WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the September 2017 issue of *CERN Courier.*

Particle physics and superconductivity are deeply entwined. Magnets built from superconducting cables, especially those made from niobium-titanium, allow higher-energy beams to circulate in colliders and provide stronger fields for particle detectors. The LHC is the largest superconducting machine ever, while two of its detectors contain superconducting magnets on an unprecedented scale, allowing the Higgs boson to be discovered five years ago. Demand for higher-performing machines, such as the LHC luminosity upgrade and future circular colliders, requires next-generation conductors such as niobium-tin and CERN is making rapid progress towards such technologies. After MRI, particle physics is the biggest customer for superconductor firms, and the ITER fusion experiment has also had a massive impact on global niobium-tin production. Alongside superconducting magnets has been a rapid evolution of superconducting radio-frequency cavities to accelerate particle beams – as showcased by the upgrade of the LHC's predecessor, LEP, in the 1990s and today with the realisation of the European X-ray free-electron laser and a possible linear collider. A leap in performance is promised by high-temperature superconductors, which were discovered 30 years ago yet are still an enigma. CERN is making important progress in this domain and has initiated programmes to train the next generation of superconductivity researchers. Together with industry, particle physics is helping us realise the full potential of superconductivity.

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, CERN
DIGITAL EDITION CREATED BY DESIGN STUDIO/IOP PUBLISHING, UK

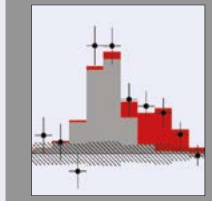
INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERNCOURIER

VOLUME 57 NUMBER 7 SEPTEMBER 2017

SUPERCONDUCTIVITY

From cables to colliders



HIGGS TO BB

Boson spotted decaying into b quarks **p10**

PROTON MASS

Precise measurement suggests proton lighter than thought **p8**

HIGHLIGHTS FROM EPS

European Physical Society meeting held in Venice **p52**

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 Peter Jenni, Christine Sutton, Claude Amsler, Philippe Bloch, Roger Forty

Laboratory correspondents:
Argonne National Laboratory (US) Tom LeCompte
Brookhaven National Laboratory (US) Achim Franz
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) Melinda Baker
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 Sian Giles, Science and Technology Facilities Council, Polaris House,
North Star Avenue, Swindon, SN2 1SZ
E-mail: sian.giles@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 COURIER

VOLUME 57 NUMBER 7 SEPTEMBER 2017

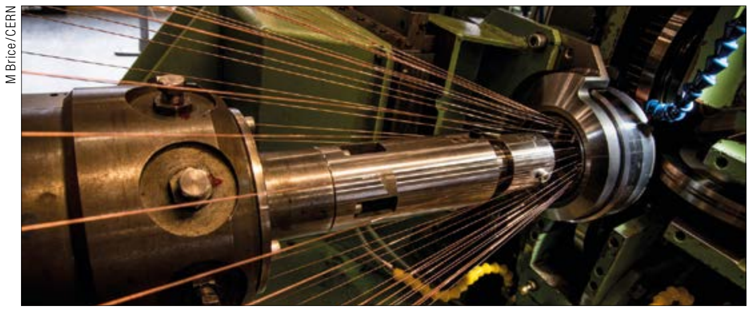
On the cover: CERN's Amalia Ballarino holding next-generation superconducting cables. (Image credit: S Bennett/CERN.)

Viewpoint

Celebrating a super partnership

Particle physics and superconductivity grow closer thanks to projects such as HL-LHC and FCC.

M Brice/CERN



Cable for the High-Luminosity LHC magnets being produced at CERN.

By Lucio Rossi

This month more than 1000 scientists and engineers are gathering in Geneva to attend the biennial European Conference on Applied Superconductivity (EUCAS 2017). This international event covers all aspects of the field, from electronics and large-scale devices to basic superconducting materials and cables. The organisation has been assigned to CERN, home to the largest superconducting system in operation (the Large Hadron Collider, LHC) and where next-generation superconductors are being developed for the high-luminosity LHC upgrade (HL-LHC) and Future Circular Collider (FCC) projects.

When Karl H Onnes discovered superconductivity in 1911, Ernest Rutherford was just publishing his famous paper unveiling the structure of the atom. But superconductivity and nuclear physics, both with their own harvests of Nobel prizes, were unconnected for many years. Accelerators have brought the fields together, as this issue of *CERN Courier* demonstrates.

The constant evolution of high-voltage radio-frequency (RF) cavities and powerful magnets to accelerate and guide particles around accelerators drove a transformation of our understanding of fundamental physics. But by the 1970s, the limit of RF power and magnetic-field strength had nearly been reached and gigantism seemed the only option to reach higher energies. In the meantime, a few practical superconductors had become available: niobium-zirconium alloy, niobium-tin compound (Nb_3Sn) and niobium-titanium alloy (Nb-Ti). Its reliability in processing and uniformity of production made Nb-Ti the superconductor of choice for all projects.

