available (Fig. 2).

In 2010, the German research ministry (BMBF) project "Development and experimental test of a laser system for producing quasi 3D ellipsoidal laser pulses" started in the framework of the German-Russian collaboration "Development and Use of Accelerator-Based Photon Sources". Its goal is to provide 3D ellipsoidal laser beams which, as shown in simulations, are able to further reduce the emittance of the electron beams they produce. Further advantages are the reduction of beam halo effects, a better linearity of the longitudinal phase space and less sensitivity to machine parameters. Within the framework of this project, a new laser system is to be installed at PITZ at the end of 2012.

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

The International Linear Collider.

Pushing the limits of superconducting accelerator technology

The International Linear Collider (ILC) is a proposal for a 500 GeV centre-of-mass energy electron-positron collider, upgradable to 1 TeV centre-of-mass energy. Over the last five years, the project has been developed by a global collaboration of over 30 institutes worldwide. The proposed two 12-km superconducting radiofrequency (SCRF) linacs are based on the same 1.3-GHz technology that is being used for the European XFEL, and DESY's primary contributions to the ILC rely heavily on the clear synergies between the two projects.

Development and operation of SCRF cryomodules

DESY has supported two key ILC experimental programmes: the S1-Global cryomodule development at KEK in Japan and the 9 mA experiment at the FLASH facility at DESY in Hamburg. Both programmes are international collaborations and part of the broader ILC programme.

S1-Global (Fig. 1) is a collaboration between DESY, Fermilab (USA), INFN Milan (Italy), SLAC (USA), and hosted and coordinated by KEK (Japan). The goal was to construct an eight-cavity cryomodule using high-performance cavities and auxiliaries supplied by the participating labs. DESY contributed two such fully-equipped cavities, of the design that will be used in the European XFEL. Fermilab supplied two cavities using the same design for the couplers, but with a different type of mechanical tuner developed at INFN Milan. INFN Milan also supplied the four-cavity cryomodule that was used to house the DESY and Fermilab cavities. The remaining four cavities, couplers, tuners and cryomodule were supplied by KEK. The S1-Global cryomodule thus represented a unique opportunity to directly compare different component designs of couplers in the same setup. Attention was also paid to aspects such as assembly, with a view to possible simplification for future cost-effective mass production of the ILC cryomodules.

DESY personnel visited KEK and participated directly in both the assembly of the Fermilab and DESY cavities into the cryomodule, and during the high-power processing and operational tests (Fig. 2 and 3). The many years of experience of the DESY experts was extremely appreciated by the KEK staff. The S1-Global programme is now complete and analysis of the data is underway. Final conclusions are expected towards the end of 2011.

Figure 1

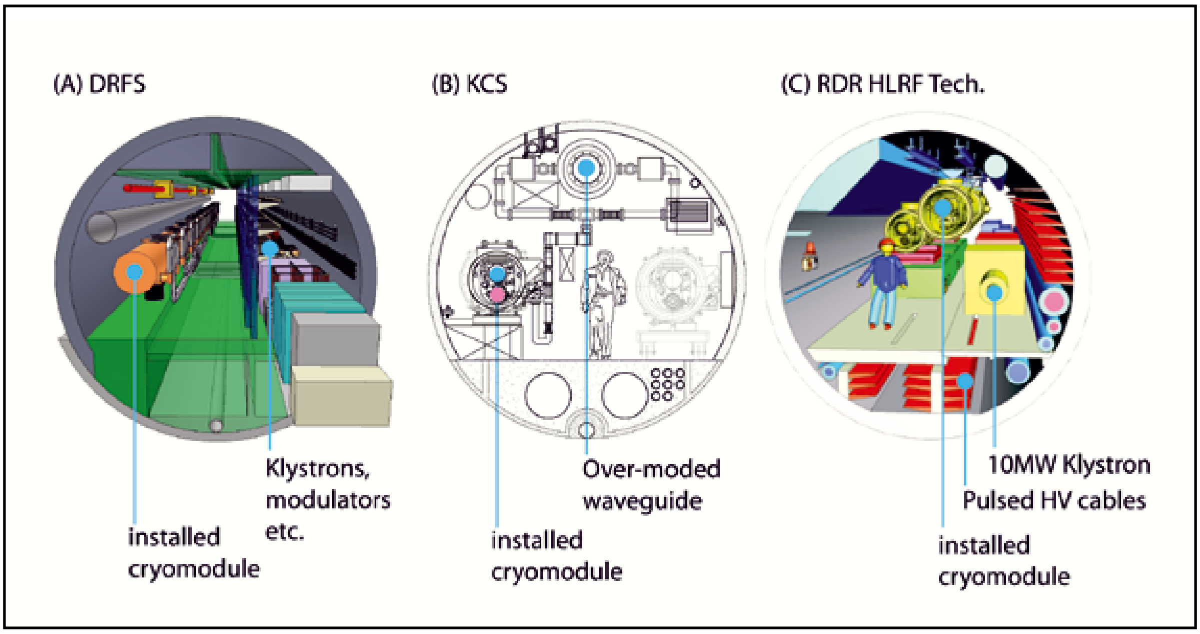
Module C of the S1-Global cryomodule at the STF facility in KEK (Japan), which contains two DESY fully-dressed SCRF cavities, as well as two similar cavities supplied by Fermilab (USA). (Photo courtesy of KEK.)

Figure 2

DESY personnel work alongside their KEK and Fermilab counterparts at the STF facility at KEK (Japan) to assemble the DESY and Fermilab cavity string for S1-Global.
(Photo courtesy of KEK.)

Figure 4

The three proposed tunnel cross sections for the ILC: (A) Solution for the distributed radio-frequency scheme (DRFS); (B) Klystron cluster scheme (KCS); (C) the European XFEL solution



FLASH – a testbed for the ILC

For the ILC, the FLASH accelerator at DESY represents a unique facility worldwide for studying beam acceleration and other operational aspects of the SCRF technology. Since 2009, an international team has driven a programme of long bunch train, high beam-loading experiments at the FLASH accelerator, which represents one of the ILC community's highest-profile activities. The 9 mA experiment is aimed at understanding the operation of the linac at the limits of the technology, and pushes the demands on the machine beyond that typically required for FLASH photon user operation. The programme addresses questions of RF control, stability, RF power overhead, and operation close to cavity quench limits – all critical issues for the ILC. By direct synergy, the programme feeds back into improved hardware, tuning algorithms and control system automation, which benefit both FLASH and the European XFEL. During the last year (2010), the effort has been in preparation for studies planned in February 2011. A final experimental run is foreseen in early 2012.

Figure 3

High-power testing of the DESY S1-Global cavities at KEK (October 2010): from left to right: Akira Yamamoto (KEK), Masato Satoh (KEK), Eiji Kako (KEK), Dennis Kostin (DESY), Yasuchika Yamamoto (KEK), Hitoshi Hayano (KEK), Toshihiro Matsumoto (KEK), Shuichi Noguchi (KEK). (Photo courtesy of KEK.)

Tunnel layout

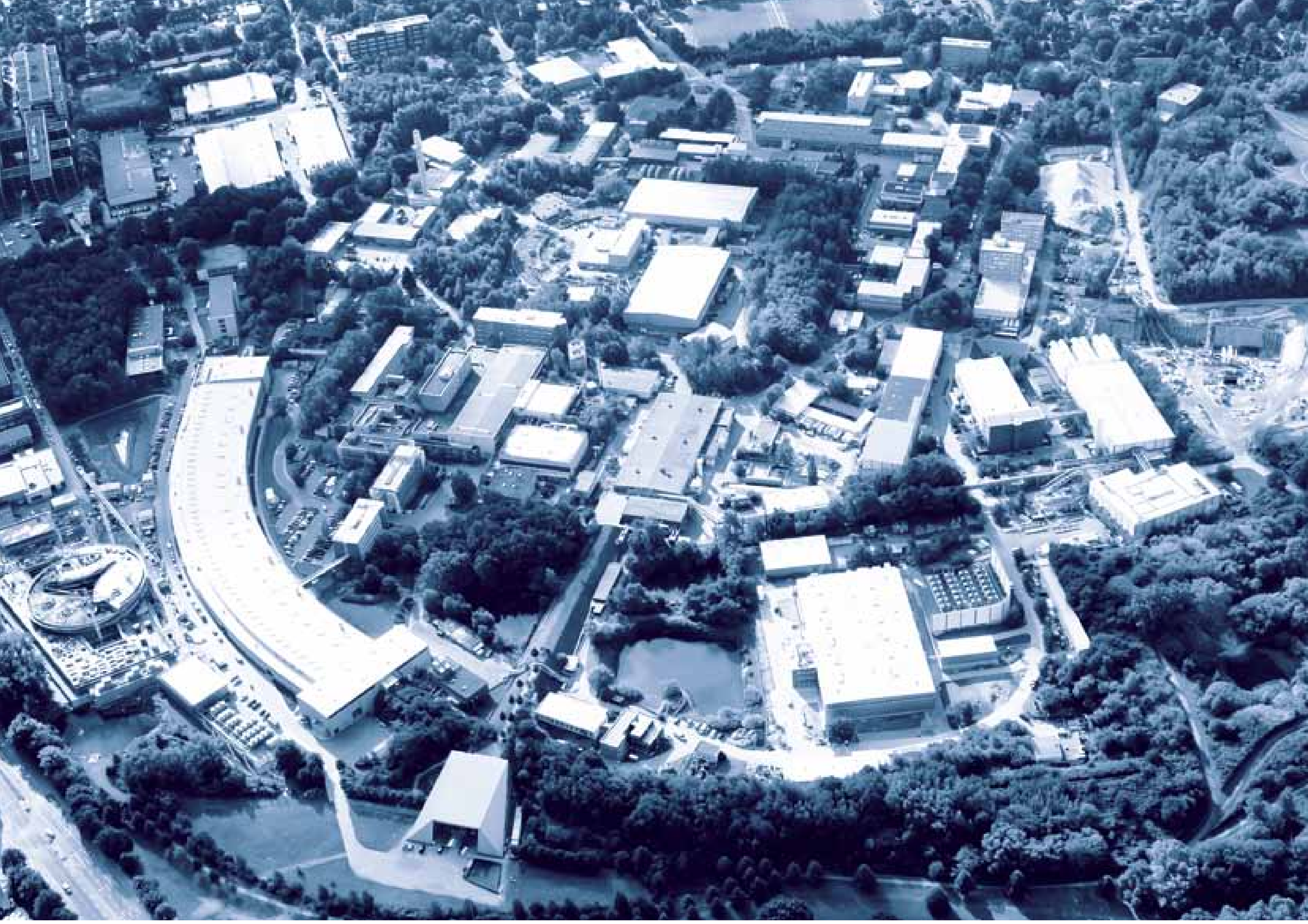
Another important area where DESY contributes to the ILC design is the layout of the tunnel for the superconducting linacs. In November 2010, four members of the Global Design Effort Conventional Facilities and Siting group and two guests from Japanese industry visited DESY in Hamburg to find out about the European XFEL civil construction, DESY's FLASH accelerator and the infrastructure for the European XFEL cavity and cryomodule testing.

Several options for tunnel layout are being considered for the ILC (Fig. 4). These are strongly driven by the solutions for the klystrons and modulators, as well as by site-specific issues such as topology, geology, local safety requirements and, not least, cost. The ILC has recently adopted two possible site-dependent solutions. The European XFEL design currently under construction is recognized as a third potential solution for the ILC, possibly more suited to a shallow site.

The next steps

The Global Design Effort for the ILC will publish an R&D status report in April 2011. This report will mark a halfway stage to producing the final Technical Design Report (TDR) at the end of 2012, intended to lay the foundations for a construction project. The ongoing activities at DESY serve as valuable input to the design choices made for the TDR. DESY continues to contribute to the ILC, wherever it may be realized.

Contact: Nicholas Walker, nicholas.walker@desy.de
Wilhelm Bialowons, wilhelm.bialowons@desy.de



Highlights · New technology · Developments.

New power supplies for DESY II.

Increased performance and reliability of DESY II

DESY II serves as a pre-accelerator for the DORIS III and PETRA III storage rings. It therefore has to perform with high reliability. The DESY II power supplies were renewed in the years 2007 to 2009 and operated throughout 2010 with a high level of reliability. The renewal of the power supply system was performed in a close collaborative effort by the control groups MSK, MCS and the power supply group MKK6. The power supplies were built in Spain by JEMA following a European bid for tender.

Accelerator

DESY II is operated in the beam energy range from 456 MeV to 6.3 GeV, at a resonance frequency of 12.5 Hz. This is ¼ of the mains frequency. To reduce the power drawn from the mains, the magnet loads are designed as resonant circuits. The resonant elements include the magnets, capacitors and chokes, all of which can store energy. As a result, the power supplies only have to replace the losses in the magnets.

There are two different types of magnet loads. The dipole is a so-called white circuit (Fig. 1). In terms of power, it is the world's largest circuit of this type, featuring a reactive power of about 14 Mvar. The dipole circuit needs two power supplies. One provides an AC current at the resonance frequency, while the second delivers a DC current. The quadrupole and sextupole circuits are double resonant circuits.

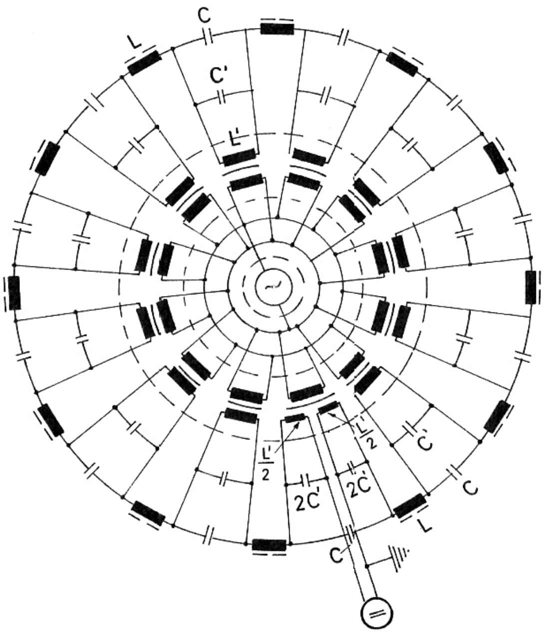


Figure 1

DESY II dipole ring with white circuit

Power supplies

The old thyristor-controlled supplies were replaced by bipolar switch-mode power supplies. These consist of a transformer, input rectifier DC link and IGBT bridges forming an H bridge (Fig. 2). The DC link is used also for decoupling the 12.5 Hz operation frequency of the magnet load from the mains using harmonic resonant filters. The electrical data of the power supplies are given in Table 1.

To improve reliability, a universal power supply was purchased. This power supply can replace any large power supply in case of a severe failure. The exchange procedure takes about one hour. In the control system, the required set points and regulation parameters are stored and are ready for operation.

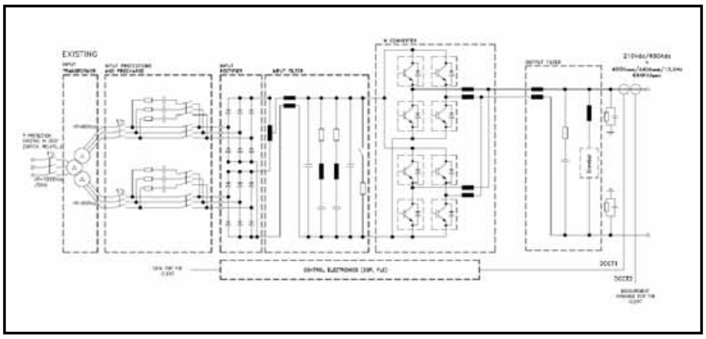


Figure 2

Schematic of the power supply

Table 1: Electrical data of the power supplies

Magnet load	Current (Peak value)	Voltage (Peak value)	Power (Peak value)
Dipole AC	+/-755 A	+/-1330 V	1 MVA
Dipole DC	520 A	1560 V	811 kW
Quadrupole	1090 A	610 V	665 kVA
Sextupole	300 A	150 V	65 kVA
Universal	1090 A	1560 V	811 kW

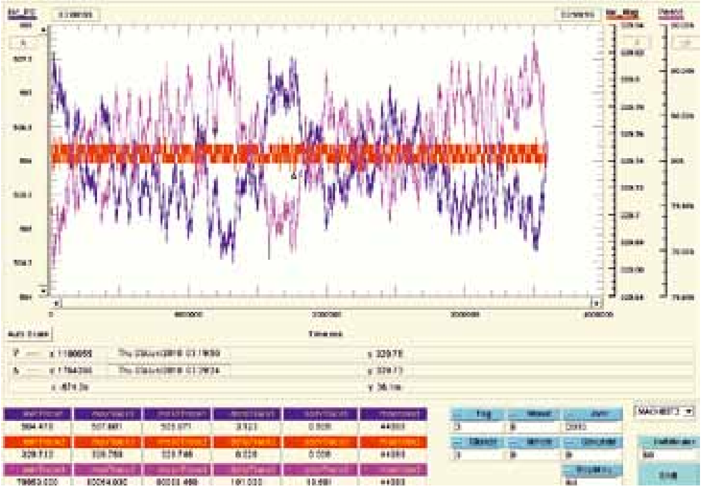


Figure 3

Archive data with actual value of the AC magnet current (red), set point value of the PS current for the regulation (blue) through fluctuation of the 12.5 Hz period (magenta)

Control of the supplies

The magnet current control system uses a fast PI regulation with feed-forward control for the PS current in each power supply, in combination with a precise software-controlled PI regulation with feed-forward control of the magnet current, within a VME control system. The control system includes data acquisition, set point control and regulation, VME electronics, VxWorks-based servers and JAVA-based client software.

All power supplies are controlled with digitized sine wave signals with a frequency of about 12.5 Hz. This frequency is synchronized with the 50 Hz of the mains. A DC offset along with every point of the sine wave is transmitted with 18 bits over an optical link, connecting the VME set point generator modules to the corresponding power supplies.

The external regulation of the magnet current for each circuit is implemented with three independent, simultaneously operating PI regulation loops for sine amplitude, DC offset and phase. Every external and internal regulation loop can be opened or closed for diagnostics and trouble-shooting.

In addition, a programmed saturation mechanism is implemented in all regulators to prevent the power supplies from crashing because of crosstalk between magnets, which can result from turning a magnet on or off, or from the crash of one power supply. This mechanism can also handle a too large transient of set point values resulting from improper operation at the control console.

Archive

A history server is implemented for diagnostic purposes. It provides access to up to 130 different parameters of the system with a time resolution of 80 ms. Two years of DESY operation can be stored in the archive. Figure 3 shows data from the history server. The measurement time is one hour. Since the 50 Hz mains frequency is not stable, as the curve in magenta shows, the set point value for the PS current for the regulation (blue) is changed to compensate for this effect. The magnet current stays stable (red). With this tool, very precise diagnosis of the system is possible.

Accuracy

The new DESY II magnet control system provides a stability for the beam energy that is about 10 times better than with the old system. Figure 4 illustrates the stability of injection/ejection energy and the AC amplitude of the magnet current measured at the same time. The stability of the magnet current is about ±40 ppm. Here the amplitude of the dipole AC magnet current was 329 A, corresponding to 6.3 GeV.

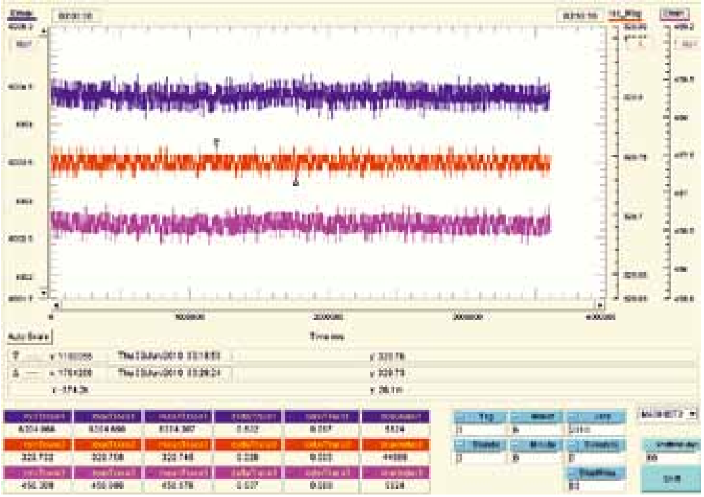


Figure 4

Stability of E_{min}, E_{max} and magnet current amplitude

Contact: Hans-Jörg Eckoldt, hans-joerg.eckoldt@desy.de
Björn Näser, bjoern.naeser@desy.de
Sergej Ruzin, sergej.ruzin@desy.de

PETRA III power supplies.

Let's go digital

The demands placed on the PETRA III power supplies with respect to precision, resolution and reliability are very high. To meet these requirements, digital technology for the regulation and pulse firing electronics was developed. The resolution of the current set values is 20 bit, corresponding to approximately 2 ppm (parts per million) of the nominal bipolar current of the supply. Changes of the reference values are thus possible without any disturbing digitizing steps. The overall stability is less than 10 ppm in the long term. This includes drifts in components, drifts due to temperature change, and so on.

There are 552 power supplies including spares installed in PETRA III. They can be divided into seven different groups (Fig. 1). The power supplies were developed and built from 2007 to 2009. Commissioning of the power supply system took place in spring 2009. 2010 was the first full year of operation, showing a very good performance with very few failures.

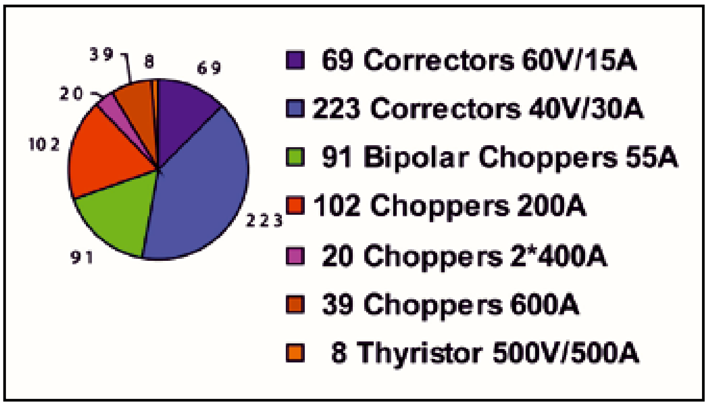


Figure 1

Numbers and types of PETRA III power supplies

Development of components at DESY

Digital regulation electronics with this performance was not available on the market and had to be developed at DESY. The development included the regulation electronics and the precision measurement, the power part for the corrector magnets, interface cards for large power parts, service boxes for the connection of oscilloscopes for analysis, a power part for 200 A chopper and programmable logic controllers (PLC). In addition, the entire software had to be programmed at the same time. The components are described in detail below.

Regulation electronics

A common regulation board was designed which suits large power supplies as well as the correction supplies (Fig. 2). The core of the digital board is a programmable Altera FPGA. Here the precision current measurement, precision current regulator, CAN bus links and control of interlocks are implemented. An Internet chip allows the communication via Ethernet, CAN bus and USB. To achieve the required accuracy, two 25 bit analogue-to-digital converters (ADC) are used. They are permanently calibrated three times a second with a temperature-stabilized 10 V reference.

