WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the September 2016 issue of *CERN Courier*.

As the LHC continues with its record-breaking 2016 performance, a new "super-B factory" designed to search for new weak interactions in the flavour sector – Belle II at SuperKEKB – is nearing completion at the KEK laboratory in Japan. The inauguration of the MAX IV light source in Sweden, meanwhile, showcases another machine milestone: a novel lattice design that produces the brightest X-rays on Earth. Sticking with the accelerator theme, we also report on an attempt to use a storage ring to pinpoint the electric dipole moment of particles. Finally, the CMS collaboration describes how a new trigger system is taming the harsh collision environment of LHC Run 2, while CERN considers how to deal with the computing and data challenges presented by its major machine upgrade, the HL-LHC.

To sign up to the new-issue alert, please visit:
http://cerncourier.com/cws/sign-up.

To subscribe to the magazine, the e-mail new-issue alert, please visit:
http://cerncourier.com/cws/how-to-subscribe.

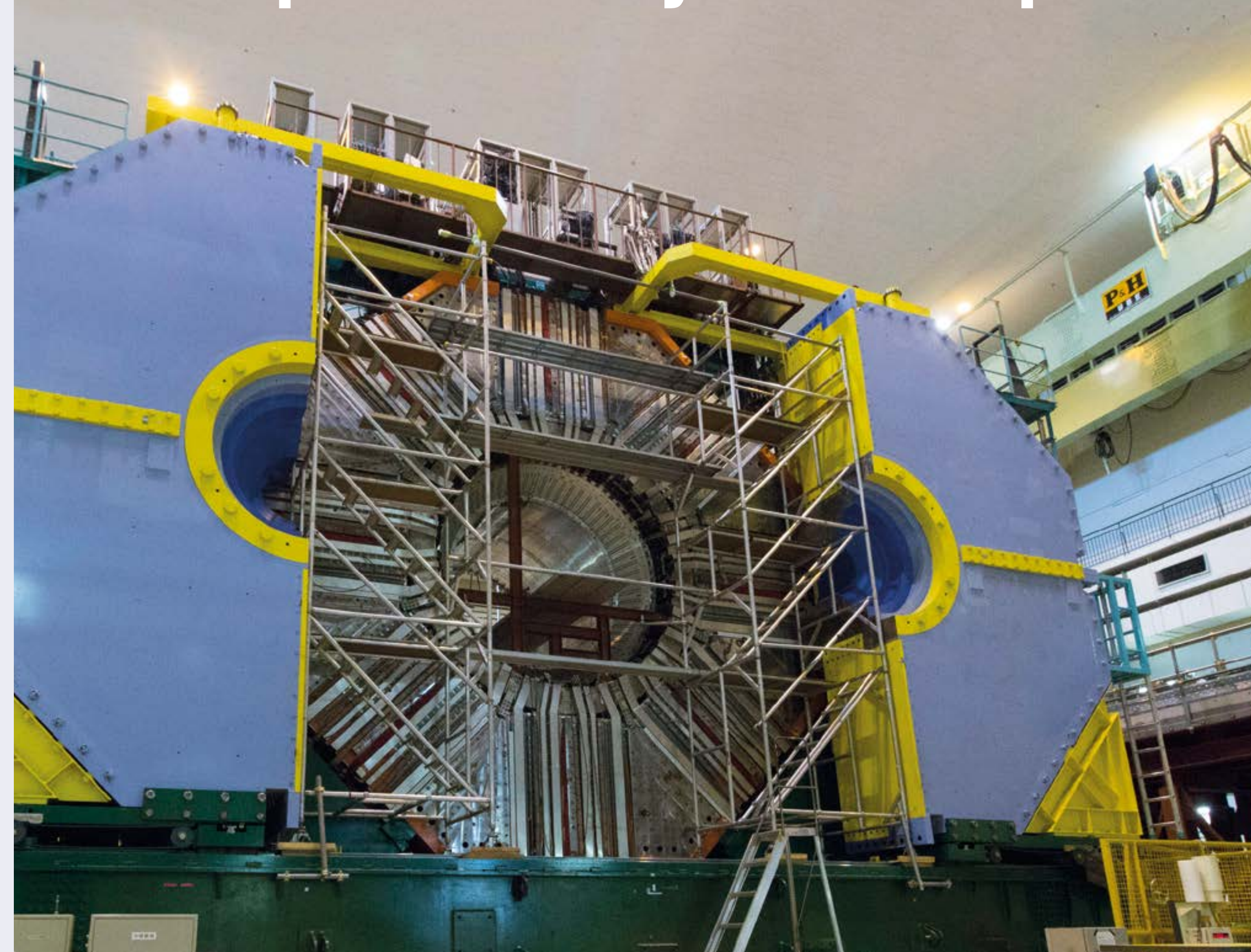
EDITOR: MATTHEW CHALMERS
DIGITAL EDITION CREATED BY JESSE KARJALAINEN/IOP PUBLISHING, UK

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 56 NUMBER 7 SEPTEMBER 2016

Super-B factory takes shape



DETECTORS

CMS trigger upgrade tames collisions at LHC Run 2
p21

FACILITIES

MAX IV takes X-ray science into uncharted territory
p38

COMPUTING IN THE CLOUD

CERN prepares for the HL-LHC and beyond **p5**

Contents

Covering current developments in high-energy physics and related fields worldwide

CERN Courier is distributed to member-state governments, institutes and laboratories affiliated with CERN, and to their personnel. It is published monthly, except for January and August. The views expressed are not necessarily those of the CERN management.

Editor Matthew Chalmers
Books editor Virginia Greco
CERN, 1211 Geneva 23, Switzerland
E-mail cern.courier@cern.ch
Fax +41 (0) 22 76 69070
Web cerncourier.com

Advisory board Luis Alvarez-Gaume, Peter Jenni, Christine Sutton, Claude Amsler, Roger Bailey, Philippe Bloch, Roger Forty

Laboratory correspondents:
Argonne National Laboratory (US) Tom LeCompte
Brookhaven National Laboratory (US) P Yamin
Cornell University (US) D G Cassel
DESY Laboratory (Germany) Till Mundzeck
EMFCSC (Italy) Anna Cavallini
Enrico Fermi Centre (Italy) Guido Piragino
Fermi National Accelerator Laboratory (US) Katie Yurkewicz
Forschungszentrum Jülich (Germany) Markus Buescher
GSI Darmstadt (Germany) I Peter
IHEP, Beijing (China) Tongzhou Xu
IHEP, Serpukhov (Russia) Yu Ryabov
INFN (Italy) Antonella Varaschin
Jefferson Laboratory (US) Kandice Carter
JINR Dubna (Russia) B Starchenko
KEK National Laboratory (Japan) Saeko Okada
Lawrence Berkeley Laboratory (US) Spencer Klein
Los Alamos National Laboratory (US) Rajan Gupta
NCSL (US) Ken Kingery
Nikhef (Netherlands) Robert Fleischer
Novosibirsk Institute (Russia) S Eidelman
Orsay Laboratory (France) Anne-Marie Lutz
PSI Laboratory (Switzerland) P-R Kettle
Saclay Laboratory (France) Elisabeth Locci
Science and Technology Facilities Council (UK) Jane Binks
SLAC National Accelerator Laboratory (US) Farnaz Khadem
TRIUMF Laboratory (Canada) Marcello Pavan

Produced for CERN by IOP Publishing Ltd
IOP Publishing Ltd, Temple Circus, Temple Way,
Bristol BS1 6HG, UK
Tel +44 (0)117 929 7481

Publisher Susan Curtis
Production editor Lisa Gibson
Technical illustrator Alison Tovey
Group advertising manager Chris Thomas
Advertisement production Katie Graham
Marketing & Circulation Angela Gage

Head of B2B & Marketing Jo Allen
Art director Andrew Giaquinto

Advertising
Tel +44 (0)117 930 1026 (for UK/Europe display advertising)
or +44 (0)117 930 1164 (for recruitment advertising);
E-mail: sales@cerncourier.com; fax +44 (0)117 930 1178

General distribution Courrier Adressage, CERN, 1211 Geneva 23, Switzerland
E-mail: courrier-adressage@cern.ch
In certain countries, to request copies or to make address changes, contact:
China Ya'ou Jiang, Institute of High Energy Physics,
PO Box 918, Beijing 100049, People's Republic of China
E-mail: jiangyo@mail.ihep.ac.cn
Germany Antje Brandes, DESY, Notkestr. 85, 22607 Hamburg, Germany
E-mail: desypr@desy.de
UK Mark Wells, Science and Technology Facilities Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1SZ
E-mail: mark.wells@stfc.ac.uk
US/Canada Published by Cern Courier, 6N246 Willow Drive,
St Charles, IL 60175, US. Periodical postage paid in St Charles, IL, US
Fax 630 377 1569. E-mail: creative_mailing@att.net
POSTMASTER: send address changes to: Creative Mailing Services, PO Box 1147,
St Charles, IL 60174, US

Published by European Organization for Nuclear Research, CERN,
1211 Geneva 23, Switzerland
Tel +41 (0) 22 767 61 11. Telefax +41 (0) 22 767 65 55

Printed by Warners (Midlands) plc, Bourne, Lincolnshire, UK

 ISSN 0304-288X

IOP Publishing

CERN

CERNCOURIER

VOLUME 56 NUMBER 7 SEPTEMBER 2016

On the cover: The Belle II detector at Japan's KEK laboratory. (Image credit: Shota Takahashi, KEK.)

Viewpoint

The end of computing's steam age

Cloud technology offers a promising solution for the computing needs of particle physics.

Sophia Elizabeth Bennett

The CERN data centre is the heart of the Worldwide LHC Computing Grid, but the future of scientific computing could be on a dedicated Science Cloud.

By Eckhard Elsen

Steam once powered the world. If you wanted to build a factory, or a scientific laboratory, you needed a steam engine and a supply of coal. Today, for most of us, power comes out of the wall in the form of electricity.

The modern-day analogue is computing: if you want to run a large laboratory such as CERN, you need a dedicated computer centre. The time, however, is ripe for change.

For LHC physicists, this change has already happened. We call it the Worldwide LHC Computing Grid (WLCG), which is maintained by the global particle-physics community. As physicists move towards the High Luminosity LHC (HL-LHC), however, we need a new solution for our increasingly demanding computing and data-storage needs. That solution could look very much like the Cloud, which is the general term for distributed computing and data storage in broader society.

There are clear differences between the Cloud and the Grid. When developing the WLCG, CERN was able to factor in technology that was years in the future by banking on Moore's law, which states that processing capacity doubles roughly every 18 months. After more than 50 years, however, Moore's law is coming up against a hard technology limit. Cloud technology, by contrast, shows no sign of slowing down: more bandwidth simply means more fibre or colour-multiplexing on the same fibre.

Cloud computing is already at an advanced stage. While CERN was building the WLCG, the Googles and Amazons of the world were building huge data warehouses to host commercial Clouds. Although we could turn to them to satisfy our computing needs, it is doubtful that such firms could guarantee the preservation of our data for the decades that it would be needed. We therefore need a dedicated "Science Cloud" instead.

CERN has already started to think about the parameters for such a facility. Zenodo, for example, is a future-proof and non-proprietary data repository that has been adopted by other big-data communities. The virtual nature of the technology allows various scientific disciplines to coexist on a given infrastructure, making it very attractive to providers. The next step requires co-operation with governments to develop computing and data warehouses for a Science Cloud.

CERN and the broader particle-physics community have much to bring to this effort. Just as CERN played a pioneering role in developing Grid computing to meet the needs of the LHC, we can contribute to the development of the Science Cloud to meet the demands of the HL-LHC. Not only will this machine produce a luminosity five times greater than the LHC, but data are increasingly coming straight from the sensors in the LHC detectors to our computer centre with minimal processing and reduction along the way. Add to that CERN's open-access ethos, which began in open-access publishing and is now moving towards "open data", and you have a powerful combination of know-how relevant to designing future computing and data facilities. Particle physics can therefore help develop Cloud computing for the benefit of science as a whole.

In the future, scientific computing will be accessed much as electrical power is today: we will tap into resources simply by plugging in, without worrying about where our computing cycles and data storage are physically located. Rather than relying on our own large computer centre, there will be a Science Cloud composed of computing and data centres serving the scientific endeavour as a whole, guaranteeing data preservation for as long as it is needed. Its location should be determined primarily by its efficiency of operation.

CERN has been in the vanguard of scientific computing for decades, from the computerised control system of the Super Proton Synchrotron in the 1970s, to CERNET, TCP/IP, the World Wide Web and the WLCG. It is in that vanguard that we need to remain, to deliver the best science possible. Working with governments and other data-intensive fields of science, it's time for particle physics to play its part in developing a world in which the computing socket sits right next to the power socket. It's time to move beyond computing's golden age of steam.

Eckhard Elsen became CERN director for research and computing in January 2016. His research has led him to positions at Hamburg University, SLAC National Accelerator Laboratory and Heidelberg University, where he first made contact with CERN as a member of the OPAL collaboration. (Image credit: M Brice.)

Advertising feature

Positioning Loads Accurately to the Micrometer: Hexapod at PETRA III

Since 2010, PETRA III (Fig. 1) is the most brilliant storage-ring-based X-ray light source in the world and it provides international scientists with excellent experimentation facilities. In particular, this benefits researchers investigating very small samples or those requiring tightly collimated and very short-wavelength X-rays for their experiments. The high-energy radiation of up to and above 100,000 electron volts with high light intensity offers versatile capabilities, for example in the broad field of materials research for the inspection of welded seams, or for the examination of fatigue symptoms in workpieces. In some cases, this involves accurately positioning really heavy loads down to the micrometer. At the heart of the P07 beamline, which delivers the high-energy X-ray radiation required for materials research, is therefore a heavy-duty Hexapod. Thanks to its accuracy, it facilitates in-situ measurements of material properties under realistic process conditions.

Fig 1: *PETRA III offers scientists from around the world superlative experimentation facilities. In particular, this benefits researchers investigating very small samples or those requiring tightly collimated and very short-wavelength X-rays for their experiments, e.g. in the field of materials research (image: DESY/Reimo Schaaf)*

Hexapods are parallel kinematic positioning systems (Fig. 2), available in many versions with travel ranges of up to a few hundred millimeters. With precision below a micrometer, they can position loads weighing from a few kilograms to a few hundred kilograms, or even several tons. Their advantages compared with serial, i.e. stacked systems, are that they have much better path accuracy, repeatability and flatness. In addition, the moved mass is lower, enabling better dynamic performance, which is the same for all motion axes. Depending on the geometry of the Hexapod, rotations from a few degrees up to 60° and translations of a few millimeters to several centimeters are possible.

Short-Wave X-Ray Radiation for Materials Research

The PETRA III short-wave X-ray radiation penetrates very deeply into the material and thus is also capable of passing through material of greater thickness. This enables welded seams to be inspected and fatigue symptoms in workpieces to be measured as an aid to quantifying the anticipated durability and service lives, or to analyze new metal alloys. Here effects can be proven down to the level of domain or crystal structures.

Fig 2: *Basic design: In parallel-kinematic systems, all actuators act directly on the same platform. (image: PI)*

The opportunities that proceed from this in respect of materials research are leveraged by Helmholtz-Zentrum Geesthacht (HZG) at the High Energy Materials Science Beamline (HEMS), P07, for example when conducting in-situ measurements of the material properties that occur during reshaping processes such as welding, pressing, rolling or stamping. The application of a mechanical load causes tensile and elongation stresses to occur inside the material. The investigation involving X-ray radiation then indicates the chronological sequence of effects occurring within a material at a crystalline level in micrometer-sized domain areas.

Powerful Positioning System for the Experimentation Chamber

At the heart of the described experimentation chamber is a Hexapod, developed by Physik Instrumente (PI). Dr. Norbert Schell, the scientist in charge of the HEMS Beamline, illustrates the context: "For an increasingly large range of in-situ investigations of 'real' processes, that is processes that actually occur in industry (but of course not only there) – associated with the cutting of workpieces, the coating of surfaces for the hardening or improvement of tribological properties, reshaping, welding, heat treatment as well as combinations of these techniques – it is our ultra-rigid Hexapod with its tremendous load-bearing capability and micrometer precision positioning that makes it possible for the first time for us to conduct scientifically rigorous examinations of the structural changes that occur at an atomic level. This is highly interesting, and is also important in helping us to understand the processes that are occurring and that, ultimately, enable customized materials to be optimized."

The parallel-kinematic custom model, the M-850K (Fig. 3), delivers micrometer-precision positioning for loads of up to one ton in every orientation. It stands ±20° approx. 700 mm high and has a diameter of 800 mm (top platform with large aperture) and 900 mm (bottom). The lower platform is installed on a 360° rotation table and the cabling was designed to be dragchain compatible. With its high load capacity of up to one ton, the Hexapod can carry the entire measurement setup including the equipment where mechanical forces are applied. The Hexapod positions even these large masses over distances of 400 mm to a precision of ±1 micron, and performs rotational motions of ±20° with a resolution to 0.5 µrad. Inside the experimental hutch, this enables complete engine blocks, turbine components, sinter furnaces and cryogenic chambers as well as welding fixtures or other machining units to be aligned precisely for the planned investigations and to be moved accordingly during the analysis.

Fig 3: Hexapod in the experimentation station EH3 on the P07 beam guidance unit on PETRA III: With its high load capacity, it can carry the entire measuring setup including the structure where mechanical forces are applied – in this figure a chamber for the laser-welding of titanium aluminides. (image: PI / HZG)

PI (Physik Instrumente) in Brief

In the past four decades, PI (Physik Instrumente) with headquarters in Karlsruhe, Germany has become the leading manufacturer of nanopositioning systems with accuracies in the nanometer range. With four company sites in Germany and ten sales and service offices abroad, the privately managed company operates globally. Over 700 highly qualified employees around the world enable the PI Group to meet almost any requirement in the field of innovative precision positioning technology. All key technologies are developed in-house. This allows the company to control every step of the process, from design right down to shipment: precision mechanics and electronics as well as position sensors.

Author: Dipl.-Phys. Birgit Schulze, Marketing & Products at PI (Physik Instrumente)

PI WWW.PI.WS

News

INTERNATIONAL

Romania becomes CERN Member State

Romania has become the 22nd Member State of CERN, having acceded to the Organization's founding convention, which is deposited with UNESCO, on 17 July. The accession crowns a period of co-operation that stretches back 25 years. "This is a very special moment for Romania and its relationship with CERN," says ambassador Adrian Vierita, Romania's permanent representative to the United Nations in Geneva.

Bilateral discussions between the Romanian government and CERN began in 1991. Aspiring to become a Member State and therefore to contribute fully to the governance of the laboratory, Romania submitted its formal application to join CERN in April 2008.

M Brice/CERN

The Romanian seat in the CERN Council chamber.

Today, Romania has around 100 visiting scientists at CERN and a particularly strong presence in the LHC experiments ATLAS, ALICE and LHCb, in addition to the DIRAC, n_TOF and NA62 experiments. "The accession of Romania to full CERN membership underlines the importance of European research collaboration in the quest to understand nature at its most fundamental level," says the president of CERN Council, Sijbrand de Jong. "United, we can do so much more than as individual countries." The Romanian flag will be raised alongside 21 others at the CERN entrance on 5 September.

ICHEP HIGHLIGHTS

LHC experiments weigh up 2016 data

ICHEP2016CHICAGO

The 38th International Conference on High-Energy Physics (ICHEP 2016) took place on 3–10 August in Chicago, US. Among numerous results presented, the LHC experiments released their latest analyses of 13 TeV proton–proton collision data recorded in 2016.

Based on a data set of 12 fb^{-1}, ATLAS released many new results including 50 conference notes. Highlights included new and highly precise measurements of WZ production that constrain anomalous boson couplings. ATLAS also searched in many final states for signs of direct production of supersymmetric and other new particles from beyond the Standard Model. No compelling evidence was found. In particular, the intriguing hint of a possible new state with a mass of 750 GeV decaying into photon pairs seen in the 2015 data has not reappeared. The larger data set also allowed ATLAS to "rediscover" the Higgs boson with high statistical significance.

The CMS collaboration presented more than 70 new results based on an integrated luminosity of 13 fb^{-1}, also including a rediscovery of the Higgs. In line with the findings from ATLAS, an updated search for a 750 GeV diphoton resonance by CMS did not confirm the excess observed previously, setting a limit on its cross-section of 1.5 fb at the 95% CL. Searches for supersymmetric and exotic particles also showed no significant excesses, allowing mass limits to be increased by a few hundred GeV. New massive Z bosons up to 4 TeV and string resonances decaying into pairs of jets up to 7.4 TeV have now been excluded, while searches for dark matter exclude mediator masses up to 2 TeV in several standard scenarios.

LHCb presented many interesting new results in the domain of flavour physics. A particular highlight was the discovery of the decay mode $B^0 \to K^+K^-$, which is the rarest B-meson decay into a hadronic final state ever observed, as well as searches for CP violation in the charm system. Another first was a measurement of the photon polarisation in radiative decays of B_s mesons, and determinations of the production cross-sections of several key processes at a collision energy of 13 TeV – some of which at first sight are at variance with current predictions.

Based on lead–lead collisions with an energy of 5 TeV per nucleon pair, the ALICE collaboration presented new measurements of the properties of the quark–gluon plasma. These included fundamental measurements of the production of quarkonium at the highest collision energy ever reached at an accelerator. ALICE also measured the viscosity of the plasma at the new energy, showing that the system still behaves almost as an ideal liquid.

● *CERN Courier* went to press as ICHEP 2016 got under way. A full report will appear in the next issue.

Sommaire en français

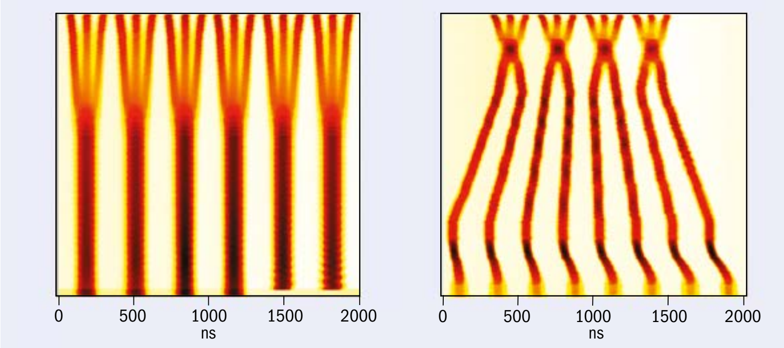
THE LHC

New bunch-production scheme breaks luminosity record

The LHC relies on the injector complex to deliver proton beams with well-defined transverse and longitudinal characteristics, which fold directly into luminosity performance. On 16 July, LHC Operations made use of a new bunch-production scheme called Batch Compression Merging and Splitting (BCMS) which offers significantly lower transverse beam size. Although the LHC has already broken several performance records this year, the new scheme increased the peak luminosity of the LHC by around 20% and set a new record of $1.2 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$.

Proton beams emerging from Linac2 in the LHC's accelerator chain are injected sequentially into each of the four rings of the Proton Synchrotron Booster (PSB) using a multiturn injection process. The total beam intensity per ring is controlled by varying the number of PSB turns during which beam is injected. The transverse emittance (a combined measure of the beam's transverse size and angular divergence) is also determined by the multiturn nature of the injection process, and in general more injected protons translates to a larger transverse emittance. The eventual number of bunches and their temporal spacing are governed by radio-frequency (RF) gymnastics in the Proton Synchrotron (PS), which injects protons into the Super Proton Synchrotron (SPS) – from where they are fed into the LHC.

The nominal scheme for LHC beam production is based on injecting four and then two bunches from the PSB into the PS.



Triple splitting in the Proton Synchrotron (PS) of six bunches in the nominal scheme (left) and following compression and merging in the new BCMS scheme (right). The horizontal axis is the circumference of the PS in nanoseconds.

The six PSB bunches are injected into the PS RF "harmonic 7". The harmonic number is the number of bunch slots – or RF buckets – available in the full circumference of the ring, and this parameter is fully controlled by the RF system. Each of the six bunches is then split into three to reach harmonic 21, and then split into two twice more to result in 72 bunches spaced by 25 ns. To reduce the emittance, it is desirable to inject fewer turns from Linac2 into the PSB and to reduce the bunch-splitting factor in the PS, while still delivering nominal bunch population for 25 ns beam.

The new BCMS scheme makes maximal use of the PSB rings by taking eight bunches (four plus four) into the PS on harmonic 9. A batch compression is then performed by incrementing the harmonic number from harmonic 9 to 14, after which a bunch-merging puts the harmonic number back to 7 (see figure). From this point onwards, the RF gymnastics are similar to those used for the nominal beam but the number of bunches produced is different: eight bunches are merged into four, split by three, two and two again. This results in 48 bunches spaced by 25 ns being injected into the SPS, which is less than the nominal 72 bunches. The scheme wins by taking lower intensities and thus smaller bunches into the PS, and then establishing the basis for the nominal bunch population in the compression and merging process.

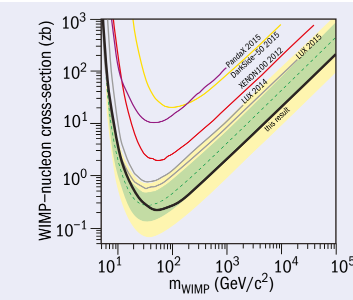
ASTROPARTICLE PHYSICS

LUX draws a blank on dark matter

The Large Underground Xenon (LUX) experiment located at Sanford Underground Research Facility (SURF) in South Dakota, US, has released its latest results in the search for dark matter. Following the completion of its final 20 month-long run, during which the detector amassed a data set that is four times larger than before, no signal was found and the results were consistent with background expectations.

LUX is based on a 370 kg liquid-xenon dual-phase time-projection chamber that offers a high sensitivity to spin-independent nuclear-recoil interactions. It entered operation in 2013 to search directly for WIMPs in addition to other dark-matter candidates. The experiment's latest results, which were presented on 21 July at the 2016 International Dark Matter conference in Sheffield, UK, carve out previously un-probed parameter space and exclude spin-independent WIMPS at the level of

LUX Collaboration



The latest and final LUX results exclude the parameter space above the black line, representing a four-fold over the previous LUX result for high WIMP masses. Green and yellow bands show the one- and two-sigma range of expected sensitivities based on random background-only experiments.