The first large application of Nb-Ti was for high-energy physics, driving the bubble-chamber solenoids for Argonne National Laboratory in the US (see p22). But it was accelerators, even more than detectors or fusion applications, that drove the development of technical superconductors. Following the birth of the modern Nb-Ti superconductor in 1968, rapid R&D took place for large high-energy physics projects such as the proposed but never born Superconducting SPS at CERN, the ill-fated Isabelle/CBA collider at BNL and the Tevatron at Fermilab (see p17). By the end of the 1980s, superconductors had to be produced on industrial scales, as did the niobium RF accelerating cavities (see p27) for LEPII and other projects. MRI, based on 0.5–3 T superconducting magnets, also took off at that time, today dominating the market with around 3000 items built per year.

The LHC is the summit of 30 years of improvement in Nb-Ti-based conductors. Its 8.3 T dipole fields are generated by 10 km-long, 1 mm-diameter wires containing 6000 well-separated Nb-Ti filaments, each 6 μm thick and protected by a thin Nb barrier, all embedded in pure copper and then coated with a film of oxidised tin-silver alloy. The LHC contains 1200 tonnes of this material, made by six companies worldwide, and five years ago it powered the LHC to produce the Higgs boson.

But the story is not finished. The increased collision rate of the HL-LHC requires us to go beyond the 10 T wall and, despite its brittleness, we are now able to exploit the superior intrinsic properties of Nb_3Sn to reach 11 T in a dipole and almost 12 T peak field in a quadrupole. Wire developed for the LHC upgrade is also being used for high-resolution NMR spectroscopy and advanced proton therapy, and Nb_3Sn is being used in vast quantities for the ITER fusion project (see p34). Testing the Nb_3Sn technology for the HL-LHC is also critical for the next jump in energy: 100 TeV, as envisaged by the CERN-coordinated FCC study. This requires a dipole field of 16 T, pushing Nb_3Sn beyond its present limits, but the superconducting industry has taken up the challenge. Training young researchers will further boost this technology – for example, via the CERN-coordinated EASITrain network on advanced superconductivity for PhD students, due to begin in October this year (see p31).

The virtuous spiral between high-energy physics and superconductivity is never ending (see p37), with pioneering research also taking place at CERN to test the practicalities of high-temperature superconductors (see p43) based on yttrium or iron. This may lead us to dream about a 20–25 T dipole magnet – an immense challenge that will not only give us access to unconquered lands of particle physics but expand the use of superconductors in medicine, energy and other areas of our daily lives.

Lucio Rossi is project leader of the High Luminosity LHC, and chairman of EUCAS 2017.

News

INTERNATIONAL

Slovenia accedes to associate membership

On 4 July, the Republic of Slovenia became an associate member of CERN in the pre-stage to membership. It follows official notification to CERN that Slovenia has completed internal approval procedures, entering into force an agreement signed in December 2016. "It is a great pleasure to welcome Slovenia into our ever-growing CERN family as an associate Member State in the pre-stage to membership," said CERN Director-General Fabiola Gianotti. "This now moves CERN's relationship with Slovenia to a higher level."

Slovenian physicists contributed to CERN's programme long before Slovenia became an independent state in 1991, participating in an experiment at LEAR (the Low Energy Antiproton Ring) and on the DELPHI experiment at CERN's previous large accelerator, the Large Electron–Positron collider (LEP). In 1991, CERN and Slovenia concluded a co-operation agreement concerning the further development of scientific and technical co-operation in the research projects of CERN. In 2009, Slovenia applied to become a Member State of CERN. For the past 20 years, Slovenian physicists have participated in the ATLAS experiment at the Large Hadron Collider. Their focus has been on silicon tracking, protection devices and computing at the Slovenian TIER-2 data centre, and on the tracker upgrade, making use of the research reactor in Ljubljana for neutron irradiation studies.

S Bennett/CERN

Slovenia ambassador Vojislav Šuc with CERN Director-General Fabiola Gianotti.

"Slovenia's membership in CERN will on the one hand facilitate, strengthen and broaden the participation and activities of Slovenian scientists (especially in the field of experimental physics), on the other it will bring full access of Slovenian industry to CERN orders, which will help to break through in demanding markets with products with a high degree of embedded knowledge," said Maja Makovec Brenčič, Slovenian minister of education, science and sport.

Slovenia joins Cyprus and Serbia as an associate Member State in the pre-stage to membership. After a period of five years, the CERN Council will decide on the admission of Slovenia to full membership.

HIE-ISOLDE

Revamped HIE-ISOLDE serves experiments

CERN's long-running radioactive-ion-beam facility ISOLDE, which produces beams for a wide range of scientific communities, has recently been upgraded to allow higher-energy beams.