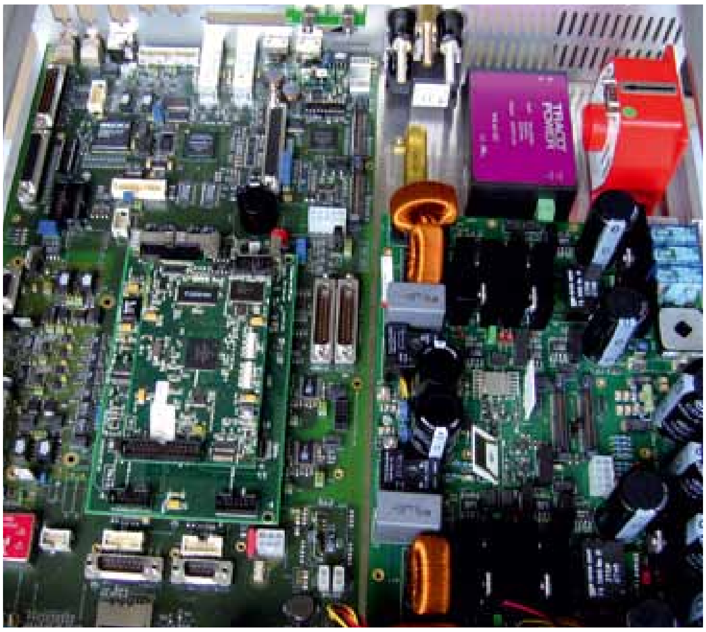


Figure 2

Corrector power supply with digital regulation board

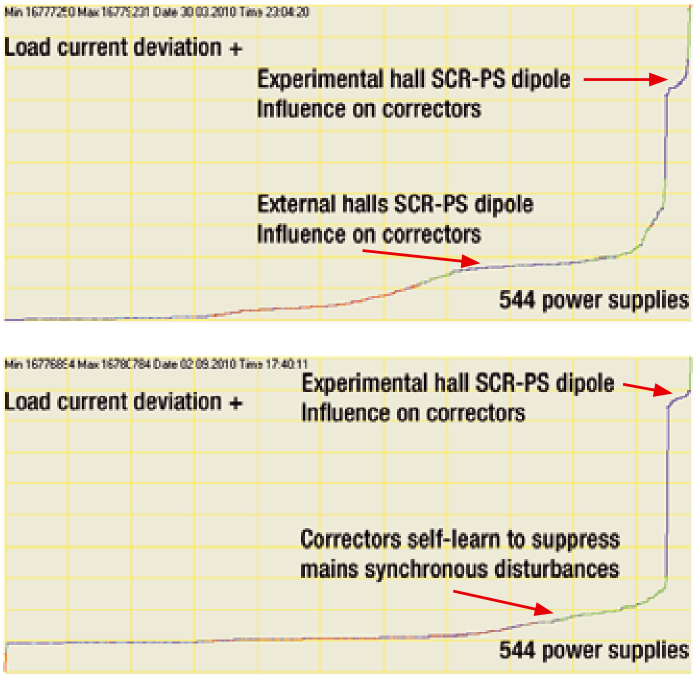


Figure 4

Live minimum and maximum values of the output ripple

Power part corrector supply

The power parts achieve high efficiency by using primary switching and active secondary rectification. This special design requires a minimum amount of power components, which ensures a long lifetime and good reliability. The supplies are using 50 kHz planar transformers to isolate the output galvanically. To increase the reliability, the power part is built redundantly. If one power part fails, the second one can take over without interruption of the operation.

Figure 3

200 A choppers. There are four 50 A power modules plus two identical ones for redundancy.

Power part 200 A chopper

A power part for 200 A nominal current was developed. Again the reliability was the driving element. Six modules are installed, each of them able to deliver 50 A. The power parts are working at a phase-shifted 50 kHz frequency. The output frequency sums up to 300 kHz.

Software and diagnostics

The use of the digital regulation required the development of software. This includes the programs for the operation of the power supply, such as regulation, measurement, interlock control, programming of interfaces for communication and pulse-firing. To reduce development work, a single software package was written to handle all types of power supplies. Another advantage of the digital regulation is the possibility of intense remote analysis. For comprehensive remote diagnostics, every power supply generates a web page that illustrates 512 parameters such as current, voltage, frequency, ripple, temperature, single event values, interlocks, etc.

Automatic remote analysis of all power supplies

The web pages of the operating 544 power supplies are scanned every 15 minutes. Each parameter can be sorted by value and displayed in a graph. This results in 512 graphs (512 parameters per power supply web page) that are periodically updated. An example is given in Fig. 4, which shows the ripple of the output current called “load current deviation”. Every pixel in the graph corresponds to the ripple of one power supply. The colour represents the power supply type. Using this graph, the power supplies with large ripples can easily be detected and checked in preventive maintenance.

Failure follow-up and alarms

In case of a failure, the power supply sends an email to a local mail server. This email includes all web pages and an online scope screenshot shortly before and directly after the failure. The email is archived, sorted by date and failure type. Additionally, a server sends an SMS to the shift crew and other experts to speed up repair.

Contact: Niels Heidbrook, niels.heidbrook@desy.de
Hans-Jörg Eckoldt, hans-joerg.eckoldt@desy.de

PETRA III beam position monitoring system.

Synchrotron light source implementation of a customized commercial-of-the-shelf (COTS) BPM system

Today's commercial state-of-the-art beam position readout electronics cover most features needed by modern third-generation light sources. The full implementation of such a customized readout system for high precision beam position measurements and orbit control requires the stepwise integration and validation of these features in the control system to meet the specified accelerator design goals.

Since the beginning of the commissioning of the PETRA III third-generation synchrotron light source in April 2009, the beam position monitoring (BPM) system has been put into operation step by step and integrated into the accelerator control system. The BPM system of PETRA III is based on commercial Libera Brilliance electronics modules. Meanwhile all BPM processor modules have been fully integrated into the machine control system and all features needed from these units were successfully tested under normal conditions of use.

To meet the very high demands on stability and low emittance of the electron beam, the resolution of the beam position measurement must be better than 0.3 μm (1σ, vertically) and 2 μm (1σ, horizontally) in the undulator section of the machine.

A transverse fast orbit feedback (FOFB) is used in combination with other feedback systems to ensure these requirements. The BPM system delivers the corresponding measurement data for the transverse FOFB within the appropriate time frame conditions. Fast beam interlock signal response is needed from the BPM system in case of excessive beam excursions. In addition, the BPM system has to deliver several other data on demand for commissioning, machine studies, service and maintenance purposes. In case of beam loss, single-turn-resolved post-mortem data are needed as a valuable tool for analysis.

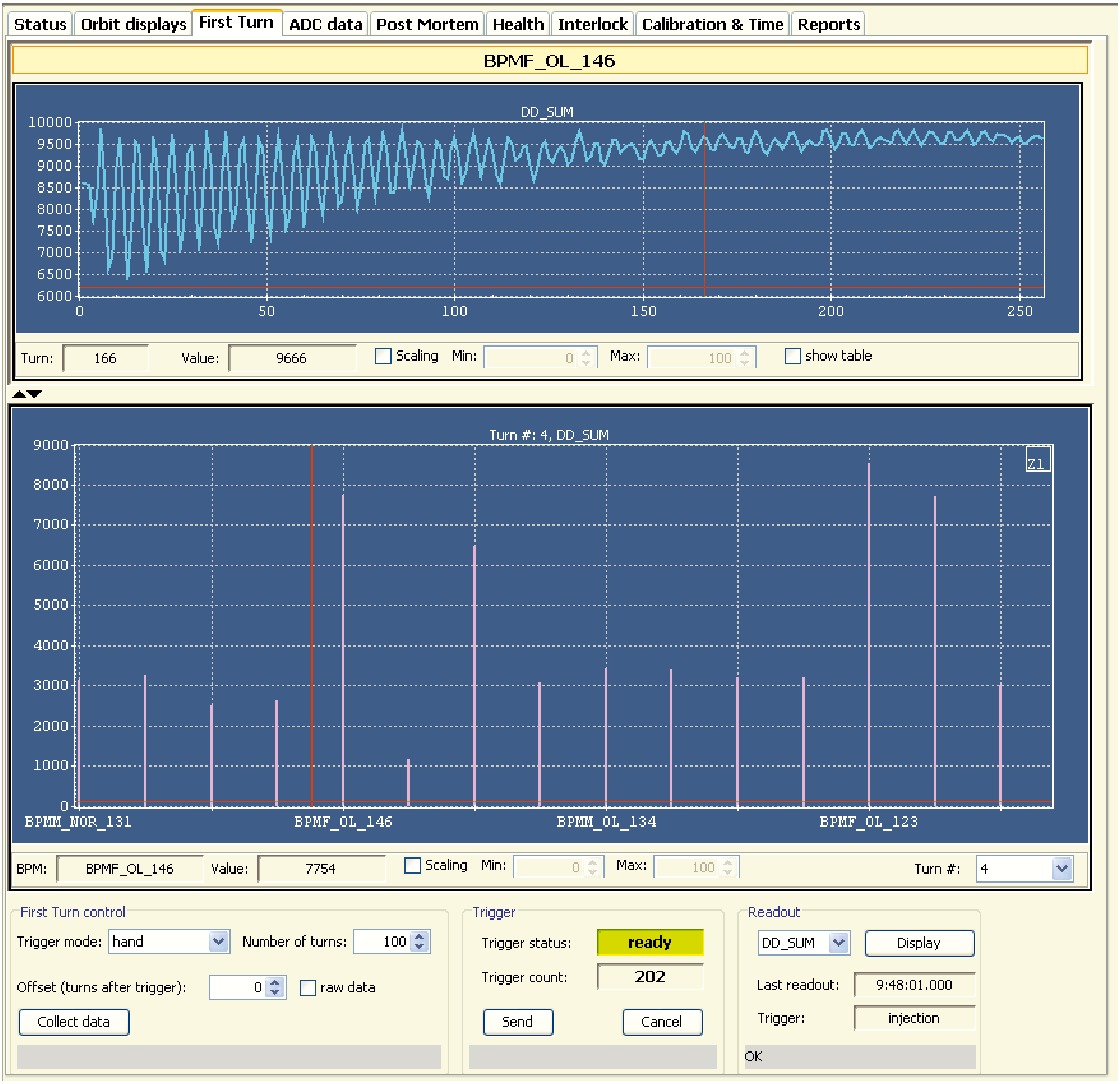
Tests and measurements

In 2010, all data paths and functionalities of the 227 BPMs around the 2.3 km long PETRA III ring were successfully tested and evaluated in combination with other subsystems of the accelerator control system. During the tests, the demonstrated vertical BPM resolution of approx. 0.1 μm clearly surpassed the specified 1σ value of 0.3 μm. A dedicated FOFB data link interface was also successfully commissioned in intensive tests.

For first- and consecutive-turns analysis of a decaying beam after injection, as well as for revolution-synchronous bunch position measurements of a stored beam, the BPM system delivers so-called turn-by-turn data on demand. An example of corresponding turn analysis data is shown in Fig. 1. The measured position resolution of approx. 10 μm rms (BW > 40 kHz) also exceeded the previously specified minimum limit of 50 μm rms (BW ≥ 300 Hz) for balanced operation. In this context, the whole trigger and data acquisition chain, incorporating the timing system, transverse feedback system, the Libera BPM readout electronics up to the BPM readout control system server (hardware and software), were also successfully tested and functionally validated.

The beam injection properties and the orbit stability of the beam-conducting transport line (E-Weg) have an important influence on the stability of the stored beam. For PETRA III in top-up mode in particular (which is the normal operation mode), further optimizations of the transport line are planned for optimum efficiency of the regular injections.

Contact: Frank Schmidt-Föhre, frank.schmidt-foehre@desy.de



Turn: 166 Value: 9666 ☐ Scaling Min: 0 Max: 100 ☐ show table

BPM: BPMF_OL_146 Value: 7754 ☐ Scaling Min: 0 Max: 100 Turn #: 4

Trigger mode: hand
Number of turns: 100
Offset (turns after trigger): 0
☐ raw data

Trigger status: ready
Trigger count: 202

DD_SUM
Last readout: 9:48:01.000
Trigger: injection
OK

Figure 1

Simultaneous display of first-turns data showing a slowly decaying beam oscillation on the BPM sum signal (upper diagram) and a selected part of the orbit at certain BPM positions during the 4th turn observed in an early commissioning phase. All displayed information is based on the turn-by-turn data stream from the BPM system as acquired and displayed by the corresponding PETRA III control system (TINE) BPM client/server application.

Safe experiments.

A new personnel interlock system

The successful commissioning of new personnel interlock systems was an important milestone and prerequisite for starting up photon science experiments at PETRA III. The DESY accelerator division has a long experience and expertise in the construction and safe operation of personnel interlock systems. For PETRA III a new technical solution was realized, customized to the needs of a modern user facility. A high level of personnel safety was achieved in the system architecture, which also meets the demands on high availability of experiments and accelerator, user-friendly procedures and transparent system test functions.

Area search

Five of the nine insertion devices at PETRA III are equipped with canted undulators, resulting in 14 beamlines with 45 interlock areas, 45 beam shutters and 14 absorbers. Before a beam shutter can be opened, at least one associated experimental area must be searched and labelled as prohibited due to radiation. All necessary procedures can be performed by a single person, provided that he/she has received the obligatory instructions and has a corresponding flag stored on his/her card of the DESY Access Handling System (DACHS).

The area search is started with a valid card at a local DACHS card reader. A safety light barrier (1 m length, four beams, SIL3) has to be set to secure the open entrance door during the procedure. All other area doors must be shut. Each door is equipped with two interlock contacts. The search is supported by an automatic announcement and by search buttons that have to be pressed in any order. Door lamps indicate the interlock status of the area.

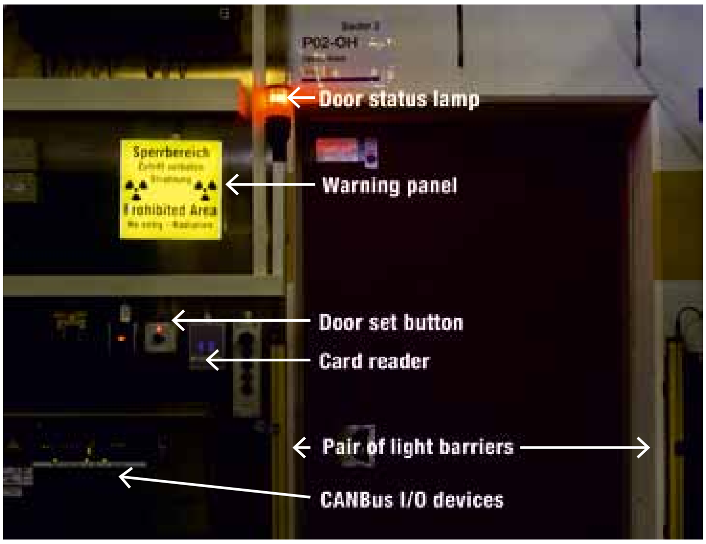


Figure 1

Interlock door at an optics hutch

To leave the area, the searching person must initialize a short time muting of the light barrier. The muting is possible only once during a search. After closing and setting the entrance door, the search procedure is finished by a confirmation at the card reader using the same card that started the search.

Warning system

A warning procedure is automatically started when the area search is finished and no emergency off button is pressed. In the interlock area an announcement and yellow beacons are running for 30 s and warning panels “Prohibited Area” at the interlock doors are switched on. The proper functioning of the warning system components is monitored. The interlock system generates a beam operation permission only after a successful warning period.

Beam shutter operation

If all corresponding areas are ready, the beam shutter can be opened. In addition, all doors involved must be locked to avoid dumping of the PETRA III beam. The interlock system provides an interface to block motor-driven doors and power magnets that hold other doors shut. More preconditions for shutter opening can be processed, such as the presence of safety keys, signals from radiation monitors and the technical interlock. Because of the high beam power, some beam shutters must be protected by an absorber when they are shut, otherwise a dumping of the PETRA III beam would occur. The interlock system therefore provides a combined steering of both elements in the right order. Interlock contacts survey all “open” and “closed” positions.

Structure of a double beamline

The design of the personnel interlock system mirrors the chain of the interlock areas and beam shutters and provides the safety signals for the PETRA III accelerator operation.

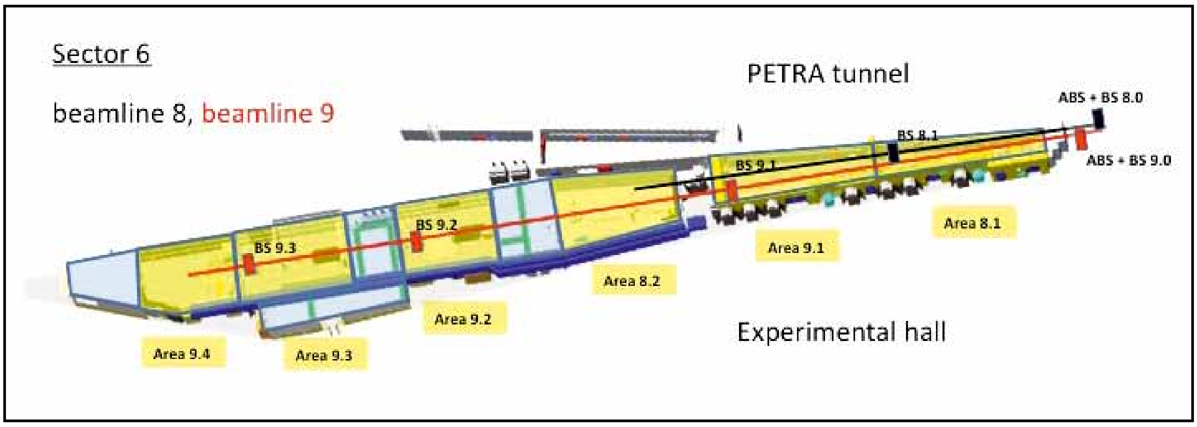


Figure 2

A typical double beamline at a canted undulator with six interlock areas, six beam shutters (BS) and two absorbers (ABS)

Technical design

The personnel interlock system is a DESY development, consisting of electronic modules and other hardware, a CANBus system and a software system. All electrical circuits processing the safety signals originating from beam shutter contacts, emergency off buttons etc. are built with two independent redundant systems in a failsafe design, using safety relays in hard-wired 60 V technology. A family of electronic standard modules can be assembled according to the required logical setup, providing a high degree of flexibility.

To cover complex functions with a lower safety level, additional field programmable gate arrays (FPGAs) are used. The racks with the electronic modules are located in a separate locked room, with typically two racks per sector. For high availability the systems are supported by uninterruptible power supplies (UPS). The interlock systems for the nine sectors are logically and electrically separated from each other to enable independent operation.

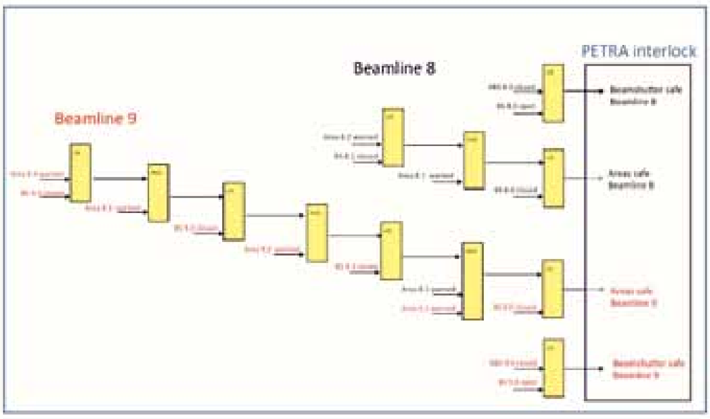


Figure 3

Logical chains of the interlock connection between the double beamline 8/9 and the PETRA III accelerator (BS: beam shutter)

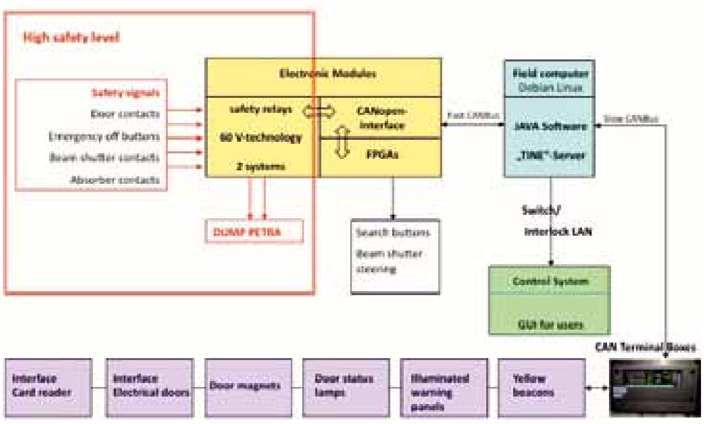


Figure 4

Structure of the interlock system

Most of the processes of the interlock system are steered and supported by a complex JAVA software tool running on protected local servers. A CANBus system using the CANopen protocol serves as the interface to the hardware. The status of the relays in the electronic modules is read out via couplers with a fast CANBus system (20 kBd) to enable a computer-aided visualization of the system status. A slow CANBus system (500 Bd) is used for many local functions like steering the optical warning components and door magnets, covering the interfaces with the card reader and the motor steering of some doors. The I/O modules are housed in special CAN terminal boxes, one in each area.

The interface between the interlock software and the control system is managed using the DESY proprietary protocol TINE. All published status information is visible for the users on a graphical user interface in local control hutches. From here, the most important operations like opening or closing a beam shutter can be carried out as well – if the hardware permits it, of course.

Contact: Brunhilde Racky, brunhilde.racky@desy.de

FLASH refrigerator – ready for future applications.

Renewal of parts of the former HERA helium refrigerator

Until the end of 2009, all three former helium refrigerators of the HERA storage ring were available for the supply of the FLASH linac. In future, two of the refrigerator plants (No. 41 and No. 43) will be modified and used for the operation of the European XFEL linac. These plants were separated from the existing helium distribution system in December 2009 to be prepared for the required modifications and extensions. As a consequence, the remaining plant (No. 42) has to take over the supply of FLASH as a stand-alone facility. In addition, other facilities like the Accelerator Module Test Facility (AMTF), the Cryomodule Test Bench (CMTB) and the Magnet Test Stand (XMTS) also need a cold helium supply. To maintain the refrigerator operation at highest availability in the future, the 25-year-old refrigerator plant No. 42 was overhauled and updated during the FLASH shutdown 2009/2010. Several subsystems were replaced. The renewal was completed just in time before the restart of FLASH.

The overhauling of the refrigerator No. 42 was started early in 2009 already, when the refrigerators No. 41 and No. 43 were still available and in operation for the supply of the consumer installations, in particular for FLASH. It was a delicate venture, which could only be realized through elaborate procedures. As a result, besides the hardware changes that had to be made, the complete process control system had to be replaced as well. The venture reached its hot phase during the FLASH shutdown 2009/2010, after the separation of the refrigerators No. 41 and No. 43 from the distribution system, when the point of no return had been passed.