0.22 zeptobarns. The collaboration plans further analyses of other dark-matter candidates, including axions.

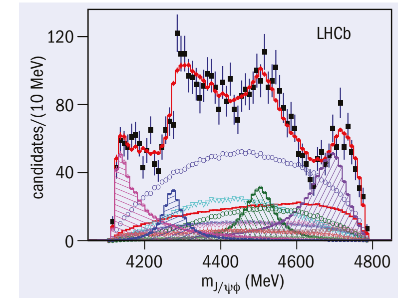
Researchers are looking ahead to the next-generation LUX-ZEPLIN (LZ) detector, also located at SURF, which is scheduled to start operations by the end of the decade. With an active mass of seven tonnes, LZ will be sensitive to WIMP masses ranging from a few GeV to hundreds of TeV, and will therefore probe even deeper into dark-matter parameter space.

LHC EXPERIMENTS

LHCb finds tetraquark candidates

The LHCb collaboration has reported the observation of three new exotic hadrons and confirmed the existence of a fourth by analysing the full data sample from LHC Run 1. Although the theoretical interpretation of the new states is still under study, the particles each appear to be formed by two quarks and two antiquarks. They also do not seem to contain the lightest up and down quarks, which means they could be more tightly bound than other exotic particles discovered so far.

Until recently, all observed hadrons were formed either by a quark–antiquark pair (mesons) or by three quarks only (baryons). The underlying reason has remained a mystery, but during the last decade several experiments have found evidence for particles formed by more than three quarks. For example, in 2009 the CDF collaboration at Fermilab in the US observed evidence for a tetraquark candidate dubbed X(4140), which was later confirmed by the CMS and D0 collaborations (the latest LHCb analysis yields a clear observation of this state, although finds a slightly larger width than the other experiments). Then, in July 2015, LHCb announced the first observation of two pentaquark particles, which are hadrons composed of five quarks.



The invariant mass distribution from decays of B^+ mesons into $J/\psi\phi$ contains several structures. The properties of the structures are consistent with their interpretation as exotic four-quark particles, with $c\bar{c}s\bar{s}$ quark content, although the details of the binding mechanism are still under discussion.

Each of the four states observed by LHCb – dubbed X(4274), X(4500) and X(4700), in addition to the X(4140) – has a statistical significance above five standard deviations. Sophisticated analysis of the angular distribution of B^+ meson decays into J/ψ, ϕ and K^+ mesons also allowed the collaboration to determine the quantum numbers of the exotic states with high precision. Alas, the data could not be described by a model that contains only ordinary mesons and baryons.

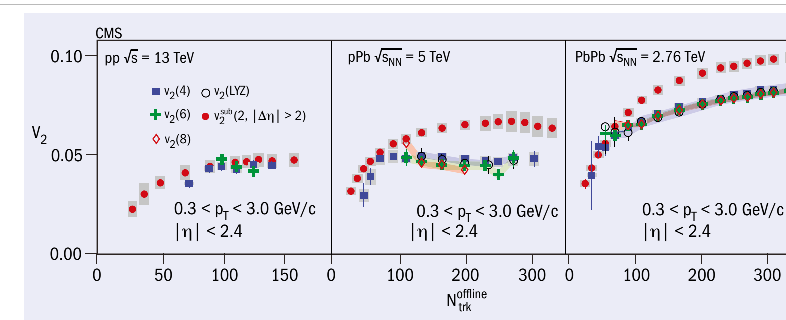
The binding mechanism of the new states could involve tightly bound tetraquarks or strange charmed meson pairs bouncing off each other and rearranging their quark content to emerge as a $J/\psi\phi$ system. The high statistics of the LHCb data set and the sophisticated techniques exploited in the analysis will help to shed further light on the production mechanisms of these particles.

LHCb has made several other important contributions to the investigation of exotic particles. In February 2013, the quantum numbers of the X(3872) particle discovered in 2003 by the Belle experiment in Japan were determined, and in April 2014 the collaboration showed that the Z(4430) particle (also discovered at Belle) is composed of four quarks: $c\bar{c}d\bar{u}$. The latest exotic results from LHCb, which were first presented in June at the Meson 2016 workshop in Cracow, Poland, have been submitted for publication.

Further reading

LHCb Collaboration 2016 arXiv:1606.07895, submitted to *Phys. Rev. Lett.*
LHCb Collaboration 2016 arXiv:1606.07898, submitted to *Phys. Rev. D.*

CMS observes collective phenomena in pp collisions



The elliptic-flow harmonic v_2 extracted using two- and multi-particle correlations, as a function of particle multiplicity in pp, pPb and PbPb collisions.

When heavy nuclei collide at high energies, a novel state of hot and dense matter – the quark–gluon plasma (QGP) – is expected to form. As a region of QGP expands and cools, it dissociates into a very large number of particles. Earlier findings at Brookhaven's RHIC and CERN's LHC revealed that the QGP exhibits strong collective behaviour comparable to a fluid. One of the key experimental pieces of evidence for this state is the observation of long-range anisotropic azimuthal correlations between particles emitted over a wide rapidity range, often referred to as the "ridge phenomenon". In a typical proton–proton (pp) collision, a ridge correlation is not expected because the system is too dilute to produce a fluid-like state.

In 2010, however, CMS reported an unexpected observation of a ridge phenomenon in pp events with high particle multiplicities. This finding was regarded as a hint for possible collective effects that might occur in rare pp interactions with similar high particle densities as those in heavy-ion collisions. Due to statistical limitations of the LHC Run 1 data set, detailed studies of the ridge phenomenon in pp collisions, especially concerning its connection to collectivity, remained inconclusive. With the increased collision energy of the LHC Run 2, high-multiplicity pp events are produced at significantly higher rates. This makes it possible to perform a detailed examination of ridge ▷

and collective phenomena in pp collisions.

The CMS silicon tracking system is ideally suited for measurements of multi-particle correlations and therefore for studies of the collective nature of the ridge. Recently, the CMS collaboration measured the "elliptic-flow" harmonic v_2 in pp events from LHC Run 2 as a function of particle multiplicity (see figure on previous page, left). This is the first extraction of v_2 – an observable that can be used to quantify the ridge signal – in pp collisions using a multi-particle correlation technique.

Strikingly, the observed v_2 signals show nearly no dependence on the number of correlated particles, providing direct evidence for a collective origin for the long-range ridge observations. Similar observations were previously made in proton–lead and lead–lead collisions (see figure, middle and right, respectively), providing a consistent picture for the collective nature of the medium in all three collision systems. Furthermore, CMS studied long-range correlations using identified K^0_s and Λ hadrons, observing a clear dependence of the v_2 signal on the particle species in high-multiplicity events. Such "mass ordering" provides further evidence for collective behaviour.

These intriguing observations, revealed through the study of small hadronic systems, therefore open up unexpected territory in the understanding and characterisation of dense quark–gluon matter. With the larger data samples of pp and pPb collisions to be collected in the future, CMS is poised for additional exciting physics discoveries in the coming years.

● **Further reading**

CMS Collaboration 2016 arXiv:1606.06198.

Probing the electroweak sector with ATLAS

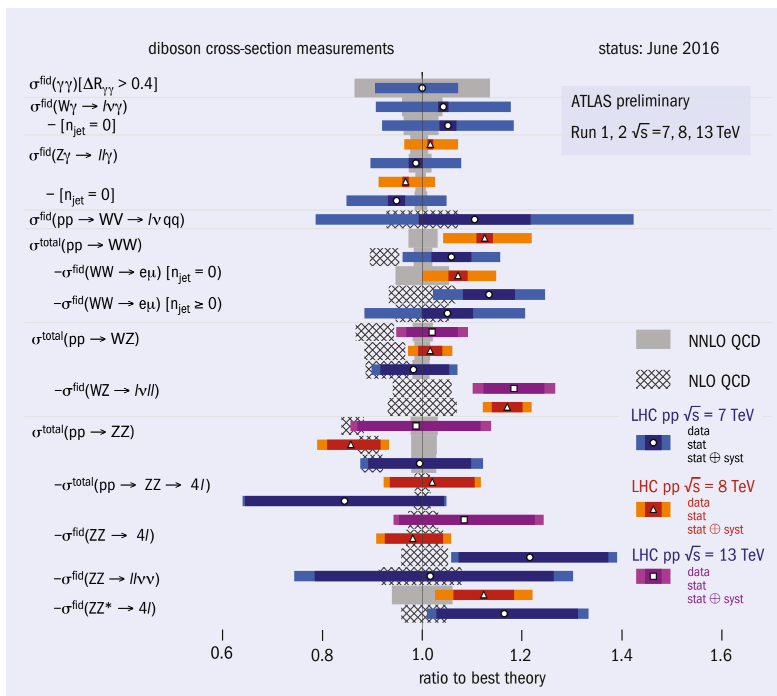
Precise measurements of final states containing multiple electroweak bosons (W, Z or γ) offer a powerful probe of the gauge structure of the Standard Model (SM), and are therefore a promising avenue to search for new physics. Using proton–proton collision data from the LHC collected at centre-of-mass energies of 7, 8 and 13 TeV, the ATLAS collaboration has recently measured the cross-section for boson-pair final states with unprecedented precision, challenging calculations from quantum chromodynamics (QCD).

For example, the uncertainty on the total production cross-section measurement of the WZ final state at 7 TeV is approximately 10%, which is large enough to cover the differences between the next-leading-order (NLO) and next-to-next-to-leading-order (NNLO) QCD predictions. At 8 and 13 TeV, the uncertainties on the ATLAS measurement reveal a tension with the NLO prediction, although this has been mitigated by recent NNLO QCD calculations.

The large size of the 8 TeV data set allowed ATLAS, for the first time, to become sensitive to tri-boson production and also to boson pairs produced through vector-boson scattering. The production cross-section of such processes in the fiducial volume where the measurement is performed is of the order of 1 fb or less, which is very difficult to measure. ATLAS performed significant cross-section measurements of the Zγγ, Wγγ, and $W^{\pm}W^{\pm}$+2j final states, while limits were set on the production cross-section of the WWW and WZ+2j final states.

These measurements probe the gauge-boson self-couplings, which are sensitive to contributions from new physics – especially at high energies. To parameterise possible anomalous gauge couplings, an effective-field-theory (EFT) approach was used. The ATLAS collaboration has searched for deviations in the coupling of three gauge bosons in the WZ final state using data collected at collision energies of 8 TeV and 13 TeV. By including the 13 TeV data, the previous sensitivity on the EFT coefficients (C_{WWW}/Λ^2, C_W/Λ^2, and C_B/Λ^2) has improved by 40%. No evidence for new physics has been found and new limits have been derived.

The large data set from LHC Run 2 will provide sensitivity to rare processes that have not been observed so far, and the expected high accuracy on multi-boson cross-sections will allow higher-order QCD and electroweak corrections to be probed.



The ratio of diboson total and fiducial production cross-section measurements to the best-available theoretical prediction, corrected for leptonic branching fractions.

● **Further reading**

ATLAS Collaboration 2016 CERN-EP-2016-172.

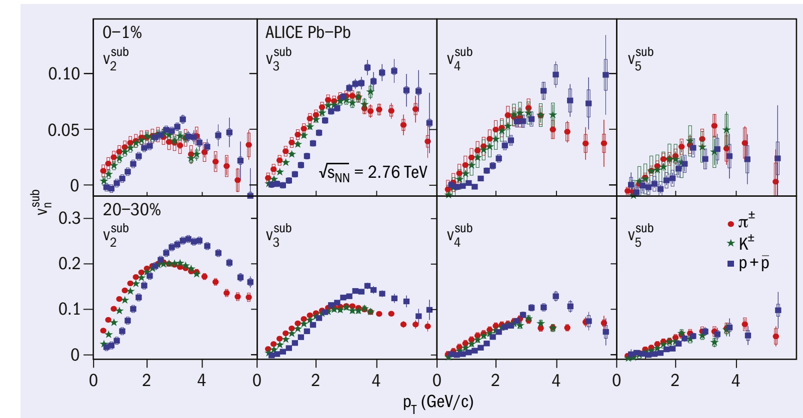
ATLAS Collaboration 2016 ATLAS-CONF-2016-043.

ALICE measures higher-flow harmonics

In a collision between two nuclei that exhibits a large impact parameter, the initial spatial anisotropy of the overlap region was conjectured to be smooth and almond shaped. In the past few years, however, experimental measurements and hydrodynamical calculations have changed this paradigm. We now know that the overlap region has an irregular shape originating from the initial random distribution of the gluons and nucleons in the nuclei, which fluctuates from one event to the next. These fluctuations appear as azimuthal correlations between final-state particles relative to the system's symmetry plane. These correlations are quantified by a Fourier series of the azimuthal distribution of particle production relative to the system's symmetry plane.

The second harmonic – v_2, which is also known as the elliptic-flow coefficient – has recently been the main focus of the heavy-ion community. Indeed, elliptic-flow measurements and hydrodynamical calculations led to the revelation that the quark–gluon plasma (QGP) generated in heavy-ion collisions behaves as an almost perfect liquid. The ratio of shear viscosity to entropy density (η/s) in the QGP, which is a measure of its fluidity, is very close to the lower bound of $\hbar/4\pi k_B$ – as conjectured by the anti-de-Sitter/conformal field theory (AdS/CFT) correspondence.

However, there are also higher-order contributions to the particle correlations and these are more sensitive probes of the QGP state than elliptic flow. Indeed, by carrying out such studies for identified particles rather than unidentified ones, it is also possible to probe the effect of the dissipative, late-stage hadronic re-scattering on the flow coefficients.



The p_T-differential v_2 (first column), v_3 (second column), v_4 (third column) and v_5 (fourth column) harmonics for different particle species for the 0–1% (upper row) and the 20–30% (lower row) centrality intervals of Pb–Pb collisions at an energy of 2.76 TeV.

Profiting from its excellent particle-identification capabilities, the ALICE collaboration has recently used lead–lead collisions recorded in 2011 at a collision energy of 2.76 TeV to measure the elliptic (v_2), triangular (v_3), quadrangular (v_4) and pentagonal (v_5) flow coefficients of charged π and K mesons, protons and antiprotons for different centrality intervals (see figure). For ultra-central collisions, in which the evolution of the system is predominantly driven by the initial-state fluctuations, one observes significant nonzero values for all harmonics and particle species. In addition, v_3 and v_4 become progressively dominant with increasing transverse momentum, while even v_5 for p_T > 4 GeV/c is comparable to v_2. For mid-central collisions, v_2 is the dominant flow harmonic and has a significantly larger value. Higher harmonics also have significant nonzero values but do not seem to change significantly with centrality.

These observations confirm that elliptic flow is driven mainly by the anisotropy in the collision geometry, whereas the initial-state fluctuations are the main driving force behind higher harmonics. A mass ordering expected in hydrodynamical calculations is seen that describes the QGP as a nearly perfect liquid. In addition, in the intermediate-p_T region, the flow harmonics of different hadrons show a baryon–meson grouping. The analysis of lead–lead collisions collected in 2015 will allow for a higher-precision measurement of such effects and therefore place more stringent limits on η/s and the initial conditions of a heavy-ion collision.

● **Further reading**

ALICE Collaboration 2016 arXiv:1606.06057.

DETECTORS

AIDA-2020 calls for breakthrough detector technologies

The European Union project AIDA-2020 (Advanced European Infrastructure for Detectors and Accelerators), in which CERN is a partner, has launched a proof-of-concept fund for breakthrough projects in the field of detector development and testing.

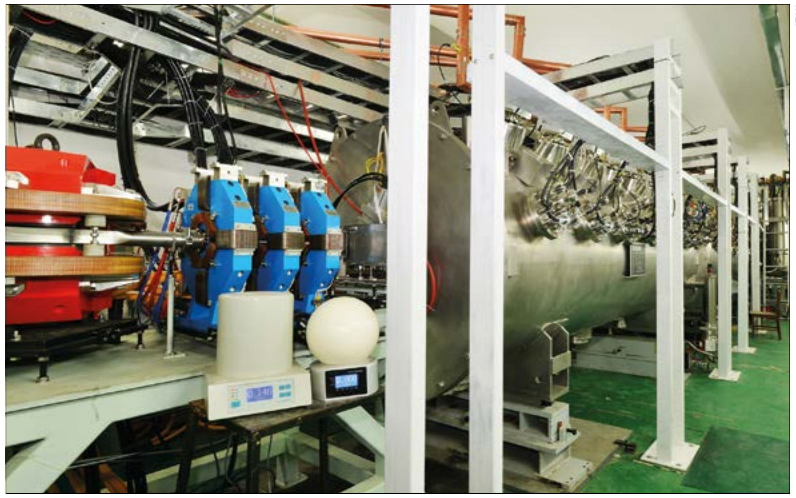
The fund will provide up to €200k in total to support innovative projects with a focus on industry-orientated applications and those beyond high-energy physics. Up to four projects will be funded based on a competitive selection process, and the deadline is 20 October 2016. More information can be found at aida2020.web.cern.ch/content/poc.

***Les physiciens des particules du monde entier sont invités** à apporter leurs contributions au CERN Courier, en français ou en anglais. Les articles retenus seront publiés dans la langue d'origine. Si vous souhaitez proposer un article, faites part de vos suggestions à la rédaction à l'adresse cern.courier@cern.ch.*

CERN Courier welcomes contributions from the international particle-physics community. These can be written in English or French, and will be published in the same language. If you have a suggestion for an article, please send proposals to the editor at cern.courier@cern.ch.

Accelerator physics

Chinese accelerator passes milestone



IHEP

Superconducting spoke cavities used to accelerate protons at Injector I.

Physicists in China have passed an important milestone towards an accelerator-driven sub-critical (ADS) system, a novel accelerator design for advanced energy and other technologies. On 2 July, teams working on "Injector I" at the Chinese Academy of Sciences' Institute of High Energy Physics (IHEP) in Beijing succeeded in accelerating a proton beam to an energy of 10.11 MeV with a peak beam current of 10.5 mA in pulse mode. "This is a major breakthrough for the ADS Injector I after five years of hard work by scientists from the Institute of High Energy Physics, and marks a new step for high-current proton-linear-accelerator technology worldwide," explains IHEP deputy-director Weimin Pan.

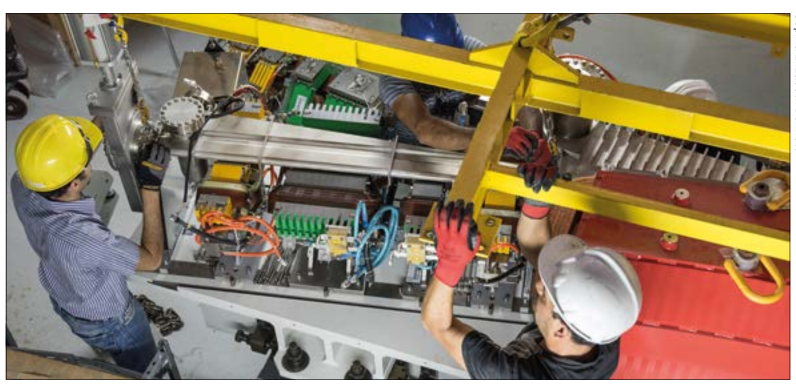
ADS technology directs high-energy protons towards a heavy target, whereupon spallation reactions produce dozens of neutrons for every proton. A portion of these neutrons may then be used to drive a sub-critical nuclear reactor, with the remaining neutrons used for nuclear-waste transmutation or other applications. Indeed, the past 10 years has seen the development of various combined ADS systems aiming at different applications – including proposals to generate nuclear power from thorium instead of uranium fuel.

The Chinese ADS Injector I is the world's first proton accelerator to use low-β superconducting "spoke cavities". It consists of an electron cyclotron resonance (ECR) ion source, a 325 MHz radio-frequency quadrupole accelerator, a superconducting linac containing 14 spoke cavities in two cryomodules, beam transport lines and a beam dump. During beam commissioning, the proton beam reached a final energy of 10.5 MeV with a beam current of 10.11 mA. The cavities achieved an accelerating gradient of 7 MV m^{-1} and beam transmission through the superconducting linac was 100%.

"This is an important focus of development for ADS accelerators, which lays the foundations for the future Chinese ADS project," says Pan.

Facilities

SESAME announces call for proposals



Sophia Elizabeth Bennett

The SESAME light source in Jordan is preparing for its first users.

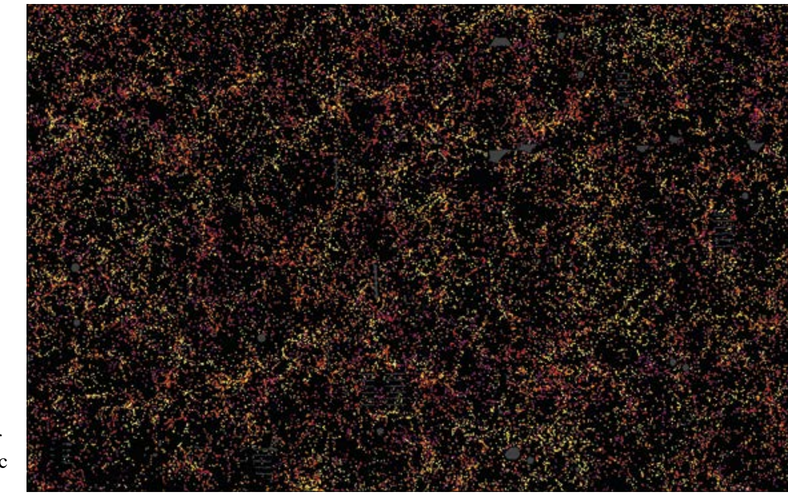
SESAME, the pioneering synchrotron facility for the Middle East and neighbouring countries, located in Jordan, has announced its first call for proposals for experiments. A third-generation light source with a broad research capacity, SESAME's first beams are due to circulate in the autumn and its experimental programme is scheduled to start in 2017. SESAME is already host to a growing user community of some 300 scientists from across the region and is open to proposals for the best science, wherever they may come from.

SESAME will start up with two beamlines, one delivering infrared light and the other X-rays. The laboratory's full scientific programme will span fields ranging from medicine and biology, through materials science, physics and chemistry to healthcare, the environment, agriculture and archaeology. Proposals can be submitted through the SESAME website (www.sesame.org.jo) and will be examined by a proposal-review committee.

"This is a very big moment for SESAME," says SESAME director-general Khaled Toukan. "It signals the start of the research programme at the first international synchrotron research facility in our region."

Cosmology

Galactic map sheds light on dark energy



D Eisenstein and SDSS-III

A slice through the universe measuring 6 billion light-years wide, 4.5 billion light-years high and 0.5 billion light-years thick, in which each dot indicates the position of a galaxy six-billion years into the past. The image contains 48,741 galaxies, about 3% of the full survey data set, with grey patches indicating regions without survey data.

The largest 3D map of distant galaxies ever made has allowed one of the most precise measurements yet of dark energy, which is currently driving the accelerating expansion of the universe. The new measurements, which were carried out by the Baryon Oscillation Spectroscopic Survey (BOSS) programme of the Sloan Digital Sky Survey-III, took five years to make and include 1.2 million galaxies over one quarter of the sky – equating to a volume of 650 cubic billion light-years.

BOSS measures the expansion rate by determining the size of baryonic acoustic oscillations, which are remnants of primordial acoustic waves. "We see a dramatic connection between the sound-wave imprints seen in the cosmic microwave background to the clustering of galaxies 7–12 billion years later," says co-leader of the BOSS galaxy-clustering working group Rita Tojeiro. "The ability to observe a single well-modelled physical effect from recombination until today is a great boon for cosmology."

The map shows galaxies being pulled towards each other by dark matter, while on much larger scales it reveals the effect of dark energy ripping the universe apart. It also reveals the coherent movement of galaxies toward regions of the universe with more matter, with the observed amount of in-fall explained well by general relativity. The results have been submitted to the *Monthly Notices of the Royal Astronomical Society*.

Nuclear physics

New super-heavy elements find names

48 **Cd** cadium 112.4	49 **In** indium 114.8	50 **Sn** tin 118.7	51 **Sb** antimony 121.8	52 **Te** tellurium 127.6	53 **I** iodine 126.9	54 **Xe** xenon 131.3
80 **Hg** mercury 200.6	81 **Tl** thallium 204.4	82 **Pb** lead 207.2	83 **Bi** bismuth 209.0	84 **Po** polonium	85 **At** astatine	86 **Rn** radon
112 **Cn** copernicium	113 **Uut** ununtrium	114 **Fl** flerovium	115 **Uup** ununpentium	116 **Lv** livermorium	117 **Uus** ununseptium	118 **Uuo** ununoctium

The temporary names for the remaining elements in row seven of the periodic table are to be replaced.

The International Union of Pure and Applied Chemistry (IUPAC) has announced the provisional names of four new super-heavy elements that complete the seventh row of the periodic table. The researchers responsible for the discoveries, which were made in Japan, Russia and the US during the past decade, proposed the following names for peer review: nihonium (Nh) for element 113; moscovium (Mc) for 115; tennessine (Ts) for 117; and oganesson (Og) for 118.

Having reviewed the proposals and recommended them for acceptance, the IUPAC Inorganic Chemistry Division set in motion a five-month public review that will come to an end on 8 November, prior to formal approval by the IUPAC Council. Keeping with tradition, newly discovered elements can be named after a mythological concept or character (including an astronomical object); a mineral or similar substance; a place or geographical region; a property of the element; or a scientist.

In conjunction with the International Union of Pure and Applied Physics, IUPAC has also attached priority to the discovery claims. Element 113 was discovered by a collaboration at RIKEN in Japan, while elements 115 and 117 were synthesised at the U-400 accelerator complex at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, via a collaboration with the Lawrence Livermore National Laboratory (LLNL) and Oak Ridge National Laboratory in the US. The discovery of element 118 was attributed to a JINR–LLNL collaboration, which in 2011 was also acknowledged by IUPAC for the discovery of elements 114 (flerovium) and 116 (livermorium).