In July, the second phase of the High-Intensity and Energy upgrade (HIE-ISOLDE) saw its first user experiments get under way using the high-resolution Miniball germanium detector, which is specially designed for studying nuclear reactions with low-intensity radioactive ion beams. One of the first experiments looked at electromagnetic interactions between selenium-70 and a platinum target, which allow researchers to determine the shape of this radioactive nucleus. It was carried out by a team from the University of the Western Cape in South Africa, marking the first African-led experiment to be carried out at CERN.

Although HIE-ISOLDE's first physics experiments began in late 2016, earlier this year the facility added a further cryomodule that had to be calibrated, aligned and tested. Each cryomodule contains five superconducting radio-frequency cavities to accelerate the beam to higher energies, and the facility is now able to accelerate nuclei up to an average energy of 7.5 MeV per nucleon, compared with 5.5 MeV last year. The higher energy allows physicists to study the properties of heavier isotopes, and in 2018 a fourth cryomodule will be added to the HIE-ISOLDE linac to reach the final design energy of 10 MeV per nucleon.

The HIE-ISOLDE beams will be available until the end of November, with 13 experiments hoping to use the facility during that time – more than double the number that took data last year.

J Ordan/CERN

The Miniball germanium array, which uses beams from the upgraded HIE-ISOLDE facility.

Sommaire en français

PROTON MASS

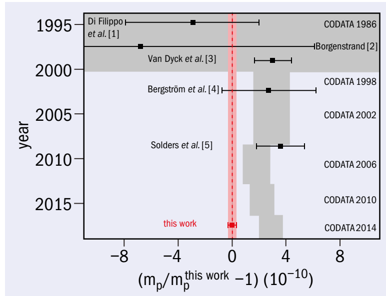
Precision study reveals proton to be lighter

A team in Germany has made the most precise measurement to date of the mass of a single proton, achieving a precision of 32 parts-per-trillion (ppt). The result not only improves on the precision of the accepted CODATA value by a factor of three but also disagrees with its central value at a level of 3.3 standard deviations, potentially shedding light on other mysteries surrounding the proton.

The proton mass is a fundamental parameter in atomic and particle physics, influencing atomic spectra and allowing tests of ultra-precise QED calculations. In particular, a detailed comparison between the masses of the proton and the antiproton offers a stringent test of the fundamental CPT invariance of the Standard Model.

The team at the Max Planck Institute for Nuclear Physics (MPIK) in Heidelberg and collaborators from RIKEN in Japan used a bespoke electromagnetic Penning trap cooled to 4 K to store individual protons and highly charged carbon ions. By measuring the characteristic cyclotron frequencies of the trapped particles using ultra-sensitive image-current detectors, the mass of the proton in natural units follows directly.

For the new measurement, the team stored one proton and one highly charged carbon ion in separate compartments of the apparatus and then transported them alternately into the central measurement compartment.



The new measurement disagrees with the latest CODATA value, which comes mainly from the Penning-trap experiments UW-PTMS at the University of Washington and SMILETRAP in Stockholm, at a level of approximately 3.3 standard deviations.

Purpose-built electronics allowed the proton to be interrogated under identical conditions as the carbon ion, despite its 12-fold lower mass and six-fold smaller charge, and the ratio of the two measured values results directly in the proton mass in atomic units: 1.007276466583±15 (stat)±29 (syst).

The sensitive single-particle detectors were partly developed by the RIKEN group, drawing on experience gained with similar traps for antimatter research at CERN's Antiproton Decelerator (AD) – specifically the BASE experiment. "The group around Sven Sturm and Klaus Blaum from MPIK Heidelberg, which did the measurement, has great expertise with carbon, whereas the BASE group contributed proton expertise based on 12 years dealing with protons and antiprotons," explains RIKEN group leader and BASE spokesperson Stefan Ulmer. "We shared knowledge such as know-how on ultra-sensitive proton detectors and the 'fast-shuttling' method developed by BASE to perform the proton–antiproton charge-to-mass ratio measurement."

Interestingly, the new value of the proton mass is significantly smaller than the accepted one and could therefore be linked to well-known discrepancies in the mass of the heaviest hydrogen isotope, tritium. "Our result contributes to solving this puzzle, since it corrects the proton's mass in the proper direction," says Blaum. The result also improves the proton–electron mass ratio by a factor two, achieving a relative precision of 43 ppt, where the uncertainty arises nearly equally from the proton and the electron mass.

Although carefully conducted cross-check measurements confirmed a series of previously published values of the proton mass and showed that no unexpected systematic effects were imposed by the new method, such a striking departure from the accepted value will likely challenge other teams to revisit the proton mass. The discrepancy has already inspired the MPIK-RIKEN team to further improve the precision of its measurement, for instance by storing a third ion in the trap and measuring it simultaneously to eliminate uncertainties originating from magnetic-field fluctuations, which are the main source of the systematic error using the new technique.