All related screw compressors received in-depth maintenance. Parts of the primary power supply were replaced and new starting transformers installed. The old-fashioned programmable logic controllers (PLCs) for the local compressor controls were replaced by up-to-date PLCs. The related new PLC programs were created and debugged. In the course of the overhauling, the outdated I/O system was replaced by a state-of-the-art fieldbus. Profibus was implemented, connecting all sensor devices and valve actuators to the new central control system. Profibus is well established in process engineering and features several advantages: all up-to-date transmitters (temperature and pressure sensors, valve actuators) can be connected directly to Profibus and the related process data can be sampled in a deterministic way. The effort for cabling is low. Simple copper wires are used. Where electrical potential separation is needed, glass fibres are installed. The glass fibre net is arranged in a ring structure to increase reliability.

The cold-box components and auxiliary systems were connected to Profibus as well. A newly developed low-temperature Profibus-compatible measuring system was incorporated. The inner parts of the cold box were not touched. Nevertheless, substantial renewal took place: insulation vacuum pumps were serviced or replaced, equipped with PLCs and connected to the controls. One of the two large liquid-helium dewars was separated and prepared for the future European XFEL refrigerator. The last cut, the transfer line to the HERA south ring, was the deepest. In future, this branch connection will supply the AMTF with cold helium. A valve box, which was designed and constructed by the MKS group and installed at this connection, will accomplish the installation of the helium transfer line to AMTF at any time, without interruption of the FLASH operation.

The central process control system was changed to the Experimental Physics and Industrial Control System (EPICS). Besides the basic functions and tools of the system, which are supplied by the international EPICS collaboration, several functions and tools were developed and added by the MKS2 group. A new operator environment was compiled: Control System Studio (CSS) provides access to all process data for visualization, archiving and automatic alarms. Additional modules enable the overall configuration of the system: process controls, function charts and graphics.

In line with the implementation of EPICS for process controls, all sequence and monitoring programs were changed to the EPICS-proprietary State Notation Language (SNL). Using SNL, complex sequence controls like the automatic start and stop of complete plant sections can be implemented in a straightforward, logical way. The existing old batch programs could not be simply copied to SNL, however. It turned out that the sequences had to be programmed from the very beginning and debugged during real plant operation.

Figure 1

View of the DESY refrigerator plant

Here are some numbers related to the control system: 3 redundant process computers; 7 SNL programs including 430 states, 4070 process points, each including 20 properties; 4 Profibus segments with 198 stations (including 138 PA devices); 675 I/O modules covering 2855 hardware channels.

The versatile, complex tasks were finished just in time before the cooldown of the FLASH linac, thanks to the combined efforts of the MKS2 cryocontrols group, the MKS1 cryo-operators and – last but not least – the LINDE/COFELY operator team. As a result, the upgraded FLASH helium refrigerator was restarted in parallel to the restart of FLASH operation in spring 2010. Since the restart, an availability of about 98.8% has been achieved for the cryoplant. As is the rule, some components and subsystems still need further improvement. Furthermore, additional weak components, which were not yet on the list, were identified during the overhauling. FLASH service days are used to implement these further improvements.

The overhauling and renewal of the FLASH refrigerator will set an example for the European XFEL refrigerator. Several parts of the hard- and software that were implemented for the FLASH refrigerator will be transferred to the future European XFEL refrigerator.

Contact: Tobias Schnautz (MKS1), tobias.schnautz@desy.de
Matthias Clausen (MKS2), matthias.clausen@desy.de

European XFEL-type RF waveguide distribution for FLASH.

RF developments for the European XFEL

During the FLASH shutdown 2009/2010, new RF waveguide distributions were installed in the facility. Since these distributions resemble those that will be used at the European XFEL, this was an excellent opportunity to compile and test the procedures for installation, commissioning and operation of such waveguide distributions.

During the FLASH shutdown, a new accelerator module (ACC 7) was installed. This additional module will allow for higher beam energy and therefore shorter laser wavelength. The RF power for the cavities in the modules is generated by high-power 5 MW or 10 MW klystrons. It is transmitted to the modules and finally distributed to the individual cavities of each module by WR650 waveguide components.

The new waveguide distribution is of the same type than the one that will eventually be installed at the European XFEL. It has several advantages over the old type previously used at FLASH: It allows for the adjustment of the RF power distributed to pairs of cavities. The maximum power per cavity is 350 kW. It requires a smaller number of components and a smaller number of different types of components, thus reducing the costs of the distribution. It has a smaller size and weight, and it enables the module to be mounted and tuned before installation in the accelerator tunnel, which simplifies the installation and commissioning procedure.

Figure 1 shows the layout of the distribution. The power generated by the klystron enters the RF waveguide distribution module from the right. The power for a pair of cavities is branched off by asymmetric shunt tees. The coupling factor can be adjusted by placing two tuning stubs at the right position inside the tees. Fixed phase shifters between the asymmetric shunt tees are used to adjust the phase between two pairs of cavities. In front of a pair of cavities the power is distributed equally by a shunt tee. The phase can be changed with tuneable integrated phase shifters. 400 kW isolators (circulator plus load) protect the klystron from power reflected from the cavities.

The entire waveguide distribution module was tested before mounting onto the accelerator module. In addition to the pure waveguide components, cables for control and measurement and tubes for cooling were mounted on the distribution too.

Figure 1

Layout of the RF waveguide distribution system for ACC 7

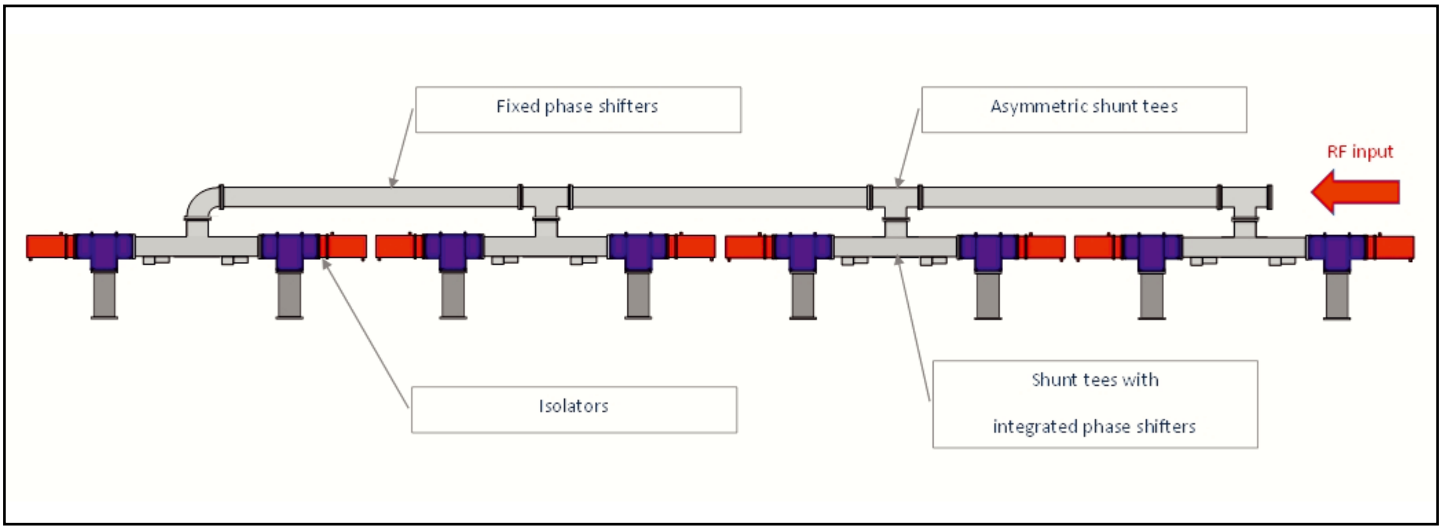


Figure 2

RF waveguide distribution and accelerator module during transport

Figure 2 shows the accelerator module and RF waveguide distribution before installation in the tunnel.

A distribution of similar type was also installed on the already existing accelerator module ACC 1. A specific characteristic of this distribution is that the power for the first and second four cavities is split by a combination of hybrids and phase shifters, enabling operation of the two halves at different and adjustable gradient set points. The distributions for the first and second four cavities are of the same type as for the eight cavities of ACC 7, with the exception that no tuneable phase shifters were installed. Therefore each of the distributions was phase-tuned with a precision of 3 degrees before installation.

The waveguide distribution for the RF gun was modified to allow for the installation of a 10 MW multibeam klystron with two output ports. At present, a 5 MW klystron with only one output port is used, and the power is therefore split into two waveguides just after the output. The power is transmitted to the RF gun by two 30-m-long waveguides. In front of the RF gun, a shunt tee combines both arms into one waveguide, which finally feeds the power into the RF gun. To realize stable phase and amplitude conditions in the RF gun, it is essential that both long waveguide arms operate at stable phase conditions. This is achieved by controlling the air pressure inside each waveguide. Small changes of air pressure convert into small changes of the transverse waveguide dimensions and thus into phase changes. The phase could be stabilized to 0.1 degree.

The experience gained from the installation, commissioning and operation has been a successful proof-of-principle of these waveguide layouts. Further improvements, especially concerning procedures, are underway.

Contact: Stefan Choroba, stefan.choroba@desy.de
Valery Katalev, valery.katalev@desy.de

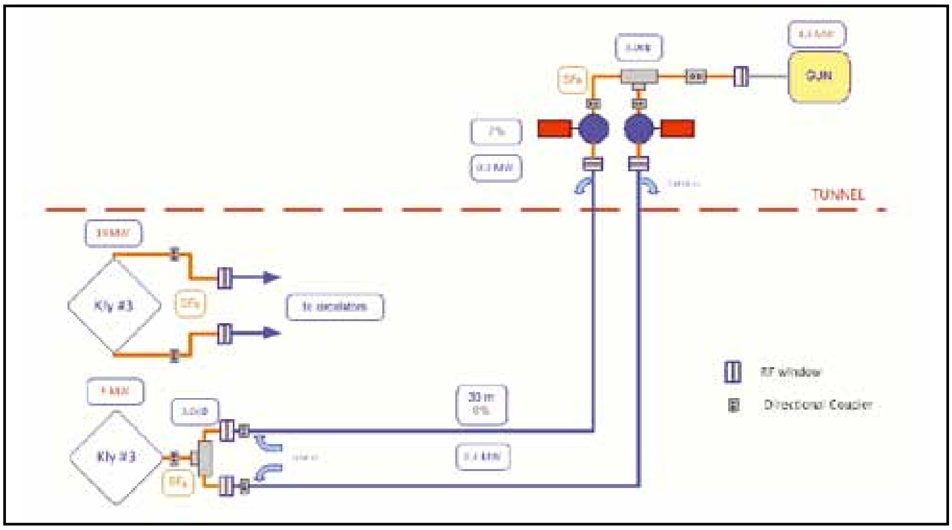


Figure 3

RF waveguide distribution for the RF gun

FLASH LLRF injector upgrade.

Significant enhancement of energy stability in FLASH

During the FLASH shutdown 2009/2010, the hardware of the low-level radio frequency (LLRF) system for the FLASH injector (RF gun, ACC 1 and ACC 39) was reorganized and cleaned up. One of the main improvements is a reduction of the beam energy jitter by a factor of about three and less sensitivity of the RF hardware and cables to ambient changes, such as temperature and mechanical vibrations.

During the FLASH shutdown, the RF gun and first accelerator module (ACC 1) LLRF systems were upgraded and reorganized. In addition, a brand-new LLRF system for the third-harmonic module (ACC 39) was installed.

The LLRF structure, hardware, distribution and cabling, have been constantly changed, upgraded and rebuilt during the last years of operation. The aim of these modifications was to fulfil the requirements of a stable user facility. Despite all these many improvements, a long-term stable machine operation had not been achieved.

Dedicated measurements showed strong influences of thermal drift on the phase stability of the RF field detection. This was caused by the exposed construction of the electronics racks. In addition, the distribution of the individual hardware components resulted in long cable distances. Long cables are sensitive to mechanical vibrations and disturbances, which produce measurement errors that corrupt the stability of the machine. The wide distribution of the LLRF also creates signal crosstalk between the LLRF of the RF gun and ACC 1.

The main focus of the LLRF injector upgrade was to optimize the LLRF structure and distribution of the individual hardware components so that cable lengths were reduced and crosstalk between components was removed. Additionally, all hardware had to be installed in closed, RF-shielded and air-conditioned racks to minimize the impact of ambient changes on the RF signals. A further reason for rebuilding the system was the installation of a new accelerating module (ACC 39) in the injector, which required a third LLRF system. The limited space in the old LLRF racks entailed a reorganization of the structure.

Before disassembling all the old LLRF hardware and racks, an inventory of the structure, the hardware components, connections and cables of the two LLRF systems in the injector hut was made. This inventory was later used as a basis for the structural redesign and reorganization. After this, all old LLRF hardware, cables and racks were disassembled, and the injector hut was professionally cleaned. The old LLRF racks were replaced by

Figure 1

New LLRF system at FLASH. Racks left to right: ACC 1, ACC 39 and RF gun regulation

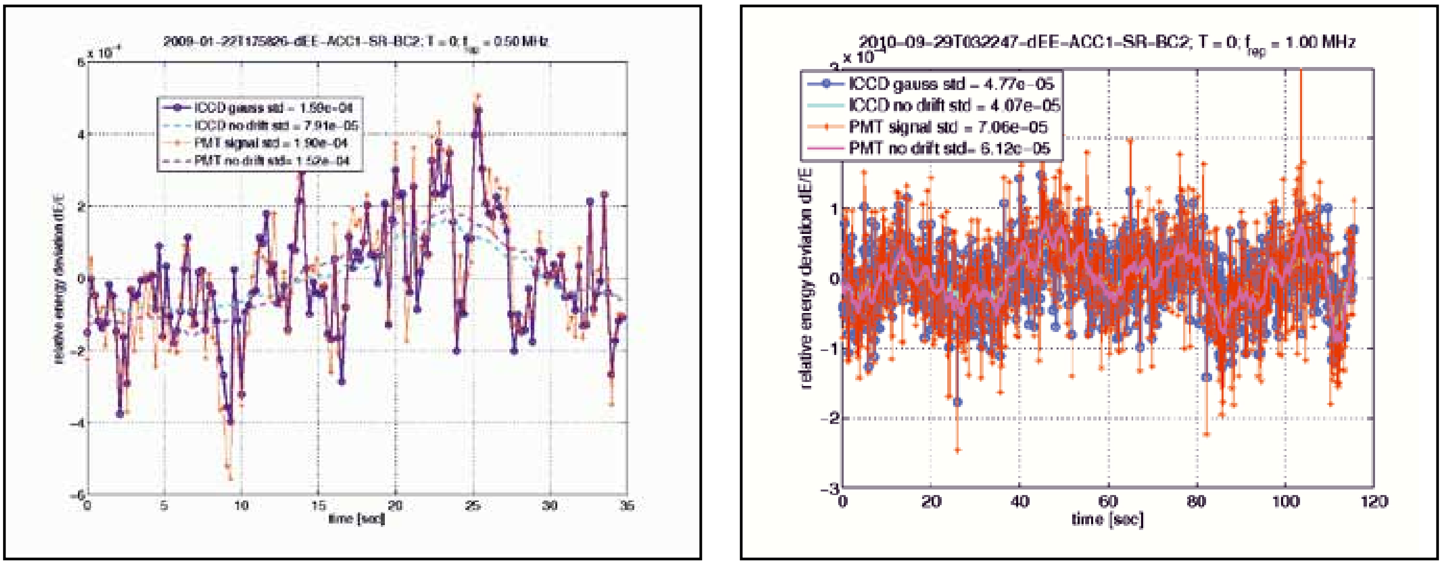


Figure 3

Pulse-to-pulse energy jitter of the electron bunches after ACC 1, measured with a position-sensitive synchrotron radiation monitor in the first bunch compressor (BC 2). Left: Measurements before the LLRF injector upgrade gave a typical value of about $1.5 \cdot 10^{-4}$; right: measured energy jitter of $5 \cdot 10^{-5}$ after the LLRF injector upgrade. (Note the difference in vertical scale by a factor two.)

new racks with lockable doors, air-conditioning and RF shielding (Fig. 1). These new racks are compatible with the newly developed system based on the xTCA crate standard. The xTCA system will be installed in the new racks for tests and developments of LLRF systems for the European XFEL.

To decouple the three LLRF systems and prevent crosstalk in the new structure, each individual system is placed in one rack and each controller gets its own reference signals from the master oscillator. The distribution of the hardware inside the rack was arranged in a top-down structure to reduce the required cable lengths. The sensitive RF detection hardware is on top, followed by the monitor system in the middle and the controller hardware for the digital signal processing at the bottom. To prevent disturbances from mechanical vibrations and human contact, all sensitive RF cables are fixed on patch panels, routed in channels and hidden within the rack. All cables are numbered, labelled and well documented. For maintainability, a complete documentation was generated with signal plans, diagrams and system overviews.

Figure 2

The new RF downconverter for the 3.9 GHz signal of the third harmonic cavities

The third-harmonic structures in the new ACC 39 module have an operating frequency that is three times higher than that of the standard accelerator modules. This higher operating frequency requires new RF detection hardware and a new reference frequency generation and distribution system. The new RF detection concept developed for the 3.9 GHz system is also foreseen as a later upgrade for the 1.3 GHz system. This new RF detection concept allows for easier diagnosis of RF detection hardware problems. The new RF detection hardware, shown in Fig. 2, was assembled in a 19 inch chassis with metal shielding and an external, ultralow-ripple power supply.

The real, measurable improvements in the system performance are the reduced crosstalk from the RF gun to ACC 1 and enhanced pulse-to-pulse energy stability of the electron bunches after ACC 1. The crosstalk from the RF gun is now below the measurement sensitivity. The energy stability of ACC 1, measured in the dispersive section of the first bunch compressor (BC 2) with the help of a position-sensitive synchrotron radiation monitor, has improved by a factor of about three: from typically $1.5 \cdot 10^{-4}$ down to $6 \cdot 10^{-5}$. Figure 3 shows the energy jitter measured with the synchrotron radiation monitor before and after the LLRF injector upgrade. The synchrotron radiation monitor is equipped with two independent detectors: an intensified CCD camera and a multi-anode photomultiplier tube. For the CCD camera a Gauss fit to the beam profiles is displayed. The standard deviation of the energy jitter for both detectors is given in the legends for the cases with and without subtraction of drifts, which are indicated as dashed lines.

Contact: Matthias Hoffmann, matthias.hoffmann@desy.de

Precision RF field regulation at FLASH.

Minimizing the bunch arrival time jitter to the 20 fs level

Precise control of the FLASH accelerator RF fields is essential for stable and reproducible photon production. To achieve a relative amplitude and absolute phase error below 0.01% (rms) and 0.01 degrees (rms), model-based designed feed-forward and feedback controllers are used. In addition, beam-based measurements are processed in real time in the RF control system to further improve the electron beam stability. This beam-based feedback reduces the beam arrival time jitter from 48 fs (rms), which reflects the RF regulation performance, to below 22 fs (rms). This combination of feedback systems has significantly improved the performance of the LLRF control system and allows for femtosecond precision pump-probe and seeding experiments at FLASH.

A major upgrade of hardware, firmware and software of the FLASH RF control system was completed in 2010, providing:

- improved RF field stability
- higher reproducibility of the phase and amplitudes selected by the operatorss
- beam-based feedbacks to remove residual field errors and undesired machine fluctuations.

The ~30 fs pulse arrival time stability desired by the users is the most challenging goal to meet. The arrival time jitter must be stabilized with respect to pump-probe experiments with optical lasers and to experiments in which the free-electron laser is seeded by an external seed laser. Thus, the electron bunch arrival time must be stabilized with respect to an external optical source which synchronizes these laser systems. This is accomplished using an optical synchronization system that delivers fine corrections to the RF field control.

An overview of the RF field control is sketched in Fig. 1. The accelerating fields of up to 16 cavities are measured by I-Q-type downconverters operated at a switching frequency of 250 kHz. The signals at the mixer output are sampled by 14 bit high-speed ADCs. The in-phase (I) and in-quadrature (Q) voltages are then summed up, compared to the set point table and fed to the digital controller. The digital control comprises a feed-forward drive and the feedback correction for the removal of pulse-to-pulse variations. The output of the digital controller is converted to analogue signals (DAC) connected to a vector modulator which varies the amplitude and phase of the 1.3 GHz master oscillator RF reference signal. This signal is used to drive a 10 MW multibeam klystron.

Due to the very low bandwidth of the superconducting cavities, it is not possible to either suppress high-frequency distortions or achieve zero steady-state errors with the feedback only. With the feed-forward drive, by learning from previous pulses, the residual control errors can be minimized. The optimization is done by a model-based technique of iterative learning control, named learning feed-forward. This control strategy keeps the relative amplitude and absolute phase error below 0.01% (rms) and 0.01 degrees (rms).

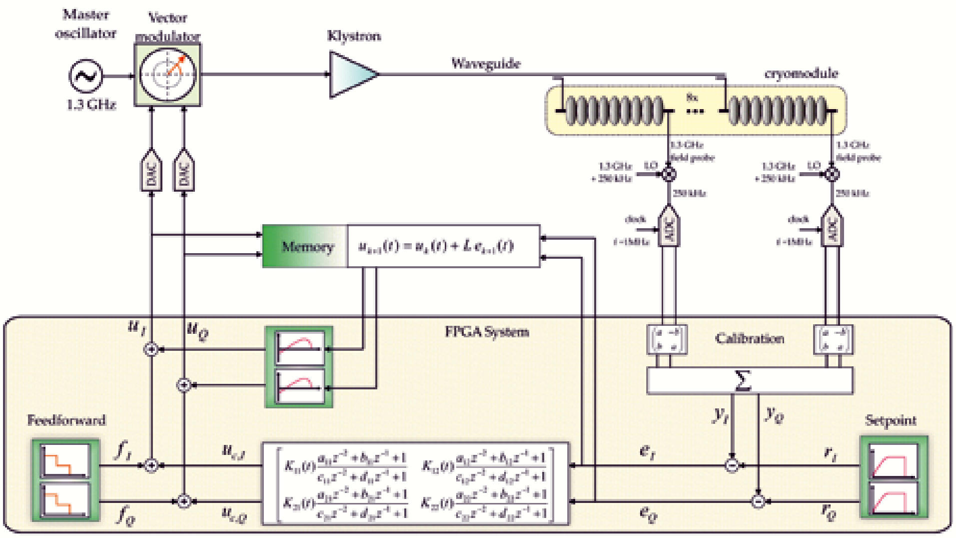


Figure 1

LLRF system for RF field control of multiple superconducting cavities

The performance criteria differ for intra-pulse and pulse-to-pulse variations. Fluctuations for consecutive pulses are not predictable and must be compensated by the feedback controller. This controller used to be a proportional feedback, which has now been updated to a multivariable, second-order controller whose coefficients are automatically tuned by model-based controller methods. With such controllers one primarily achieves a higher closed-loop system bandwidth without amplifying high-frequency noise. The performance of the controllers must be benchmarked using the achieved beam stability, which can be measured through the arrival time variation after dispersive sections in the accelerator.