Sciencewatch

Compiled by John Swain, Northeastern University

Mathematics on the brain

Mathematics is often dubbed the language of science, but does mathematical aptitude itself have anything to do with language? To investigate, Marie Amalric and Stanislas Dehaene of the Université of Paris-Sud and Université Paris-Saclay, France, used functional MRI (fMRI) imaging to image the brains of professional mathematicians and non-mathematicians of equal academic standing when asked questions about the truth or falsity of mathematical and non-mathematical statements. Among the professional mathematicians, fMRI clearly showed activation in the bilateral frontal, intraparietal and ventrolateral temporal regions – regardless of whether the questions concerned algebra, analysis, topology or geometry. Intriguingly, the subjects did not rely on areas of the brain that relate to language and general-knowledge semantics, and instead used areas that were activated by numbers and formulae in the non-mathematician group. This, claim the authors, suggests that high-level mathematical expertise and basic number sense share common roots in a non-linguistic brain circuit.

New study probes the relationship between mathematics and language.

● **Further reading**
M Amalric and S Dehaene 2016 *PNAS* **113** 4909.

Chirality detected in deep space

Chiral molecules, which cannot be superimposed on their mirror image, are a key feature of biological life on Earth and have already been detected in other solar-system objects. Now, for the first time, a chiral molecule has been detected in interstellar space. Brett McGuire of the National Radio Astronomy Observatory in the US and colleagues used data from the Green Bank Telescope in West Virginia, with some help from the Parkes radio telescope in Australia, to detect propylene oxide near the centre of our Galaxy in the star-forming dust and gas cloud Sagittarius B2. The identification was made via multiple spectral lines, but the data did not allow the team to determine the molecule's absolute handedness. The result should help in the ongoing struggle to understand the origin of the bimolecular chirality that is so important to life as we know it.

● **Further reading**
B McGuire *et al.* 2016 *Science* **352** 1449.

Bio-inspired robotic fish

Batoid fishes, which include stingrays, have served as inspiration for a bizarre robot that is a hybrid of machines and living cells. Kevin Kit Parker of Harvard University and colleagues put living muscle cells from a rat's heart on an elastomeric body enclosing a microfabricated gold skeleton, so that the structure could mimic the undulating swimming motion of a batoid fish. The muscle cells, which were genetically engineered to contain an optogenetic molecular switch, were controlled externally via an optical signal. The artificial animal, which replicated fish morphology at the 1/10th scale (corresponding approximately to the size of a one-cent coin) including the basic fin deflection patterns of batoid fish, uses these light cues to navigate simple obstacle courses.

● **Further reading**
S-J Park *et al.* 2016 *Science* **353** 158.

Feathers in amber

Plumage in the Cretaceous period, which holds important evolutionary clues, is notoriously difficult to study due to the poor preservation of details in compression fossils. Fortunately, however, two ancient bird wings trapped in Burmese amber 99 million years ago have been found in which feathers have been preserved in stunning detail. The samples have allowed Lida Xing of the China University of Geosciences in Beijing and colleagues to make detailed studies, for example using synchrotron X-ray micro-CT techniques, to reveal the first examples of several physiological structures – including follicles and feather tracts – that until now have not been preserved. The feathers are likely to be from hatchlings of enantiornithines, a group of extinct flying dinosaurs.

● **Further reading**
L Xing *et al.* 2016 *Nature Communications* **7** 12089.

A mummified partial wing preserved in a few cubic centimetres of amber, revealing rachis, skin, muscle and claw.

Burying carbon dioxide

Carbon capture and storage (CCS) technologies aim to reduce harmful carbon-dioxide emissions by diverting them underground, rather than into the atmosphere. Now, for the first time, Juerg Matter of the University of Southampton in the UK and colleagues have shown that carbon dioxide can be disposed of permanently by being mineralised to benign carbonate minerals in basaltic rocks. The team found that it took less than two years for more than 95% of the carbon dioxide injected into the CarbFix site about 25 km from Reykjavik in Iceland to be immobilised this way. Previously, it was thought that such processes take several hundreds to thousands of years, and the results therefore hold promise for CCS solutions.

● **Further reading**
J M Matter *et al.* 2016 *Science* **352** 1312.

Astrowatch

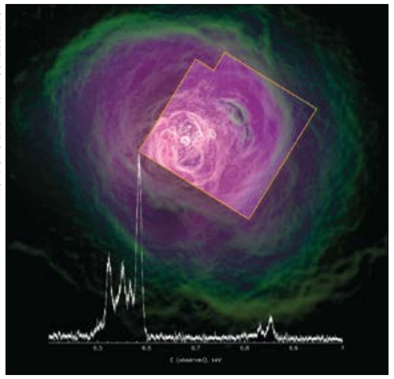
Compiled by Marc Türler, ISDC and Observatory of the University of Geneva, and CHIPP, University of Zurich

Hitomi probes turbulence in galaxy cluster

With its very first observation, Japan's Hitomi X-ray satellite has discovered that the gas in the Perseus cluster of galaxies is much less turbulent than expected. The unprecedented measurement opens the way towards a better determination of the mass of galaxy clusters, which has important cosmological implications.

Hitomi, which translates to "pupil of the eye", is an X-ray observatory built and operated by the Japanese space agency (JAXA) in collaboration with more than 60 institutes and 200 scientists and engineers from Japan, the US, Canada and Europe. Launched on 17 February this year, Hitomi functioned for just over a month before operators lost contact on 26 March, when the spacecraft started to spin very rapidly, leading to its partial disintegration. It was a tragic end to a very promising mission that would have used a micro-calorimeter to achieve unprecedented spectral resolution in X-rays. Cooled down to 0.05 K, the soft X-ray spectrometer (SXS) was designed to record the precise energy of each incoming X-ray photon.

Hitomi targeted the Perseus cluster just a week after it arrived in space to measure the turbulence in the cluster to a precision of 10 km s^{-1}, compared with the upper limit set by XMM-Newton of 500 km s^{-1}. The SXS micro-calorimeter met expectations and measured a velocity of only 164±10 km s^{-1} along the line-of-sight. This low velocity came as a surprise for the Hitomi collaboration, especially because at the core of the cluster



NASA/CXO and Hitomi Collaboration

A portion of the spectrum from the Perseus cluster of galaxies, as measured by the Hitomi micro-calorimeter (squared area), which is highlighted on the background image showing bubbles of hot gas.

lies the highly energetic active galaxy NGC 1275. It indicates that the cluster gas has very little turbulent motion, with a turbulent pressure being only four per cent of the heat pressure of the hot intra-cluster gas. This is extraordinary, considering that NGC 1275 is pumping jetted energy into its surroundings to create bubbles of extremely hot gas.

Previously, it was thought that these bubbles induce turbulence, which keeps the central gas hot, but researchers now have to think of other ways to heat the gas. One possibility is sound waves, which would allow energy to be spread into the medium without global movement of the gas. The precise determination of the turbulence in the Perseus cluster allows a better determination of its mass, which depends on the ratio of turbulent to quiescent gas. Generalising the result of an almost negligible contribution of turbulent pressure in the central core of galaxy clusters impacts not just cluster physics but also cosmological simulations.

The impressive results of Hitomi only reinforce astronomers' sense of loss. As this and several missions have shown, equipping an X-ray satellite with a micro-calorimeter is a daunting challenge. NASA's Chandra X-ray Observatory, which launched in 1999, dropped the idea due to budget constraints. JAXA took over the calorimeter challenge on its ASTRO-E spacecraft, but the probe was destroyed in 2000 shortly after rocket lift-off. This was followed by the Suzaku satellite, launched in 2005, in which a leak in the cooling system destroyed the calorimeter. This series of failures is especially dramatic for the scientists and engineers developing such high-precision instruments over two decades – especially in the case of Hitomi, for which the SXS instrument worked perfectly until the loss of the satellite due to problems with the attitude control. Researchers may now have to wait more than a decade to use a micro-calorimeter in space, until ESA's Athena mission, which is tentatively scheduled for launch in the late 2020s.

Further reading

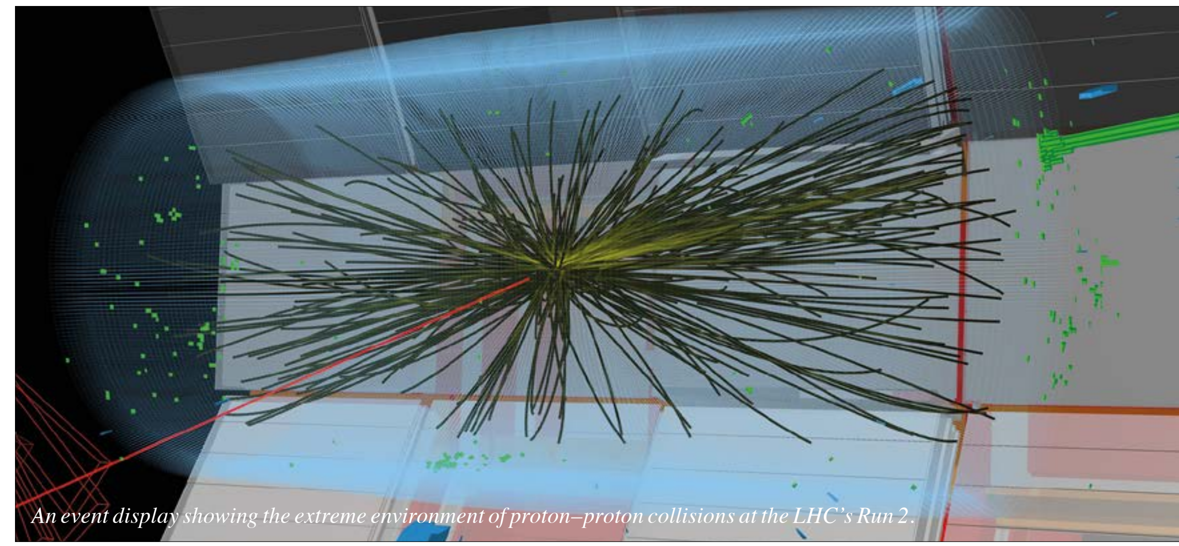
Hitomi Collaboration 2016 *Nature* **535** 117.

Picture of the month

This spectacular infrared image of the Orion Nebula is the deepest view ever of this archetypical star-forming region. The famous Orion Nebula spans about 24 light-years within the constellation of Orion, and is visible from Earth with the naked eye as a fuzzy patch in Orion's sword. In visible light, it is brightly illuminated by ultraviolet radiation from the many hot stars it contains. In infrared light, however, it is possible to see inside the star-forming clouds and detect fainter objects. This image was obtained using the HAWK-I infrared camera on ESO's Very Large Telescope in Chile, and reveals objects as small as brown dwarfs and isolated planets. The new image also reveals an unexpected wealth of very faint planetary-mass objects, which suggests that the Orion Nebula may be forming proportionally far more low-mass objects than do closer and less active star-formation regions.

ESO/H Drass *et al.*

CMS gears up for the LHC data deluge


CMS Collaboration

An event display showing the extreme environment of proton–proton collisions at the LHC's Run 2.

The CMS experiment has completed an ambitious upgrade to the trigger system that forms the first level of its data selection for physics studies, describe **Darin Acosta**, **Costas Foudas** and **Dave Newbold**.

ATLAS and CMS, the large general-purpose experiments at CERN's Large Hadron Collider (LHC), produce enormous data sets. Bunches of protons circulating in opposite directions around the LHC pile into each other every 25 nanoseconds, flooding the detectors with particle debris. Recording every collision would produce data at an unmanageable rate of around 50 terabytes per second. To reduce this volume for offline storage and processing, the experiments use an online filtering system called a trigger. The trigger system must remove the data from 99.998% of all LHC bunch crossings but keep the tiny fraction of interesting data that drives the experiment's scientific mission. The decisions made in the trigger, which ultimately dictate the physics reach of the experiment, must be made in real time and are irrevocable.

The trigger system of the CMS experiment has two levels. The first, Level-1, is built from custom electronics in the CMS underground cavern, and reduces the rate of selected bunch crossings from 40 MHz to less than 100 kHz. There is a period of only four microseconds during which a decision must be reached, because data cannot be held within the on-detector memory buffers for longer than this. The second level, called the High Level Trigger (HLT), is software-based. Approximately 20,000 commercial CPU cores, housed in a building on the surface above the CMS cavern, run software that further reduces the crossing rate to an average of about 1 kHz. This is low enough to transfer the remaining data to the CERN Data Centre for permanent storage.

The original trigger system served CMS well during Run 1 of the LHC, which provided high-energy collisions at up to 8 TeV from 2010–2013. Designed in the late 1990s and operational by 2008, the system allowed the CMS collaboration to co-discover the Higgs boson in multiple final-state topologies. Among hundreds of other CMS measurements, it also allowed us to observe the rare decay $B_s \to \mu\mu$ with a significance of 4.3σ. ▷

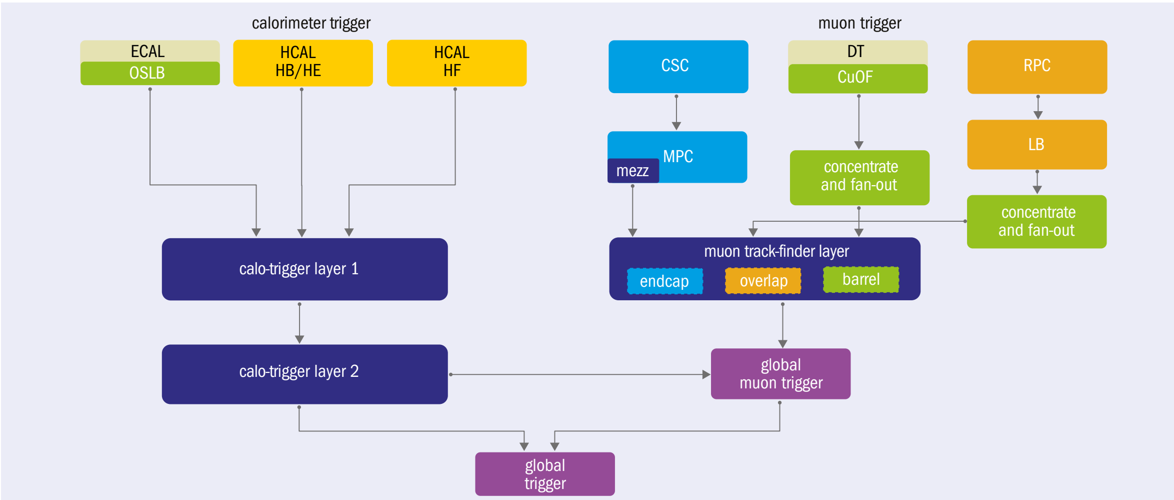


Fig. 1. Data-flow chart for the CMS Level-1 trigger upgrade, where each box represents a physical device. Data from the calorimeter-detector systems start from the top left, and the muon detectors at top right. Processing of these data takes place in two layers, and the results are combined for final decision-making in the global trigger (bottom).

In Run 2 of the LHC, which got under way last year, CMS faces a much more challenging collision environment. The LHC now delivers both an increased centre-of-mass energy of 13 TeV and increased luminosity beyond the original LHC design of $10^{34}\,s^{-1}cm^{-2}$. While these improve the detector's capability to observe rare physics events, they also result in severe event "pile-up" due to multiple overlapping proton collisions within a single bunch crossing. This effect not only makes it much harder to select useful crossings, it can drive trigger rates beyond what can be tolerated. This could be partially mitigated by raising the energy thresholds for the selection of certain particles. However, it is essential that CMS maintains its sensitivity to physics at the electroweak scale, both to probe the couplings of the Higgs boson and to catch glimpses of any physics beyond the Standard Model. An improved trigger system is therefore required that makes use of the most up-to-date technology to maintain or improve on the selection criteria used in Run 1.

Thinking ahead

In anticipation of these challenges, CMS has successfully completed an ambitious "Phase-1" upgrade to its Level-1 trigger system that has been deployed for operation this year. Trigger rates are reduced via several criteria: tightening isolation requirements on leptons; improving the identification of hadronic tau-lepton decays; increasing muon momentum resolution; and using pile-up energy subtraction techniques for jets and energy sums. We also employ more sophisticated methods to make combinations of objects for event selection, which is accomplished by the global trigger system (see figure 1).

These new features have been enabled by the use of the most up-to-date Field Programmable Gate Array (FPGA) processors, which provide up to 20 times more processing capacity and 10 times more communication throughput than the technology used in the original trigger system. The use of reprogrammable FPGAs throughout the system offers huge flexibility, and the use of fully optical communications in a standardised telecommunication architecture (microTCA) makes the system more reliable and easier to maintain compared with the previous VME standard used in high-energy physics for decades (see the panel opposite).

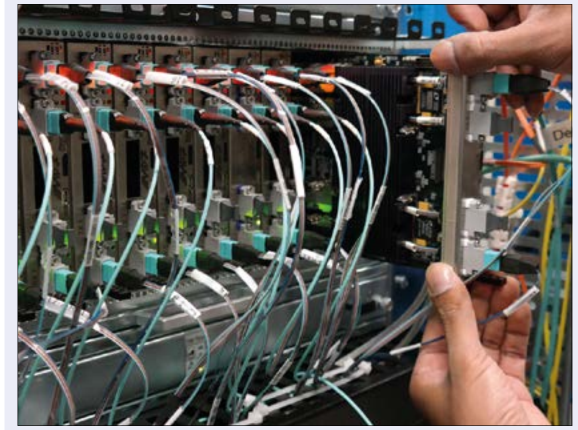
The Level-1 trigger requires very rapid access to detector information. This is currently provided by the CMS calorimeters and muon system, which have dedicated optical data links for this purpose. The calorimeter trigger system – which is used to identify electrons, photons, tau leptons, and jets, and also to measure energy sums – consists of two processing layers. The first layer is responsible for collecting the data from calorimeter regions, summing the energies from the electromagnetic and hadronic calorimeter compartments, and organising the data to allow efficient processing. These data are then streamed to a second layer of processors in an approach called time-multiplexing. The second layer applies clustering algorithms to identify calorimeter-based "trigger objects" corresponding to single particle candidates, jets or features in the overall transverse-energy flow of the collision. Time-multiplexing allows data from the entire calorimeter for one beam crossing to be streamed to a single processor at full granularity, avoiding the need to share data between processors. Improved energy and position resolutions for the trigger objects, along with the increased logic space available, allows more sophisticated trigger decisions.

The most crucial decisions in the analysis chain happen underground and within microseconds of a proton–proton collision.

The muon trigger system also consists of two layers. For the original trigger system, a separate trigger was provided from each of the three muon-detector systems employed at CMS: drift tubes (DT) in the barrel region; cathode-strip chambers (CSC) in the endcap regions; and resistive plate chambers (RPC) throughout the barrel and endcaps. Each system provides unique information useful for making a trigger decision; for example, the superior timing of the RPCs can correct the time assignment of DTs and CSC track segments, as well as provide redundancy in case a specific DT or CSC is malfunctioning.

In Run 2, we combine trigger segments from all of these units at an earlier stage than in the original system, and send them to the muon track-finding system in a first processing layer. This approach creates an improved, highly robust muon trigger that can take advantage of the specific benefits of each technology earlier in the processing chain. The second processing layer of the muon trigger takes as input the tracks from 36 track-finding processors to identify the best eight candidate muons. It cancels duplicate tracks that occur along the boundaries of processing layers, and will in the future also receive information from the calorimeter trigger to identify isolated muons. These are a signature of interesting rare particle decays such as those of vector bosons.

Decisions down to the wire



Overall, about 70 processors comprise the CMS Level-1 trigger upgrade. All processors make use of the large-capacity Virtex-7 FPGA from the Xilinx Corporation, and three board variants were produced. The first calorimeter trigger layer uses the CTP7 board, which highlights an on-board Zync system-on-chip from Xilinx for on-board control and monitoring. The second calorimeter trigger layer, the barrel muon processors, and the global trigger and global muon trigger use the MP7, which is a generic symmetric processor with 72 optical links for both input and output. Finally, a third, modular variant called the MTF7 is used for the overlap and end-cap muon trigger regions, and features a 1 GB memory mezzanine used for the momentum calculation in the end-cap region. This memory can store the calculation of the momentum from multiple angular inputs in the challenging forward region of CMS where the magnetic bending is small. (Image credit: G Iles.)

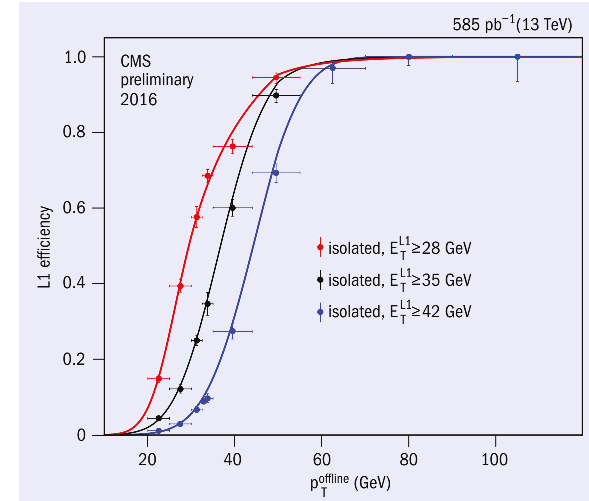


Fig. 2. One example of the improved performance from the new system, showing the efficiency for triggering on tau leptons for several thresholds as a function of the offline reconstructed transverse momentum of the tau lepton. In contrast, the trigger used during Run 1 had a plateau efficiency of only about 60%, due to limited discrimination between the narrow tau energy-deposit signature and broader jets.

A feast of physics

Finally, the global trigger processor collects information from both the calorimeter and muon trigger systems to arrive at the final decision on whether to keep the data from a given beam crossing – again, all in a period of four microseconds or less. The trigger changes made for Run 2 allow an event selection procedure that is much closer to that traditionally performed in software in the HLT or in offline analysis. The global trigger applies the trigger "menu" of the experiment – a large set of selection criteria designed to identify the broad classes of events used in CMS physics analyses. For example, events with a W or Z boson in the final state can be identified by the requirement for one or two isolated leptons above a certain energy threshold; top-quark decays by demanding high-energy leptons and jets in the same bunch crossing; and dark-matter candidates via missing transverse energy. The new system can contain several hundred such items – which is quite a feast of physics – and the complete trigger menu for CMS evolves continually as our understanding improves.

The trigger upgrade was commissioned in parallel with the original trigger system during LHC operations in 2015. This allowed the new system to be fully tested and optimised without affecting CMS physics data collection. Signals from the detector were physically split to feed both the initial and upgraded trigger systems, a project that was accomplished during the LHC's first long shutdown in 2013–2014. For the electromagnetic calorimeter, for instance, new optical transmitters were produced to replace the existing copper cables to send data to the old and new calorimeter triggers simultaneously. A complete split was not realistic for the barrel muon system, but a large detector slice was prepared nevertheless. The encouraging results during commissioning allowed the final decision to ▷

CMS trigger

proceed, with the upgrade to be taken in early January 2016.

As with the electronics, an entirely new software system had to be developed for system control and monitoring. For example, low-level board communication changed from a PCI-VME bus adapter to a combination of Ethernet and PCI-express. This took two years of effort from a team of experts, but also offered the opportunity to thoroughly redesign the software from the bottom up, with an emphasis on commonality and standardisation for long-term maintenance. The result is a powerful new trigger system with more flexibility to adapt to the increasingly extreme conditions of the LHC while maintaining efficiency for future discoveries (figure 2, previous page).

Although the "visible" work of data analysis at the LHC takes place on a timescale of months or years at institutes across the world, the first and most crucial decisions in the analysis chain happen underground and within microseconds of each proton–proton collision. The improvements made to the CMS trigger for Run 2 mean that a richer and more precisely defined data set can be delivered to physicists working on a huge variety of different searches and measurements in the years to come. Moreover, the new system allows flexibility and routes for expansion, so that event selections can continue to be refined as we make new discoveries and as physics priorities evolve.

The CMS groups that delivered the new trigger system are now turning their attention to the ultimate Phase-2 upgrade that will be possible by around 2025. This will make use of additional information from the CMS silicon tracker in the Level-1 decision, which is a technique never used before in particle physics and will approach the limits of technology, even in a decade's time. As long as the CMS physics programme continues to push new boundaries, the trigger team will not be taking time off.

Further reading

CMS Collaboration 2013 CMS-TDR-012.

Résumé

CMS se prépare au déluge de données du LHC

CMS a achevé une amélioration ambitieuse de son système de déclenchement, qui constitue le premier niveau du système de sélection des données pour les études de physique. Pour la seconde période d'exploitation du LHC, qui a commencé l'année passée, CMS s'est retrouvé dans un environnement de collisions bien plus difficile à gérer que celui de la première exploitation. L'augmentation de l'énergie dans le centre de masse ainsi que de la luminosité dans le LHC entraîne en effet un important phénomène d'« empilement » des événements, vu la multitude de collisions de protons ayant lieu à chaque rencontre entre deux paquets. Il était donc nécessaire de disposer d'un système de déclenchement amélioré, qui utilise les technologies les plus récentes, pour continuer à appliquer les même critères de sélection que pendant la première exploitation, voire les améliorer, et permettre ainsi à l'expérience d'atteindre son objectif de physique.

Darin Acosta, **Costas Foudas** and **Dave Newbold**, on behalf of the CMS Level-1 Trigger Group.

Storage ring steps up search for electric dipole moments

The JEDI collaboration aims to use a storage ring to set the most stringent limits to date on the electric dipole moments of hadrons, describe **Paolo Lenisa**, **Jörg Pretz** and **Hans Ströher**.


Forschungszentrum Jülich

The COSY storage ring at the Forschungszentrum Jülich in Germany is being modified to search for very small electric dipole moments.

The fact that we and the world around us are made of matter and only minimal amounts of antimatter is one of the fundamental puzzles in modern physics, motivating a variety of theoretical speculations and experimental investigations. The combined standard models of cosmology and particle physics suggest that at the end of the inflation epoch immediately following the Big Bang, the number of particles and antiparticles were almost in precise balance. Yet the laws of physics contrived to act differently on matter and antimatter to generate the apparently large imbalance that we observe today.

One of the necessary mechanisms required for this to happen – namely CP violation – is very small in the Standard Model of particle physics and therefore only able to account for a tiny fraction of the actual imbalance. New sources of CP violation are needed, and one such potential signature would be the appearance of electric dipole moments (EDMs) in fundamental particles.