"It is also planned to tune the magnetic field to even higher homogeneity, which will reduce additional sources of systematic error," explains BASE member Andreas Mooser. "The methods that will be pioneered in the next step of this experiment will have immediate positive feedback to future BASE measurements, for example to improve the precision in the antiproton-to-proton charge-to-mass ratio."

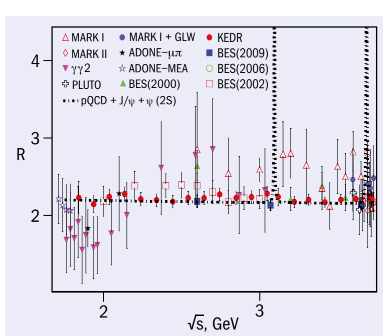
Further reading

F Heiße *et al.* 2017 *Phys. Rev. Lett.* **119** 033001.

HADRONIC PHYSICS

KEDR pins down R at low energies

The KEDR collaboration has used the VEPP-4M electron–positron collider at the Budker Institute in Russia to make the most precise measurement of the quantity "R" in the low-energy range. R is defined as the ratio of the radiatively corrected total hadronic cross-section in electron–positron annihilation to the Born cross-section of muon pair production. The dependence of R on the centre-of-mass energy is critical for determining the running strong coupling constant and heavy-quark masses, the anomalous magnetic moment of the muon and the value of the electromagnetic



Measured R value versus the centre-of-mass energy and the sum of the prediction of perturbative QCD and a contribution from narrow resonances.

fine structure constant at the Z peak. A substantial contribution to the uncertainties on these quantities comes from the energy region below charm threshold, where KEDR measurements were made.

The KEDR team performed a precise measurement of R at 20 points: in the energy ranges 1.84–3.05 and 3.12–3.72 GeV the weighted averages of R are 2.225±0.051 and 2.189±0.047, respectively, in good agreement with perturbative QCD. At present, it is the most accurate measurement of R in this energy range, to which more than 10 experiments have contributed. It involved a challenging analysis in which the hadronisation of light quarks at low energies was modelled by tuning distributions of parameters essential for the event selection in the various generator codes.

The collaboration now plans to measure R in the range 5–7 GeV, where the last similar experiment was carried out more than a quarter of a century ago.

Further reading

KEDR Collaboration 2016 *Phys. Lett. B* **753** 533.

KEDR Collaboration 2017 *Phys. Lett. B* **770** 174.

BIG DATA

SKA and CERN co-operate on extreme computing

On 14 July, the Square Kilometre Array (SKA) organisation signed an agreement with CERN to formalize their collaboration in the area of extreme-scale computing. The agreement will address the challenges of "exascale" computing and data storage, with the SKA and the Large Hadron Collider (LHC) to generate an overwhelming volume of data in the coming years.

When completed, SKA will be the world's largest radio telescope with a total collecting area of more than 1 km^2 using thousands of high-frequency dishes and many more low- and mid-frequency aperture array telescopes distributed across Africa, Australia and the UK. Phase 1 of the project, representing approximately 10% of the final array, will generate around 300 PB of data every year – 50% more than has been collected by the LHC experiments in the last seven years. As is the case at CERN, SKA data will be analysed by scientific collaborations distributed across the planet.

S Bennett/CERN

CERN Director-General Fabiola Gianotti and SKA director-general Philip Diamond signing a big-data co-operation agreement.

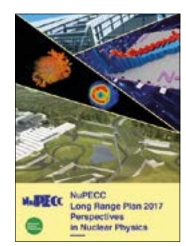
The acquisition, storage, management, distribution and analysis of such volumes of scientific data is a major technological challenge.

"Both CERN and SKA are and will be pushing the limits of what is possible technologically, and by working together and with industry, we are ensuring that we are ready to make the most of this upcoming data and computing surge,"says SKA director-general Philip Diamond.

CERN and SKA have agreed to hold regular meetings to discuss the strategic direction of their collaborations, and develop demonstrator projects or prototypes to investigate concepts for managing and analysing exascale data sets in a globally distributed environment. "The LHC computing demands are tackled by the Worldwide LHC computing grid, which employs more than half a million computing cores around the globe interconnected by a powerful network," says CERN's director of research and computing Eckhard Elsen. "As our demands increase with the planned intensity upgrade of the LHC, we want to expand this concept by using common ideas and infrastructure into a scientific cloud. SKA will be an ideal partner in this endeavour."

NUCLEAR PHYSICS

NuPECC sets out long-range plan



NuPECC's latest report includes CERN facilities.

On 19 June, the Nuclear Physics European Collaboration Committee (NuPECC) released its long-range plan for nuclear research in Europe, following 20 months of work involving extensive discussions with the scientific community. The previous long-range plan was issued in 2010.