As shown in Fig. 2, RF field disturbances can be reduced from 4 ps to about 500 fs through learning feed-forward. This self-adapting process also leads to a higher machine reproducibility. Without learning feed-forward, the residual control errors must be minimized through a variety of expert manual tuning measures whenever the beam loading changes.

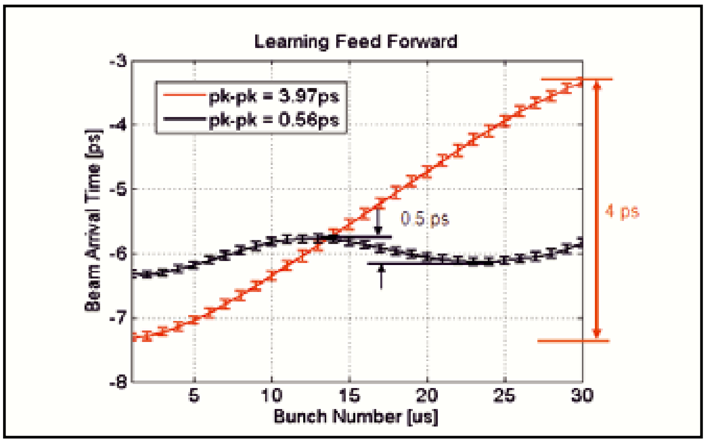


Figure 2

Arrival time variation after BC2 with learning feed-forward and feedback

Because of small field detection errors, systematic errors due to the calibration of the cavity field probes, common mode errors caused by jitter and drifts of the RF reference, long-range wakefields, variations of the photo injector drive laser pulses and small current fluctuations of the magnetic chicane power supplies, measurements of the electron beam do not necessarily precisely match the vector sum calculated from cavity field probes. Therefore, to further improve the electron beam stability, beam-based measurements are processed in real time in the RF control system. To avoid conflicts with the RF probe-based regulation, the beam-induced correction changes the set point tables used for the RF feedback system with a microsecond intra-bunch train response time. Beam-based measurements for intra-bunch train regulations are:

- bunch-by-bunch arrival times and
- bunch-by-bunch compression factor,

after each magnetic bunch compressor chicane. Due to the large longitudinal dispersion of the first magnetic chicane, an arrival time of 7 ps per % voltage modulation of the first cryomodule is induced, dominating the electron beam arrival time jitter at FLASH. Since RF phase variations change both the compression of the electron bunch and its arrival time, the control algorithm must always act on amplitude and phase simultaneously. From the experimentally determined response, a feedback matrix is calculated and applied to the field programmable gate array (FPGA) of the controller. For compression monitoring, a newly installed 140 GHz photodetector was used with a significantly improved signal-to-noise ratio (SNR) compared to pyro-electric detectors. The improved SNR allowed for stabilization of the bunch compression without compromising the arrival time jitter.

Figure 3 shows the rms arrival time jitter of each bunch in a macropulse over a period of 8 min when intra-bunch train feedbacks are activated on each accelerator station upstream of each chicane. Due to causality and the system delay, the first four bunches are not affected by the intra-train feedback system. The arrival time jitter of 48 fs rms reflects the stability of the RF regulation without beam-based feedback. After about 15 µs, the arrival time jitter approaches a steady state and is reduced to below 22 fs (rms) for the remaining 85 electron bunches. The transient time of the feedback is caused by the narrow bandwidth of the cavities (~300 Hz) and limitations on the applicable feedback gain of the RF controls.

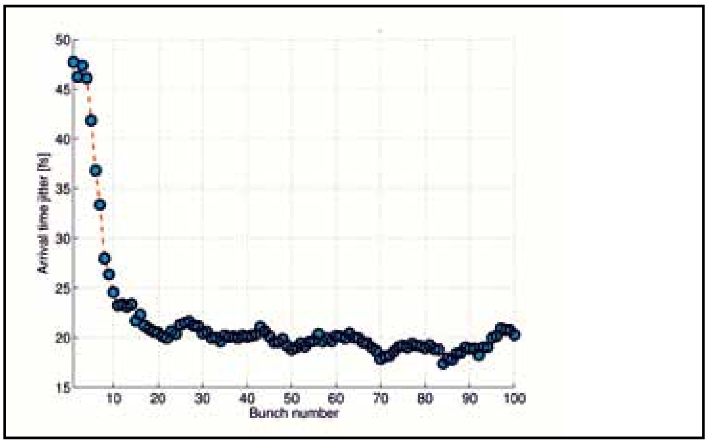


Figure 3

Buch train arrival time jitter mesaaured over 500 pulses

This combination of pulse-to-pulse learning feed-forward drive correction, a multivariable, second-order feedback controller and a fast beam-based set point adaptation has significantly improved the performance of the LLRF control system and allows for femtosecond precision pump-probe and seeding experiments at FLASH. Further improvements of the arrival time stability from dE/E ~ 0.003% toward dE/E $\leq 1\cdot10^{-5}$ (< 7 fs rms) most likely requires a fast, e.g. normal-conducting cavity with a 15 kV acceleration voltage, but sufficient bandwidth installed upstream of the BC 2 chicane.

Contact: Christian Schmidt, christian.schmidt@desy.de

Ultrashort bunches at FLASH.

Controlled bunch compression with a higher-harmonic RF system

The generation of ultrashort electron bunches with a higher-harmonic cavity for the linearization of electron energy chirp and bunch compression is leading the way to new records of photon beam peak brilliance at FLASH.

Certain experiments carried out at the FLASH facility require ultrashort photon bunches with a width of less than 50 fs (FWHM). Through the self-amplified spontaneous emission (SASE) process, an electron bunch with a Gaussian-like distribution produces a photon pulse of roughly half its length.

Such short electron bunches (< 100 fs) cannot be produced in electron guns with the intensity required for a SASE FEL. Space charge forces inside densely populated bunches with beam energies of only a few MeV would corrupt the transverse beam quality, thereby increasing the necessary undulator section length to impractical size and severely reducing the amount of transverse coherence in the SASE photon beam.

Therefore, the relatively long (~10 ps) electron bunches produced by the gun are shortened and thus intensified in stages along the FEL driver linac, a technique called (longitudinal) bunch compression. Because of the energy dependence of their deflection angle, magnetic chicanes, i.e. chains of bending magnets, cause particles with different energies to follow paths of different lengths. So if an energy offset proportional to the longitudinal particle position is induced in the electron bunch (energy chirp) by ensuring it passes through the upstream linac RF section not on top of the RF wave but with a proper phase angle, the chicane will shorten the bunch.

A sinusoidal RF wave not too far off-crest is in good approximation parabola-shaped, so the induced chirp is slightly parabolic (Fig. 1). Bunch compression now shifts particles with (relatively) lower energies to the right, while those with higher energies move to the left. A monochromatic electron bunch with purely linear chirp could theoretically be compressed to zero length, forming an upright line in phase space. In reality, nonlinearities of the chirp reduce the size of the “upright” region, and the “natural” energy spread of the particles of that region determines the width and height of the resulting spike in the intensity distribution.

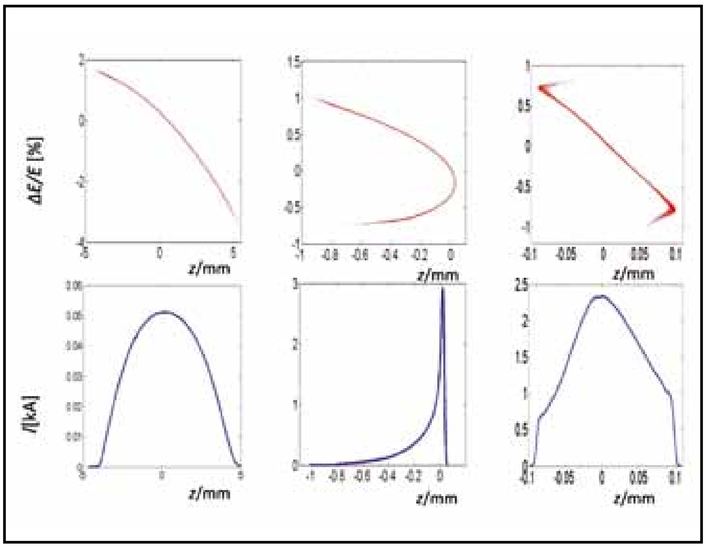


Figure 1

Upper left: longitudinal position and energy offsets of the electron bunch before compression (phase space plot). Lower left: the corresponding current profile. Centre: phase space and current profile after roll-over compression. Right: linearized phase space and current profile after bunch compression with a higher-harmonic RF system.

Because the actual sheering in phase space resembles a rotation, such a manner of bunch compression is called roll-over compression. It involves only a small part of the charge for lasing (< 10%) and produces short photon pulses (~20 fs) whose length is determined by the “natural” energy spread out of the gun, a parameter that cannot be adjusted.

In 2010, an RF system operating at a frequency corresponding to the third harmonic of the normal FLASH frequency was installed to linearize the energy chirp for bunch compression. Now the bunch is close to being on a straight line in phase space and could be compressed to very short lengths. The peak intensity of the bunch at some point in the linac, however, is limited. The simulation in Fig. 1 does not include self-interactions like

Figure 2

Third-harmonic RF module (red) downstream of first acceleration module (yellow)

the space charge force. If we include these effects, the phase space is severely distorted. These results are in good qualitative agreement with measured data at FLASH (Fig. 3).

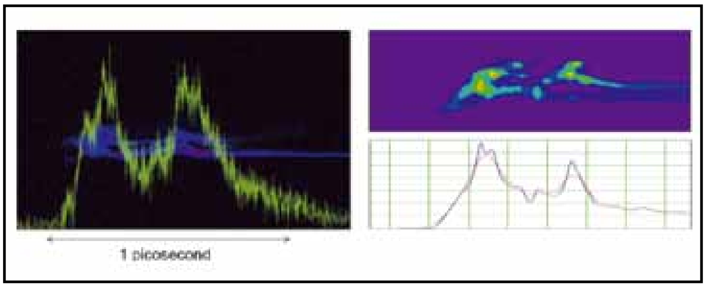


Figure 3

Measurement (left) and simulation (right) of bunch profile and horizontal particle offsets vs. longitudinal particle positions at FLASH

Here, an RF section operating in a vertical deflecting mode serves as an ultrafast streak camera: the particles in the bunch receive a vertical kick proportional to their relative longitudinal position. Screens downstream thus resolve longitudinal parameters vertically.

Simulations of the same kind show that for linear compression, lowering the total bunch charge to values closer to the actual charge involved in lasing in the roll-over compression case, we get pulses just as short, higher peak current and better transverse beam quality.

To tune the bunch compression system in a systematic manner, it is necessary to treat the fundamental RF system and the third-harmonic RF system as a unit. The bunch experiences the sum voltage of two RF systems with different frequencies, thus the impact of changes of single phases and/or amplitudes is hard to judge.

However, to change the beam parameters energy, linear energy chirp and second- and third-order energy chirp, the necessary change in amplitudes and phases is given by a simple matrix operation. If we implement this into the control system, we can provide “knobs” that allow us to change these beam parameters independently. We can for instance optimize the chirp without affecting the beam energy or the higher-order chirp terms which have an impact on the symmetry of the final bunch profile (second order) or on the shape of its tail (third order).

The bunch profile on the right side of Fig. 5 was optimized by increasing the linear chirp to further shorten the bunch. A more centralized distribution could be achieved by adjusting the third-order chirp. Afterwards, the SASE photon intensity was optimized.

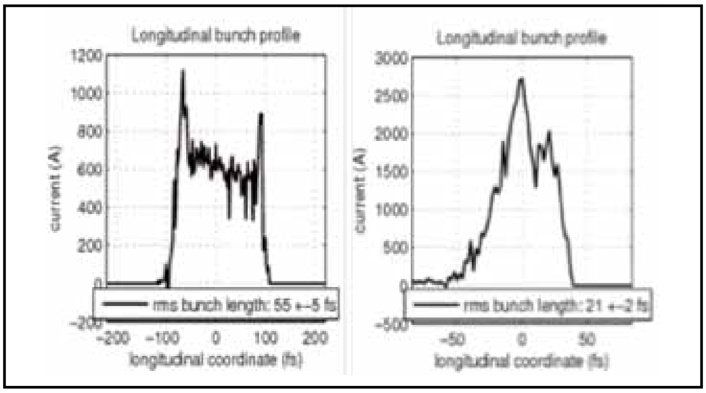


Figure 5

Bunch profile as measured by the transverse deflecting cavity before and after optimization with RF knobs. The bunch charge was 0.13 nC.

Measurements of SASE statistics and the analysis of a high-resolution, single-shot spectrometer tentatively confirm photon bunch lengths below 50 fs. This process has been repeated several times now and needs to be turned into a routine machine operation procedure.

Contact: Torsten Limberg, torsten.limberg@desy.de

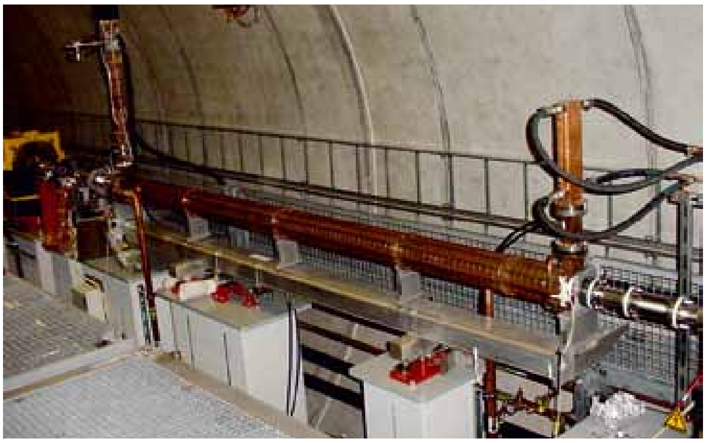


Figure 4

The transverse deflecting RF structure

Improved optical link design at FLASH.

Development of fs timing techniques

To achieve femtosecond synchronization of systems at FLASH and the European XFEL, optical pulses are distributed in glass fibres with lengths that have been adjusted to keep the round-trip times of the pulses constant. A new round-trip time stabilization scheme with significantly reduced complexity compared to other schemes has demonstrated femtosecond measurement precision over 30 hours.

Free-electron lasers like FLASH and the future European XFEL require ultrashort electron bunches with high peak current. The length scales of these bunches have increased the demands placed on the accelerator subsystem synchronization from picosecond (10^{-12} s) to femtosecond (10^{-15} s) accuracy. To meet these synchronization goals, optical synchronization techniques have been employed and intensively researched throughout the past few years. These optical techniques have been used to improve and, in some cases, replace traditional RF-based methods. Since femtosecond-accuracy optical synchronization is a very young discipline, compared to more than 50 years of experience with RF synchronization, it still suffers from low reliability and high costs. For this reason, both optical and RF technologies have been employed in FEL synchronization systems.

The heartbeat of the FLASH optical synchronization system is a passively mode-locked master laser oscillator with a repetition rate of 216.7 MHz. It generates laser pulses with durations of 200 fs (FWHM). These pulses are distributed through free-space optics to a number of optical fibre links. The round-trip propagation times of the pulses in these fibre links are actively stabilized so that the arrival times of the pulses at the ends of the links remain stable despite the several 100 m distances within FLASH and the 3.5 km distances within the European XFEL. The pulses exiting the fibre links are used for a multitude of synchronization purposes: detecting the electron bunch arrival time, generating an RF signal, or locking optical lasers to the master laser oscillator reference.

Like RF cables, optical fibre properties change due to environmental conditions such as temperature, humidity and mechanical vibrations. To fix the laser pulse arrival time at the end of a fibre link, a small fraction of a pulse at the end of a link is reflected back to the source and its round-trip time is measured relative to laser pulses emitted directly from the master laser oscillator. This measurement is used to determine how the length of the link has to be adjusted.

A purely optical method to measure the round-trip time uses sum-harmonic generation, a phenomenon which occurs when two laser pulses are temporally and spatially overlapped in a nonlinear crystal. This technique was successfully tested and implemented at FLASH. The drawbacks of the technique include:

- optical power levels that are large enough to cause pulse shape distorting self-phase modulation
- precise dispersion compensation so that the pulses are short after the round-trip propagation through the fibre link
- fibre link length must be cut to a precision of below 1 cm to maintain adjustability of the temporal overlap
- complicated optomechanics and feedbacks that keep the link propagation time within the 200 fs dynamic range of the detector.

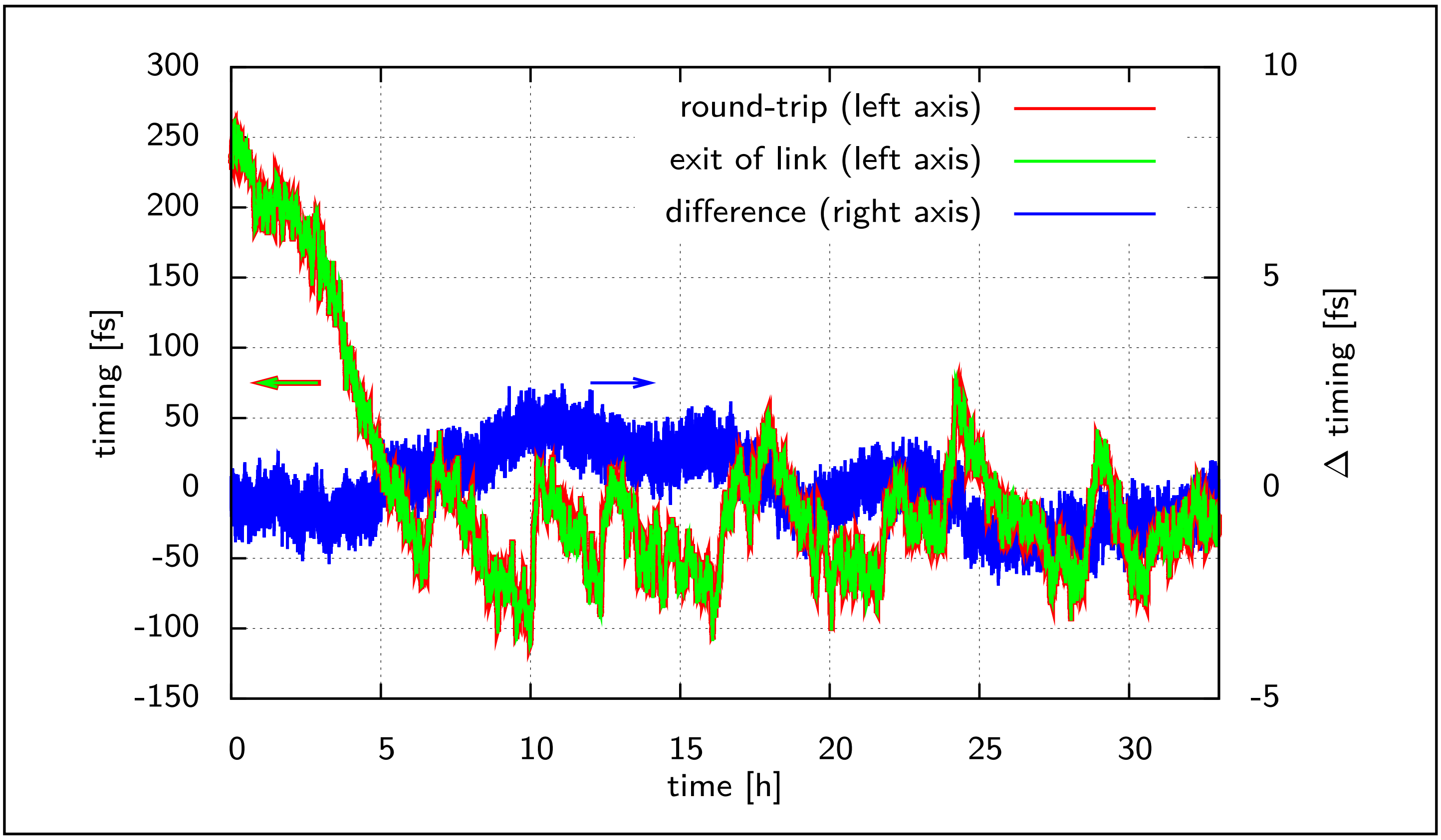


Figure 1

Long-term drift measurement (33 h). The difference between the round-trip timing and the exit of the link timing gives the performance of the measurement.

Recently, a significant reduction in the complexity and costs of the optical fibre links was achieved by combining the advantages of both optical and RF techniques. This new method is particularly suited for end stations where an RF reference for the RF accelerator field control is required. The new technique transports the optical pulses over the fibres, but it makes use of a non-optical round-trip propagation time measurement. In this method, one laser pulse train from the master laser and one pulse train back-reflected from the link are guided onto a broadband photodetector. With an RF bandpass filter, the 45th harmonic of the laser repetition rate at 9.75 GHz is extracted, amplified and downmixed to baseband using a 9.75 GHz LO signal extracted from the master laser.

The sensitivity of the method relies on constructive or destructive interference in the RF filter, depending on the relative arrival times of the pulse trains incident on the photodetector. For example, if the arrival time difference between the pulse trains amounts to half the period length of the laser repetition rate, then only even harmonics will be produced and the RF power vanishes at the 45th harmonic. The microwave mixer is operated as an amplitude detector providing an output signal that is proportional to the timing change.

Compared to the optical arrival time detector for the link stabilisation, the RF detector:

- works with 10 times less optical power in the fibre link
- has multiple operation points
- does not required precise dispersion compensation
- overcomes amplitude-to-phase conversion changes at the photodetector
- is robust against phase drifts of the LO or RF detection branches.

Figure 1 shows the measured arrival times extracted for the round-trip (divided by 2) and at the exit of a 30 m long fibre link using two independent detector branches. The blue curve shows the measurement error between both detector branches, which deviated by 0.8 fs rms and 4.8 fs peak-to-peak only over a time period of more than 30 hours. Similar results have been achieved when the round-trip time is used for propagation time stabilization.

Contact: Thorsten Lamb, thorsten.lamb@desy.de

AMTF – Progress is obvious.

Main parts of the AMTF infrastructure ready for operation

All of the approximately 800 superconducting RF cavities and 100 assembled cryomodules of the European XFEL will be tested at the Accelerator Module Test Facility (AMTF) at DESY before being installed in the European XFEL accelerator tunnel. In addition, the RF waveguides will be assembled and qualified in a special section of the AMTF, the Waveguide Assembly and Test Facility (WATF). The AMTF hall was erected and substantial parts of the infrastructure are ready for operation.

The construction of the AMTF hall (Fig. 1) was completed just in time for the celebration of the DESY 50 year jubilee in May 2010. The MKK group was thus able to start installing the infrastructure components. The AMTF control building was equipped in August 2010. The pump house infrastructure for the cooling water supply followed in September. Among other components, the basic infrastructure of the AMTF hall comprises three large hall cranes. As soon as the cranes were available, the heavy-concrete blocks for the radiation shielding of the future cryomodule test stands were assembled (Fig. 2).