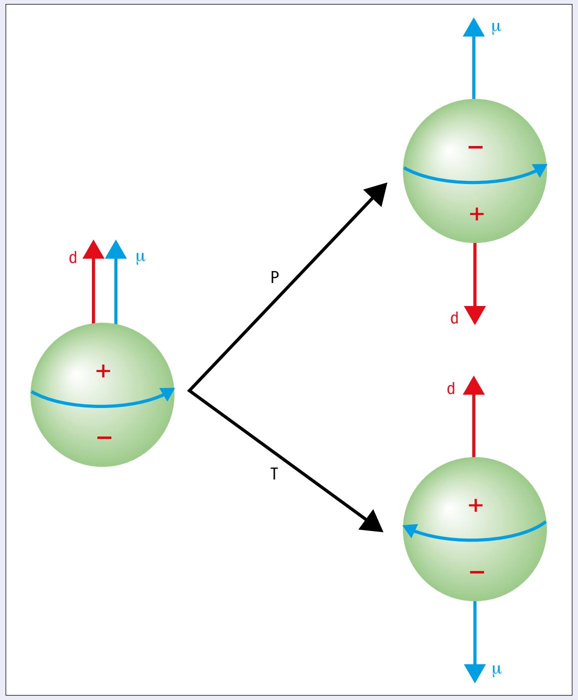
Electric dipole moments

An EDM originates from a permanent charge separation inside the particle. In its centre-of-mass frame, the ground state of a subatomic particle has no direction at its disposal except its spin, which is an axial vector, while the charge separation (EDM) corresponds to a polar vector (see panel overleaf). Therefore, if such a particle with nonzero mass and spin possesses an EDM, it must violate both parity (P) and time-reversal (T) invariance. If the combined CPT symmetry is to be valid, T violation also implies breaking of the combined CP symmetry. The Standard Model predicts the existence of EDMs, but their sizes (in the range of 10^{-31} to 10^{-33} e·cm for nucleons) fall many orders of magnitude below the sensitivity of current measurements and still far below the expected levels of projected experiments. An EDM observation at a much higher value would therefore be a clear and convincing sign of new physics beyond the current Standard Model (BSM).

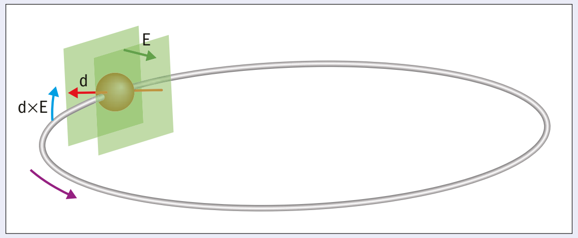
BSM theories such as supersymmetry (SUSY), technicolour, multi-Higgs models and left–right symmetric models generally predict nucleon EDMs in the range of 10^{-24} to 10^{-28} e·cm (part of the upper region of this range is already excluded by experiment). Although tiny, EDMs of this size would be large enough to be observed by a new generation of highly sensitive accelerator-based experiments with charged particles such as the proton and deuteron. In this respect, EDMs offer a complementary approach to searches for BSM physics at collider experiments, probing scales far beyond the reach of present high-energy machines such as the LHC. For example, in certain SUSY scenarios the present observed EDM limits provide information about physics at the TeV or even PeV scales, depending on the mass scale of the supersymmetric mechanisms and the strength of the CP-violating SUSY phase parameters (figure 1 overleaf).

Researchers have been searching for EDMs in neutral particles, especially neutrons, for more than 50 years, by trapping and cooling particles in small volumes and using strong electric fields. Despite an enormous improvement in sensitivity, however, these experiments have only produced upper bounds. The current upper limit of approximately 10^{-26} e·cm for the EDM of the neutron is an amazingly accurate result: if we had inflated the neutron so that it had the radius of the Earth, the EDM would correspond to a separation between positive and negative charges of about 1 μm. An upper limit of less than 10^{-29} e·cm has also been reported for a special isotope of mercury, but the Coulomb screening by ▷

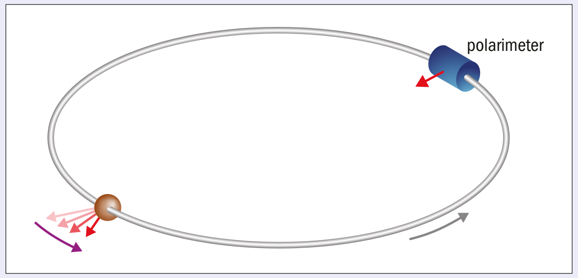
Electromagnetic gymnastics



Naively, an electric dipole moment (d) and a magnetic dipole moment (μ) transfer differently under P and T. In a fundamental particle, both quantities are proportional to the spin vector (s). Therefore, the interaction term (ds·E) is odd under P and T, whereas (μs·B) is even under these transformations.



In the final experiment to measure the EDM of a charged particle, a radial electric field is applied to an ensemble of particles circulating in a storage ring with polarisation vector aligned to their momentum. The existence of an EDM would generate a torque that slowly rotates the spin out of the ring plane into the vertical direction.



After rotation into the horizontal plane at COSY, the polarization vector starts to precess. At a measurement point along the ring, the rapidly rotating polarisation direction of the beam is determined by using the count-rate asymmetry of deuterons elastically scattered from a carbon target.

the atom's electron cloud makes it difficult to directly relate this number to the permanent EDMs of the neutrons and protons in its nucleus. For the electron, meanwhile, the reported EDM limits on more complicated polar molecules can be used to deduce a bound of about 10^{-28} e·cm – which is even further away from the Standard Model prediction (10^{-38} e·cm) than is the case for the neutron.

Storage-ring solution

Although these experiments provide useful constraints on BSM theories, a new class of experiments based on storage rings is needed to measure the electric dipole moment of charged particles (such as the proton, deuteron or helium-3). These highly sensitive accelerator-based experiments will allow the EDM of charged particles to be inferred from their very slow spin precession in the presence of large electric fields, and promise to reach a sensitivity of 10^{-29} e·cm. This is due mainly to the larger number of particles available in a stored beam compared with the ultra-cold neutrons usually found in trap experiments, and also the potentially longer observation time possible because such experiments are not limited by the particle decay time. Storage-ring experiments would span the range of EDM sizes where new CP violation is expected to lie. Furthermore, the ability to measure EDMs of more than one type of particle will help to constrain the origin of the CP-violating source because not all particles are equally sensitive to the various CP-violating mechanisms.

At the Cooler Synchrotron "COSY" located at the Forschungszentrum Jülich (FZJ), Germany, the JEDI (Jülich Electric Dipole moment Investigations) collaboration is working on a series of feasibility studies for such a measurement using an existing conventional hadron storage ring. COSY, which is able to store both polarised proton and deuteron beams with a momentum up to 3.7 GeV/c, is an ideal machine for the development and commissioning of the necessary technology. This R&D work has recently replaced COSY's previous hadron-physics programme of particle production and rare decays, although some other service and user activities continue.

A first upper limit for an EDM directly measured in a storage ring was obtained for muons at the (g–2) experiment at Brookhaven National Laboratory (BNL) in the US, but the measurement was not optimised for sensitivity to the EDM. Subsequently, scientists at BNL began to explore what would be needed to fully exploit the potential of a storage-ring experiment. While much initial discussion

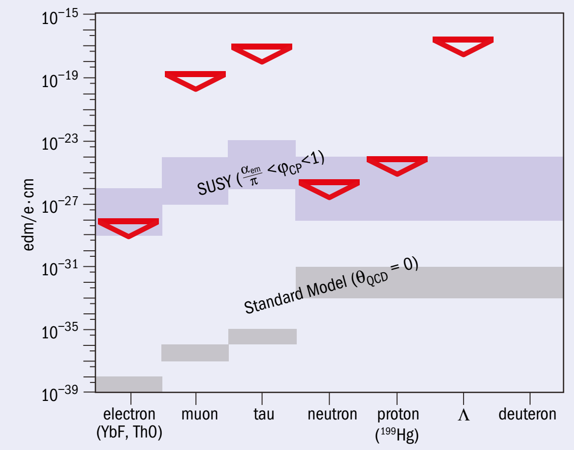


Fig. 1. Experimental upper limits for the EDMs of different particles (red arrows) plotted together with the prediction from SUSY (blue bands) and the Standard Model (grey). No experimental limit exists yet for the deuteron.

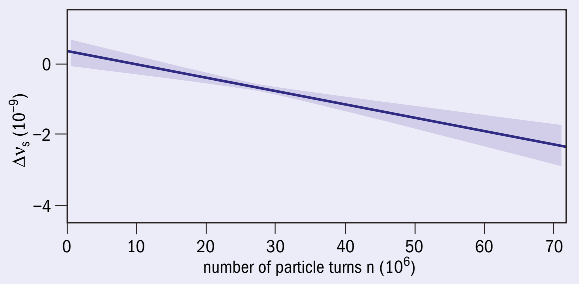


Fig. 2. Deviation of the spin tune ν_s, which is defined as the number of spin precessions per turn, as a function of the number of turns in the ring. At t = 38 s (about 28×10^6 turns), the interpolated spin tune amounts to $16097540628.3 \pm 9.7 \times 10^{-11}$, which represents the most precise measurement of this quantity ever performed. The previous best measurement, performed for the muon at the (g–2) experiment, had a precision of 3×10^{-8} per year. The higher precision achieved here is mainly attributed to the much longer measurement time of 100 s compared with 600 μs in the (g–2) experiment.

for an EDM experiment also took place at Brookhaven, commitments to the Relativistic Heavy Ion Collider (RHIC) operation and planning for a potential Electron–Ion Collider have prevented further development of such a project there. Therefore the focus shifted to FZJ and the COSY storage ring in Germany, where the JEDI collaboration was formed in 2011 to address the EDM opportunity.

The measuring principle is straightforward: a radial electric field is applied to an ensemble of particles circulating in a storage ring with their polarisation vector (or spin) initially aligned with their momentum direction. Maintaining the polarisation in this direction requires a storage ring in which the bending elements are a carefully matched set of both vertical magnetic fields and radial electric fields. The field strengths must be chosen such that the precession rate of the polarisation matches the circulation rate of the beam (called the "frozen spin"). For particles such as the proton with a positive gyromagnetic anomaly, this can be achieved by using only electric fields and choosing just the right "magic" momentum value (around 0.7 GeV/c). For deuterons, which have a negative gyromagnetic anomaly, a combination of electric and magnetic fields is required, but in this case the frozen spin condition can be achieved for a wide range of momentum and electric/magnetic field combinations.

The JEDI collaboration has passed a series of important milestones in recent years.

Such combined fields may also be used for the proton and would allow the experiment to operate at momenta other than the magic value.

The existence of an EDM would generate a torque that slowly rotates the spin out of the plane of the storage ring and into the vertical plane (see panel opposite). This slow change in the vertical polarisation is measured by sampling the beam with elastic scattering off a carbon target and looking for a slowly increasing left–right asymmetry in the scattered particle flux. For an EDM of 10^{-29} e·cm and an electric field of 10 MV/m, this would happen at an angular velocity of $3 \cdot 10^{-9}$ rad·s^{-1} (about 1/100th of a degree per day of continuous operations). This requires the measurement to be sensitive at a level never reached before in a storage ring. To obtain a statistically significant result, the polarisation in the ring plane must last for approximately 1000 s during a single fill of the ring, while the scattering asymmetry from the carbon target must reach levels above 10^{-6} to be measurable within a year of running.

Milestones passed

Following the commissioning of a measurement system that stores the clock time of each recorded event in the beam polarimeter with respect to the start of the accelerator cycle, the JEDI collaboration has passed a series of important milestones in recent years. Working with the deuteron beam at COSY, these time stamps make it possible to unfold for the first time the rapid rotation of the polarisation in the ring plan (which has a frequency of around 120 kHz) that arises from the gyromagnetic anomaly. In a one-second time interval, the number of polarisation revolutions may be counted and the final direction of the polarisation known to better than 0.1 rad (see figure 2). The magnitude of the polarisation may decline slowly due to decoherence effects in storage ring, as can be seen in subsequent polarisation measurements within a single fill.

Maintaining the polarisation requires the cancellation of effects that may cause the particles in the beam to differ from one another. Bunching and electron cooling serves to remove much of this spurious motion, but particle path lengths around the ring may differ if particles in the beam have transverse oscillations with different amplitudes. Recently, we demonstrated that the effect of these differences on polarisation decoherence can be removed by applying correcting sextupole fields to the ring. As a result, we can now achieve polarisation lifetimes in the horizontal plane of more than ▷

Electric dipole moment

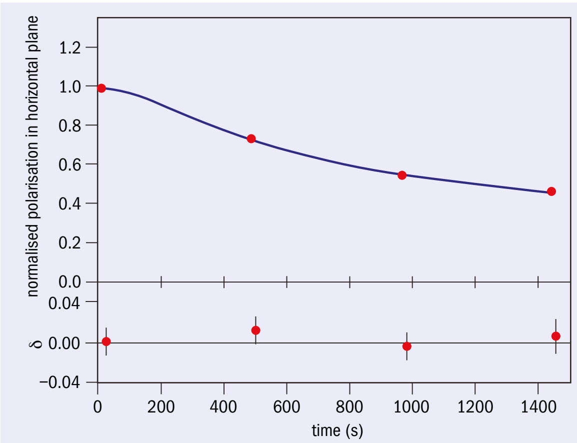


Fig. 3. One of the longest polarisation lifetimes recorded for the COSY ring. Measurements made at four separate times (to conserve beam) are matched to a depolarisation curve that assumes a Gaussian distribution of transverse oscillation amplitudes. The half-life of the polarisation is 1173±172 s, which is three orders of magnitude longer than previous results using electron beams. δ shows the difference between the model and the data.

1000 s – as required for the EDM experiment (figure 3). In the past year, the JEDI group has also shown that by determining errors in the polarisation direction and feeding this back to make small changes in the ring's radio-frequency, the direction of the polarisation may be maintained at the level of 0.1 rad during any chosen time period. This is a further requirement for managing the polarisation in the ring for the EDM measurement.

In early 2016, the European Research Council awarded an advanced research grant to the Jülich group to support further developmental efforts. The five-year grant, starting in October, will support a consortium that also includes RWTH Aachen University in Germany and the University of Ferrara in Italy. The goal of the project is to conduct the first measurement of the deuteron EDM. Since the COSY polarisation cannot be maintained parallel to its velocity (because no combined electric and magnetic bending elements exist), a novel device called a radiofrequency Wien filter will be installed in the ring to slowly accumulate the EDM signal (the filter influences the spin motion without acting on the particle's orbit). The idea is to exploit the electric fields created in the particle rest system by the magnetic fields of the storage-ring dipoles, which would allow the first ever measurement of the deuteron EDM.

COSY is also an important test facility for many EDM-related technologies, among them new beam-position monitoring, control and feedback systems. High electric fields and combined electric/magnetic deflectors may also find applications in other fields, such as accelerator science. Many checks for systematic errors will be undertaken, and a technical design report for a future dedicated storage ring will be prepared. The most significant challenges will come from small imperfections in the placement and orientation of ring elements, which may cause stray field components that generate the accumulation of an EDM-like signal. The experiment is most sensitive to radial magnetic fields and vertical electric fields. Similar effects may arise through the non-commutativity of spurious rotations within the ring system, and efforts are under way to model these effects via spin tracking supported with beam testing. Eventually, many such effects may be reduced or eliminated by comparing the signal accumulation rates seen with beams travelling in opposite directions in the storage ring. During the next decade, this will allow researchers to approach the design goals of the EDM search using a storage ring, adding a new opportunity to unveil physics beyond the Standard Model.

● Further reading

For more information about the JEDI collaboration, see collaborations.fz-juelich.de/ikp/jedi/index.shtml.

D Eversmann *et al.* 2015 *Phys. Rev. Lett.* **115** 094801.
G Guidoboni *et al.* 2016 *Phys. Rev. Lett.* **117** 054801.

Résumé

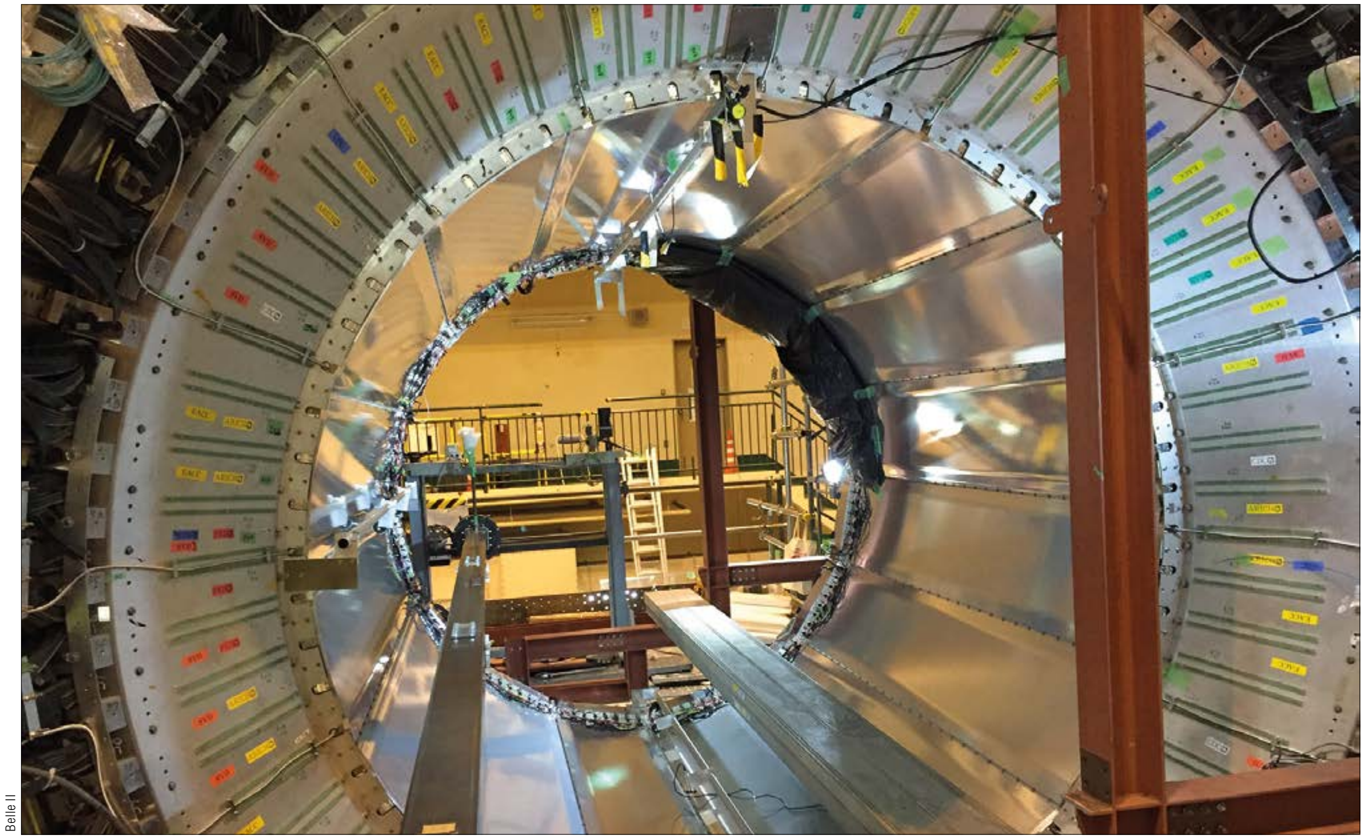
Un anneau de stockage pour intensifier la recherche des moments électriques dipolaires

La collaboration JEDI envisage l'utilisation d'un anneau de stockage afin de poser les limites les plus précises à ce jour pour les moments électriques dipolaires des hadrons. L'existence d'un moment électrique dipolaire engendrerait un moment de torsion faisant lentement passer la direction du spin du plan de l'anneau de stockage au plan vertical. L'observation d'un moment électrique dipolaire non nul serait un signe clair d'une nouvelle physique au-delà du Modèle standard, mais la sensibilité actuelle des expériences n'est pas suffisante pour qu'on puisse mettre à l'épreuve entièrement cette hypothèse. En travaillant à l'adaptation de l'anneau de stockage COSY du Forschungszentrum Jülich (Allemagne), des scientifiques élaborent les techniques qui pourront, en fin de compte, leur permettre de mesurer les moments électriques dipolaires avec une précision de 10^{-29} e·cm.

Paolo Lenisa, University of Ferrara and INFN, **Jörg Pretz**, RWTH-Aachen (and co-spokesperson of the JEDI collaboration), and **Hans Ströher**, Forschungszentrum Jülich, Germany.

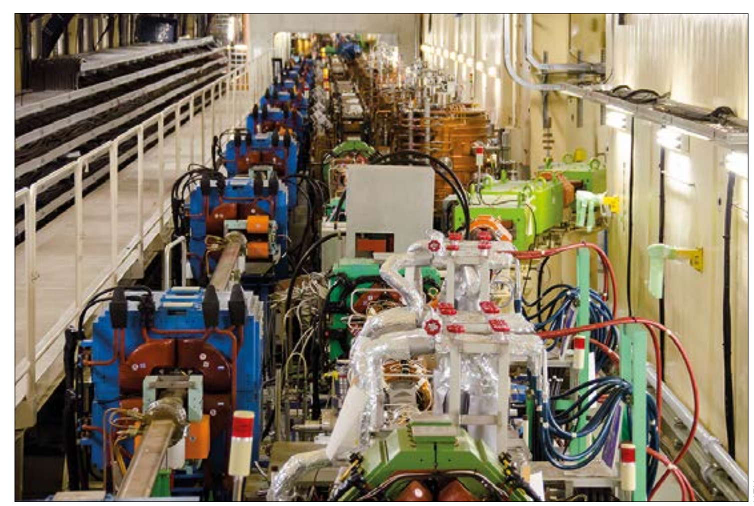
Belle II super-B factory experiment takes shape at KEK

The super-B factory under construction at Japan's KEK laboratory seeks to reveal new weak interactions in the flavour sector and discover new strongly interacting particles, describe **Tom Browder**, **Toru Iijima**, **Katsunobu Oide** and **Phillip Urquijo**.



Belle II

Peter Lewis



KEK

The newly built time-of-propagation (TOP) detector, which was installed in May, is part of the cylindrical barrel of Belle II designed for precision identification of π and K mesons. (Bottom left) The BEAST-II background commissioning detector being installed at Tsukuba Hall, where the large crossing angle of the two beams is clearly visible. (Bottom right) A section of the 3 km-long SuperKEKB accelerator in which the two rings as well as the copper ARES room-temperature radio-frequency cavities are visible.

Since CERN's LHC switched on in the autumn of 2008, no new particle colliders have been built. SuperKEKB, under construction at the KEK laboratory in Tsukuba, Japan, is soon to change that. In contrast to the LHC, which is a proton–proton collider focused on producing the highest energies possible, SuperKEKB is an electron–positron collider that will operate at the intensity frontier to produce enormous quantities of B mesons.

At the intensity frontier, physicists search for signatures of new particles or processes by measuring rare or forbidden reactions, or finding deviations from Standard Model (SM) predictions. The "mass reach" for new-particle searches can be as high as 100 TeV/c^2, provided the couplings of the particles are large, which is well beyond the reach of direct searches at current colliders. The flavour sector provides a particularly powerful way to address the many deficiencies of the SM: at the cosmological scale, the puzzle of the baryon–antibaryon asymmetry remains unexplained by known sources of CP violation; the SM does not explain why there should be only three generations of elementary fermions or why there is an observed hierarchy in the fermion masses; the theory falls short on accounting for the small neutrino mass, and it is also not clear whether there is only a single Higgs boson.

SuperKEKB follows in the footsteps of its predecessor KEKB, which recorded more than 1000 fb^{-1} (one inverse attobarn, ab^{-1}) of data and achieved a world record for instantaneous luminosity of 2.1×10^{34} cm^{-2} s^{-1}. The goals for SuperKEKB are even more ambitious. Its design luminosity is 8×10^{35} cm^{-2} s^{-1}, 40 times that of previous B-factory experiments, and the machine will operate in "factory" mode with the aim of recording an unprecedented data sample of 50 ab^{-1}.

The trillions of electron–positron collisions provided by SuperKEKB will be recorded by an upgraded detector called Belle II, which must be able to cope with the much larger beam-related backgrounds resulting from the high-luminosity environment. Belle II, which is the first "super-B factory" experiment, is designed to provide better or comparable performance to that of the previous Belle experiment at KEKB or BaBar at SLAC in Stanford, California. With the SM of weak interactions now well established, Belle II will focus on the search for new physics beyond the SM.

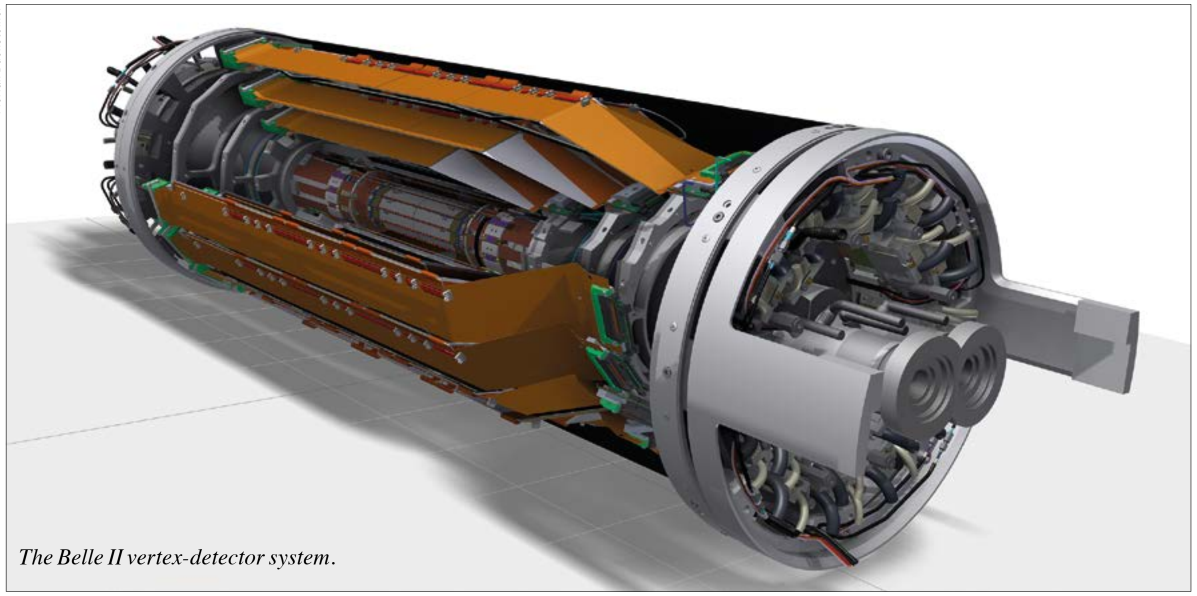
SuperKEKB was formally approved in October 2010, began construction in November 2011 and achieved its "first turns" in February this year (*CERN Courier* April 2016 p11). By the time of completion of the initial accelerator commissioning before Belle-II roll-in (so-called "Phase 1"), the machine was storing a current of 1000 mA in its low-energy positron ring (LER) and 870 mA in the high-energy electron ring (HER). As currently scheduled, SuperKEKB will produce its first collisions in late 2017 (Phase 2), and the first physics run with the full detector in place will take place in late 2018 (Phase 3). The experiment will operate until the late 2020s.