Today, nuclear physics is a broad field covering nuclear matter in all its forms and exploring their possible applications. It encompasses the origin and evolution of the universe, such as the quark deconfinement at the Big Bang, the physics of neutron stars and nucleosynthesis, and addresses open questions in nuclear structure, among other topics.

A number of research programmes are at the interface between nuclear and particle physics, where CERN plays an important role. This can be seen clearly in the six chapters of the NuPECC report devoted to: hadron physics; properties of strongly interacting matter; nuclear structure and dynamics; nuclear astrophysics; symmetries and fundamental interactions; and applications. For symmetries and fundamental interactions, particular emphasis is given to experiments (such as those with antihydrogen) where nuclei are sensitive to physics beyond the Standard Model. Concerning broader societal benefits, CERN's MEDICIS facility, based on expertise from ISOLDE, is of particular interest (*CERN Courier* October 2016 p28).

The Facility for Antiproton and Ion Research (FAIR), a major investment that just entered construction in Germany (*CERN Courier* July/August 2017 p41), also has high prominence. Three other prominent recommendations have particular relevance to CERN: support for world-leading isotope-separation facilities (ISOLDE at CERN together with SPIRAL2 in France and SPES in Italy); support for existing and emerging facilities (including the new ELENA synchrotron at CERN's Antiproton Decelerator); and support for the LHC's heavy-ion programme, in particular ALICE. Emerging facilities – the extreme-light source ELI-NP in Bucharest, and NICA and a superheavy element factory in Dubna – are also highlighted.

Research in nuclear physics involves several facilities of different sizes that produce complementary scientific results, and in Europe they are well co-ordinated. International collaborations beyond Europe, mainly in the US (JLAB in particular) and in Asia (Japan in particular), add much value to this field.

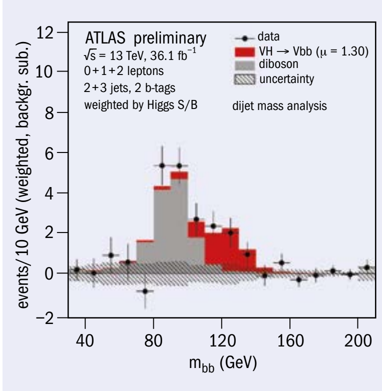
NuPECC's latest report is expected to help co-ordinate and guide this rich field of physics for the next 6–7 years. Its recommendations were extensively discussed and can be read in full at nupecc.org/pub/lrp2017.pdf.

LHC EXPERIMENTS

ATLAS finds evidence for Higgs to bb

Five years ago, the ATLAS and CMS collaborations at the LHC announced the discovery of a new particle with properties consistent with those of a Standard Model Higgs boson. Since then, based on proton–proton collision data collected at energies of 7 and 8 TeV during LHC Run 1 and at 13 TeV during Run 2, many measurements have confirmed this hypothesis. Several decay modes of the Higgs boson have been observed, but the dominant decay into pairs of b quarks, which is expected to contribute at a level of 58%, had up to now escaped detection – largely due to the difficulty in observing this decay mode at a hadron collider.

On 6 July, at the European Physical Society conference in Venice, the ATLAS collaboration announced that they had found evidence for H → bb, representing an immense analysis achievement. By far the largest source of Higgs bosons is their production via gluon fusion, gg → H → bb, but this is overwhelmed by the huge background of bb events, which are produced at a rate 10 million times higher. The associated production of a Higgs with a W or Z vector boson (jointly denoted V) offers the most sensitive alternative, despite having a production rate roughly 20 times lower than H → bb, because the vector bosons are detected via their decay to leptons and therefore allow efficient triggering and background rejection. Nevertheless, the signal remains orders of magnitude smaller than the backgrounds, which arise from the associated production of vector bosons with jets and from top-quark production.



Mass distribution of the two-b-jet system after subtraction of all backgrounds except for those arising from VZ and Z → bb. The contribution of the Higgs boson is shown in red and the contribution of VZ in grey, the observation of which provides a powerful validation of the analysis.

To find evidence for the H → bb decay in the VH production channel, it is necessary to use detailed information on the properties of the decay products. The jets arising from b quarks contain b hadrons, whose long lifetime can be used in sophisticated b-tagging algorithms to discriminate them from jets originating from the fragmentation of gluons or other quark species. These algorithms have benefitted significantly from the new innermost pixel layer installed in ATLAS before Run 2. The kinematic properties of the decay products can also be used to enhance the signal-over-background ratio.

The property with the most discriminatory power is the invariant mass of the two-b-jet system, which for the signal accumulates at the mass of the Higgs boson (see figure). To increase the sensitivity of the analysis, this mass is used together with several other kinematic variables as input to a multivariate analysis.