A new piping bridge was constructed. It will bear the helium transfer line leading to the helium refrigerator in Building 54. Several warm helium pipes and cable trays have already been installed on the piping bridge. Two large helium pump sets are required in the AMTF to lower the helium vapour pressure in the test cryostats and test stands to the superconducting cavity operating temperature of 2 K. These pump sets were assembled in autumn 2010 (Fig. 3) and are ready for commissioning.

Figure 2

Radiation protection elements of one of the cryomodule test stands inside the AMTF

Figure 1

The AMTF hall (control building in the front) in June 2010

Figure 3

One of the two AMTF helium pump sets

Modulators and pulse transformers for the RF supply of the cryomodule test stands were installed, and the Waveguide Assembly and Test Facility (WATF) section of the AMTF was prepared. Other less obvious preparations were conducted just as efficiently and intensely. The RF measuring equipment for the cavity tests and the complex electronic components for the safety interlocks were procured and assembled. The frames and devices that will support the cavities during the tests were designed and constructed. A call for tender for missing cryogenic components was launched. The AMTF operating team from IFJ-PAN Krakow started the detailed planning of the test sequences, procedures and schedules.

Substantial parts of the DESY in-kind contributions to the AMTF have already been delivered – on time and within budget. The AMTF is ready to receive the helium transfer line and vertical cryostats from Poland (WUT, Wrocław) by the end of 2011. First parts of the cryomodule test stands from Russia (BINP, Novosibirsk) will arrive already in spring 2011. As a result, the AMTF should be ready in time for the serial tests of the European XFEL cavities and cryomodules.

Contact: Bernd Petersen, bernd.petersen@desy.de

LLRF development for the European XFEL.

Towards extreme amplitude and phase stability of the European XFEL low-level radio frequency system

The demands placed on the short- and long-term amplitude and phase stability of the 1.3 GHz accelerating field for the European XFEL are of the order of 0.01% and 0.01 degrees. To guarantee this stability, we present the European XFEL low-level radio frequency (LLRF) system structure, which uses the new µTCA standard and approved 19” modules. First laboratory measurements of the system front-end showed promising results of a short-term amplitude and phase stability of less than 0.005% and 0.005 degrees.

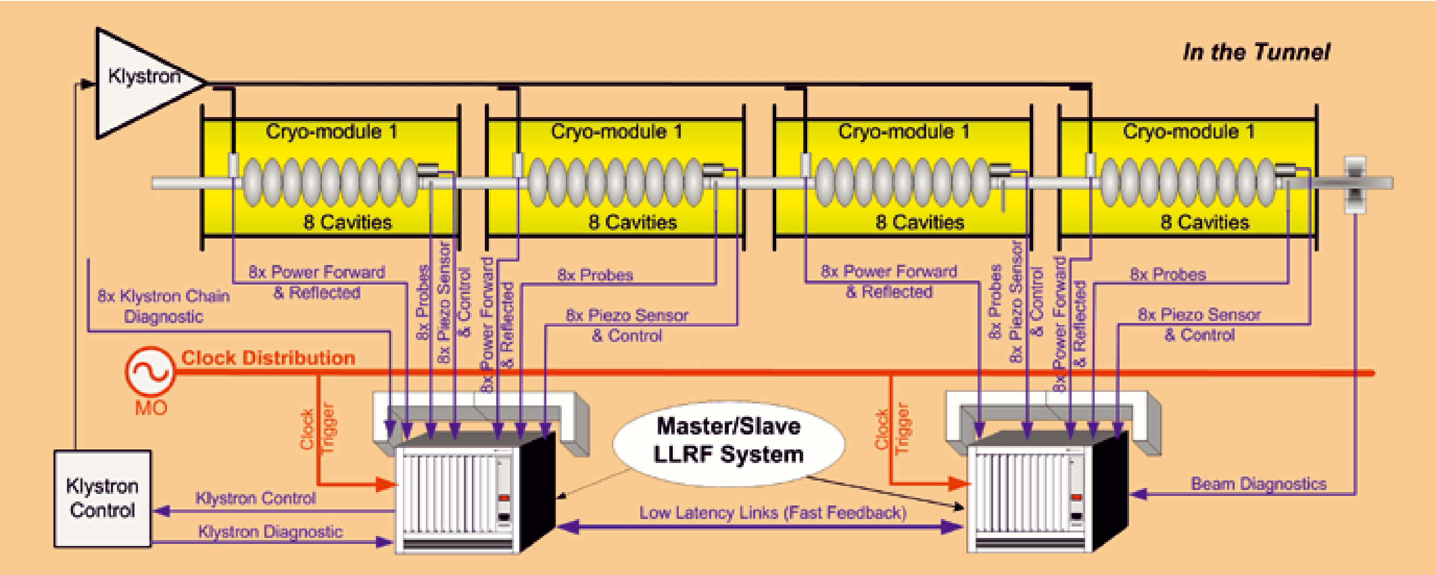
Robust and stable accelerator operation of the European XFEL will be achieved using passive thermal stabilization and calibration of the field detection chain through injection of the master oscillator reference. Residual beam arrival time jitter and drift caused by signal transport on unstabilized cables will be eliminated by beam-based feedbacks. Short-term stability requires ultralow-noise electronic design, low-distortion power supply chains and approved grounding and shielding concepts. At FLASH, the testbed for the European XFEL, an excellent energy stability of 0.005% has already been demonstrated.

Since the underground rack space near the European XFEL cavities is limited, the LLRF design must be more compact than the FLASH design. In addition, the system must be capable of processing all signals in real time. Real-time signal processing will allow the incorporation of more sophisticated control algorithms, improving operation flexibility, system robustness, failure diagnostics and failure handling. This will also lead to further improvement of the RF field stability and increase the reproducibility of operating points.

Figure 1 shows the layout of a single European XFEL LLRF high-frequency station. Each station is responsible for processing and controlling 32 cavities based on probe, forward and reflected power signals. To keep the unstabilized cables from the pickups as short as possible, two LLRF stations will process 16 cavity vector sum signals.

Figure 1

Two semi-distributed µTCA LLRF systems supply four cavity modules.



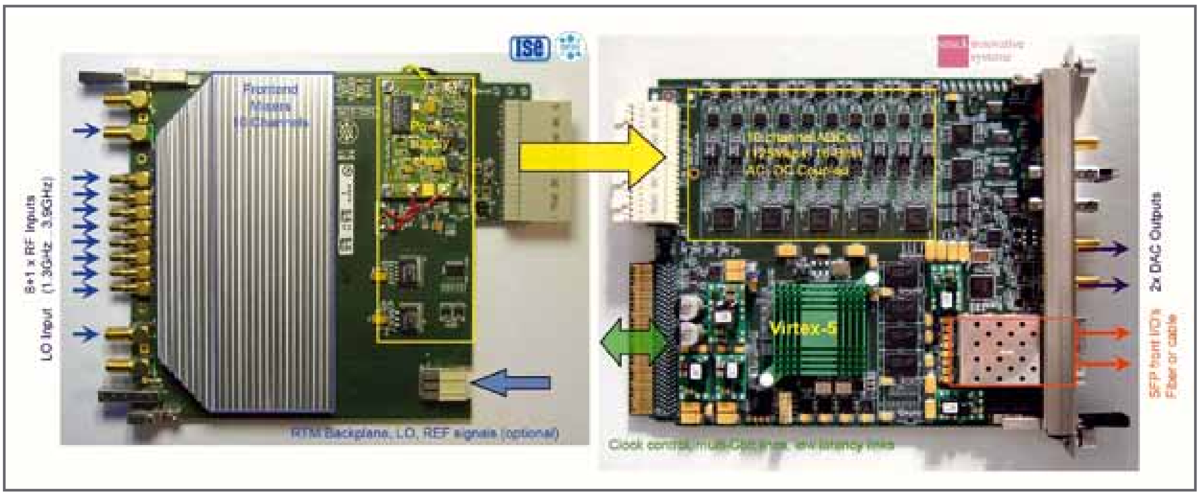


Figure 3

(a) Multichannel downconverter (DWC8300 R1.0) for 1.3 GHz–3.9 GHz. (b) 10 channel 16 bit ADC digitizer for the partial vector sum (SIS8300 R1.0).

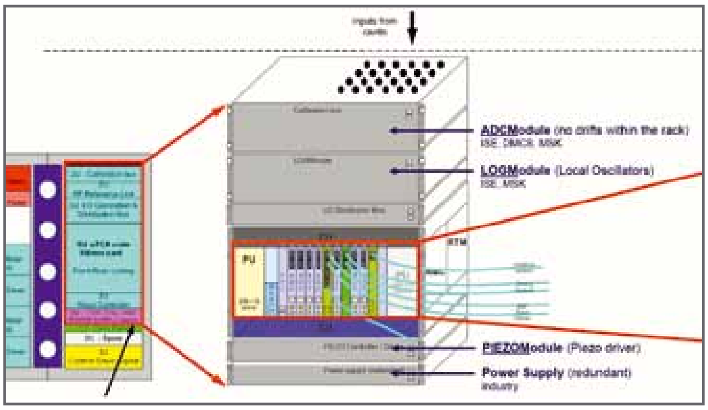


Figure 2

LLRF system based on 19” modules and a µTCA system

The amplitude and phase are measured through downconversion and digitization of the 1.3 GHz cavity signals. The vector sum of all cavity signals is processed and regulated using a field programmable gate array (FPGA). This FPGA generates a signal which is upconverted and used to drive the high-power klystron.

The system must be robust, maintainable, easy to service, low-cost and scalable in performance. Design resources should be shared within DESY, as well as with industry and collaboration partners. The LLRF group therefore decided to package the European XFEL systems in the new µTCA standard and approved 19” modules. Figure 2 shows the rack packaging of the LLRF system. Long-term stable 3/8” Heliax high-frequency cables guide the cavity signals into a 19” module for reference injection calibration. Local oscillator signals for the downconversion are generated in a local oscillator generator (LOG) module. An additive jitter of less than 10 fs within a bandwidth of [10 Hz, 1 MHz] at the 1354 MHz LO frequency has been achieved. The cavity pickup signals are downconverted from 1.3 GHz in rear transition modules (RTMs) of the µTCA crate. They are then digitized in µTCA AMCs (two-sized advanced-mezzanine cards) which also process the cavities’ partial vector sums.

Figure 3 shows a 10 channel downconversion RTM module for 1.3 GHz and 3.9 GHz cavity signals. The downconverted CW intermediate frequency of about [10 MHz, 60 MHz] is non-IQ sampled with approximately 100 MSPS using 16 bit low-noise ADCs and a ZONE3 connector.

Using a Virtex-5 FPGA for preprocessing, the cavities’ partial vector sums are chipped via low-latency multi-Gbit links on the µTCA AMC bus to the µTCA LLRF FPGA controller board. First laboratory measurements of the multichannel downconverter front-end (DWC8300 R1.0) showed a short-term amplitude and phase stability of less than 0.005% and 0.005 degrees.

Altogether, the LLRF system consists of five full-sized 19” carrier boards (calibration, LO generation, reference, piezo driver, temperature controller) and five RTMs or AMCs (downconverter, digitizer, controller, vector modulator, timing). Each uses between 8 and 16 analogue and digital printed-circuit board layers. Besides excellent in-house engineering, signal integrity for the European XFEL requires a sophisticated µTCA crate design from industry manufacturers and careful characterization of the complete system.

Contact: Tomasz Jezynski, tomasz.jezynski@desy.de
Frank Ludwig, frank.ludwig@desy.de

European XFEL cavities.

Automated RF measurements for superconducting cavity mass production

For the European XFEL, more than 680 superconducting accelerating resonators (cavities) have to be fabricated from niobium material. Since all the cavities must be delivered by the companies ready for the acceptance test at DESY, the radio frequency (RF) measurement methods necessary for the fabrication – which have so far been provided DESY – must be transferred to the companies. At the same time, the techniques have to be adapted to mass production.

Half-cell measurement machine

One important element of the cavity fabrication is the RF measurement of the parts and subassemblies, such as half-cells and dumb bells. It is an established method that guarantees the correct length and frequency of the final resonator.

The standard half-cell forming method for the production of 1.3 GHz niobium cavities is deep drawing. Precise optical 3D measurements done on deep-drawn half-cells have shown that a shape accuracy of 0.4 mm is the realistically achievable tolerance for fine-grain niobium. Furthermore, the final shape of the cavity cells is undefined because the cavity is completed with equator welding seams. After the welding process, the cell will be deformed again because of the high temperature during welding and the stress relaxation. The correct shape has to be determined by a frequency measurement. The MHF-sl group developed a trimming procedure to compensate for the deviation from the theoretical RF shape. The group built a simple device to carry out the frequency measurement (Fig. 1) and used it for the fabrication of 72 cavities for FLASH.

Due to the large number of more than 680 cavities for the European XFEL, the necessary amount of RF measurements has strongly increased to about 30 000. Hence, new arrangements concerning ergonomic and economic aspects are required. The MHF-sl group therefore developed and designed an RF measurement machine named HAZEMEMA, an abbreviation for the German word “Halbzellenmessmaschine” (half-cell measurement machine).

The heart of the machine consists of an automatic clamping system that can adapt to the different types of resonator subsystems. It provides an appropriate electrical contact while at the same time avoiding deformations of the test object. This minimizes measurement errors.

Three portable and compact machines have been built (Fig. 2), and one has already been delivered to a company. Tests have proven the robustness and the measurement precision. The machines can be operated near the fabrication areas. HAZEMEMA requires only one single person for operation. The RF test duration could be considerably reduced compared to manual operation.

Figure 1

Simple RF measurement device with clamped dumb bell

Figure 2

HAZEMEMA RF measurement machine

Tuning machine

Another important part of the fabrication is the field flatness tuning of the resonators. For a $\beta \approx 1$ multicell superconducting resonator, the fields in adjacent cells must be π rad out of phase from each other and the accelerated particle must cross a cell during one-half of an RF period. This flat field profile is achieved when the cells are properly tuned relative to each other and the cavity frequency is equal to the design frequency (e.g., 1.3 GHz for a European XFEL cavity at 2 K in vacuum). In addition, the tuned cavity must meet dimensional tolerances such as length, straightness and concentricity of cells.

Cell-to-cell tuning is usually accomplished by slightly plastically deforming each cell until the desired cell frequency is achieved. This procedure is normally foreseen for each cavity after fabrication, after relevant preparation steps like etching, and to compensate for deformations caused by heat treatments or welding. So far, the cells were tuned manually by an expert operator. This very time-consuming procedure is not adequate for the resonator mass production required for superconducting RF-based projects like the European XFEL. The new machines built for the European XFEL production significantly reduce the duration of the tuning procedure. In addition, they can be operated by non-RF experts. The use of the machines is not limited to laboratories and institutes. It is planned to operate them in industry.

In a collaborative effort of Fermilab, KEK and DESY, four machines were mechanically designed and fabricated by DESY's MHF-sl group. Four completely improved control sets with totally renewed software including calculation algorithms provided by Fermilab are an important contribution towards the intended objectives.

The main component of the new tuning machines (Fig. 3) is the tuning frame which accommodates all the mechanics, such as vice units, sensors and the actuators needed for the plastic deformation of the cavity cells. A major component for feedback during the tuning procedure is the eccentricity measurement device. With its 11 linear distance generators and two laser sensors, it provides information on the concentricity of single cells to the cavity axis and displays the length of the cavity and the perpendicularity of reference planes, end flanges and beam tube flanges.

The measurement of field flatness is done with a bead pull system. One completely new device in the machines is the cavity alignment tool. It gives the possibility to (qualitatively) measure the direction of the cavity deformation compared to its straightness during the tuning procedure.

From the four tuning machines constructed, one was delivered to Fermilab, USA, one to KEK, Japan, and two are located at DESY. As the first part of the resonator fabrication for the European XFEL, the reference resonators will be tuned at DESY. The operators from the companies will be trained at the same time. For the mass production, both tuning machines will be delivered to the companies, which will be responsible for the operation during the entire resonator production. Only the maintenance will be carried out by MHF-sl personnel.

Figure 3

Complete cavity tuning machine with machine housing

Contact: Wolf-Dietrich Möller, wolf-dietrich.moeller@desy.de

Niobium material for European XFEL cavities.

Quality inspection of the semi-finished niobium products at DESY

More than 22 000 semi-finished niobium parts have to be purchased by DESY and delivered to the companies responsible for the European XFEL cavity fabrication. A new infrastructure with new scanning machines was built for the necessary extensive receiving inspection.

The niobium raw material for the production of 680 superconducting resonators for the European XFEL will be purchased by DESY and delivered to the companies. This means that DESY has to handle more than 22 000 niobium parts. All semi-finished parts must undergo a receiving inspection, various quality checks and a procedure for unmistakable numbering in accordance with the pressure vessel regulations, which have to be applied to the final resonator. The MHF-sl group set up a new infrastructure to perform this highly important task.

The most important parts determining the resonators' performance are the niobium sheets for the resonator cells. The RF surface of the individual niobium sheet must be free of inclusions, flaws and other imperfections that could lead to a later reduction or limitation of the superconducting resonator performance. DESY and the German federal institution for materials research and inspection in Berlin (Bundesanstalt für Materialforschung und -prüfung, BAM) developed an eddy current inspection system that was used to inspect all the niobium sheets for the FLASH resonators.

More than 13 000 niobium sheets are needed for the European XFEL. We have therefore ordered two new and advanced machines. They are able to detect imperfections with a size smaller than 0.1 mm within a variable depth of 0.1 mm to more than 2 mm (usually 0.2 mm). Figure 1 shows a scan of a test sheet with intentionally applied defects, which is used to test and calibrate the machines. All other semi-finished parts must undergo a strong quality check comprising visual inspections, mechanical measurements and measurements of the electrical and mechanical characteristics.

The new reception inspection facility is now ready for operation and has been used for the semi-finished products of the reference resonators for the European XFEL.

Contact: Wolf-Dietrich Möller, wolf-dietrich.moeller@desy.de

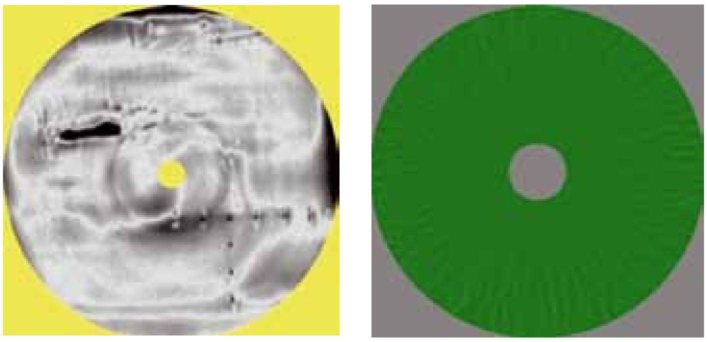


Figure 1

Scanning data of a test niobium sheet with defined defects applied (left) and of a perfect niobium surface (right)

Figure 2

The niobium sheet scanning laboratory with two eddy current scanning machines

Surface investigation on prototype cavities for the European XFEL.

Towards European XFEL cavity production

The performances of around 50 European XFEL prototype cavities fabricated by industry and treated at DESY mostly satisfy the European XFEL specification. To understand the cause of reduced accelerating gradients in a few cavities and obtain more detailed information on the origin of the defects, some samples were extracted from two cavities and investigated using several methods.

The prototype cavities manufactured by industry and treated at DESY achieve accelerating gradients between 15 and 41 MV/m. Most cavities satisfy the European XFEL specification. About 10% of the cavities with low performance (15–17 MV/m) are limited by thermal breakdown. The quench areas identified by temperature-mapping analysis lie mainly close to the equator. Optical control of the cavities with a high-resolution camera essentially showed a good correlation with the T map results.

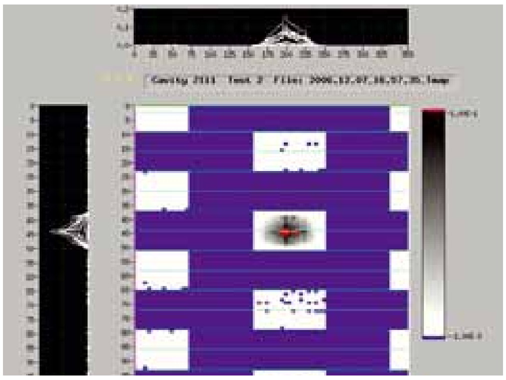


Figure 1a

T map of Cavity Z111

Figure 1b

High-resolution camera inspection of the hot spot of Fig. 1a

Figure 2a

Light microscope image of the hot spot represented in Fig. 1a

Figure 2b

Magnified SEM image of holes represented in Fig. 1a

To investigate the cause of the reduced performance and the origin of the defects, samples were extracted from two cavities and studied using different methods: a light microscope, a digital light microscope with 3D profile measurement, a scanning electron microscope (SEM), energy-dispersive X-ray spectroscopy (EDX) and Auger spectroscopy. The electron backscattered diffraction (EBSD) method in an SEM was used to make localized measurements of the lattice curvature. Both foreign material inclusions and topographical flaws can be identified as sources of the thermal breakdown in the investigated cavities.

An example of one of the detected topographical defects, which limited the accelerating gradient by thermal breakdown at 16 MV/m on the equator weld of Cell 6 of Cavity Z111, is shown in Fig. 1 and 2. There are several holes positioned mainly along a grain boundary. Our impression is that local corrosion has taken place in this area.

Contact: Waldemar Singer, waldemar.singer@desy.de

Advances in large-grain resonators for SCRF technology.

Activities in the test programme for the European XFEL cavities

We report on the DESY activities on large-grain (LG) material from high-purity niobium ingots for superconducting radio frequency (SCRF) application. It was shown that nine-cell cavities can be built from LG material without significant difficulties. Eleven resonators were produced, treated and successfully RF tested. Two of the LG cavities are currently in operation in FLASH.

More than 200 LG discs were manufactured, and eleven nine-cell resonators (AC112–AC114 and AC151–AC158) were produced, treated and RF tested. In the process, it was shown that nine-cell cavities can be built from LG material without significant difficulties or special problems. Performance in accelerating gradient (E_{acc}) on the level of 25–30 MV/m (Fig. 1), which corresponds to the average quench magnetic field of 110–130 mT, can be achieved in a stable and reproducible manner with buffered chemical polishing (BCP) treatment for TESLA-shape LG cavities. Already after the first surface treatment, the specification for the European XFEL, $E_{acc} = 24.3$ MV/m with a quality factor $Q = 1 \cdot 10^{10}$, was exceeded in most cases. Accelerating gradients on the level of 40 MV/m can be achieved in TESLA-shape LG cavities by applying electropolishing (EP) treatment.

The complete chain of the LG cavity technique from raw material production to cavity installation into a cryomodule was successfully tested. Cavity AC112 was installed into Cryomodule 3***, and Cavity AC113 was installed in Cryomodule PXFEL1 of the FLASH accelerator at DESY. Both cavities are currently operating in FLASH and contribute to accelerating the electron beam to 1.25 GeV. The corresponding radiation wavelength of 4.12 nm lies in the water window wavelength region, which creates unprecedented measuring conditions for the FLASH users.