B-physics background

The Belle experiment took data at the KEKB accelerator between 1999 and 2010. At roughly the same time, the BaBar experiment operated at SLAC's PEP-II accelerator. In 2001, these two "B factories" established the first signals of CP violation, therefore revealing matter–antimatter asymmetries, in the B-meson sector. They also provided the experimental foundation for the 2008 Nobel Prize in Physics, which was awarded to theorists Makoto Kobayashi and Toshihide Maskawa for their explanation through complex phases in weak interactions.

In addition to the observation of large CP violation in the low-background "golden" $B \rightarrow J/\psi\ K_S$-type decay modes, these B-factory experiments allowed many important measurements of weak interactions involving bottom and charm quarks as well as τ leptons. The B factories also discovered an unexpected crop of new strongly interacting particles known as the X, Y and Z states. Since 2008, a third major B factory, LHCb, entered the game. One of the four main LHC detectors, LHCb has made a large number of new measurements of B and B_s mesons and B baryons produced in proton–proton collisions. The experiment has tightly constrained new physics phases in the mixing-induced weak decays of B_s mesons, confirmed Belle's discovery of the four-quark state Z(4430), and discovered the first two clear pentaquark states. Together with LHCb, Belle II is expected to be equally prolific and may discover signals of new physics in the coming decade. ▷

Florian Buchsteiner



The Belle II vertex-detector system.

Asymmetric collisions

The accelerator technology underpinning B factories is quite different from that of high-energy hadron colliders. For the coherent production of quantum-mechanically entangled pairs of B and $\bar{B}$ mesons, measurements of time-dependent CP asymmetries require that we know the difference in the decay times between the two B mesons. With equal energy beams, the B mesons travel only tens of microns from their production point and cannot experimentally be distinguished in silicon vertex detectors. To allow the B factory experiments to observe the time difference or spatial separation of the B vertices, the beams have asymmetric energies, and the centre of mass system is therefore boosted along the axis of the detector. For example, at PEP-II, 9 GeV electron and 3.1 GeV positron beams were used, while at KEKB the beam energies were 8 GeV and 3.5 GeV.

Charged particles within a beam undergo thermal motion just like gas molecules: they scatter to generate off-momentum particles at a rate given by the density and the temperature of the beam. Such off-momentum particles reduce the beam lifetime, increase beam sizes and generate detector background. To maximise the beam lifetime and reduce intra-beam scattering, SuperKEKB will collide 7 and 4 GeV electron and positron beams, respectively.

Belle II will serve as our most powerful probe yet of new physics in the flavour sector.

Two strategies were employed at the B factories to separate the incoming and outgoing beams: PEP-II used magnetic separation in a strong dipole magnet near the interaction point, while KEKB used a crossing angle of 22 mrad. SuperKEKB will extend the approach of KEKB with a crossing angle of 83 mrad, with separate beamlines for the two rings and no shared magnets between them. While the beam currents will be somewhat higher at SuperKEKB than they were at KEKB, the most dramatic improvement in luminosity is the result of very flat low-emittance "cool beams" and much stronger focusing at the interaction point. Specifically, SuperKEKB uses the nano-beam scheme inspired by the design of Italian accelerator physicist Pantaleo Raimondi, which promises to reduce the vertical beam size at the interaction point to around 50 nm – 20 times smaller than at KEKB.

Although the former TRISTAN (and KEKB) tunnels were reused for the SuperKEKB facility, many of the other accelerator components are new or upgraded from KEKB. For example, the 3 km-circumference vacuum chamber of the LER is new and is equipped with an antechamber and titanium-nitride coating to fight against the problem of photoelectrons. This process, in which low-energy electrons generated as photoelectrons or by ionisation of the residual gas in the beam pipe are attracted by the positively charged beam to form a cloud around the beam, was a scourge for the B factories and is also a major problem for the LHC. Many of the LER magnets are new, while a significant number of the HER magnets were rearranged to achieve a lower emittance, powered by newly designed high-precision power supplies at the ppm level. The RF system has been rearranged to double the beam current with a new digital-control system, and many beam diagnostics and control systems were rebuilt from scratch.

During Phase 1 commissioning, after many iterations the LER optics were corrected to achieve design emittance. To achieve low-emittance positron beams, a new damping ring has been constructed that will be brought into operation in 2017. To meet the charge and emittance requirements of SuperKEKB, the linac injector complex has been upgraded and includes a new low-emittance electron gun. Key components of the accelerator – including the beam pipe, superconducting magnets, beam feedback and diagnostics – were developed in collaboration with international partners in Italy (INFN Frascati), the US (BNL),

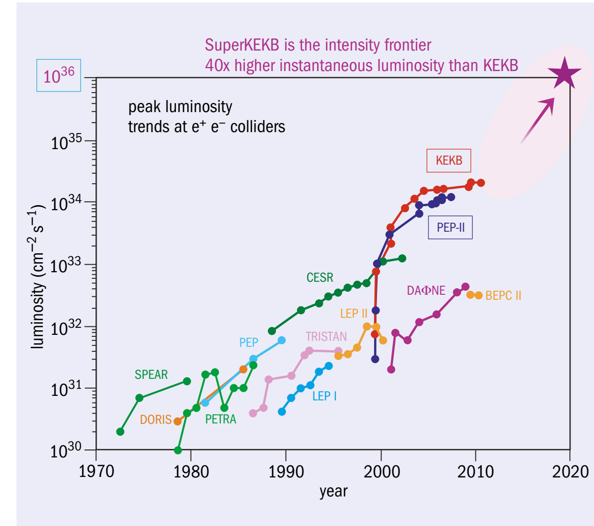


Fig. 1. Peak luminosity trends of electron–positron colliders.

Phil Urquijo

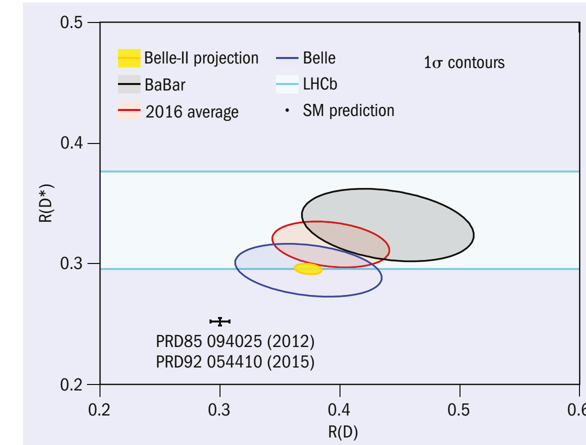


Fig. 2. The ratio of $B \to D^* \tau \nu$ to $B \to D^* l \nu$ (y-axis) versus the ratio of $B \to D \tau \nu$ to $B \to D l \nu$ (x-axis) shows an interesting departure from the SM prediction, which will be tested further by the Belle-II physics programme.

and Russia (BINP), and further joint work, which will also involve CERN, is expected.

During Phase 1, intensive efforts were made to tune the machine to minimise the vertical emittances in both rings. This was done via measurements and corrections using orbit-response matrices. The estimated vertical emittances were below 10 pm in both rings, which is close to the design values. There were discrepancies, however, with the beam sizes measured by X-ray size monitors, especially in the HER, which is under investigation.

The early days of Belle and BaBar were plagued by problems, with beam-related backgrounds resulting from the then unprecedented beam currents and strong beam focusing. In the case of Belle, the first silicon vertex detector was destroyed by an unexpected synchrotron radiation "fan" produced by an electron beam passing through a steering magnet. Fortunately, the Belle team was able to build a new replacement detector quickly and move on to compete in the race with BaBar to measure CP asymmetries in the B sector. As a result of these past experiences, we have adopted a rather conservative commissioning strategy for the SuperKEKB/Belle-II facility. This year, during the earliest Phase 1 of operation, a special-purpose device called BEAST II consisting of seven types of background measurement devices was installed at the interaction point to characterise the expected Belle-II background.

At the beginning of next year, the Belle-II outer detector will be "rolled in" to the beamline and all components except the vertex detectors will be installed. The complex quadrupole superconducting final-focusing magnets are among the most challenging parts of the accelerator. In autumn 2017, the final-focusing magnets will be integrated with Belle II and the first runs of Phase 2 will commence. A new suite of background detectors will be installed, including a cartridge containing samples of the Belle-II vertex detectors. The first goal of the Phase-2 run is to achieve a luminosity above $10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ and to verify that the backgrounds are low enough for the vertex detector to be installed.

Belle reborn

With Belle II expected to face beam-related backgrounds 20 times higher than at Belle, the detector has been reborn to achieve the experiment's main physics goals – namely, to measure rare or forbidden decays of B and D mesons and the τ lepton with better accuracy and sensitivity than before. While Belle II reuses Belle's spectrometer magnet, many state-of-the-art technologies have been included in the detector upgrade. A new vertex-detector system comprising a two-layer pixel detector (PXD) based on "DEPFET" technology and a four-layer double-sided silicon-strip detector (SVD) will be installed. With the beam-pipe radius of SuperKEKB having been reduced to 10 mm, the first PXD layer can be placed just 14 mm from the interaction point to improve the vertex resolution significantly. The outermost SVD layer is located at a larger radius than the equivalent system at Belle, resulting in higher reconstruction efficiency for K_s mesons, which is important for many CP-violation measurements.

A new central drift chamber (CDC) has been built with smaller cell sizes to be more robust against the higher level of beam background hits. The new CDC has a larger outer radius (1111.4 mm as opposed to 863 mm in Belle) and 56 compared to 50 measurement layers, resulting in improved momentum resolution. Combined with the vertex detectors, Belle II has improved D^* meson reconstruction and hence better full-reconstruction efficiency for B mesons, which often include D^*s among their weak-interaction decay products.

Because good particle identification is vital for successfully identifying rare processes in the presence of very large background (for example, the measurement of $B \to X_d \gamma$ must contend with $B \to X_s \gamma$ background processes that are an order-of-magnitude larger), two newly developed ring-imaging Cherenkov detectors have been introduced at Belle II. The first, the time-of-propagation (TOP) counter, is installed in the barrel region and consists of a finely polished and optically flat quartz radiator and an array of pixelated

Key physics questions to be addressed by SuperKEKB and Belle II

● **Are there new CP-violating phases in the quark sector?** The amount of CP violation (CPV) in the SM quark sector is orders-of-magnitude too small to explain the baryon–antibaryon asymmetry. New insights will come from examining the difference between B^0 and $\bar{B}^0$ decay rates, namely via measurements of time-dependent CPV in penguin transitions (second-order W interactions) of $b \to s$ and $b \to d$ quarks. CPV in charm mixing, which is negligible in the SM, will also provide information on the up-type quark sector. Another key area will be to understand the mechanisms that produced large amounts of CPV in the time-integrated rates of hadronic B decays, such as $B \to K\pi$ and $B \to K\pi\pi$, observed by the B factories and LHCb.

● **Does nature have multiple Higgs bosons?** Many extensions to the SM predict charged Higgs bosons in addition to the observed neutral SM-like Higgs. Extended Higgs sectors can also introduce extra sources of CP violation. The charged Higgs will be searched for in flavour transitions to τ leptons, including $B \to \tau\nu$, as well as $B \to D\tau\nu$ and $B \to D^*\tau\nu$, where 4σ anomalies have already been observed.

● **Does nature have a left–right symmetry, and are there flavour-changing neutral currents beyond the SM?** The LHCb experiment finds 4σ evidence for new physics in the decay $B \to K^*\mu^+\mu^-$, which is sensitive to all heavy particles in the SM. Left–right symmetry models provide interesting candidates for this anomaly. Such extensions to the SM introduce new heavy bosons that predominantly couple to right-handed fermions that allow a new pattern of flavour-changing currents, and can be used to explain neutrino mass generation. To further characterise potential new physics, here we need to examine processes with reduced theoretical uncertainty, such as inclusive $b \to s\,l^+l^-$, $b \to s\nu\bar{\nu}$ transitions and time-dependent CPV in radiative B meson decays. Complementary constraints coming from electroweak precision observables and from direct searches at the LHC have pushed the mass limit for left–right models to several TeV.

● **Are there sources of lepton-flavour violation (LFV) beyond the SM?** LFV is a key prediction in many neutrino mass-generation mechanisms, and may lead to $\tau \to \mu\gamma$ enhancement at the level of 10^{-8}. Belle II will analyse τ lepton decays for a number of searches, which include LFV, CP violation and measurements of the electric dipole moment and (g–2) of the τ. The expected sensitivities to τ decays at Belle II will be unrivalled due to correlated production with minimal collision background. The detector will provide sensitivities seven times better than Belle for background-limited modes such as $\tau \to \mu\gamma$ (to about 5×10^{-9}) and up to 50 times better for the cleanest searches, such as $\tau \to eee$ (at the level of 5×10^{-10}).

● **Is there a dark sector of particle physics at the same mass scale as ordinary matter?** Belle II has unique sensitivity to dark matter via missing energy decays. While most searches for new physics at Belle II are indirect, there are models that predict new particles at the MeV to GeV scale – including weakly and non-weakly interacting massive particles that couple to the SM via new gauge symmetries. These models often predict a rich sector of hidden particles that include dark-matter candidates and gauge bosons. Belle II is implementing a new trigger system to capture these elusive events.

● **What is the nature of the strong force in binding hadrons?** With B factories and hadron colliders having discovered a large number of states that were not predicted by the conventional meson interpretation, changing our understanding of QCD in the low-energy regime, quarkonium is high on the agenda at Belle II. A clean way of studying new particles is to produce them near resonance, achievable by adjusting the machine energy, while Belle II has good detection capabilities for all neutral and charged particles.

micro-channel-plate photomultiplier tubes that can measure the propagation time of internally reflected Cherenkov photons with a resolution of around 50 ps. The second, the aerogel ring-imaging Cherenkov counter (A-RICH), is located in Belle II's forward endcap region and will detect Cherenkov photons produced in an aerogel radiator with hybrid avalanche photodiode sensors.

The electromagnetic calorimeter (ECL) reuses Belle's thallium-doped cesium-iodide crystals. New waveform-sampling read-out electronics have been implemented to resolve overlapping signals such that π^0 and γ reconstruction is not degraded, even in the high-background environment. The flux return of the Belle-II solenoid magnet, which surrounds the ECL, is instrumented to detect K_L mesons and muons (KLM). All of the endcap KLM layers and the innermost two layers of the barrel KLM were replaced with new scintillator-based detectors read out by solid-state photomultipliers. Signals from all of the Belle-II sub-detector components are read out through a common optical-data-transfer system and backend modules. GRID computing distributed over KEK-Asia-Australia-Europe-North America will be used to process the large data volumes produced at Belle II by high-luminosity collisions, which, like LHCb, are expected to be in the region of 1.8 GB/s.

Construction of the Belle-II experiment is in full swing, with fabrication and installation of sub-detectors progressing from the outer to the inner regions. A recent milestone was the completion of the TOP installation in June, while installation of the CDC, A-RICH and endcap ECL will follow soon. The Belle-II detector will be rolled into the SuperKEKB beamline in early 2017 and beam collisions will start later in the year, marking Phase 2. After verifying the background conditions in beam collisions, Phase 3 will see the installation of the vertex-detector system, after which the first physics run can begin towards the end of 2018.

Unique data set

As a next-generation B factory, Belle II will serve as our most powerful probe yet of new physics in the flavour sector, and may discover new strongly interacting particles such as tetraquarks, molecules or perhaps even hybrid mesons. Collisions at SuperKEKB will be tuned to centre-of-mass energies corresponding to the masses of the Υ resonances, with most data to be collected at the $\Upsilon(4S)$ resonance. This is just above the threshold for producing quantum-correlated B-meson pairs with no

fragmentation particles, which are optimal for measuring weak-interaction decays of B mesons.

SuperKEKB is both a super-B factory and a τ-charm factory: it will produce a total of 50 billion $b\bar{b}$, $c\bar{c}$ and $\tau^+\tau^-$ pairs over a period of eight years, and a team of more than 650 collaborators from 23 countries is already preparing to analyse this unique data set. The key open questions to be addressed include the search for new CP-violating phases in the quark sector, lepton-flavour violation and left–right asymmetries (see panel opposite).

Rare charged B decays to leptonic final states are the flagship measurements of the Belle-II research programme. The leptonic decay $B \to \tau\nu$ occurs in the SM via a W-annihilation diagram with an expected branching fraction of $0.82^{+0.05}_{-0.03} \times 10^{-4}$, which would be modified if a non-standard particle such as a charged Higgs interferes with the W. Since the final state contains multiple neutrinos, it is measurable only in an electron–positron collider experiment where the centre-of-mass energy is precisely known. Belle II should reach a precision of 3% on this measurement, and observe the channel $B \to \mu\nu$ for tests of lepton-flavour universality.

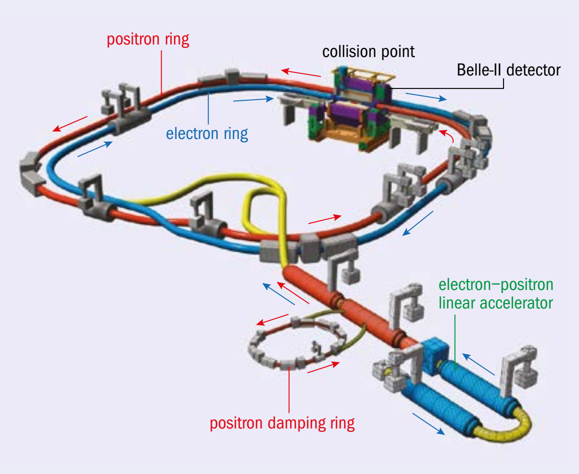
Perhaps the most interesting search at Belle II will be the analogous semi-leptonic decays, $B \to D^*\tau\nu$ and $B \to D\tau\nu$, which are similarly sensitive to charged Higgs bosons. Recently, the combined measurements of these processes from Babar, Belle and LHCb have pointed to a curious 4σ deviation of the decay rates compared to the SM prediction (see figure X). Since no such deviation is seen in $B \to \tau\nu$, making it difficult to resolve the nature of the potential underlying new physics, the Belle-II data set will be required to settle the issue.

Another 4σ anomaly persists in $B \to K^*\,l^+l^-$ flavour-changing neutral-current loop processes observed by LHCb, which may be explained by the actions of new gauge bosons. By allowing the study of closely related processes, Belle II will be able to confirm if this really is a sign of new physics and not an artifact of theoretical predictions. More precisely calculable inclusive transitions $b \to s\gamma$ and $b \to s\,l^+l^-$ will be compared to the exclusive ones measured by LHCb. The ultimate data set will also give access to $B \to K^*\nu\bar{\nu}$ and $K\nu\bar{\nu}$, which are experimentally challenging channels but also the most precise theoretically.

Beyond the Standard Model

There are many reasons to choose Belle II to address these and other puzzles with the SM, and in general the experiment will complement the physics reach of LHCb. The lower-background environment at Belle compared to LHCb allows researchers to reconstruct final states containing neutral particles, for instance, and to design efficient triggers for the analysis of τ particles. With asymmetric beam energies, the Lorentz boost of the electron–positron system is ideal for measurements of lifetimes, mixing parameters and CP violation.

The B factories established the existence of matter–antimatter asymmetries in the b-quark sector, in addition to the CP violation that was discovered 52 years earlier in the s-quark sector. The B factories established that a single irreducible complex phase in the weak interaction is sufficient to explain all CP-violating effects observed to date. This completed the SM description of the weak-



A schematic of the SuperKEKB accelerator complex.

interaction couplings of quarks.To move beyond this picture, two super-B factories were initially proposed: one at Tor Vegata near Frascati in Italy, and one at KEK in Japan. Although the former facility was not funded, there was a synergy and competition in the two designs. The super-B factory at KEK follows the legacy of the B factories, with Belle II and LHCb both vying to establish the first solid existence of new physics beyond the SM.

● Further reading

Babar Collaboration 2012 *Phys. Rev. Lett.* **109** 101802.
Babar Collaboration 2013 *Phys. Rev. D* **88** 072012.
Belle Collaboration 2015 *Phys. Rev. D* **92** 072014.
Belle Collaboration 2016 arXiv:1607.07923, submitted to *Phys. Rev. D.*
Belle II Technical Design Report https://arxiv.org/abs/1011.0352.
LHCb Collaboration 2015 *Phys. Rev. Lett.* **115** 111803.
The Physics of the B Factories (Springer Verlag) arxiv.org/abs/1406.6311.

Résumé

Belle II prend forme au laboratoire KEK

Le projet d'installation Super-B, en construction dans le laboratoire japonais KEK, a pour but de révéler de nouvelles interactions faibles dans le secteur des saveurs, et de découvrir de nouvelles particules interagissant fortement. Ce collisionneur électron-positon, successeur du KEKB, produira d'énormes quantités de mésons B, ce qui permettra aux physiciens de chercher les signatures de nouvelles particules ou de nouveaux processus en mesurant des réactions rares ou interdites. Le domaine de masse accessible pour la recherche de nouvelles particules peut aller jusqu'à 100 TeV/c², soit bien au-delà de la portée des recherches directes menées auprès des collisionneurs actuels. Les collisions, qui doivent commencer en 2018, seront analysées par un détecteur amélioré, Belle II.

Tom Browder, University of Hawaii (spokesperson of the Belle II collaboration), **Katsunobu Oide**, KEK, **Phil Urquijo**, University of Melbourne (Belle II physics co-ordinator), and **Toru Iijima**, Nagoya University.

The newly completed MAX IV facility near Lund, Sweden.

Image credit: Perry Nordeng.

MAX IV paves the way for ultimate X-ray microscope

Sweden's MAX IV facility is the first storage ring to employ a multi-bend achromat. **Mikael Eriksson** and **Dieter Einfeld** describe how this will produce smaller and more stable X-ray beams, taking synchrotron science closer to the X-ray diffraction limit.

Since the discovery of X-rays by Wilhelm Röntgen more than a century ago, researchers have striven to produce smaller and more intense X-ray beams. With a wavelength similar to interatomic spacings, X-rays have proved to be an invaluable tool for probing the microstructure of materials. But a higher spectral power density (or brilliance) enables a deeper study of the structural, physical and chemical properties of materials, in addition to studies of their dynamics and atomic composition.

For the first few decades following Röntgen's discovery, the brilliance of X-rays remained fairly constant due to technical limitations of X-ray tubes. Significant improvements came with rotating-anode sources, in which the heat generated by electrons striking an anode could be distributed over a larger area. But it was the advent of particle accelerators in the mid-1900s that gave birth to modern X-ray science. A relativistic electron beam traversing a circular storage ring emits X-rays in a tangential direction. First observed in 1947 by researchers at General Electric in the US, such synchrotron radiation has taken X-ray science into new territory by providing smaller and more intense beams.

Generation game

First-generation synchrotron X-ray sources were accelerators built for high-energy physics experiments, which were used "parasitically" by the nascent synchrotron X-ray community. As this community started to grow, stimulated by the increased flux and brilliance at storage rings, the need for dedicated X-ray sources with different electron-beam characteristics resulted in several second-generation X-ray sources. As with previous machines, however, the source of the X-rays was the bending magnets of the storage ring.

The advent of special "insertion devices" led to present-day third-generation storage rings – the first being the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, and the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory in Berkeley, California, which began operation in the early 1990s. Instead of using only the bending magnets as X-ray emitters, third-generation storage rings have straight sections that allow periodic magnet structures called undulators and wigglers to be introduced. These devices consist of rows of short magnets with alternating field directions so that the net beam deflection cancels out. Undulators can house 100 or so permanent short magnets, each emitting X-rays in the same direction, which boosts the intensity of the emitted X-rays by two orders of magnitude. Furthermore, interference effects between the emitting magnets can concentrate X-rays of a given energy by another two orders of magnitude.

Third-generation light sources have been a major success story, thanks in part to the development of excellent modelling tools that allow accelerator physicists to produce precise lattice designs. Today, there are around 50 third-generation light sources worldwide, with a total number of users in the region of 50,000. Each offers a number of X-ray beamlines (up to 40 at the largest facilities) that fan out from the storage ring: X-rays pass through a series of focusing and other elements before being focused on a sample positioned at the end station, with the longest beamlines (measuring 150 m or more) at the largest light sources able to generate X-ray spot sizes a few tens of nanometres in diameter. Facilities typically operate around the clock, during which teams of users spend anywhere between a few hours to a few days undertaking experimental shifts, before returning to their home institutes with the data.

Although the corresponding storage-ring technology for third-generation light sources has been regarded as mature, a revolutionary new lattice design has led to another step up in brightness. The MAX IV facility at Maxlab in Lund, Sweden, which was inaugurated in June, is the first such facility to demonstrate the new lattice. Six years in construction, the facility has demanded numerous cutting-edge technologies – including vacuum systems developed in conjunction with CERN – to become the most brilliant source of X-rays in the world.

The multi-bend achromat

Initial ideas for the MAX IV project started at the end of the 20th century. Although the flagship of the Maxlab laboratory, the low-budget MAX II storage ring, was one of the first third-generation synchrotron radiation sources, it was soon outcompeted by several larger and more powerful sources entering operation. Something had to be done to maintain Maxlab's accelerator programme.