Based on data collected during the first two years of LHC Run 2 in 2015 and 2016, evidence for the H → bb decay is obtained at the level of 3.5σ, slightly increased to 3.6σ after combination with the Run 1 results (compared to an expected significance of 4σ). The measured signal yield is in agreement with the Standard Model expectation, within an uncertainty of 30%. The associated VZ production, with Z → bb, allows for a powerful cross-check of the analysis, as the final states are very similar except for the location of the two-b-jet mass peak (see figure); VZ production is observed with a significance of 5.8σ in the Run 2 data, in agreement with the Standard Model prediction.

This analysis opens a way to study about 90% of the Higgs boson decays expected in the Standard Model, which is a sharp increase from the approximately 30% observed previously. With much more data expected by the end of Run 2 in 2018, a definitive 5σ observation of the H → bb decay may be in sight, with the increased precision providing new opportunities to challenge the Standard Model.

● Further reading

ATLAS Collaboration 2015 JHEP 01 069.
ATLAS Collaboration 2016 ATL-PHYS-PUB-2016-012.
ATLAS Collaboration 2017 ATLAS-CONF-2017-041.

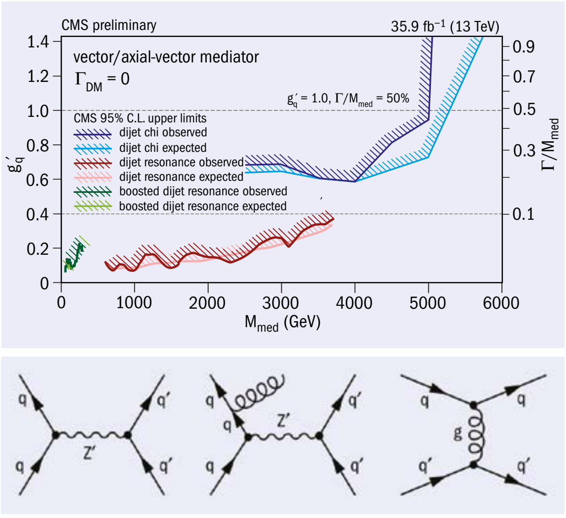
CMS expands scope of dark-matter search in dijet channel

The quest to find dark matter (DM) has inspired new searches at CMS, specifically looking for interactions between DM and quarks mediated by particles of previously unexplored mass and width. If the DM mediator is a leptophobic vector resonance coupling only to quarks with a universal coupling g'_q, for instance, its decay also produces a dijet resonance (see bottom figure, left) and the value of g'_q determines the width of the mediator.

CMS has traditionally searched for peaks from narrow resonances on the steeply falling dijet invariant mass spectrum predicted by QCD. This search has been updated with the full 2016 data set and limits set on a DM mediator, constraining g'_q for resonances with a mass between 0.6 and 3.7 TeV and width less than 10% of the resonance mass. Two additional dijet searches have now been released: a boosted-dijet search sensitive to lower mediator masses, and an angular-distribution search sensitive to larger couplings and widths.

The first search gets round the limitations of the narrow-resonance search, which only applies above a minimum mass that satisfies the dijet trigger requirements, by requiring resonance production in association with a jet (bottom figure, middle). In such events the resonance is highly boosted and by analysing the jet substructure the QCD background can be highly suppressed, making the search sensitive in a lower mass range. The mass spectrum of the single jet was used to search for resonances over a mass range of 50–300 GeV, and the corresponding constraints on g'_q and the mediator width from boosted dijets explore the lowest mediator masses.

For large couplings and widths, the sensitivity of searches for dijet resonance peaks is strongly reduced. However, a search for a very wide resonance can be performed by studying dijet angular distributions such as the scattering angle between the incoming and outgoing partons. These distributions differ significantly, depending on whether a new particle is produced in the s-channel or from the QCD dijet background, which is dominated by t-channel production (bottom figure, right). Being sensitive to both large-width resonances and non-resonant signatures, this search also sets lower limits on the scale of contact interactions that may arise from quark compositeness in the range 6–22 TeV, as well as signatures of large extra dimensions and quantum black holes. The same search, when interpreted in the context of a vector mediator coupling to DM, excludes values of g'_q greater than 0.6, corresponding to widths higher than 20% of the resonance mass, and extending to mediator masses as high as 5 TeV.



Top: 95% C.L. upper limits on the universal quark coupling g'_q (left vertical axis), and the resonance decay width Γ divided by mass (right vertical axis) as a function of the mass of the mediator (a leptophobic resonance). Bottom: Feynman diagrams showing the production of a new particle and its decay to quarks (left), with a gluon radiated from the initial state (middle) and a t-channel diagram governing the QCD dijet background (right).

Using these three complementary techniques, CMS has now explored a large range in mass, coupling and width, extending the scope of searches for DM mediators. The expected volume of data from the LHC in upcoming years will allow CMS to extend this reach even further, with the study of three-jet topologies allowing the uncovered mass range of 300–600 GeV to be explored.