Unfortunately, the industry is presently not able to produce the amount of around 20 tonnes of LG material required for the European XFEL on the time scale of 1.5 years. Nevertheless, there is no doubt that the high potential of LG cavities will be beneficial for future accelerators.

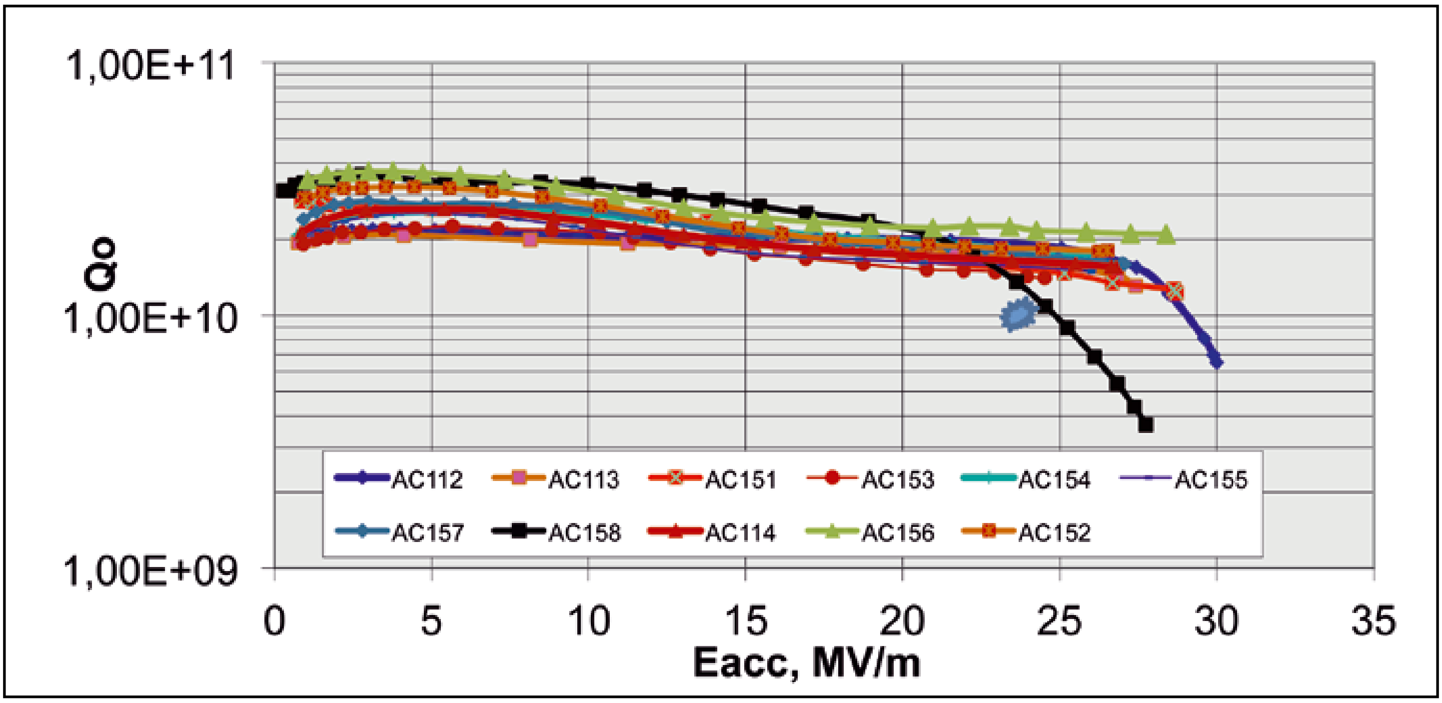


Figure 2

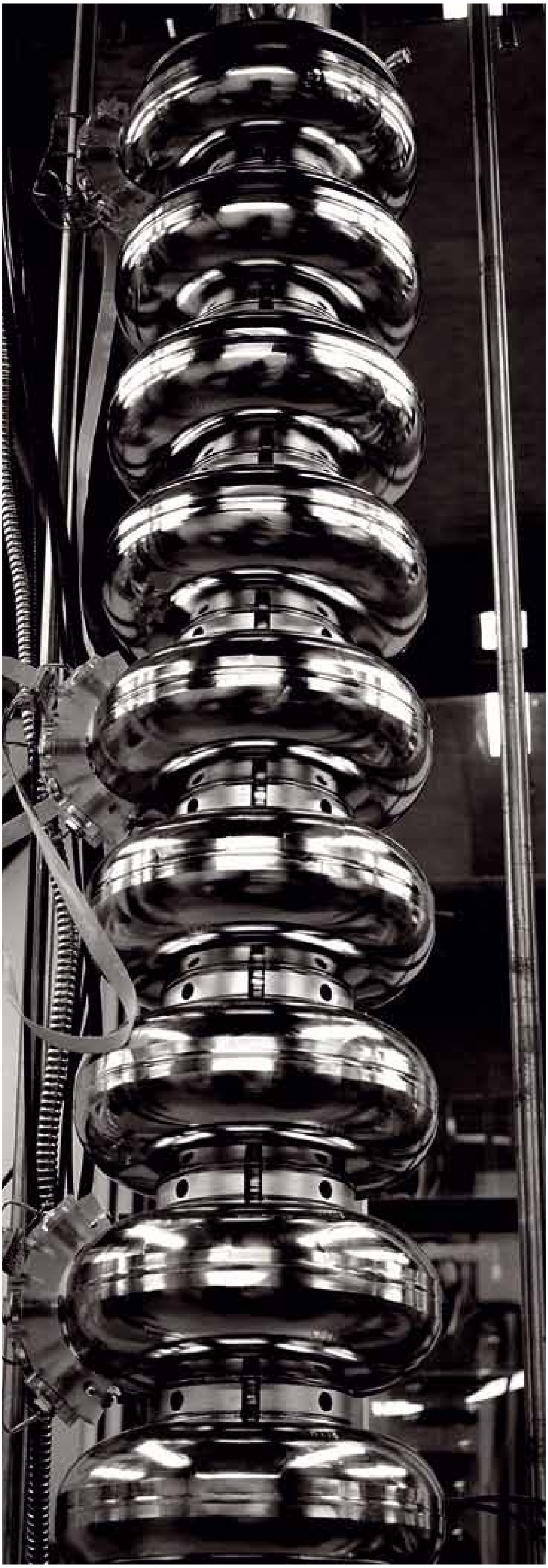
A superconducting nine-cell resonator manufactured from high-purity large-grain niobium

Considering the high quality factor, the simple preparation procedure and the small scattering in performance, BCP-treated LG cavities can be recommended for application in accelerators with medium requirements on accelerating gradients, in particular for continuous-wave (CW) operation. In conjunction with the low-loss (LL) cavity shape, where the magnetic to electric field ratio is lower by around 15% and the limit in the achievable accelerating gradient is correspondingly enhanced, LG BCP cavities are also of interest for the International Linear Collider (ILC) project.

Contact: Waldemar Singer, waldemar.singer@desy.de

Figure 1

Quality factor (Q) and accelerating gradient (E_{acc}) of the LG cavities AC112–AC114 and AC151–AC158 at 2 K. The cavities were treated using 100 µm rough BCP, annealing at 800°C for 2 h, followed by a fine BCP of 20 µm and baking at 120°C for 48 h (AC112 was not baked). The star shows the European XFEL requirements.



Cavities for electron accelerator diagnostics in the European XFEL.

Cavity beam position and dark-current monitors for improved beam diagnostics

For optimum free-electron laser performance, the electron beam position must be controlled with high precision in the undulator sections. For this purpose, cavity beam position monitors with dipole mode coupling have been developed for the European XFEL. These monitors have the potential to achieve resolutions below 1 µm. First oscilloscope measurements at FLASH already show resolutions between 1 and 2 µm, to be improved with dedicated electronics. Another cavity type will be used to measure the dark current produced from field emission in the accelerator. First measurements at PITZ verify the principle and demonstrate the additional potential of this cavity for beam charge and bunch length measurements.

To ensure reliable accelerator operation, the properties of the beam must be tightly controlled. When a charged beam passes a cavity, it induces electromagnetic fields. These fields contain information on the beam properties. The signal can be extracted in a non-destructive manner, with better resolution compared to conventional methods.

The signal of a cavity beam position monitor (BPM) detecting the field strength of a dipole mode is proportional to the beam offset and its charge. The charge and phase normalization is done by a second cavity where a monopole mode, proportional to charge only, is detected. The smaller the amplitude from the dipole field, the smaller the offset. Compared to a button BPM where two adjacent signals have to be subtracted, the cavity BPM will deliver better resolution. The higher resolution is necessary in the undulator area of the European XFEL to align the quadrupole magnets so that the electron and photon beam can overlap on a straight line.

To check the operation of cavity BPM prototypes, a test setup was installed at FLASH (Fig. 1). It contains three undulator cavity BPMs with an inner tube diameter of 10 mm and one beamline cavity BPM with the standard European XFEL inner tube diameter of 40.5 mm. The latter monitor is foreseen for special positions in the beamline where high resolution is required. To avoid crosstalk due to the large tube diameter between dipole and monopole cavities, a larger distance between the two is required, resulting in a total length of 25 cm, compared to a length of 10 cm for the undulator BPM with a 10 mm beam pipe. To avoid individual tuning of the BPMs, the mechanics is machined very precisely so that the resonance frequency does not deviate by more than ±25 MHz from the 3.3 GHz centre frequency. This range is within the acceptable limits for the electronics.

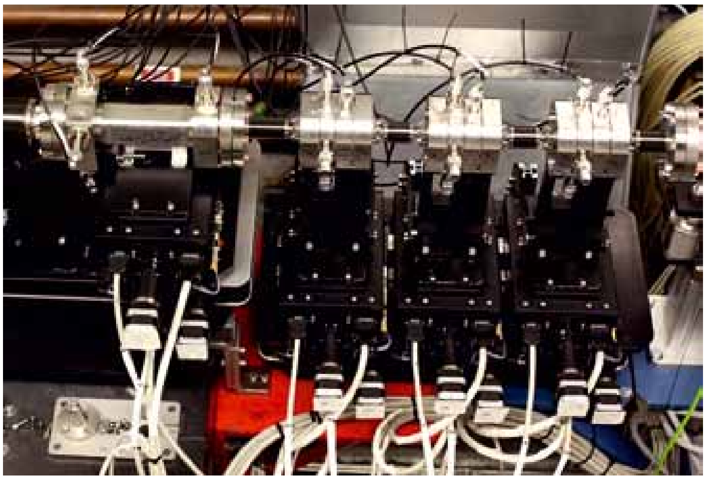


Figure 1

Three undulator cavity BPMs and one beamline cavity BPM at FLASH. The beam passes through the setup from right to left.

So far, laboratory and beam measurements are in good agreement with expectation. The decoupling of horizontal and vertical planes exceeds the specification. This confirms the high machining precision.

First resolution measurements were made with an oscilloscope, as the dedicated electronics system will be available from 2011. Figure 2 shows that within the error bars, the resolution is independent of beam charge. As expected, the beamline BPM has an inferior resolution due to higher-order modes. Nevertheless, it still is better than the specified resolution of 10 µm. Strong suppression of higher-order modes by the dedicated electronics promises even better performance. The resolution of the undulator cavity BPM is between 0.9 and 2 µm for the complete charge range, which shows the potential of these

BPMs for low-charge operation. Limitations of the oscilloscope, especially due to the 8 bit ADC, will be overcome by the dedicated electronics, which features a 16 bit ADC, so that significant improvements are expected.

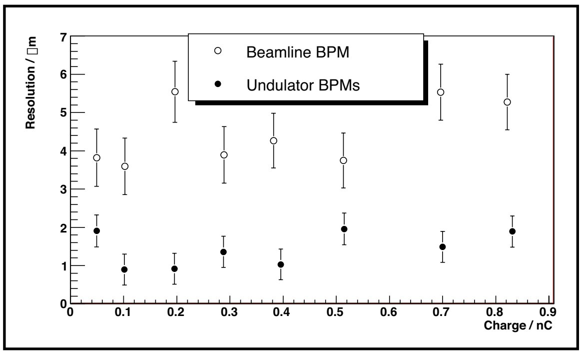


Figure 2

Resolution of the undulator and beamline cavity BPM as a function of beam charge

Another cavity type was developed to detect the dark current caused by field emission in the accelerator. This dark current generates radiation background in the tunnel which destroys the electronics and activates components. Kickers, doglegs and collimators are used to eliminate it. Up to now, the efficiency of dark-current reduction was measured with beam loss monitors (indirect) and destructive Faraday cups (FC). To improve the measurement, a dark-current monitor (DaMon) that allows non-interceptive measurements was developed. It consists of a monopole mode cavity tuned to the acceleration frequency. The fields induced from successive weakly-charged dark-current bunches add up resonantly to a measurable field level. To prove the method, a DaMon with the resonance frequency of the first monopole mode of 1.3 GHz was installed at PITZ (Fig. 3). The beam charge is directly proportional to the monopole mode field strength that determines the sensitivity. The factor of proportionality was taken from a simulation of the DaMon. In Fig. 4, this beam charge measurement is compared to a measurement with an FC. Both charge measurements are in good agreement over more than three orders of magnitude. This confirms the expected DaMon sensitivity. In addition, the statistical errors from the DaMon are much smaller compared to the FC, indicating a non-destructive charge measurement with better resolution. The dark current is also measured as a function of the injector solenoid current (Fig. 5). It could be shown that the dark current can be measured down to a lower limit of 50 nA. Since the FC cannot detect such low dark-current values, the DaMon is a significant improvement.

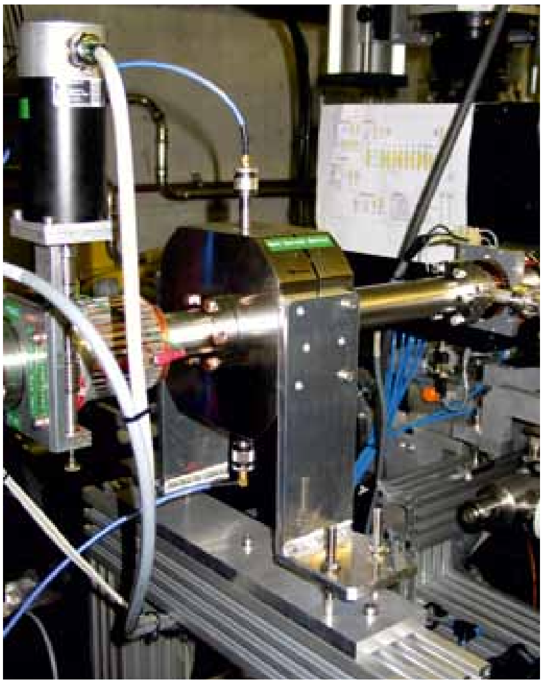


Figure 3

DaMon at PITZ

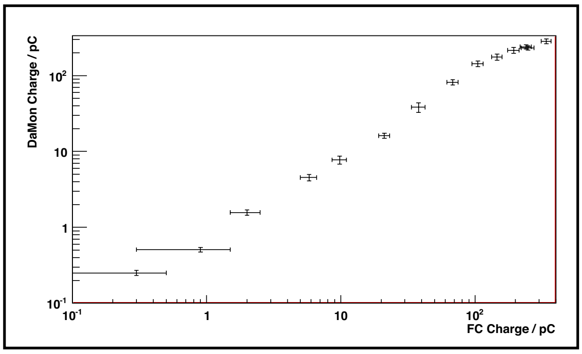


Figure 4

Beam charge measured with the DaMon as a function of the FC measurement

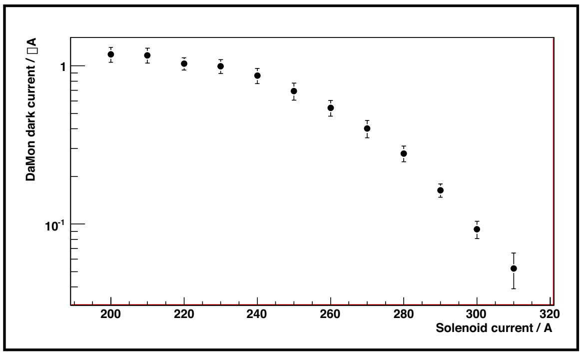


Figure 5

Dark current as a function of solenoid current

As the amplitudes of higher-order monopole modes are also a function of bunch length, the ratio of amplitudes from higher-order monopole modes can be used to determine the bunch length. The amplitudes are measured with a spectrum analyser without any dedicated electronics. This results in a bunch length of s = 11 ± 3 ps at the highest beam energy, which is in agreement with destructive streak camera measurements. Such a cavity can thus be used to measure the bunch length as well. Dedicated electronics for the detection of higher-order mode amplitudes should improve the resolution and could allow for online detection of the bunch length of single bunches.

In summary, cavity monitors can measure different beam properties in a non-destructive manner and provide better resolutions compared to conventional methods. Dedicated electronics will improve the resolutions. More interesting developments and results are therefore expected in the near future.

Contact: Dirk Lipka, dirk.lipka@desy.de

Temperature calculations for the European XFEL.

Hot stuff, cool calculation

To achieve a good stability of the European XFEL facility during the commissioning phase, the temperature variation in the tunnels must be minimized. It is therefore important to have precise calculation methods to predict the temperature. The first calculations were started to resolve the question whether the pulse cables installed in the linear accelerator (LINAC) tunnel would be operating within the allowed temperature range or not. In doing so, it was found that there might be a temperature problem in the LINAC tunnel. The aim of the calculations was therefore enhanced and the temperature profile of the entire LINAC tunnel calculated. These calculations have been extended to other European XFEL tunnels like XTD1, XTD2 and XTD10.

Layout and geology

The European XFEL facility will be located mainly in underground tunnels at depths between 6 and 38 m. Figure 1 shows a cross section of the LINAC tunnel. It is divided into three parts: main tunnel, left and right cable channel. The LINAC tunnel lies entirely underground. It has a total length of about 2 km, a diameter of 5.2 m and a depth between 6 and 15 m.

To visualize the temperature variation inside the tunnel, the heat transfer balance in the tunnel has to be calculated. This heat transfer depends partially on the geology of the ground surrounding the tunnel. Most of the LINAC tunnel is surrounded by glacial till. Part of it, at the beginning and at the end, is running through sand in groundwater. In addition to the boundary conditions, the tunnel requirements, such as heat sources and heat sinks, air volume of the tunnel, magnet power supply, water supply, air conditioning, racks, etc., were taken into account.

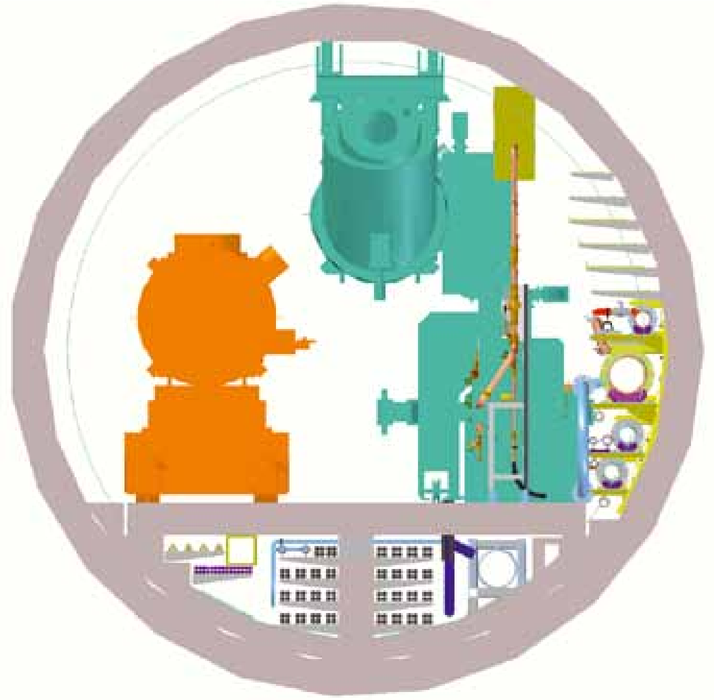


Figure 1

Cross section of the LINAC tunnel

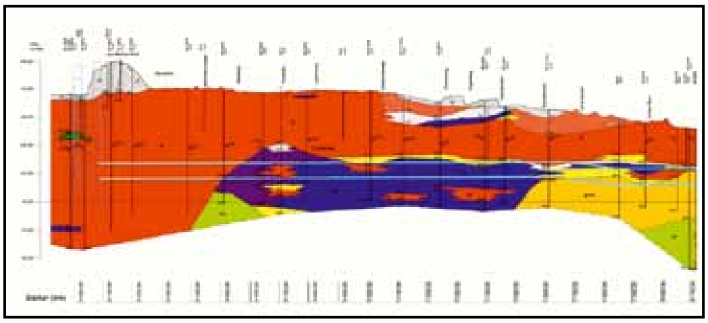


Figure 2

Geology of the LINAC tunnel

Mathematical approach

The fundamental equation of thermodynamics states that thermal change is proportional to energy change. The temperature variation in the longitudinal direction is therefore proportional to the sum of changes in the tunnel. The energy balance in the entire tunnel can be determined and solved with a differential equation. Since the LINAC tunnel consists of three parts, this leads to a system of three coupled differential equations showing crosstalk behaviour between the tunnel parts. For instance, the temperature change in the main tunnel influences the temperature in the left and right cable channel.

Only free convection is considered in the calculations. The heat transfer by radiation and conduction can be neglected. The calculations are done in the longitudinal direction of the tunnel, with a fixed iteration size of 5 m. This step size has been checked to yield converging solutions.

The temperature calculations were solved using MATLAB, a high-level language and interactive environment that enables intense computational tasks to be performed more easily than with traditional programming languages such as C, C++ and FORTRAN. To exchange parameters quickly and in a simple way, a graphical user interface (Fig. 3) was implemented within MATLAB.

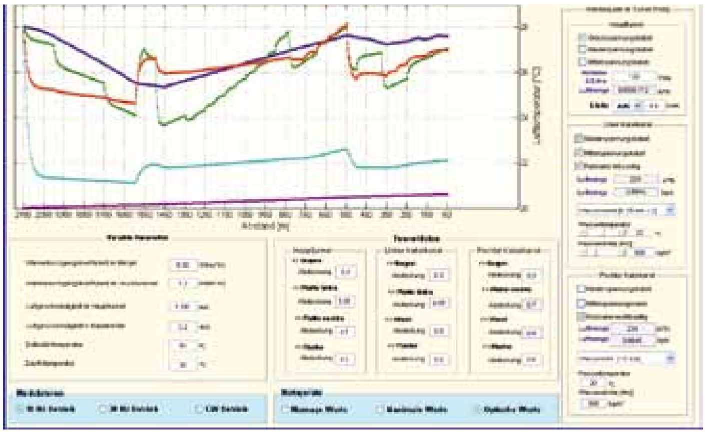


Figure 3

First graphical user interface

In the first graphical application, several parameters, like air volume, water temperature, transfer coefficient, turn on/off of heat sources and heat sink, etc., are variables. The associated values can be changed easily to investigate the temperature profile along the tunnel. The inlet temperature is given as the initial value. A second graphical user interface (Fig. 4) was implemented to determine the temperature profile along the LINAC tunnel according to the different operating conditions of the European XFEL facility.