The dominant magnetic lattice at third-generation light ▷

Towards the X-ray diffraction limit

Electromagnetic radiation faces a fundamental limit in terms of how sharply it can be focused. For visible light, it is called the Abbe limit, as shown by Ernst Karl Abbe in 1873. The diffraction limit is defined as $\lambda/(4\pi)$, where λ is the wavelength of the radiation. Reaching the diffraction limit for X-rays emitted from a storage ring (approximately 10 pm rad) is highly desirable from a scientific perspective: not only would it bring X-ray microscopy to its limit, but material structure could be determined with much less X-ray damage and fast chemical reactions could be studied *in situ*. Currently, the electron beam travelling in a storage ring dilutes the X-ray emittance by orders of magnitude. Because this quantity determines the brilliance of the X-ray beam, reaching the X-ray diffraction limit is a case of reducing the electron-beam emittance as far as possible.

The emittance is defined as C_q*E^2/N^3, where C_q is the ring magnet-lattice constant, E is the electron energy and N is the number of dipole magnets. It has two components: horizontal (given by the magnet lattice and electron energy) and vertical (which is mainly caused by coupling from the horizontal emittance). While the vertical emittance is, in principle, controllable and small compared with the horizontal emittance, the latter has to be minimised by choosing an optimised magnet lattice with a large number of magnet elements.

Because C_q can be brought to the theoretical minimum emittance limit and E is given by the desired spectral range of the X-rays, the only parameter remaining with which we can decrease the electron-beam emittance is N. Simply increasing the number of achromats to increase N turns out not to be a practical solution, however, because the rings are too big and expensive and/or the electrons tend to be unstable and leave the ring. However, a clever compromise called the multi-bend achromat (MBA), based on compact magnets and vacuum chambers, allows more elements to be incorporated around a storage ring without increasing its diameter, and in principle this design could allow a future storage ring to achieve the diffraction limit.


Johan Bävman

An undulator at MAX IV, which generates intense synchrotron X-rays as electrons pass through a periodic magnetic structure.

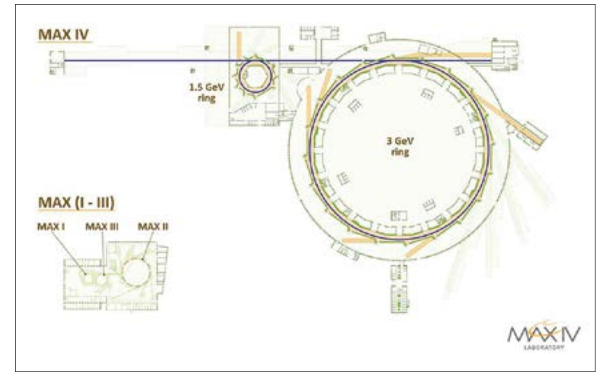
sources consists of double-bend achromats (DBAs), which have been around since the 1970s. A typical storage ring contains 10–30 achromats, each consisting of two dipole magnets and a number of magnet lenses: quadrupoles for focusing and sextupoles for chromaticity correction (at MAX IV we also added octupoles to compensate for amplitude-dependent tune shifts). The achromats are flanked by straight sections housing the insertion devices, and the dimensions of the electron beam in these sections is minimised by adjusting the dispersion of the beam (which describes the dependence of an electron's transverse position on its energy) to zero. Other storage-ring improvements, for example faster correction of the beam orbit, have also helped to boost the brightness of modern synchrotrons. The key quantity underpinning these advances is the electron-beam emittance, which is defined as the product of the electron-beam size and its divergence.

Despite such improvements, however, today's third-generation storage rings have a typical electron-beam emittance of between 2–5 nm rad, which is several hundred times larger than the diffraction limit of the X-ray beam itself. This is the point at which the size and spread of the electron beam approaches the diffraction properties of X-rays, similar to the Abbe diffraction limit for visible light (see panel, left). Models of machine lattices with even smaller electron-beam emittances predict instabilities and/or short beam lifetimes that make the goal of reaching the diffraction limit at hard X-ray energies very distant.

Although it had been known for a long time that a larger number of bends decreases the emittance (and therefore increases the brilliance) of storage rings, in the early 1990s, one of the present authors (DE) and others recognised that this could be achieved by incorporating a higher number of bends into the achromats. Such a multi-bend achromat (MBA) guides electrons around corners more smoothly, therefore decreasing the degradation in horizontal emittance. A few synchrotrons already employ triple-bend achromats, and the design has also been used in several particle-physics machines, including PETRA at DESY, PEP at SLAC and LEP at CERN, proving that a storage ring with an energy of a few GeV produces a very low emittance. To avoid prohibitively large machines, however, the MBA demands much smaller magnets than are currently employed at third-generation synchrotrons.

In 1995, our calculations showed that a seven-bend achromat could yield an emittance of 0.4 nm rad for a 400 m-circumference machine – 10 times lower than the ESRF's value at the time. The accelerator community also considered a six-bend achromat for the Swiss Light Source and a five-bend achromat for a Canadian light source, but the small number of achromats in these lattices meant that it was difficult to make significant progress towards a diffraction-limited source. One of us (ME) took the seven-bend achromat idea and turned it into a real engineering proposal for the design of MAX IV. But the design then went through a number of evolutions. In 2002, the first layout of a potential new source was presented: a 277 m-circumference, seven-bend lattice that would reach an emittance of 1 nm rad for a 3 GeV electron beam. By 2008, we had settled on an improved design: a 520 m-circumference, seven-bend lattice with an emittance of 0.31 nm rad, which will be reduced by a factor of two once the storage ring is fully equipped with undulators. This is more or less the design of the final MAX IV storage ring.

In total, the team at Maxlab spent almost a decade finding ways to keep the lattice circumference at a value that was financially realistic, and even constructed a 36 m-circumference storage ring



The MAX IV 3 GeV ring, which has a diameter of 168 m, compared to previous machines at Sweden's Max lab facility.


Nils Bergendal

Part of the MAX IV 3 GeV ring showing iron-block magnets.

called MAX III to develop the necessary compact magnet technology. There were tens of problems that we had to overcome. Also, because the electron density was so high, we had to elongate the electron bunches by a factor of four by using a second radio-frequency (RF) cavity system.

Block concept

MAX IV stands out in that it contains two storage rings operated at an energy of 1.5 and 3 GeV. Due to the different energies of each, and because the rings share an injector and other infrastructure, high-quality undulator radiation can be produced over a wide spectral range with a marginal additional cost. The storage rings are fed electrons by a 3 GeV S-band linac made up of 18 accelerator units, each comprising one SLAC Energy Doubler RF station. To optimise the economy over a potential three-decade-long operation lifetime, and also to favour redundancy, a low accelerating gradient is used.

The 1.5 GeV ring at MAX IV consists of 12 DBAs, each comprising one solid-steel block that houses all the DBA magnets (bends and lenses). The idea of the magnet-block concept, which is also used in the 3 GeV ring, has several advantages. First, it enables the magnets to be machined with high precision and be aligned with a tolerance of less than 10 μm without having to invest in aligning laboratories. Second, blocks with a handful of individual magnets come wired and plumbed direct from the delivering company, and no special girders are needed because the magnet blocks are rigidly self-supporting. Last, the magnet-block concept is a low-cost solution.

It was the advent of particle accelerators in the mid-1900s that gave birth to modern X-ray science.

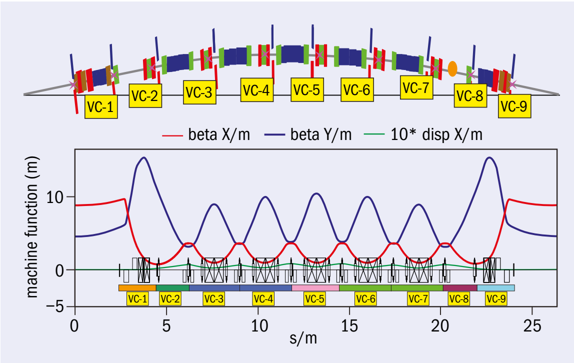
We also needed to build a different vacuum system, because the small vacuum tube dimensions (2 cm in diameter) yield a very poor vacuum conductance. Rather than try to implement closely spaced pumps in such a compact geometry, our solution was to build 100% NEG-coated vacuum systems in the achromats. NEG (non-evaporable getter) technology, which was pioneered at CERN and other laboratories, uses metallic surface sorption to achieve extreme vacuum conditions. The construction of the MAX IV vacuum system raised some interesting challenges, but fortunately CERN had already developed the NEG coating technology to perfection. We therefore entered a collaboration that saw CERN coat the most intricate parts of the system, and licences were granted to companies who manufactured the bulk of the vacuum system. Later, vacuum specialists from the Budker Institute in Novosibirsk, Russia, mounted the linac and 3 GeV-ring vacuum systems.

Due to the small beam size and high beam current, intra beam scattering and "Touschek" lifetime effects must also be addressed. Both are due to a high electron density at small-emittance/high-current rings in which electrons are brought into collisions with themselves. Large energy changes among the electrons bring some of them outside of the energy acceptance of the ring, while smaller energy deviations cause the beam size to increase too much. For these reasons, a low-frequency (100 MHz) RF system with bunch-elongating harmonic cavities was introduced to decrease the electron density and stabilise the beam. This RF system also allows powerful commercial solid-state FM-transmitters to be used as RF sources.

When we first presented the plans for the radical MAX IV storage ring in around 2005, people working at other light sources thought we were crazy. The new lattice promised a factor of 10–100 increase in brightness over existing facilities at the time, offering users unprecedented spatial resolutions and taking storage rings within reach of the diffraction limit. Construction of MAX IV began in 2010 and commissioning began in August 2014, with regular user operation scheduled for early 2017.

On 25 August 2015, an amazed accelerator staff sat looking at the beam-position monitor read-outs at MAX IV's 3 GeV ring. With just the calculated magnetic settings plugged in, and the precisely CNC-machined magnet blocks, each containing a handful of integrated magnets, the beam went around turn after turn with proper behaviour. For the 3 GeV ring, a number of problems remained to be solved. These included dynamic issues – such as betatron tunes, dispersion, chromaticity and emittance – in addition to more trivial technical problems such as sparking RF cavities and faulty power supplies. ▷

Synchrotron science



The MAX IV magnet lattice and machine functions for one of the 20 achromats. Blue rectangles depict dipole magnets, red quadrupoles and green sextupoles. The bottom graph shows the machine functions – how the beam sizes vary and the dispersion.

As of MAX IV's inauguration on 21 June, the injector linac and the 3 GeV ring are operational, with the linac also delivering X-rays to the Short Pulse Facility. A circulating current of 180 mA can be stored in the 3 GeV ring with a lifetime of around 10 h, and we have verified the design emittance with a value in the region of 300 pm rad. Beamline commissioning is also well under way, with some 14 beamlines under construction and a goal to increase that number to more than 20.

Sweden has a well-established synchrotron-radiation user community, although around half of MAX IV users will come from other countries. A variety of disciplines and techniques are represented nationally, which must be mirrored by MAX IV's beamline portfolio. Detailed discussions between universities, industry and the MAX IV laboratory therefore take place prior to any major beamline decisions. The high brilliance of the MAX IV 3 GeV ring and the temporal characteristics of the Short Pulse Facility are a prerequisite for the most advanced beamlines, with imaging being one promising application.

Towards the diffraction limit

MAX IV could not have reached its goals without a dedicated staff and help from other institutes. As CERN has helped us with the intricate NEG-coated vacuum system, and the Budker Institute with the installation of the linac and ring vacuum systems, the brand new Solaris light source in Krakow, Poland (which is an exact copy of the MAX IV 1.5 GeV ring) has helped with operations, and many other labs have offered advice. The MAX IV facility has also been marked out for its environmental credentials: its energy consumption is reduced by the use of high-efficiency RF amplifiers and small magnets that have a low power consumption. Even the water-cooling system of MAX IV transfers heat energy to the nearby city of Lund to warm houses.

The MAX IV ring is the first of the MBA kind, but several MBA rings are now in construction at other facilities, including the ESRF, Sirius in Brazil and the Advanced Photon Source (APS) at Argonne National Laboratory in the US. The ESRF is developing a hybrid MBA lattice that would enter operation in 2019 and achieve a horizontal emittance of 0.15 nm rad. The APS has decided to pursue a similar design that could enter operation by the end of the decade and, being larger than the ESRF, the APS can strive for an even lower emittance of around 0.07 nm rad. Meanwhile, the ALS in California is moving towards a conceptual design report, and Spring-8 in Japan is pursuing a hybrid MBA that will enter operation on a similar timescale.

Indeed, a total of some 10 rings are currently in construction or planned. We can therefore look forward to a new generation of synchrotron storage rings with very high transverse-coherent X-rays. We will then have witnessed an increase of 13–14 orders of magnitude in the brightness of synchrotron X-ray sources in a period of seven decades, and put the diffraction limit at high X-ray energies firmly within reach.

One proposal would see such a diffraction-limited X-ray source installed in the 6.3 km-circumference tunnel that once housed the Tevatron collider at Fermilab, Chicago. Perhaps a more plausible scenario is PETRA IV at DESY in Hamburg, Germany. Currently the PETRA III ring is one of the brightest in the world, but this upgrade (if it is funded) could result in a 0.007 nm rad (7 pm rad) emittance or even lower. Storage rings will then have reached the diffraction limit at an X-ray wavelength of 1 Å. This is the Holy Grail of X-ray science, providing the highest resolution and signal-to-noise ratio possible, in addition to the lowest-radiation damage and the fastest data collection. Such an X-ray microscope will allow the study of ultrafast chemical reactions and other processes, taking us to the next chapter in synchrotron X-ray science.

● Further reading

E Al-Dmour *et al.* 2014 *J. Synchrotron Rad.* **21** 878.
D Einfeld *et al.* 1995 *Proceedings: PAC* p177.
M Eriksson *et al.* 2008 *NIM-A* **587** 221.
M Eriksson *et al.* 2016 IPAC 2016, MOYAA01, Busan, Korea.
MAX IV Detailed Design Report www.maxlab.lu.se/maxlab/max4/index.html.

Résumé

MAX IV ouvre la voie pour un microscope à rayons X dernier cri

Les sources synchrotron de rayons X de troisième génération ont révolutionné l'étude de la structure des matériaux. De nombreuses installations de ce type sont exploitées dans le monde entier, et sont utilisées par une communauté d'environ 50 000 personnes ; elles permettent aux chercheurs d'étudier les sujets les plus variés, de la structure des protéines utilisées pour le développement de médicaments à l'étude des fossiles ou du patrimoine culturel. L'installation suédoise MAX IV, qui a commencé à fonctionner cette année, est le premier anneau de stockage utilisant un achromat à courbure multiple ; grâce à cette conception novatrice, les faisceaux de rayons X produits sont plus petits et plus stables que ceux des autres installations, ce qui fait de MAX IV la source de rayons X la plus brillante du monde. D'autres infrastructures suivent la même voie, le but ultime étant la construction d'un synchrotron fonctionnant à la limite de la diffraction des rayons X.

Mikael Eriksson, Maxlab, Lund, Sweden, and **Dieter Einfeld**, ESRF, Grenoble, France.

Faces & Places

APPOINTMENT

New chair of Brookhaven physics department

Hong Ma has been named chair of the physics department at the Brookhaven National Laboratory in Upton, New York. He succeeds Laurence Littenberg, who became physicist emeritus at the end of June after having worked in the department since 1974. Ma, who took up the post on 1 July, will oversee a staff of 244 and an annual budget of about $100 million for nuclear and particle physics.

Ma earned a bachelor-of-science degree from Fudan University in Shanghai in 1983 and a PhD in physics in 1988 from the California Institute of Technology, where he continued as a research fellow until joining Brookhaven as a research associate in 1989. He is best known for developing detector components for particle-physics experiments at colliders, and since 1999 he has played a major role in designing and commissioning various detector systems and data-analysis software for the ATLAS experiment at CERN's LHC. Ma was involved at every stage of the construction of ATLAS, including making important contributions to the liquid-argon calorimeter, and is currently contributing to Brookhaven's efforts to upgrade the ATLAS silicon detector and liquid-argon calorimeter for the High Luminosity LHC. Brookhaven also serves as the host laboratory for US scientists involved in ATLAS research.

"It is a huge honour and responsibility to serve as the chair of this great department," says Ma. "We are proposing, designing, and constructing the next-generation detectors while exploring the unknown with our currently running experiments. I am committed to maintaining the excellence required to do this fascinating science."


Brookhaven National Laboratory

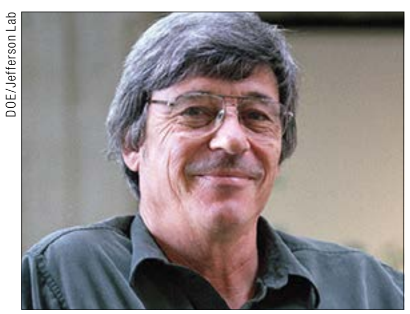
Brookhaven physics-department chair, Hong Ma.

AWARDS

Jefferson Lab director wins Glazebrook Medal

Hugh Elliot Montgomery, director of the Thomas Jefferson National Accelerator Facility and president of Jefferson Science Associates LLC, has been awarded the Glazebrook Medal by the UK's Institute of Physics (the IOP).

The Glazebrook Medal, which is named after the first director of the UK National Physical Laboratory and first president of the IOP, Richard Tetley Glazebrook, was first awarded in 1966. It is one of four gold medals awarded annually by the IOP in recognition of those who display outstanding leadership within the physics community. Montgomery was recognised for his leadership at Jefferson Lab and distinguished research in high-energy physics. He will receive the medal and a prize of £1000 at an event to be held later this year. "It is flattering and pleasing to receive such a prestigious award," Montgomery says. "Of course, it is also a reflection of the people with whom it has been my privilege to work during my career."


DOE/Jefferson Lab

Medal-winner Hugh Elliot Montgomery.

Non-locality bags Dirac Medal

Sandu Popescu of the University of Bristol, UK, has been awarded the 2016 Dirac Medal and Prize by the UK's Institute of Physics for his influential research into non-locality.

Popescu identified non-locality as a defining aspect of quantum mechanics that is central to quantum information, and his work has played a crucial role in the modern view of non-locality as a resource that can be stored, transformed and consumed while performing useful tasks. In particular, he developed a scheme for quantum teleportation and collaborated in the first experimental realisation of this phenomenon. In collaboration with Daniel Rohrlich, Popescu identified the Popescu–Rohrlich correlations – which are now regarded as the basic unit of non-locality. He has also deepened our understanding of quantum thermodynamics – demonstrating that almost all subsystems are canonical, and that thermal equilibrium is reached for almost all initial states.

Sandu Popescu wins one of four gold medals.

Daresbury physicist wins Rutherford Medal

Nuclear-structure expert John Simpson.

John Simpson of the STFC Daresbury Laboratory, UK, has won the 2016 Rutherford Medal and Prize of the Institute of Physics for his outstanding leadership in the development of new detector technologies and systems for experimental nuclear-physics research, and for his seminal contributions to our understanding of the structure of atomic nuclei. Simpson has made important contributions in areas such as the discovery of robust exotic triaxial super-deformed collective structures, which represent possibly the highest spin values ever observed in atomic nuclei, and has contributed significantly to the health and vitality of world-leading nuclear-physics research over the past four decades through his leadership. This includes germanium detectors used in the European gamma-ray spectrometer collaboration EXOGAM, for example, and Simpson also played a leading role in the development of the EUROBALL gamma-ray spectrometer.

APS recognises nucleon structure

Anatoly Radyushkin, a scientist at the Thomas Jefferson National Accelerator Facility and Old Dominion University in Virginia, US, has received the 2015 Jesse W Beams Research Award from the Southeastern Section of the American Physical Society. The award has been presented since 1973 to honour those whose "research led to the discovery of new phenomena or states of matter, provided fundamental insights into physics, or involved the development of experimental or theoretical techniques that enabled others to make key advances in physics".

The citation for Radyushkin's medal reads: "For the development of generalised parton distributions within the framework of quantum chromodynamics, enabling for the first time experimental measurements of the 3D structure of the nucleons."

DOE/Jefferson Lab

The 2015 Jesse W Beams Research Award, first presented in 1973, goes to theorist Anatoly Radyushkin.

Artist wins CERN residency

South Korean artist Yunchul Kim has been awarded a two-month-long residency at CERN, having been announced as the winner of the 5th COLLIDE International Award in June.

Kim, whose work focuses on the artistic potential of fluid dynamics and metamaterials, will take up his residency in February 2017. He plans to develop a project called "Cascade", which concerns the propagation of light through colloidal suspensions of photonic crystals.

The COLLIDE awards are a collaboration between CERN and an international cultural partner, which this year is the Foundation for Art and Creative Technology (FACT). Arts@CERN and FACT opened a call for entries in March, and this year more than 904 entries were received from a record 71 countries.

COLLIDE International Artist 2016, Yunchul Kim.

EXHIBITION

Milan exhibition opens its doors

On 13 July, a new exhibition opened in Milan, Italy, with the aim of opening visitors' eyes to what makes the universe tick at the most fundamental level. Designed and produced by the Leonardo da Vinci National Museum of Science and Technology in partnership with CERN and the Italian National Institute of Nuclear Physics (INFN), the exhibition – titled "Extreme. In search of particles" – transports visitors into the history of particle physics. They discover a prototype of Carlo Rubbia's UA1 detector, the Delphi experiment's vertex detector and the University of Milan's cloud chamber.

"Extreme" opened in July.

LHC EXPERIMENTS

Next ATLAS spokesperson selected

Karl Jakobs of the Albert-Ludwigs-Universitaet Freiburg, Germany, has been selected by the ATLAS collaboration board as the next spokesperson of the ATLAS experiment.

Jakobs, who has previously also worked on the UA2 and ALEPH experiments at CERN, and the D0 experiment at Fermilab, will start his term on 1 March 2017. He succeeds Dave Charlton of the University of Birmingham, who has been in the post since March 2013.

University of Freiburg

Karl Jacobs will take over in March next year.

CONFERENCE

SUSY reports from down under

Laura Vanags

Delegates at SUSY 2016 in Melbourne.

From 4 to 8 July, 254 physicists gathered at the University of Melbourne in Australia for the 24th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2016). Around 65 students participated in the pre-SUSY school leading up to the event.

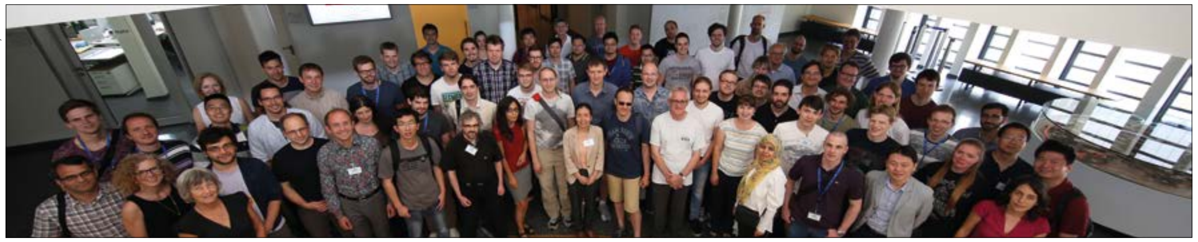
Summaries from ATLAS and CMS on their continued searches for supersymmetric particles confirmed no striking excesses in data recorded by the LHC at 13 TeV during 2015. These results have enabled the experiments to eclipse previous limits on the masses of squarks and gluinos set by data recorded at 8 TeV. While no evidence for SUSY was presented, the data points to several interesting hints – including a lingering excess in dileptons, jets and missing transverse momentum from ATLAS, for instance – that will surely be followed up as the LHC continues to deliver stable beams at high luminosity throughout 2016.

In particular focus at SUSY 2016 were corners of phase space that are difficult for the conventional searches to probe. CMS introduced their "data-scouting" technique, which allows them to probe lower in H_T than their typical trigger strategy permits. Interesting new ideas to probe "compressed" spectra were also discussed, in addition to the range of techniques being used to search for SUSY now and potential improvements for the future. A busy flavour-physics session served as a timely reminder of indirect constraints on SUSY from the B factories, neutrinos and other low-energy observables.

SUSY 2016 saw a diverse range of talks representing many sectors of the vibrant theory community. The mass and properties of the Higgs boson continue to be a strong motivational force, leading to new results in higher-order precision Higgs-mass calculations in a variety of models and detailed studies of the alignment limit. The absence of any signal thus far from the LHC has also led to much work on "non-minimal" SUSY, which goes beyond the usual minimal supersymmetric Standard Model.

As expected, there was strong interest from the theory community in the recent 750 GeV diphoton excess observed by ATLAS and CMS, with a cornucopia of models presented in parallel sessions. Theorists were also interested in probing new directions, and the conference saw a number of parallel talks devoted to the opportunities for new-physics studies presented by the LIGO experiment's discovery of gravitational waves.

SUSY 2017 will be held at the Tata Institute in Mumbai, India.


Dirk Noelle, DESY

School

X-ray focus for CERN Accelerator School

A special course devoted to free electron lasers (FELs) and energy recovery linacs (ERLs), which was jointly organised by the CERN Accelerator School (CAS) and DESY, took place in Hamburg in Germany from 31 May to 10 June. The intensive programme comprised 44 lectures and one seminar, and was attended by 68 participants from 13 different countries including China, Iran and Japan.

FELs and ERLs produce extremely intense beams of X-rays by harnessing the synchrotron radiation emitted by electrons manipulated by powerful linacs, and are used by scientists from a broad range of disciplines to study the structure of materials.

Following introductory lectures on electromagnetism, relativity and synchrotron radiation, the school taught students the basic requirements of linacs and ERLs followed by detailed lectures on the theory of FEL science. Undulators and the process of lasing and seeding were treated in some detail, as were the topics of beam dynamics and beam control. Case studies also saw students split into small groups to pursue given tasks to complete the basic design of an FEL or an ERL.

Next year CAS will hold a specialised course devoted to beam injection, extraction and transfer on 10 to 19 March 2017 in Erice, Italy. A specialised course in collaboration with the Max IV Laboratory on vacuum for particle accelerators will also take place on 6 to 16 June in Lund, Sweden. Further information on forthcoming accelerator courses can be found on the CAS website https://www.cern.ch/schools/CAS.

(Above) Participants learnt about the technology underpinning modern light sources.