● Further reading

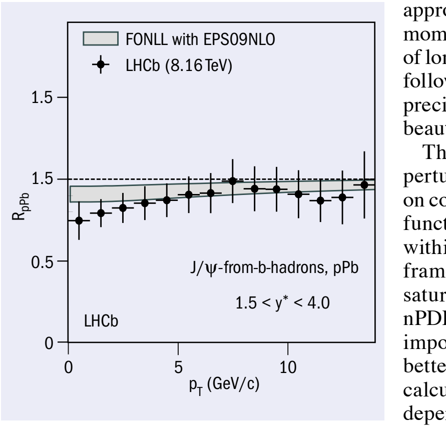
CMS Collaboration 2016 CMS-PAS-EXO-16-046.
CMS Collaboration 2016 CMS-PAS-EXO-16-056.
CMS Collaboration 2017 CMS-PAS-EXO-17-001.

Lead nuclei under scrutiny at LHCb

In 2016 the LHC collided protons and lead nuclei for the first time at a centre-of-mass energy of 8.16 TeV per nucleon–nucleon pair. In lead–lead collisions, the formation of the quark–gluon plasma (QGP), a deconfined system where quarks and gluons can move freely, is a subject of intense studies at the LHC. By contrast, proton–lead collisions represent the best available environment to quantify nuclear effects that are not related to the QGP.

Our knowledge of the partonic content of nuclei suffers from large uncertainties, particularly at low momentum where large modifications of the partonic flux with respect to the free nucleon are expected. The particular design of the LHCb experiment, with its fully instrumented forward acceptance, offers a unique opportunity to access production processes in which one parton carries a momentum fraction of the incoming nucleon inside the lead nucleus of approximately 10^{-5}–10^{-4} (covering the proton fragmentation region) and 10^{-3}–10^{-1} for the lead fragmentation region.

The LHCb collaboration recently submitted the first paper at the LHC based on results obtained with the 2016 proton–lead data sample. This measurement of J/ψ production profits from an integrated luminosity about 20 times larger than the proton–lead sample collected by LHCb during the 2013 run. The nuclear modification factor R_{pPb} as a function of transverse momentum is shown in the figure: J/ψ mesons produced in the interaction point (prompt) are found to be suppressed by about a factor two at low transverse momentum, while R_{pPb} approaches unity at higher transverse momenta. Those arising from the decays of long-lived beauty hadrons (non-prompt) follow a similar pattern. This is the most precise measurement to date of inclusive beauty production in nuclear collisions.



Nuclear modification factor $R_{pPb} = \sigma(J/\psi, pPb)/[A_{Pb} \times \sigma(J/\psi, pp)]$ of J/ψ production from b hadrons in proton–lead collisions.

The results can be compared with perturbative QCD calculations based on collinear nuclear parton distribution functions (nPDFs) or with calculations within the colour-glass condensate (CGC) framework, which takes into account gluon saturation. The large uncertainties on the nPDFs compared to the data show the importance of new experimental data to better constrain them, while the CGC-based calculation reproduces the observed dependence accurately.

The large 2016 data set will allow for a precise study of heavy-flavour production with different hadron species, and also of cleaner electromagnetic/electroweak probes. These measurements will test which frameworks adequately describe the modification of the partonic flux in nuclear collisions. Additionally, other mechanisms such as partonic energy loss due to gluon radiation, which is very relevant for nuclear modifications.

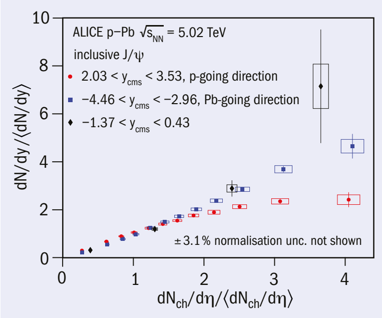
● Further reading

LHCb Collaboration 2017 LHCB-PAPER-2017-014.

J/ψ mesons reveal stronger nuclear effects in pPb collisions

Quarkonium states, such as the J/ψ meson, are prominent probes of the quark–gluon plasma (QGP) formed in high-energy nucleus–nucleus (AA) collisions. That bulk J/ψ production is suppressed in AA collisions with respect to proton–proton collisions had been reported by ALICE five years ago. However, measurements of J/ψ production in proton–lead collisions, where the formation of the QGP is not expected, are essential to quantify effects that are present in AA collisions but not associated with the QGP. In a recent study, ALICE has shown that the production of J/ψ mesons in proton–lead collisions is strongly correlated with the total number of produced particles in the event (event multiplicity), and that this correlation varies as a function of rapidity.