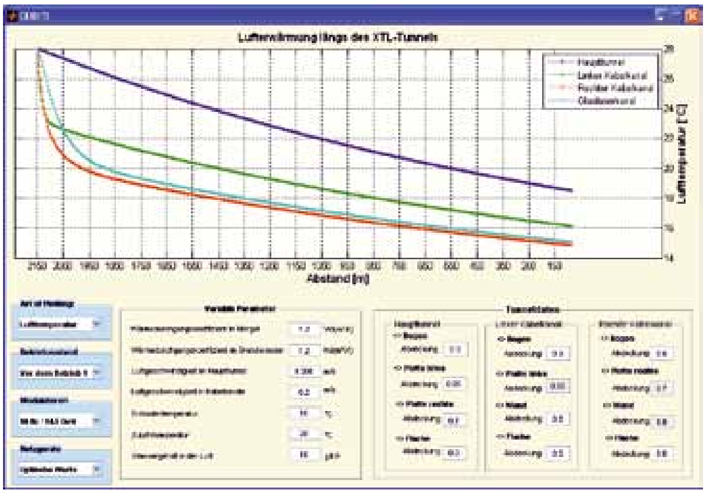


Figure 4

Second graphical user interface

Verifying the simulation results

Depending on the operating conditions, maximum equilibrium temperatures of about 29 to 37°C can occur in the LINAC tunnel. Figure 5 presents an example of the temperature profile in the tunnel. It assumes a worst-case scenario with an inlet temperature of 32°C. This profile would be reached after a few years of machine operation, when part of the LINAC tunnel surrounded by glacial till will get warm. The results of the calculation were compared to measurements done in the HERA tunnel at DESY. During HERA operation, temperatures in the same range were measured inside the tunnel.

Models are also available for the SASE tunnels XTD1, XTD2 and the photon beamline tunnel XTD10. Models for the other tunnels will be finished soon to have the possibility to investigate all possible questions.

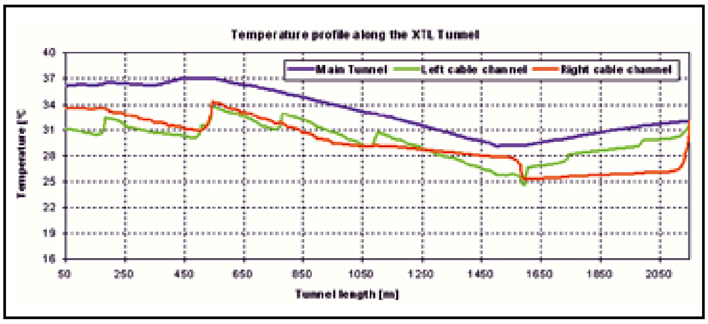


Figure 5

Worst-case scenario of temperature profile along the LINAC tunnel

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Contact: Frank-Reinhard Ullrich, frank-reinhard.ullrich@desy.de
Hans-Jörg Eckoldt, hans-joerg.eckholdt@desy.de
Narcisse Ngada, narcisse.ngada@desy.de

Electron interactions in our FELs.

Numerical modelling of collective effects in a free-electron laser

To realize a free-electron laser of high performance, we need to design and optimize it by taking into account the dynamics of electrons and their interactions with each other and with their surroundings. An accurate self-consistent simulation of collective effects in the charged beams remains a challenging problem for numerical analysis. To understand the complicated collective particle behaviour, we are developing new numerical and analytical techniques and carrying out extensive numerical simulations on modern parallel computer clusters.

Over the past decades, there has been a steady advance in the use of numerical methods to explore the physics of accelerators and free-electron lasers. The computations are done to discover new physics, design new devices and check analytical theory. We use numerical studies on computers for failure analysis and optimization of existing systems. With the help of numerical experiments, we try to understand what is going on in the real facilities. Computational resources are always limited and we need to continually develop new numerical methods for solving larger problems on the existing hardware.

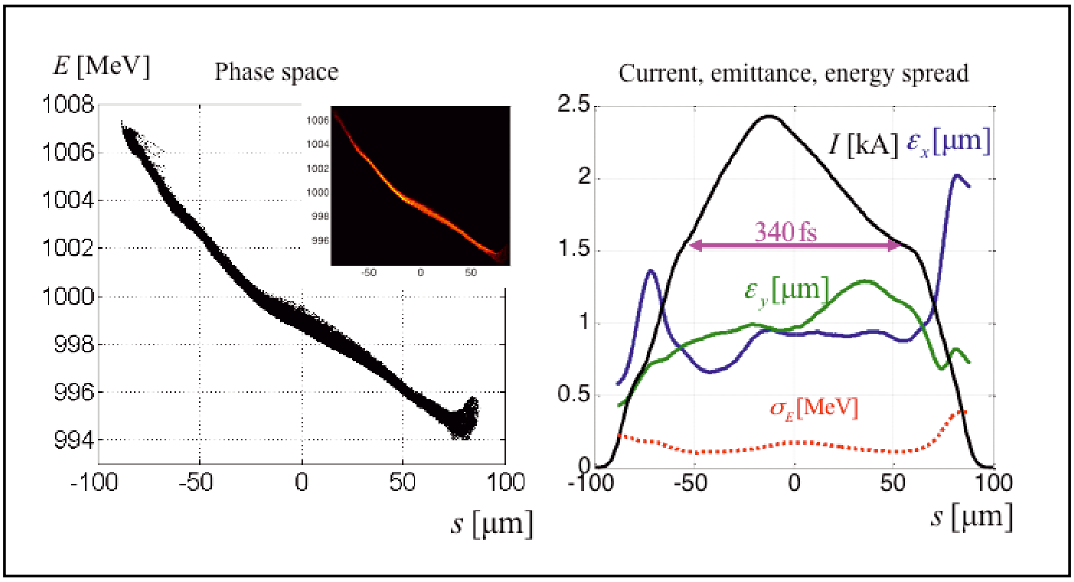

Figure 1

The properties of the bunch after the second bunch compressor, as obtained by 3D self-consistent simulations

FELs are usually based on a linear accelerator followed by a high-precision insertion device. The accelerated electrons travel through a spatially periodic magnetic field (the undulator) which causes them to radiate light. The intensity of this radiation is proportional to the square of the electron density. The beam quality thus critically determines the performance of the FEL. To study and optimize our design, self-consistent beam dynamics of many charged particles interacting with each other and with their surroundings (external fields and the vacuum chamber) must be considered. The main difficulty is the large number of electrons contained in one bunch. A multiparticle system of this size cannot be efficiently simulated in full complexity even with modern parallel computers. Additional difficulties are the very different scales of various processes (e.g. photon wavelength, bunch length, undulator length).

To achieve high phase space density, several bunch compressors are used and nonlinearities of the radio frequency (RF) fields are corrected with a higher-harmonic RF system. Analytical estimations of RF tolerances are used to pre-optimize the parameters of the accelerator and bunch compression system. These solutions neglect collective effects that are considered in tracking calculations and further optimizations. Important collective effects are wake fields (interaction with surrounding), space charge effects and coherent synchrotron radiation (CSR). To take the CSR in bunch compressors into account, we use the code CSRtrack. This code tracks particle ensembles on arbitrary curved trajectories. It offers different algorithms for the field calculation: from the fast "projected" one-dimensional method to the most rigorous one, the three-dimensional integration over 3D Gaussian sub-bunch distributions. Tracking on straight trajectories is done with analytical estimations or based on the straightforward tracking code ASTRA. This program tracks particles through user-defined external fields, taking into account distortions and nonlinearities as well as space charge fields of the particle cloud.

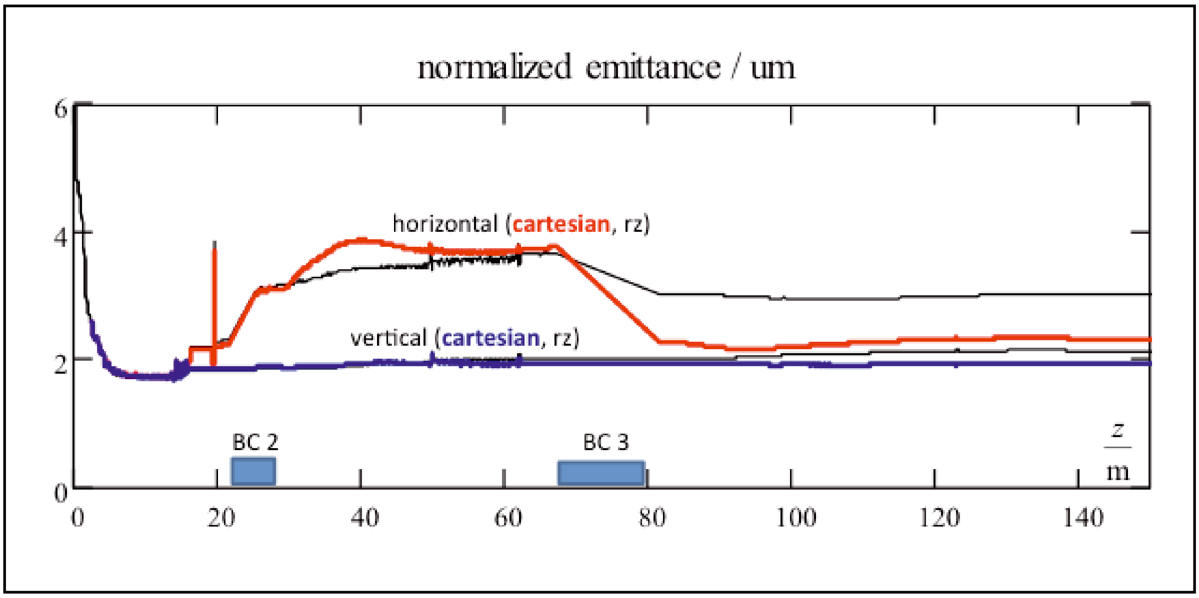

Figure 2

Emittance of the electron bunch as it travels along FLASH

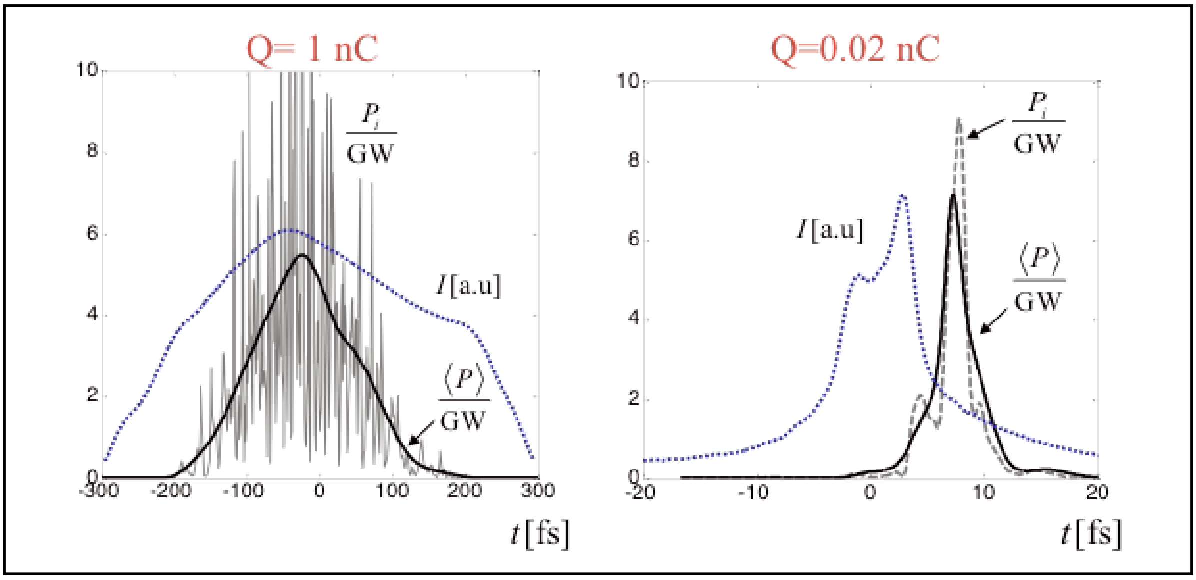

Figure 3

Temporal structure of the radiation pulse at saturation for charges of 1 nC (left) and 20 pC (right). The solid and dashed lines correspond to an averaged and single pulse profile, respectively. The dotted line shows the profile of the electron bunch.

The codes CSRtrack and ASTRA neglect the impact of the vacuum chamber. This is considered by coupling impedances (or wake functions). The wake field code ECHO was used to extrapolate the wake of different beamline elements for ultrashort bunches. For example, the wake functions of accelerating cavities, third-harmonic modules and many other elements used in the accelerator design for the European XFEL are estimated with the help of this code. For the adjustment of the RF parameters, we use an iterative procedure that starts from the analytical solution without self-interaction. The iterative scheme is robust and quickly converges to the solution. We applied this iterative algorithm in our recent studies to find the working points for the two-stage bunch compressor system in FLASH and the three-stage bunch compression and acceleration system in the European XFEL.

Figure 1 presents results from simulations of FLASH with all collective effects. The left plot shows the longitudinal phase space. The current profile $\mathrm{I(s)}$, slice emittances $\varepsilon_x\,(\mathrm{s})$, $\varepsilon_y\,(\mathrm{s})$ and rms slice energy spread $\sigma_E\,(\mathrm{s})$ can be seen in the right diagram.

The projected emittance along FLASH in Fig. 2 is obtained by two ASTRA approaches: simplified rz method and 3D. The figure clearly shows that in design optics, emittance growth is partially compensated. The results of beam dynamics simulations have been used as an input for the FEL code ALICE. With the help of self-consistent simulations of the FEL process, we have estimated the properties of the radiation for different charges at the radiation wavelength $\lambda = 6.5$ nm. Figure 3 presents some properties of the radiation. The plot shows that a single X-ray spike with full longitudinal coherence may be expected for a bunch charge of 20 pC. Such a bunch may generate a radiation power of several GW at the wavelength $\lambda = 6.5$ nm and nearly a single longitudinal spike of several femtoseconds. Such high-power, ultrashort pulses will open new applications in many areas of science. The achieved beam brightness may enable a more compact design of future hard X-ray FEL facilities.

Contact: Martin Dohlus, martin.dohlus@desy.de
Igor Zagorodnov, igor.zagorodnov@desy.de

Achromatic and apochromatic beam transport.

From abstract theory to the design of the European XFEL beamlines

The optical design of the beam distribution and transport lines for the European XFEL facility must meet a very tight set of performance specifications. An important part of these specifications comes from the requirement to minimize the dependence of the optics on the particle energy, because at relatively low energies, the beam still has an appreciable energy spread due to the energy chirp created for the bunch length compression in magnetic chicanes. The transport lines from the linear accelerator to the undulators should therefore be able to accept bunches with different energy (up to ±1.5% from nominal energy) to allow fine-tuning of the FEL wavelength by changing the electron beam energy without adjusting magnet strengths, or even to scan the FEL wavelength within a bunch train by appropriate programming of the low-level RF system. The further development and application of the theory of achromatic beam transport was therefore one of the main subjects of study in 2010.

Design of magnetic optical achromats

The symmetry-based second-order achromats were introduced in the field of accelerator physics at the end of the 1970s and quickly became a part of many accelerator designs. But even if it is clear that the automatic cancellation of some aberrations in the symmetry-based achromat designs follows from the symmetry of the magnet arrangement in the system, there were several questions that were not answered by any of the previously known theories. What is the exact role of the symmetry of the magnet arrangement? Why is the system transfer matrix equal to the unit matrix in both transverse planes in almost all known achromats? And the most important question: is there a magnet arrangement that will give better cancellation of aberrations than those already known? These questions were answered by looking at the achromat designs from the point of view of the theory of finite matrix groups.

Apochromatic beam transport

An essential part of the beam transport at the European XFEL facility consists of straight beamlines, which cannot be designed in such a way that a particle transport through them will not depend on the difference in particle energies. Moreover, this dependence cannot be removed even to first order with respect to the energy deviations.

As a way to overcome this problem, we have developed a concept of apochromatic beam transport, considering dynamics not of individual particles but of particle ensembles. It is clear that the dynamics of a particle ensemble can be sufficiently different from the behaviour of a single particle. For example, the set of particles uniformly distributed on the unit circle in the plane remains unchanged for an external observer after an arbitrary rotation around the origin of the coordinate system, while every single particle changes its position.

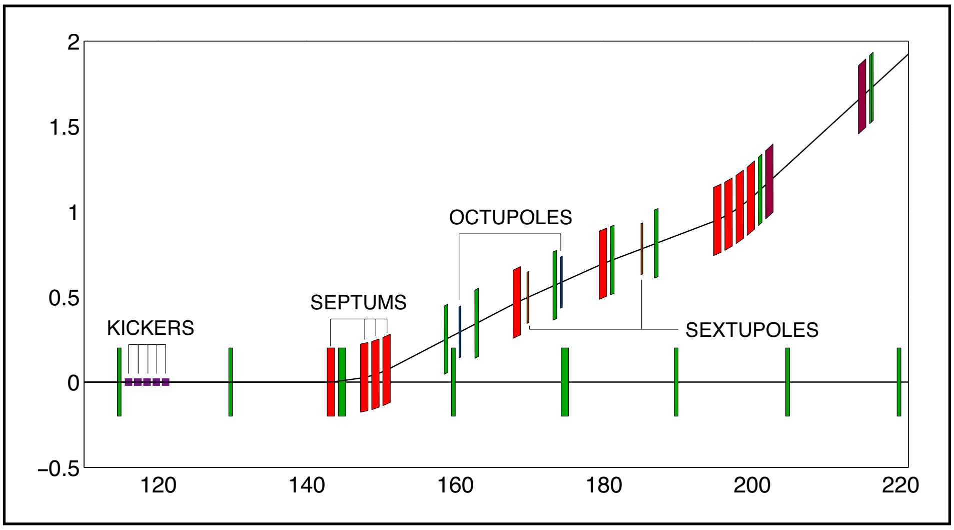

Figure 1

Top view of the separation area between two electron beamlines. Green, red and purple colours mark quadrupole magnets and horizontal and vertical dipole magnets, respectively. Horizontal and vertical distances are measured in metres.

Tilted multipoles

The beam separation between undulator beamlines at the European XFEL facility will be realized with a kicker–septum scheme. Because of the Lambertson-type septums used in the design, the deflection arc has non-zero horizontal and vertical dispersions simultaneously. This means that regardless of the fact that the linear on-energy betatron motion is still transversely uncoupled, we have not only the nonlinear dispersions generated in both transverse planes; vertical and horizontal oscillations also become chromatically coupled due to vertical dispersion in the horizontal bending magnets and horizontal dispersion in the vertical dipoles.

At first view, this will mean that the number of multipoles required for the correction of chromatic aberrations in such a beamline should be doubled compared to mid-plane symmetric systems. However, we have shown that the usage of tilted sextupoles and octupoles in such a beamline allows us to maintain the total number of multipoles required for the correction of chromatic aberrations on the same level than the one required in the mid-plane symmetric systems. Figures 1 and 2 show the design of the beam separation between two undulator beamlines with two tilted sextupoles and two tilted octupoles.

Contact: Vladimir Balandin, vladimir.balandin@desy.de

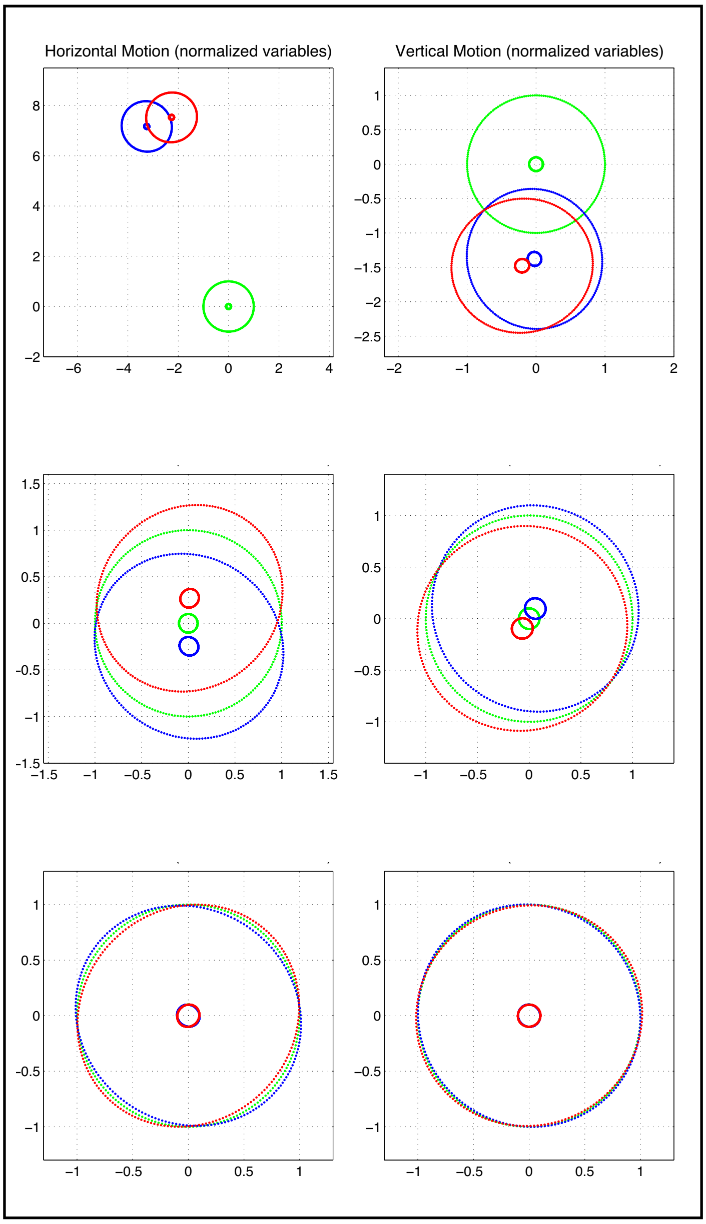

Figure 2

Phase space portraits of monochromatic 0.1 $\sigma_{x,y}$ and 1 $\sigma_{x,y}$ ellipses (matched at the entrance) after tracking through the deflection arc. The relative energy deviations are equal to −1.5%, 0% and +1.5% (red, green and blue ellipses, respectively). Sextupoles and octupoles are switched off (upper plots), sextupoles are on and octupoles are off (middle plots), sextupoles and octupoles are on (lower plots).

On the DESY accelerator ideas market.

Brainstorming for new ideas

The design and development of particle accelerators, accelerator physics and technology have a long and successful tradition at DESY. The development of novel concepts for future accelerators is of particular importance for the long-term future of the laboratory. To promote this aspect, DESY launched the "accelerator ideas market". Its purpose is to encourage all DESY employees and users interested in research and development for accelerators to participate and present their ideas in short summaries.