ESOF

The seventh EuroScience Open Forum (ESOF 2016), which is billed as Europe's largest public-facing scientific event, took place in late July in Manchester, UK. The event saw CERN Director-General Fabiola Gianotti take part in a keynote panel discussion with the science director of the European Southern Observatory, Rob Ivison (far left), and director-general of the European Molecular Biology Laboratory, Iain Mattaj (second from left). Moderated by Pallab Ghosh, the BBC's science correspondent, the panel discussed the importance of science on a European scale.

Knowledge transfer

CERN and Turkey transfer knowledge

CERN and Turkey held a joint knowledge-transfer (KT) summit in Istanbul on 30–31 May, aimed at strengthening the links between science, technology and industry. The summit, held at Istanbul Bilgi University, brought together leaders from academia and industry, and was attended by representatives of the CERN Knowledge Transfer Group, Turkish technology-transfer offices and industrialists.

Around 100 participants from more than 35 university technology-transfer offices, 20 companies and several state institutions exchanged ideas on best KT practice – including Mehmet Durman, president of Istanbul Bilgi Univesity, and Serkant Ali Çetin, director of the university's High Energy Physics Research Centre.

The summit was held roughly one year after Turkey became an Associate Member State at CERN, and the first session addressed the range of Turkish activities at CERN. There are currently 11 CERN programmes in which Turkish institutes collaborate, including the ATLAS and CMS experiments. Head of the KT Group at CERN, Giovanni Anelli, presented the broad range of activities at CERN that aim to accelerate the innovation process and maximise the impact of CERN's activities on society. These range from medical applications for cancer diagnosis and treatment to providing clean energy through novel solar panels, and include licensing of CERN's technologies and opportunities for Turkish start-ups. In addition, CERN has a Business Incubation Centre network for its full Member States. CERN has a direct link with Turkey's innovative industry via CERN's Turkish industry liaison officer Hakan Kızıltoprak.


Huseyin Aldemir, Istanbul Bilgi University

More than 100 people attended the May event.

Event spotlight

The **IEEE Nuclear Science Symposium and Medical Imaging Conference 2016** (NSS/MIC) will take place in Strasbourg, France, from **29 October to 6 November**. The NSS programme concerns the latest developments in instrumentation and data processing in fields ranging from particle physics to radiation therapy, and spans techniques from both single-channel small detectors to larger detector systems. MIC is a unique international scientific meeting devoted to nuclear medical imaging, and this year's event will cover hardware and software developments both in multimodality imaging and radiation therapy. The Strasbourg event is also being held in conjunction with the 23rd International Symposium on Room-Temperature Semiconductor Detectors (RTSD), which represents the largest forum for semiconductor radiation detectors and imaging arrays. More details can be found at 2016.nss-mic.org.

TECHNOLOGY TRANSFER

HEPTech takes research out of the lab

The third annual symposium of the High-Energy Physics Technology Transfer Network (HEPTech), held on 19 to 25 June and hosted by Romania's Horia Hulubei National Institute of Physics and Nuclear Engineering, brought together early stage researchers in high-energy physics and related scientific domains to discuss how to take their research out of the lab. Seventeen participants from nine European countries met entrepreneurs and experienced scientists to learn how science can impact society.

The topics covered intellectual-property rights and their protection, national and European funding sources for research and innovation, incubators in support of business ideas and start-ups, and rules of collaboration in physics. "Win-win" negotiation techniques were the focus of a role-play exercise to help students define business objectives, identify the interest of the other party and find a creative solution to a negotiation problem. Entrepreneurship case studies such as the Raspberry Pi and TravelTime platform API of iGeolise revealed how developments in research are transformed into marketable products.

The last two days of the symposium saw young researchers undertake exercises in preparing pitches, networking at a meeting, and introducing each other. Experts guided them through the secrets of where to find potential investors, how to attract their attention and how to identify the market share of their potential product and bring it to market.

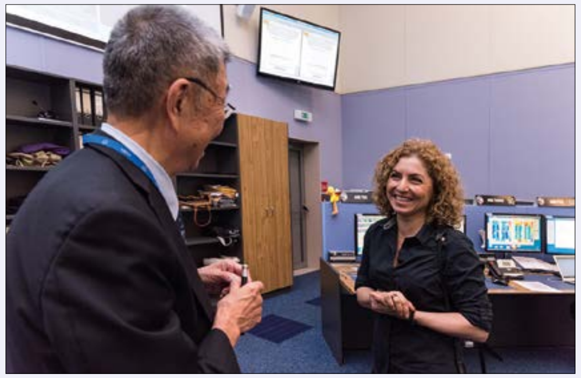
HEPTech was created by CERN Council in 2006 to enhance and broaden the impact of particle physics on society, and its members are Technology-Transfer Offices of CERN Member States. The fourth HEPTech symposium will take place in Darmstadt, Germany, hosted by GSI Helmholtzzentrum für Schwerionenforschung, on 12 to 16 June 2017.

Ian Tracey, HEPTech

Participants of the HEPTech symposium with their CERN helmets.

VISITS

On 19 July, UK rock band Muse took a tour of the CERN site, which included a trip to the Antiproton Decelerator facility and the CERN Control Centre (pictured, with Muse frontman **Matt Bellamy**). The group was in the region for the Paléo Festival in Nyon, during which they dedicated their song "Supermassive Black Hole" to "our friends at CERN" before a capacity crowd of 35,000.



M Brice

On 15 July, Iranian-US cosmonaut **Anousheh Ansari** visited the AMS (Alpha Magnetic Spectrometer) Payload Operations Control Centre on CERN's Prévessin site, where she met AMS spokesperson and Nobel laureate **Samuel Ting**. Ansari was the first ever female space-flight participant, spending eight days on the International Space Station (to which the AMS experiment is attached) in 2006.

OBITUARIES

Helen Edwards 1936–2016

Accelerator physicist Helen Edwards passed away on 21 June at her home in Illinois, US, aged 80. Her remarkable legacy includes the design and operation of high-energy accelerators around the world, to which her singular and indefatigable drive brought life to a variety of projects for five decades.

Helen completed her PhD in 1966 under the supervision of Boyce McDaniel at Cornell University, where she studied the associated photo-production of kaons. She then began her postdoctoral work with Robert Wilson, during which she managed the commissioning of Cornell's 10 GeV electron synchrotron. Shortly thereafter, Wilson was appointed founding director of the National Accelerator Lab just outside of Chicago, which would be renamed Fermilab. Helen moved to the burgeoning Illinois lab in 1970, where her first responsibility was to bring the 8 GeV "Booster" proton synchrotron to full energy.

Helen then joined the design effort of the Fermilab "Energy Doubler", which utilised high-field superconducting magnets to achieve proton energies of 1 TeV, and thus positioned the Tevatron as the world's highest energy collider for the next 28 years. Helen also held the dubious honour of shutting down the Tevatron on 30 September 2011. Her contribution to the success of the Tevatron was acknowledged in 1989 by the US National Medal of Technology, the highest national honour for technological progress.

In 1989, Helen moved to the Superconducting Super Collider Laboratory in Texas and became the project's technical director until late 1991. Soon afterwards, she was invited to DESY in Germany by Bjørn Wiik to assist him in the formation of the TESLA collaboration. Helen realised that, in addition to superconducting magnets, it was vital that superconducting technology be extended to radio-frequency cavities. Though conceived as an electron–positron linear collider based on superconducting accelerating structures, TESLA evolved into the FLASH facility, which is dedicated to the production of electron and photon beams for numerous studies such as biology and materials science. The DESY–Fermilab collaboration was a major factor in the success of FLASH.

In parallel to the development at DESY, Helen built a 15 MeV electron photoinjector laboratory at Fermilab. This machine provided an experimental platform for several advanced-accelerator concepts – including the first demonstrations of a round-to-flat beam transformer and transverse-to-longitudinal emittance exchange – and led to more than eight PhD theses in accelerator physics.

In every accelerator project that Helen led, she did so by example and in every aspect. She would perform calculations, turn wrenches, tune for beam and analyse data. Her insight was invaluable and deeply respected. She also made time to serve on advisory committees to CERN, Jefferson Laboratory, LNS at Cornell and the Facility for Rare Isotope Beams at Michigan State University. In addition to the Medal of Technology, her awards include a MacArthur Fellowship; election to the National Academy of Engineering; election to the American Academy of Arts and Sciences; and the Ernest Orlando Lawrence Award. Helen's unparalleled genius, management skills, love for nature and adventure will be sorely missed.

● *Timothy Koeth, University of Maryland.*

Reidar Hahn/Fermilab

Helen Edwards made major contributions to the Tevatron collider.

Stephen Gasiorowicz 1928–2016

Stephen Gasiorowicz, best known for his contributions to the quark model of hadrons, the theory of glueballs and mechanisms of QCD confinement, and his role in co-founding the William I Fine Theoretical Physics Institute (FTPI) at the University of Minnesota, died on 3 June aged 88.

Stephen was born on 10 May 1928 into a Jewish family in Danzig (currently Gdansk, Poland). With the rise of the Nazis in Germany in 1933, his family had to move to Warsaw. Then, when Germany invaded Poland on 1 September 1939, the Gasiorowiczes had to flee immediately. Stephen's journey to freedom lasted for seven years and saw him pass through the USSR, Romania, Turkey, Iraq, Pakistan and India – where the family obtained residence permits that allowed Stephen to receive his education.

In 1946, the Gasiorowiczes were notified that their application for immigration to the US, which they had filed before the war, was finally approved. The same year, Stephen sailed from Calcutta to San Francisco with his mother and sister (his father had died in India). He was admitted to the University of California in Los Angeles as a physics major, where he later received his BA degree in 1948 and PhD in 1952. From 1952 to 1960, Stephen was employed by Lawrence Berkeley Laboratory at the University of California as a research staff member. In 1961, he moved to the physics department of the University of Minnesota, becoming a full professor in 1963, and he stayed there for the rest of his career.

Stephen acquired a reputation of an ▷

FTPI, University of Minnesota

Stephen Gasiorowicz worked on the quark model of hadrons.

excellent lecturer and was sought after as a visiting professor by major research centres worldwide. Generations of physics students studied using the excellent textbooks he wrote, which include *Elementary Particle Physics*, *Quantum Physics*, and *Physics for Scientists and Engineers*. He was a PhD adviser to such prominent theoretical physicists as Stanley Brodsky at SLAC and William Bardeen at Fermilab.

Stephen was an intellectual and humanist with a broad knowledge of literature and arts, and his sense of humour was remarkable. He was also an absolutely great friend who was always available to help. Stephen will be missed tremendously.

● *Mikhail Shifman and Arkady Vainshtein, University of Minnesota*.

Victor Alexandrovich Karnaukhov 1930–2016

Prominent Russian scientist Victor Alexandrovich Karnaukhov passed away on 16 April after a long disease. Karnaukhov was a highly skilled physicist, applying ever-modern experimental methods and possessing fundamental theoretical knowledge in nuclear physics. A characteristic feature of his research was his choice of outstanding physical problems that could lead him to obtain qualitatively new results.

In 1954, after graduating from Moscow State University, Karnaukhov began working at the National Scientific Center in Moscow – the so-called Kurchatov Institute. The department was headed by G N Flerov, who created a team of future founders of the Laboratory of Nuclear Reactions (LNR) at JINR, where Karnaukhov moved in 1960 and was head of department until 1976.

While investigating the decay of ^{20}Ne in 1962, Karnaukhov made the first observation of an essentially new type of radioactive decay: β-delayed proton radioactivity. His research group went on to find a number of proton emitters, and today there are around 100 known sources. The emission of delayed protons is a powerful tool to study nuclear structure, and the discovery earned Karnaukhov the USSR State Prize in 1975. Previously, he and his collaborators had also observed the polonium isomer ^{212}Po, which is remarkable for its anomalous suppressed α-decay, and he also actively participated (together with S Polikanov) in the discovery and identification of spontaneous fission isomers of heavy nuclei. On the experimental side, Karnaukhov proposed and realised a new type of very fast, gas-filled mass separator at the LNR cyclotron, which ultimately enabled the discovery of more than 30 new short-lived isotopes – most of them delayed proton emitters.

JINR

Victor Karnaukhov elucidated β-delayed proton radioactivity.

In 1977, Karnaukhov became head of a department at the Laboratory of Nuclear Problems, where he initiated a large project concerning super-dense nuclei. Since the start of the 1990s, his main research interests were the detailed study of phase transitions in nuclear systems. Even today, a new project proposed by Karnaukhov is under way at the Laboratory of High Energy Physics, JINR, to study the fission of hypernuclei produced in collisions of relativistic deuterons with heavy targets. His scientific achievements are presented in more than 150 publications, and his studies of proton radioactivity are referred to in many textbooks, monographs and encyclopedias.

He had remarkable courtesy and helpfulness, and the ability to propose exciting scientific ideas and demonstrate firm principles when discussing challenging problems. Victor Karnaukhov will forever live in our memory.

● *His friends, colleagues and the DLNP staff.*

Pablo Rodríguez Pérez 1976–2016

Pablo Rodríguez Pérez, a physicist on the LHCb experiment, died suddenly on 1 July in Manchester, UK.

Pablo obtained his degree in physics at the Universidade de Santiago de Compostela (USC) in 2003, specialising in electronics, and then worked in industry. He joined the LHCb experiment in 2007, undertaking a MSc at USC during which he optimised the read-out electronics for the LHCb inner tracker. He then continued to his PhD studies, becoming the principal author of the experiment-control system of the silicon tracker. After the commissioning of the LHCb experiment, he moved his attention to the LHCb upgrade, performing the first investigation of prototypes for the upgrade of the vertex locator (VELO).

Eliseo Pérez Trigo/USC

Pablo Rodríguez Pérez in his office at USC.

Following his PhD from USC, from which he graduated *cum laude*, Pablo joined the University of Manchester in 2013 to work further on the VELO upgrade. He took the lead role in the group's FPGA firmware development and was key to the module construction for the VELO upgrade.

Pablo is survived by his wife, Sonia, and their three young children, his parents, and his brothers Iván and Carlos. He is predeceased by his brother Víctor. His warmth, kindness, dedication and competence will be deeply missed by his many friends in the LHCb collaboration.

● *LHCb Collaboration*.

Nikolai Maksimovich Shumeiko 1942–2016

On 15 June, Nikolai Maksimovich Shumeiko passed away at the age of 73, having been an outstanding scientist who was a member of the JINR Scientific Council and head of the Centre of Particle Physics and High Energy Physics of the Institute of Nuclear Problems.

Shumeiko was born on 22 September 1942 in Dubrovno, Belarus, and in 1966 he graduated in physics from Moscow State University. From 1970, he worked at Belarusian State University (BSU) at the physics department, at the Institute of Nuclear Problems BSU, and from 1993 he worked at the National Scientific and Educational Centre of Particle Physics and High Energy Physics, BSU, which was founded on his initiative.

JINR

Nikolai Shumeiko authored more than 600 papers.

He made a fundamental contribution to the universal covariant approach (the "Bardin–Shumeiko" method) to account for radiative corrections in observed values of particle interactions. Other research interests included spin physics. He was deeply involved in the design and production of important calorimetric, muon and magnetic subsystems for the CMS and ATLAS detectors at the LHC. Shumeiko was the founder of a scientific school in particle physics in Belarus and author of more than 600 papers, with an impressive Hirsch index of 54. For many years, he was responsible for the co-operation of scientific institutes and industrial enterprises in the Republic of Belarus with leading scientific centres such as JINR and CERN, and he was an official representative of the Republic of Belarus in many large experimental collaborations, including CMS, ILC and CLIC.

Shumeiko won several awards for his research and organisational activities, among them the Francysk Skaryna Medal, the Order of Friendship of the Russian Federation, Honorary Certificate of the Council of Ministers of the Republic of Belarus, and the Academician F Fedorov Prize of NAS Belarus.

Nikolai Shumeiko was a wonderful man whose unique talent, profound knowledge and exceptional diligence for many years served the basis for the national development of elementary particle physics. He led dozens of young people to science, and his competence, honesty and self-discipline were always a bright example for us.

● *The JINR directorate, scientific community of the Institute of Nuclear Problems BSU, pupils and friends*.

Guido Vegni 1931–2016

Guido Vegni, a renowned Italian particle physicist at the University of Milan, passed away on 2 June. With his death we have lost a friend, an excellent physicist and a strong supporter of the CERN programme.

Guido's long and fruitful involvement in particle physics started in 1956 when he joined the Milan Nuclear Emulsion Group led by Giuseppe Occhialini. His thesis aimed to measure the spin-parity assignment of the K^+ meson from its decay into three pions, contributing to the study of the famous "tau-theta puzzle", which was eventually solved by the discovery of the non-conservation of parity in weak interactions. In 1960, Guido was appointed as assistant to Occhialini, which led to him eventually becoming the chair of elementary particle physics at Milan – a position he held until his retirement in 2006.

From 1963 to 1966, working as a CERN fellow, Guido joined the Saclay 81 cm bubble-chamber experiment, where he participated in the discovery of the $\rho_3(1690)$ meson.

At the end of the 1960s, a "live" target composed of silicon detectors was built by the Milan group and used for the first time in an experiment to study the diffractive dissociation of mesonic states on different kinds of nuclei. In the 1970s, Guido took part in several experiments at the Serpukhov accelerator in Russia, using a large magnetic spectrometer. The live target in this experiment allowed the detailed study of several states produced diffractively in the interactions between pions and nuclear targets, leading to the observations of two states – $\pi(1300)$ and $\pi(1800)$ – that were interpreted as radial excitations of the pion.

Ferdinando Vegni

Guido Vegni in 1976 at the Institute for High Energy Physics in Protvino, Russia.

During the 1980s, Guido and his group moved to the DELPHI experiment at CERN's Large Electron–Positron (LEP) collider, where they played a pioneering role in the silicon micro-vertex detector. After LEP, his interest turned to the LHC, and Guido became an enthusiastic supporter of the ATLAS experiment. He led the Milan group engaged in the design and construction of the ATLAS silicon pixel detector and made significant contributions to this effort.

Alongside his research, Guido was a passionate teacher and educator who motivated many students to follow research careers. He was convinced of the need to improve the quality of science teaching from primary school onwards, and promoted a successful training course for physics educators, which relied on tools that anticipated the internet and the IT revolution.

Our warmest sympathy goes to his wife Anita, his daughters Isabella and Giulia, and his son Ferdinando, together with their families. We will all miss Guido sorely.

● *His friends and colleagues*.

Recruitment

For advertising enquiries, contact CERN Courier recruitment/classified, IOP Publishing, Temple Circus, Temple Way, Bristol BS1 6HG, UK.
Tel +44 (0)117 930 1264 Fax +44 (0)117 930 1178 E-mail sales@cerncourier.com
Please contact us for information about rates, colour options, publication dates and deadlines.

CERN

Newly qualified and looking for a job?

Technician Training Experience

Take part! cern.ch/TTE

What could be a better boost for your career than a two-year contract in a hi-tech Organization? Get your first work experience at CERN: take part!

The TTE programme is aimed at technicians who are looking to get a first, great professional experience to further their career, or before they embark on advanced study programmes.

We welcome applications from talented technicians who will have the opportunity to work in a diversity of fields at the cutting edge of technology: electronics, electricity, mechanics, IT, vacuum, cooling and ventilation, safety, radioprotection, survey engineering, are but a few of the examples of the many domains in which successful applicants will learn and contribute their knowledge.

For further information and details on how to apply, see **www.cern.ch/tte**.

Deadline for applications: 31st October 2016

Apply online cern.ch/TTE

A unique opportunity to develop your career, where every kind of thinking is welcome.
Join CERN's Technical, Engineering or Support teams in a wide range of fields. Take part!

Accelerators | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

DESY

PARTICLE PHYSICS.

DESY has openings for:

DESY-Fellowships - experimental particle physics

DESY

DESY is one of the world's leading research centres for photon science, particle and astroparticle physics as well as accelerator physics.

DESY develops, runs and uses accelerators and detectors for the investigation of the structure of matter.

The position

Fellows in experimental particle physics are invited to participate in a project of DESYs particle physics research Programme at Hamburg.

- Analysis and detector-upgrade in the LHC experiments ATLAS and CMS
- Preparation of the International Linear Collider ILC (accelerator and experiments)
- Participation in the Analysis Forum of the Helmholtz Alliance "Physics at the Terascale"
- Participation in the experiments ALPS and BELLE II
- Generic development of detectors and accelerators for applications in particle physics

Requirements

- Ph.D. completed within the last 4 years
- Experience in experimental particle physics

DESY-Fellowships are awarded for a duration of 2 years with the possibility of prolongation by one additional year.

Please submit your application including a resume, a curriculum vitae including a short summary of past research activities and of future research interests, a list of publications and copies of University degrees to the DESY human resources department (preferably via http://www.desy.de/about_desy/career/online_application/index_eng.html, but we also accept e-mail to recruitment@desy.de or normal mail). Make sure that you indicate the position identifier on all communications (FHFE003/2016).

It is your responsibility to arrange for three letters of reference to be sent before the application deadline to the DESY human resource department, clearly stating your name and the position identifier (FHFE003/2016).

Salary and benefits are commensurate with those of public service organisations in Germany. Classification is based upon qualifications and assigned duties. DESY operates flexible work schemes. Handicapped persons will be given preference to other equally qualified applicants. DESY is an equal opportunity, affirmative action employer and encourages applications from women. There is a bilingual kindergarten on the DESY site.

We are looking forward to your application quoting the reference code preferably via our electronic application System: Online-Application
Deutsches Elektronen-Synchrotron DESY
Human Resources Department | Code: FHFE003/2016
Notkestraße 85 | 22607 Hamburg | Germany | Phone: +49 40 8998-3392
Email: recruitment@desy.de
Deadline for applications: 30 September 2016
www.desy.de

The Helmholtz Association is Germany's largest scientific organisation.
www.helmholtz.de

HELMHOLTZ ASSOCIATION

ess EUROPEAN SPALLATION SOURCE

The European Spallation Source is preparing to construct a world-leading European materials research centre in Lund, Sweden. ESS is an international partnership of 17 European countries.

Be part of the future!

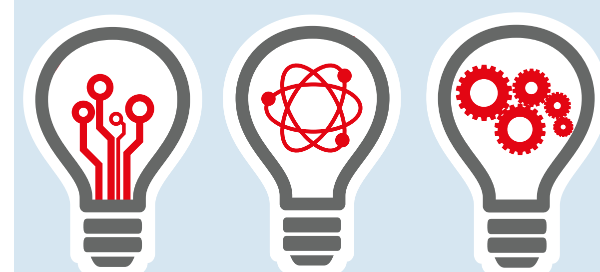
We are looking for a highly qualified:

Machine Interlocks Engineer

As machine interlocks engineer you will be part of ESS's Machine Directorate, which is responsible to deliver the accelerator and the target station. You will join the Integrated Control Systems (ICS) division, responsible for the design, construction, commissioning and operation of control systems for the ESS facility including the accelerator, target station, neutron scattering instruments and conventional facilities.

For more details, have a look at:
http://europeanspallationsource.se/vacancies

Visit
brightrecruits.com



The jobs site for physics and engineering


2016 IEEE
Nuclear Science Symposium
& Medical Imaging Conference
23rd International Symposium on Room-Temperature X-Ray and Gamma-Ray Detectors
Palais des Congrès, Strasbourg, France
29 October - 6 November 2016
Strasbourg 2016
NSS/MIC
IEEE NPSS
NUCLEAR & PLASMA SCIENCES SOCIETY
Radiation detectors and instrumentation and their application in:
- Particle and nuclear physics, astrophysics, large scale facilities, security, energy, and environmental sciences
- Medical sciences, including image reconstruction, image/data analysis, radiation therapy, and dosimetry
Scientific sessions, industrial exhibition, short courses, special focus workshops
General Chair
Maxim Titov
CEA Saclay, DSM/IRFU
email: nssmic2016@ieee.org
http://www.nss-mic.org/2016

Bookshelf

Compiled by Virginia Greco, CERN

Experimental Studies of Neutrino Oscillations

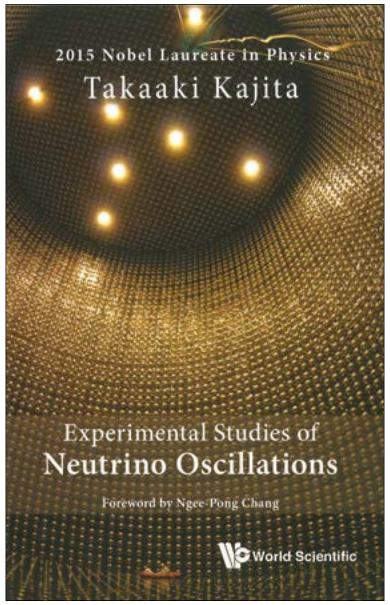
By Takaaki Kajita

World Scientific

This book on neutrino oscillations is mainly of historic interest. It consists of seven chapters that reproduce review articles written by the 2015 Nobel laureate in physics, Takaaki Kajita, which were previously published between 2000 and 2009, either in journals or in international conference proceedings (all World Scientific publications). The articles describe experiments on solar and atmospheric neutrino interactions performed using the Kamiokande and SuperKamiokande water Cherenkov detectors installed in the Kamioka mine in Japan. These experiments resulted in the 1998 discovery of atmospheric muon-neutrino (ν_μ) oscillation by observing ν_μ disappearance over a flight-path length of the order of the Earth's radius. In addition, they have provided important hints on the oscillation of solar neutrinos, which was conclusively demonstrated in 2002 by the SNO experiment in Canada (the 2015 Nobel Prize in Physics was also awarded to A B McDonald for his leading role in this experiment).

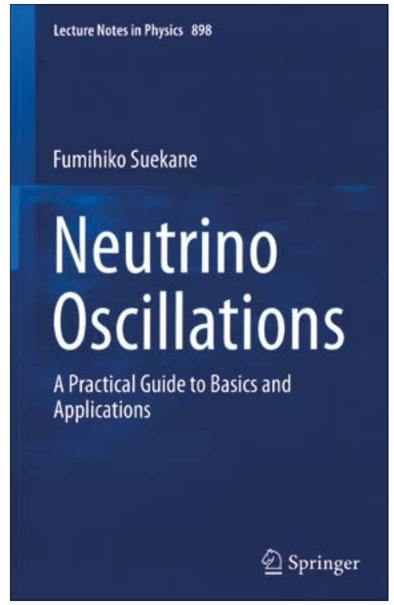
Chapter 1 includes a short description of results from experiments using neutrinos from accelerators. These include the K2K experiment in Japan and MINOS at Fermilab, which confirmed the atmospheric neutrino oscillation, and the KamLAND experiment (also located in the Kamioka mine), which has observed the disappearance of electron antineutrinos ($\bar{\nu}_e$) from nuclear reactors over an average baseline of 180 km, therefore verifying solar-neutrino oscillation with "man-made" neutrinos. Although not up to date, the values of the oscillation parameters Δm^2_{12}, Δm^2_{23}, θ_{12} and θ_{23} quoted in this book are quite precise and close to the current ones.