The first two events took place within one and a half days in June and again in one and a half days in November 2010. Everybody with a new idea for the development of accelerators and for accelerator research was invited to present it in a ten-minute talk followed by five minutes of discussion. The first event in June was already a great success. 36 contributions were presented, ranging from proposals for improving existing accelerator components, such as beam position monitors, over HERA as a synchrotron light source to a muon collider in the HERA tunnel. A team of experts evaluated the ideas using a questionnaire.

After the first event, work was performed towards the realization of the ideas, and it was proposed to present follow-up contributions reporting on those activities in November. At this second DESY accelerator ideas market, 13 follow-up contributions and 15 new ideas were presented. Both events exceeded the expectations of the organizers. The time planned for all presentations was fully used and lively discussions continued during a dinner session in the evening.

The presented subjects can be divided into two main categories. One comprises ideas driven by pure research issues, such as a Higgs, tau and Z factory, a muon collider test, European XFEL electron beams testing detectors, or doubly polarized HERA beams. The other proposals deal with challenges of accelerator physics, for example the addition of plasma acceleration sections to existing electron linacs used to drive free-electron lasers, further developments of the superconducting accelerator technology, new beam diagnostics methods, but also new operation modes of existing and future facilities like FLASH and the European XFEL.

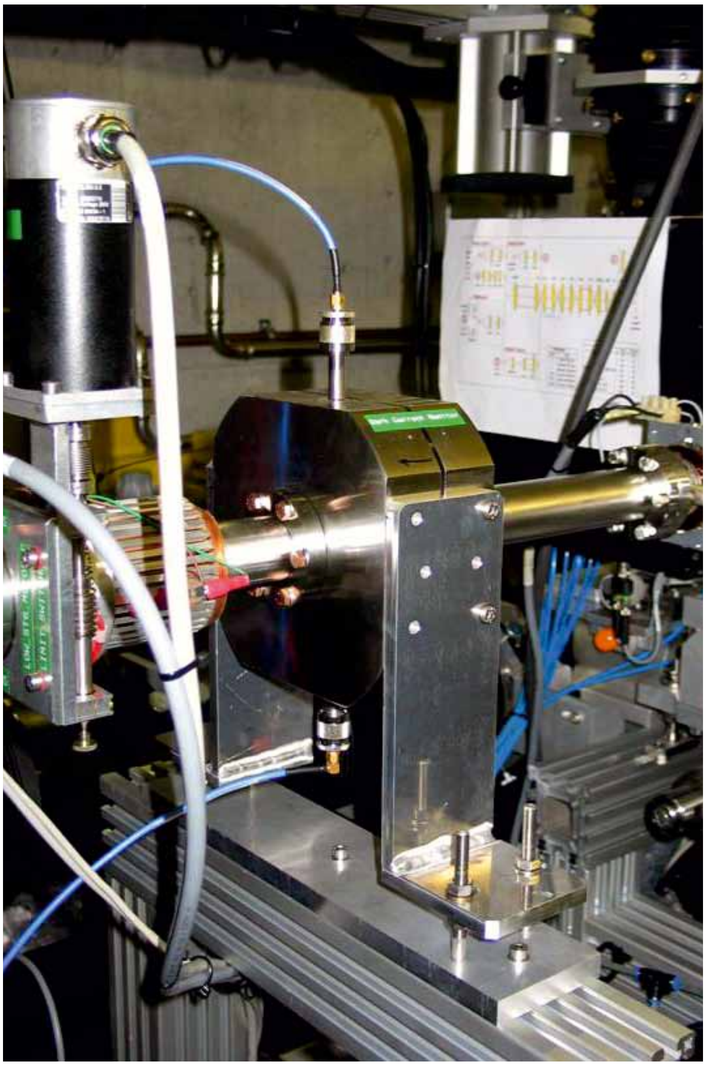

Figure 1

A new dark-current monitor already tested at PITZ

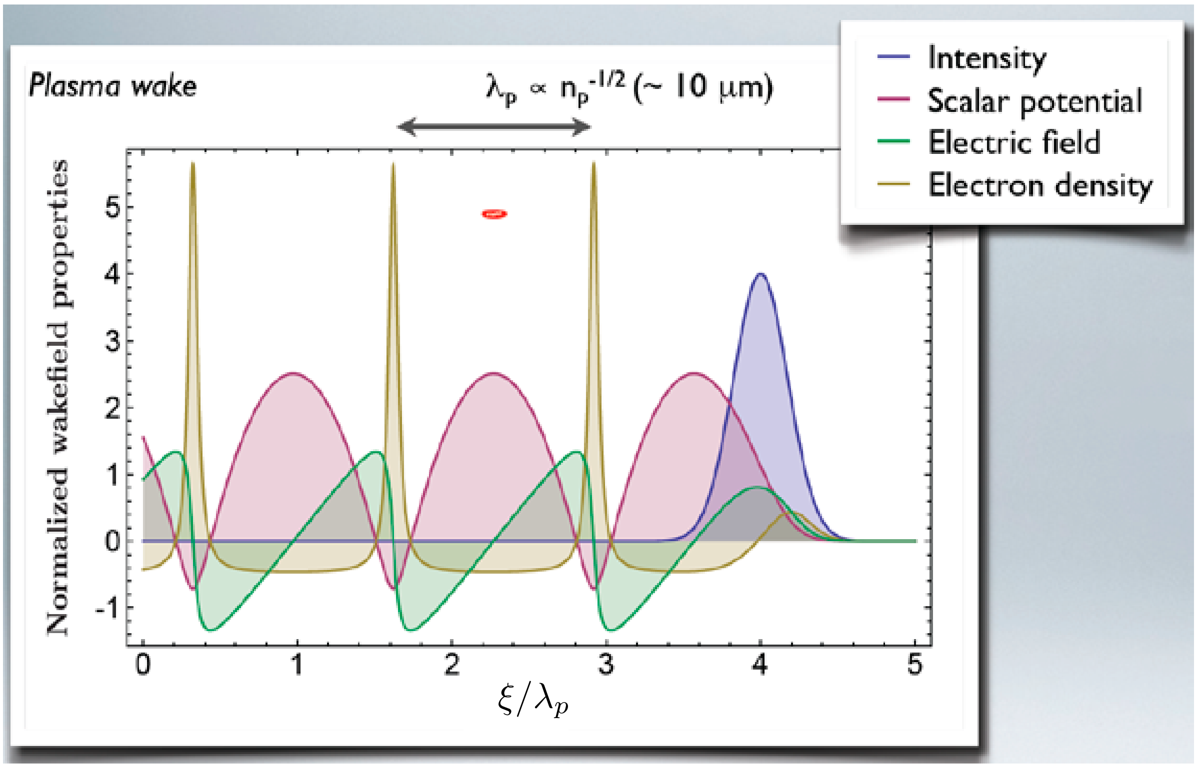

Figure 2

Plasma charge density modulation results in very high electrical fields, which can be used for acceleration. (Courtesy of Jens Osterhoff)

Several ideas for new accelerator concepts and technologies and for further development of present accelerator technology were included in a proposal from six Helmholtz research centres to set up an accelerator research and development (ARD) programme within the Helmholtz Association. Here, the DESY accelerator ideas market was very fruitful for collecting, discussing and providing new ideas.

In future, it is planned to organize one DESY accelerator ideas market every year. The next one is scheduled for late summer 2011.

Contact: Elmar Vogel, elmar.vogel@desy.de

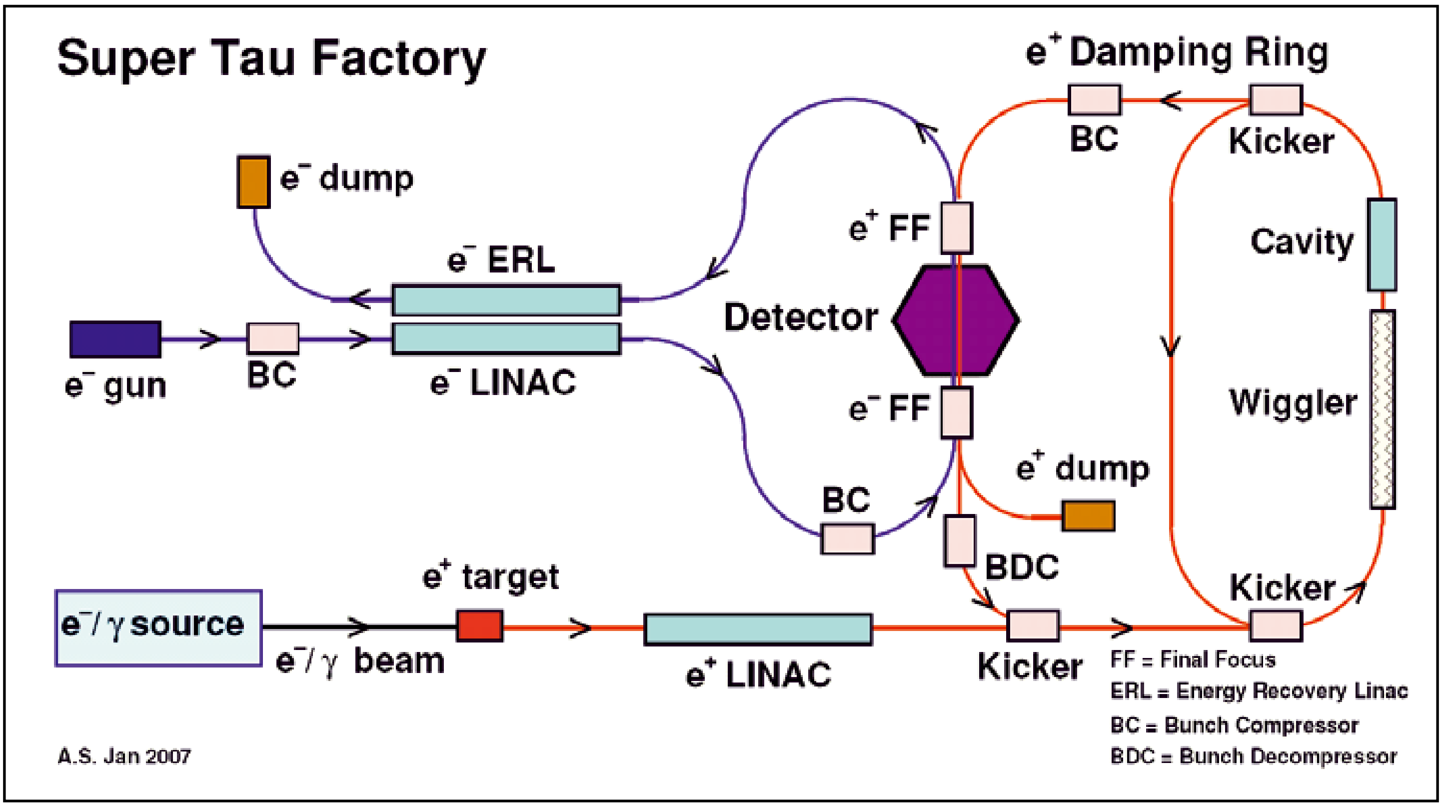

Figure 3

Study of linear collider concepts for a super-tau factory (Courtesy of Andre Schöning)

New concepts for free-electron lasers.

Improving the performance of FEL facilities

The excellent electron beam quality delivered today in linear accelerators for free-electron laser facilities makes it conceivable to generate X-ray beams of two or more different wavelengths in consecutive undulator sections. In fact, the initial design of the European XFEL facility already included a soft X-ray beamline downstream of the hard X-ray undulator, both using the same electron bunch train. Other ideas how to improve the performance of FEL facilities include a novel self-seeding scheme to enhance the typically poor longitudinal coherence of SASE FEL radiation and the use of longitudinal space charge instability to generate vacuum ultraviolet and X-ray radiation.

X-ray generation in consecutive undulator sections

At low beam emittance and thus short gain length, it is conceivable to produce two (or more) X-ray beams in the same undulator, tuned to different K parameters in subsequent sections (multi-colour scheme). One complication in such schemes is that an electron bunch that has already produced FEL radiation upstream is less useful for the FEL process in downstream sections due to its increased energy spread. A simple scheme has been worked out with which individual bunches in a train, as delivered from the superconducting linear accelerators of the European XFEL or FLASH, can be “switched on” to produce FEL radiation in certain undulator sections and “off” in other undulator sections. This could be done by deliberately inducing a trajectory betatron oscillation by means of a fast kicker and DC correction coil combination (Fig. 1).

In a two-colour scheme, for example, one bunch could pass on-axis through the first undulator section, generating X-ray FEL radiation at one wavelength, while being kicked off-axis (and thus being prevented from lasing) in the downstream undulator section. Another bunch would be treated the other way round (not lasing in the first section, lasing in the second). The timing between bunches would be variable to a large extent within the possibilities of the bunch train time structure of the superconducting linac.

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*Contact: Reinhard Brinkmann, reinhard.brinkmann@desy.de
Evgeny Shneydmiller, evgeny.shneydmiller@desy.de
Mikhail Yurkov, mikhail.yurkov@desy.de*

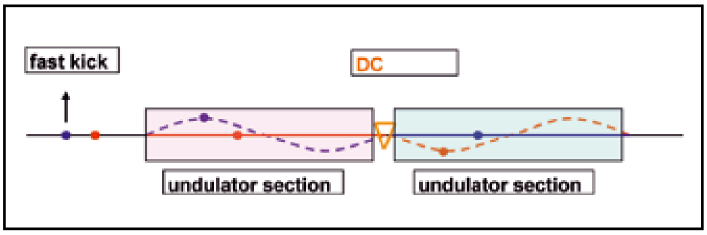


Figure 1

Switching scheme for individual bunches in a train

Self-seeding scheme

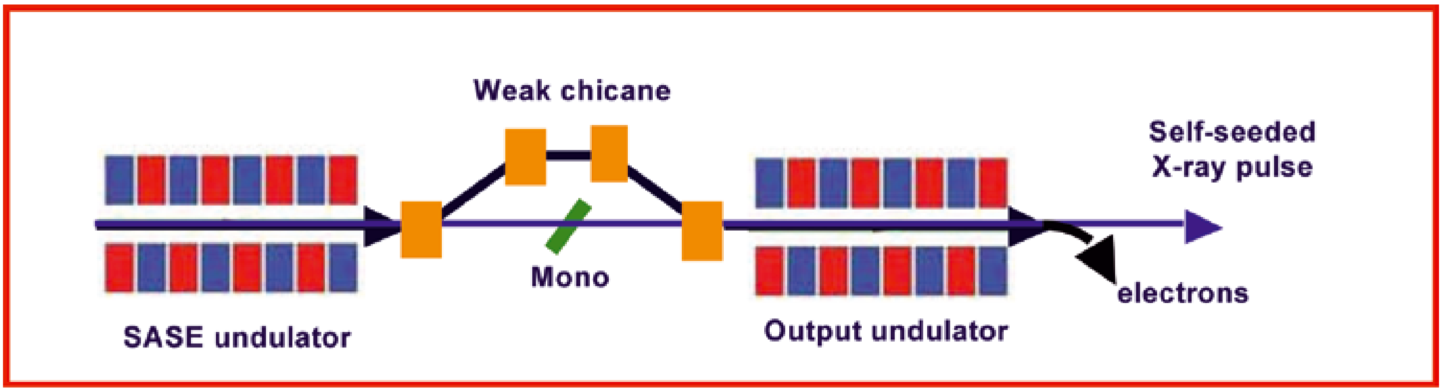
Another proposal is related to the typically poor longitudinal coherence of self-amplified spontaneous emission (SASE) FEL X-ray radiation, a characteristic inherited from the SASE process starting from shot noise. Self-seeding schemes are an answer to the call for improved longitudinal coherence. If applied to already working or designed X-ray FELs, these schemes are subject to constraints, including minimal change to the baseline design and the possibility to recover the baseline mode of operation.

Recently, a novel single-bunch self-seeding scheme was proposed. It is based on a particular kind of monochromator that relies on the use of a single crystal in Bragg transmission geometry. In its simplest configuration, the self-seeded X-ray FEL consists of an input undulator and an output undulator separated by such a monochromator (Fig. 2). However, in some experimental situations this simplest two-undulator configuration is not optimal. The obvious and technically possible extension is to use a setup with three or more undulators separated by monochromators.

With respect to performance, this amplification–monochromatization cascade scheme is characterized by a small heat-loading of crystals and a high spectral purity of the output radiation. It is particularly advantageous for the European XFEL. The power of the output signal can be further increased by tapering the magnetic field of the undulator. Once the cascade

Figure 2

Simple self-seeding scheme with input and output undulator and a monochromator



self-seeding scheme is combined with tapering in a tunable-gap baseline undulator at the European XFEL, a source of coherent radiation with unprecedented characteristics can be obtained at hard X-ray wavelengths, promising complete longitudinal and transverse coherence and a peak brightness three orders of magnitude higher than what is presently available at the LCLS X-ray free-electron laser in California.

In addition, the new source will generate hard X-ray beams at extraordinary peak (TW) and average (kW) power level. It can thus revolutionize fields like single-biomolecule imaging, inelastic scattering and nuclear resonant scattering. Our self-seeding scheme is extremely compact and takes almost no cost and time to implement. The proposed upgrade could take place during the commissioning stage of the European XFEL, opening a vast new range of applications from the very beginning of operations. We are currently preparing a feasibility study and exemplifications for the SASE2 beamline of the European XFEL.

Contact: Gianluca Geloni, gianluca.geloni@desy.de
Vitali Kocharyan, vitali.kocharyan@desy.de
Evgeni Saldin, evgeni.saldin@desy.de

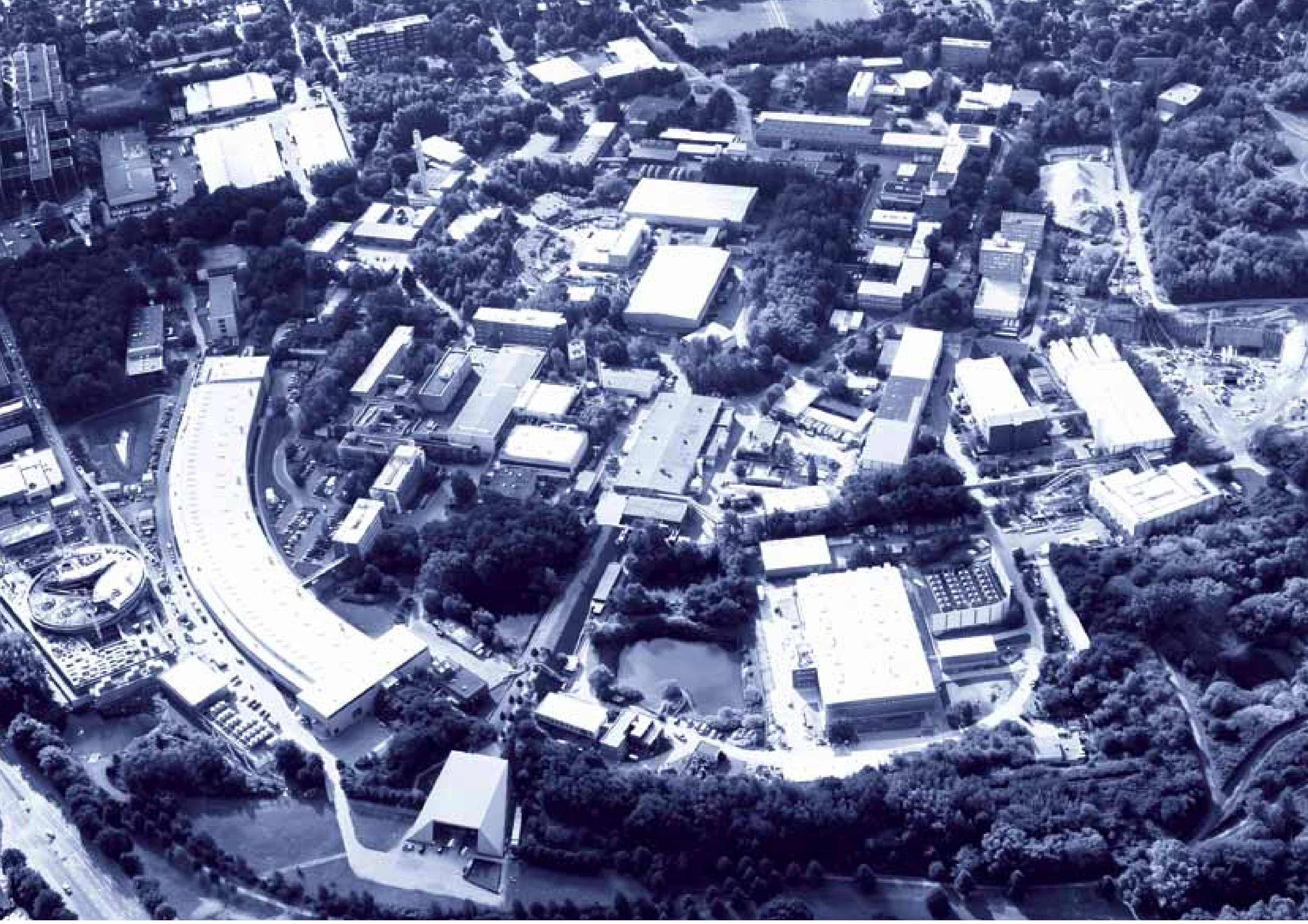
Longitudinal space charge amplifier

Yet another idea in this area of research consists of using the longitudinal space charge (LSC) instability for the generation of vacuum ultraviolet (VUV) and X-ray radiation. This instability was observed in different facilities in the infrared and visible wavelength ranges. Recent studies have shown that the LSC instability can be used in a constructive manner to generate high-power VUV and X-ray radiation by means of a longitudinal space charge amplifier (LSCA) consisting of several space charge amplification cascades (drift space plus chicane) with a short undulator behind the last cascade.

The amplification process typically starts from the shot noise in the electron beam. From the amplified wide-band density modulation, powerful radiation is produced in the final-stage undulator, which selects a narrow band (given by the inverse number of undulator periods) within the central cone. The LSCA can be used as a cheap addition to existing or planned short-wavelength FELs. In particular, it can produce the second colour for a pump-probe experiment.

It is also possible to generate attosecond pulses in the VUV and X-ray regimes. Some user experiments can benefit from a relatively large bandwidth of the radiation, which is easy to obtain in the LSCA scheme. Finally, since the amplification mechanism is broadband and robust, a LSCA can become an interesting alternative to a SASE FEL in the case of light sources driven by laser plasma accelerators.

Contact: Mikhail Yurkov, mikhail.yurkov@desy.de
Evgeny Shneydmiller, evgeny.shneydmiller@desy.de



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M. Hänel
Experimental investigations on the influence of the photocathode laser pulse parameters om the electron bunch quality in an RF Photoelectron source.
Universität Hamburg (2010)
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Diploma Thesis

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Resolution of different beam size read-out systems at PITZ.
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Publishing and contact
Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

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

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

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The Helmholtz Association contributes to solving major challenges facing society, science and industry with top scientific achievements in six research areas: Energy, Earth and Environment, Health, Key Technologies, Structure of Matter, Transport and Space. With 30 000 employees in 17 research centres and an annual budget of approximately 3 billion euro, the Helmholtz Association is Germany’s largest scientific organization. Its work follows in the tradition of the great natural scientist Hermann von Helmholtz (1821-1894).

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