Future directions and plans in the study of neutrino oscillations are also described. In particular, methods and plans to measure the mixing angle θ_{13} (not yet measured in 2009) using neutrinos from both reactors and accelerators are discussed, as well as the impact of the θ_{13} value on the possible detection of CP violation in the neutrino sector. Although the book was published in 2016, on this subject it is obsolete because θ_{13} has been measured in the first half of the current decade by a number of experiments and is presently known to better than 10%.



Finally, chapter 2, written with four co-authors, addresses the physics capabilities of possible future experiments using a water Cherenkov detector with a mass of 1 Mton.

● *Luigi Di Lella, University of Pisa & INFN, Italy.*



Neutrino Oscillations: A Practical Guide to Basics and Applications

By Fumihiko Suekane

Springer

Also available at the CERN bookshop

This is a detailed and up-to-date textbook on neutrino oscillations. After a short historical introduction (chapter 1), chapter 2 contains a concise, yet quite complete, presentation of neutrino theory in the Standard Model, including neutrino interactions and production in pion, muon and nuclear beta decay. The basic ideas of particle oscillation in quantum mechanics are introduced in chapter 3, and a detailed theory of neutrino oscillations is presented in chapter 4 – first in a two-neutrino approximation, then generalised to the three neutrino flavours – for oscillations both in vacuum and matter. In addition to the usual neutrino description in terms of plane waves, this chapter includes the mathematical treatment of a wave-packet oscillation, which helps in understanding neutrino oscillations over astronomical distances.

Chapter 5 contains a description of past and present oscillation experiments and of the results published prior to 2014, including the measurement of θ_{13}. These results are again summarised in chapter 6, where the current knowledge of three-neutrino oscillation parameters is described. Future experiments to measure the remaining oscillation parameters (the so-called neutrino mass hierarchy and the CP-violation phase) are discussed in chapter 7, together with oscillation anomalies observed by a number of experiments (LSND, MiniBoone, Gallium and recent re-analyses of old reactor experiments). These anomalies, if confirmed, would imply the existence of at least one additional "sterile" neutrino with a mass in the order of 1 eV, requiring a mixing matrix of larger dimensions and more oscillation parameters. Chapter 7 also includes a discussion of the difference between Dirac and Majorana neutrinos, and the implications of direct measurements of the effective ν_e mass and of searches for neutrinoless double beta decay. Finally, chapter 8 contains a useful appendix summarising all the symbols, abbreviations and formulae used in the book.

The textbook contains all of the information that anybody interested in neutrino oscillations would like to know. Physicists involved in neutrino experiments should each have a copy in their private libraries.

● *Luigi Di Lella, University of Pisa & INFN, Italy.*

PWA90: A Lifetime Of Emergence

By P Chandra, P Coleman, G Kotliar, P Ong, D L Stein and C Yu (eds)

World Scientific

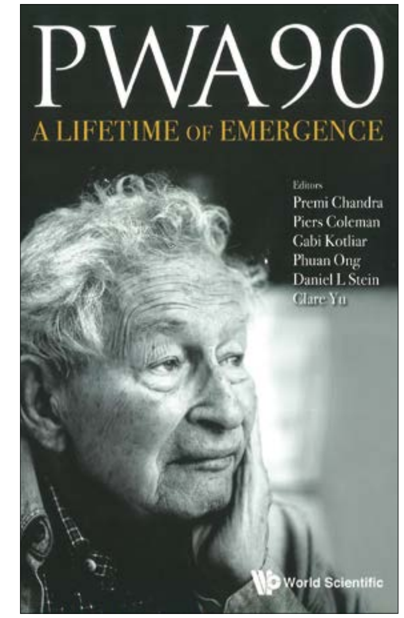
In December 2013, a community of physicists gathered in Princeton on the occasion of Philip Warren Anderson's 90th birthday to celebrate the achievements of his remarkable career. This book is the result of the event, and collects a number of intriguing and lively contributions from Anderson's students, collaborators and distinguished colleagues, which will appeal to both high-energy and condensed-matter physicists.

The description of a single helium atom is familiar to any undergraduate student, but a collection of many helium atoms produces unexpected phenomena ranging from superfluidity to magnetic phases. This occurrence could be concisely summarised by saying that "more is different", as Anderson (who shared the 1977 Nobel Prize in Physics with N Mott and J Van Vleck for their fundamental theoretical investigations of the electronic structure of magnetic and disordered systems) wrote in the title of a pedagogical article published in 1972. As Anderson would put it, "the ability to reduce everything to simple fundamental laws does not imply the ability to start from these laws and reconstruct the whole universe." The so-called "emergentism" appears then as a possible synthesis between the thesis of the reductionism (often attributed to particle physics) and the antithesis of pure constructivism. This third perspective can be appreciated in this book.

Relatively short, it contains accurate and stimulating accounts of various hot topics that are popular in condensed-matter theory, starting from the ubiquitous mechanism of the localisation of waves in random media (often referred to as "Anderson localisation"). The connections between superfluidity, superconductivity and the way that massless gauge bosons acquire a mass are explored in the contribution of Frank Wilczek (who shared the 2004 Nobel Prize in Physics with David Gross and David Politzer, for the discovery of asymptotic freedom).

The historical origins of Anderson's paper describing the relation between plasmons, gauge invariance and mass are masterly reviewed by Ed Witten (professor of mathematical physics at the Institute for Advanced Study in Princeton, US).

In a nutshell, Anderson's idea was that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged. Higgs described



his mechanism as the relativistic analogue of Anderson's idea, whose origin is instead conceptually motivated by a series of contributions by J Schwinger, speculating that gauge fields can become massive thanks to strong coupling effects in two space–time dimensions. This field theory in two dimensions is often used to introduce the concept of "bosonisation".

The contributions contained in PWA90 can be considered as an extended introduction to a more technical treatise (very popular among practitioners in the late 1980s and early 1990s) entitled *Basic Notions of Condensed Matter Physics* (Benjamin-Cummings 1984) and edited by P W Anderson together with C C Yu. In that book, Anderson managed to stress the connection between symmetry breaking, emergent phenomena and condensed-matter theory. While more than 30 years separate the two books, their common goals and inspirations remain intact: different areas of physics can and must be cross-fertilised because, ultimately, physics is one.

● *Massimo Giovannini, CERN & INFN Milan-Bicocca, Italy.*

Books received

A Lesson for the Future of Our Science: My Testimony on Lord Patrick M S Blackett

By A Zichichi

World Scientific

The book is a tribute to the great experimental physicist Lord Patrick M S Blackett, written by one of his pupils at the Sphynx Observatory, Antonio Zichichi. Blackett is well known for his work on cloud chambers and cosmic rays, which earned him the Nobel Prize in Physics in 1948.

The author offers his personal testimony, from the first time he heard Blackett's name to when he went to work with him, and then about the research he could be involved in. He provides a profile of his subject while giving an overview of Blackett's work and, in particular, of his most significant discoveries, including the so-called vacuum-polarisation effect, the first example of "virtual physics", and strange particles. The important implications of Blackett's pioneering contribution to sub-nuclear physics are also discussed.

The book also presents a portrait of the world of physics during those times, and gives insights into life and research at CERN, as well as about Blackett's ideas. He was very interested in the role of science in the culture of the time. He was convinced that physicists should be directly engaged with communicating to society, which should be informed about the contribution of science to the progress of our civilisation.

Rich in personal anecdotes, pictures and appendices, the book could appeal to physicists and students who are also interested in the history of science and in the human dimension of great scientists. As a final point, the layout and editing could be improved.

Macroscopic Electrodynamics: An Introductory Graduate Treatment

By W Wilcox and Chris Thron

World Scientific

This book provides a comprehensive treatment of classical electrodynamics for graduate students of physics and the applied sciences. The word "macroscopic" in the title refers both to the large-scale manifestations of the theory and to the applications of the so-called macroscopic Maxwell equations to idealised media, which are discussed in the book.

The topics are carefully explained, using precise but informal language that would appeal to younger students. On the mathematics side, a background in advanced calculus, linear algebra and variational methods is needed by the reader, as is a basic understanding of electrodynamics on the physics side. A large set of exercises is integrated ▷

Bookshelf

into the text. They are designed to help students to get to grips with concepts and practical methods, but also to stimulate their intuition, rather than their ability in calculus.

After an introduction on the basic concepts of electrostatic and magnetostatic fields and interactions, the authors move on to extending such concepts to time-dependent phenomena. A whole section is then dedicated to the properties, interactions and applications of electromagnetic waves. Finally, a chapter covers relativity and electromagnetic formalism. Hints of many other topics are given in conclusion, both to stimulate the curiosity of student readers and guide them towards further studies.

Besides an appendix on units, a guide to problems is also included, in which the solutions to the exercises that are not integrated in the text are provided.

An Introduction to Graphene Plasmonics

By P A D Gonçalves and N M R Peres

World Scientific

Graphene plasmonics is a fast-developing area of research, for which no textbook yet exists. Previous books on plasmonics have focused on the use of conventional metals, while scientific articles on graphene plasmonics present the subject in a fragmented and not very pedagogical way. This book aims to fill this gap in the scientific literature.

A plasmon is a quantum of plasma oscillation – the minimum amount of oscillations of the electron density in conductive media. The world "plasmonics" is used to refer to the transfer of information through nanoscale structures by means of surface plasmons, which are plasmons – confined to the surface – that can be excited by photons and electrons.

In 2011 it was demonstrated that plasmonic effects in graphene (which is a two-dimensional material, therefore all surface) could be controlled optically by shining electromagnetic radiation onto a periodic grid of graphene micro-ribbons. This was the start of a new and intriguing branch of research at the interface between condensed-matter physics and photonics.

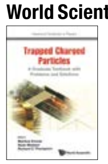
The authors have aimed to make their book as self-contained as possible, so they discuss all of the relevant aspects of the topic. Starting from graphene's electronic properties, and plasmonics at metal–dielectric interfaces and in metal thin films, the book gradually dives into the field of graphene plasmonics. Several chapters are dedicated to different methods of inducing surface plasmon polaritons in this material, and there are appendices that give calculations and in-depth analysis on some of the topics covered.

The book is intended both for students of and newcomers to the field, but it could also be a reference for researchers already working on graphene plasmonics.

Trapped Charged Particles: A Graduate Textbook with Problems and Solutions

By M Knoop, N Madsen, and R C Thompson

World Scientific



Electromagnetic trapping, which is the confinement of charged particles by the use of combined electric and magnetic fields, has emerged as a very versatile tool for manipulating charged particles. It is extremely useful for performing precise measurements, for mass spectroscopy, plasma physics, and antihydrogen creation, as well as for applications including atomic clocks and trapped-ion quantum computers.

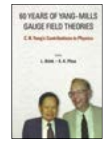
The textbook collects lectures on charged-particle trapping given by the major experts in the field at the Les Houches Winter School in January 2015. It discusses both the fundamental physics of this technique and its different applications. The first lectures are dedicated to explaining how to trap charged particles and the basic properties of Penning and radio-frequency (RF) traps. Following chapters are dedicated to practical problems related to trapping – vacuum systems and cooling techniques (including laser cooling), in particular, are discussed. Simulations, plasma physics, antihydrogen physics and other applications are then explained.

Being the result of lectures given to young physicists, the book is targeted towards advanced undergraduate and graduate students who are new to the topic. All of the chapters are accompanied by worked problems to help students to check their understanding of the subjects.

60 Years of Yang–Mills Gauge Field Theories: C N Yang's Contributions to Physics

By L Brink and K K Phua (eds)

World Scientific



Since their first formulation, and following development that took place between the end of the 1950s and the beginning of the 1970s, Yang–Mills gauge field theories have proven to be the cornerstone of theoretical physics. Up to now, they represent the only relativistic quantum many-body corpus of theories in four space–time dimensions that appear to be fully consistent. The Yang–Mills theories for the strong, weak and electromagnetic forces are the framework of the Standard Model of particle physics, which has been proven to be the correct theory at the energies that we can measure.

In May 2015, the International Conference on 60 years of Yang–Mills Gauge Theories was held at the Institute of Advanced Studies in Singapore, in order to commemorate this anniversary. Renowned physicists from all over the world participated and gave interesting talks on different aspects of the theories, as well as on their role outside particle physics, in particular in condensed-matter and statistical physics.

Chen Ning Yang, who was awarded the Nobel Prize in Physics in 1957 together with Tsung-Dao Lee for another work, the discovery of parity violations, gave a talk at the conference. The same was not possible for Robert Mills, co-father of these theories, because he passed away in 1999. The emphasis of the conference was given to Yang's contributions to physics in general.

This book collects together the talks given at the conference by Yang and the invited speakers, reviewing these remarkable contributions and their importance for the future of physics. Authors include D Gross, L Brink, M Fisher, L Faddeev, S L Wu, T T Wu, T Zee and many others.

CERN Courier Archive: 1973

A look back to CERN Courier vol. 13, September 1973, compiled by Peggie Rimmer

CERN NEWS

CERN: a source of European spirit

If we look at mid-1945 Europe, a continent broken up as it emerged from World War II, in the minds of political leaders and diplomats the restoration of Europe's place in the world meant not only the world of politics or economics but also of culture.

This was particularly evident in that post-war summer, with the demonstration of the might of a branch of advanced science which had been considered removed from immediate applications. Because of this unexpected identity between cultural achievement and worldly power, those dreaming of European restoration chose scientific research for a first manifestation of unity and, among the domains of research, nuclear physics.

The unity of European science involved not only personnel and information exchanges, but also big machines and a commonly owned piece of land under a new form of common European sovereignty. In the early 1950s Professor W Heisenberg considered that, on the way towards Germany's re-integration in the common aspirations of Western Europe, full participation in a common scientific enterprise would be a significant and readily acceptable step. In a very different region of politics, a prominent French politician, when hearing that Britain was among the signatories of the CERN Convention, exclaimed that CERN was worth founding and financing if only to prove that co-operation with the United Kingdom was no less feasible and desirable than with any continental nation.

The common enterprise in European physics did not seek to put itself apart from its counterparts in the United States, the Soviet Union and elsewhere but expected to entertain a fruitful dialogue with all these colleagues and competitors. At the beginning, contact with America was by far the easiest to maintain. Its first manifestation was the friendly rivalry between the physicists of united Europe and those of the united universities on the American East Coast. Fruitful contact was kept up by a constant stream of American visitors and research fellows, whose participation in CERN's life was, for several years, financed by the Ford Foundation.

The same years coincided with the thaw of the Cold War. Soviet scientists paid us the highest compliment – that of following our example. The nuclear institute at Dubna, already in existence for several years, was transformed into an international enterprise in which every member of the Soviet-led group of nations was invited to take part.

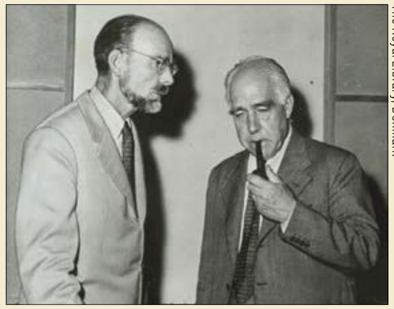
In addition, other scientifically advanced nations – Japan, Israel, India and others – developed a network of contacts which became a significant part of CERN's scientific function. Offering the use of one of the top-rank machines was largely responsible for CERN's worldwide appeal. On a somewhat more modest plane, CERN's initiatives in processing visual data have spread over the world and become the starting point for other devices invented elsewhere.

Steps were taken to avoid CERN becoming just another research institute. New forms of co-operation between CERN and the national institutes were developed and by mid-1961 CERN had assumed its character of a research "commonwealth".

First plans for the 300 GeV project [which became the Super Proton Synchrotron], finally approved in February 1971, were made approximately at the time when European unification was suffering an abortive attempt to get Britain into the Common Market (1962–1963). Towards the end of the same decade, the picture had changed and the initiation of procedures to extend the Market and to build the CERN Laboratory II took place in a nearly identical time sequence.

The enlargement of CERN into a network of inter-institute collaboration and the extension of CERN's validity from a regional to a worldwide scene may pre-figure the future role of Europe in the world at large.

● Compiled from texts on pp251–254.


The Royal Library, Denmark

An early deliberation, en route to the establishment of the European Organization for Nuclear Research, between two of its most illustrious founders – Pierre Auger (left) and Niels Bohr.

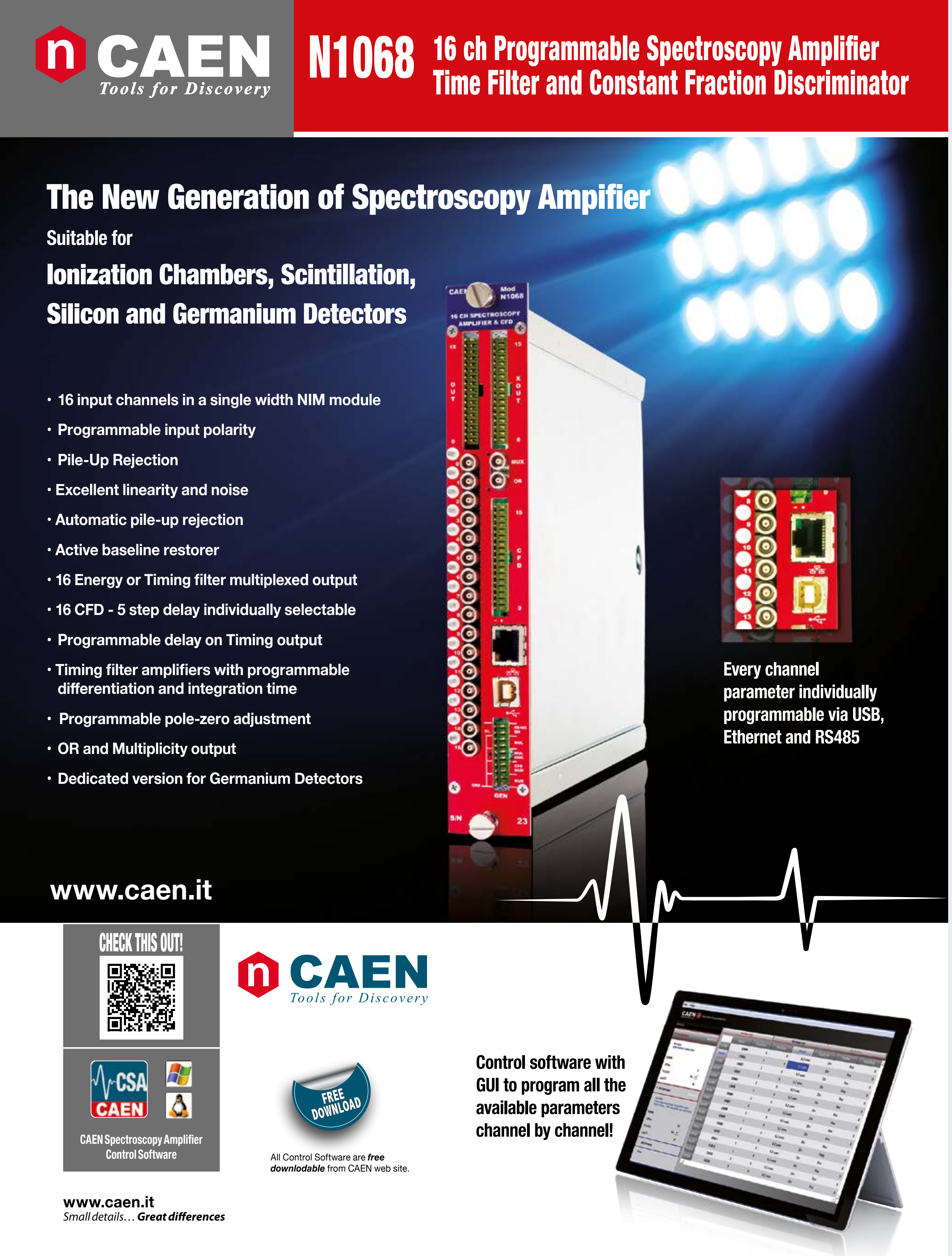

CERN 52.4.73

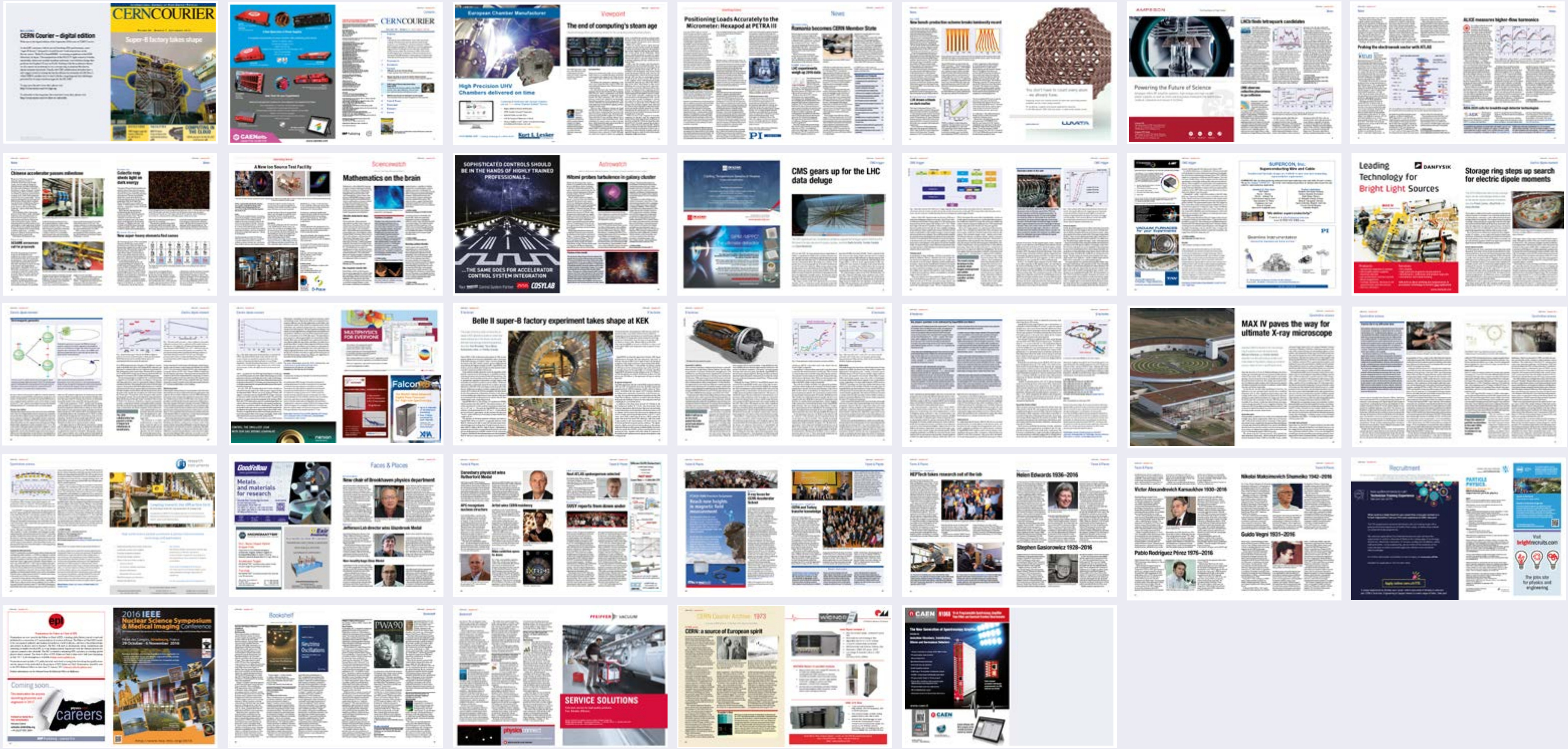
European collaboration – the flags of Austria, Belgium, Denmark, the Federal Republic of Germany, France, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland and the United Kingdom fly at the CERN site.

Compiler's Note

With Europe in post-Brexit turmoil, it is interesting to recall the mood of the 1970s. This article was written by Lew Kowarski, a naturalised French physicist born in St Petersburg. Lew fled to Poland with his parents after the Bolshevik Revolution, moved to France in 1934, and to England and Canada during World War II. He became an important founder member of CERN, and headed Scientific and Technical Services at start-up in 1954. In 1961, these became part of an evolving series of data-handling divisions. Although written more than 40 years ago, the article clearly expressed hopes for European integration and an eventual enlargement of the laboratory to become a global endeavour.

62


CAEN
Tools for Discovery
N1068
16 ch Programmable Spectroscopy Amplifier
Time Filter and Constant Fraction Discriminator
The New Generation of Spectroscopy Ampifier
Suitable for
Ionization Chambers, Scintillation,
Silicon and Germanium Detectors
• 16 input channels in a single width NIM module
• Programmable input polarity
• Pile-Up Rejection
• Excellent linearity and noise
• Automatic pile-up rejection
• Active baseline restorer
• 16 Energy or Timing filter multiplexed output
• 16 CFD - 5 step delay individually selectable
• Programmable delay on Timing output
• Timing filter amplifiers with programmable differentiation and integration time
• Programmable pole-zero adjustment
• OR and Multiplicity output
• Dedicated version for Germanium Detectors
Every channel parameter individually programmable via USB, Ethernet and RS485
www.caen.it
CHECK THIS OUT!
CSA CAEN
CAEN Spectroscopy Amplifier Control Software
CAEN
Tools for Discovery
FREE DOWNLOAD
All Control Software are free downloadable from CAEN web site.
Control software with GUI to program all the available parameters channel by channel!
www.caen.it
Small details… Great differences



CERNCOURIER

VOLUME 56 NUMBER 7 SEPTEMBER 2016

Contents