In ALICE, the J/ψ measurements are performed at forward (proton direction), mid- and at backward-rapidity (lead direction). An increase of the J/ψ yield relative to the event-averaged value with the relative charged-particle multiplicity is observed for all rapidity domains, with a similar slope at low multiplicities (see figure). At multiplicities a factor two above the event average, the trend at forward rapidity is very different from those at mid- and backward-rapidity. In the forward rapidity window, a saturation of the relative yield sets in at high multiplicities, which is interesting because the forward region with low parton fractional momentum is in the domain of gluon shadowing/saturation.



The J/ψ yield relative to the measurement in minimum-bias collisions in three rapidity regions, as a function of relative charged-particle multiplicity measured at central pseudorapidity.

Models incorporating nuclear parton distribution functions with significant shadowing have previously been shown to describe J/ψ measurements performed in event classes selected according to the centrality of the collision. The present measurement, exploring significantly more "violent" events (below 1% of the total hadronic interaction cross-section), suggests that effective gluon depletion in the colliding lead nucleus is larger in high-multiplicity events. However, there are additional concepts to describe this regime of QCD, and it remains to be seen whether such models can also describe the saturation of the yields at forward rapidities.

● **Further reading**
ALICE Collaboration 2017 arXiv:1704.00274.

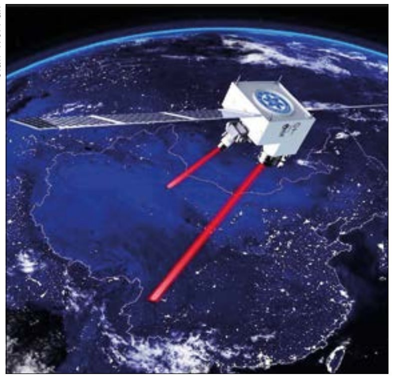
Sciencewatch

Compiled by John Swain, Northeastern University

Quantum comms in space

China's Micius satellite, launched in August last year, has been used to distribute quantum entanglement over a distance of 1200 km – beating previous terrestrial records by an order of magnitude. Juan Yin of the University of Science and Technology and co-workers used a 405 nm laser to pump a periodically poled $KTiOPO_4$ crystal inside a Sagnac interferometer on board the satellite, producing two entangled down-converted photons with a wavelength of about 810 nm. These were then sent to separate receiving stations in Delingha and Lijian located 1200 km apart in the Tibetan mountains. The team observed the survival of two-photon entanglement and measured a violation of Bell's inequality by a factor 2.37±0.09 under Einstein locality conditions. Until now, free-space demonstrations of entanglement have been limited to line-of-sight links across cities or between mountaintops, with link separations limited to around 100 km due to scattering and coherence decay. The new result therefore marks a big advance for secure communications networks and, in the future, a space-based quantum internet.

Jian-Wei Pan



High-altitude receiving stations minimise the effects of the atmosphere.

● **Further reading**
J Yin *et al.* 2017 *Science* **356** 1140.

Dialects and magnets

A remarkable analogy with magnetism can explain how regional dialects develop, according to a new study. James Burridge of the University of Portsmouth in the UK has shown that a simple spatial model of language change reproduces a wide range of observations and predictions of linguists who study dialects in which speakers adopt the dialect they most hear. This leads to a local "alignment" similar to that of spins in a ferromagnet, and the appearance of dialect domains bounded by domain walls or "isoglosses", to use the linguists' term. Taking into account varying population densities makes the isoglosses spontaneously bend, reflecting relevant geographical features.

● **Further reading**
J Burridge 2017 *Phys. Rev. X* **7** 031008.

Quantum voting

Arrow's theorem, perhaps better known to political scientists than to physicists, proves that no electoral system in which voters simply rank candidates can rank them for the population as a whole while simultaneously satisfying three "fairness criteria": if every voter prefers option A over option B, the population prefers A over B; if every voter's preference between A and B is unchanged then the population's preference remains unchanged; and there is no one voter (no dictator) who can always determine the population's preference. This assumes classical voting, but Ning Bao and Nicole Yunger Halpern of Caltech have now shown that if entanglement, superposition and interference are used, a quantum version of such voting becomes possible. This quantum version of majority rule is shown to violate the quantum Arrow conjecture, elucidating how quantum phenomena can be harnessed for strategic advantage.

● **Further reading**
N Bao and N Yunger Halpern 2017 *Phys. Rev. A* **95** 062306.

The shapes of eggs

Understanding why the shapes of avian eggs vary between species has long puzzled researchers, but a new study sheds light on the issue. Mary Caswell Stoddard of Princeton University and co-workers studied egg-shape diversity in terms of asymmetry and ellipticity using a sample of 49,175 eggs from some 1400 species of bird in 35 extant orders and two extinct ones. The team was able to explain the distribution in terms of a simple model based on geometric and mechanical properties of the egg membrane. The researchers also found that the shape of eggs correlates with the ability of birds to fly, and suggest that adaptations for flight may have been critical factors driving egg-shape variations.

● **Further reading**
M Caswell Stoddard *et al.* 2017 *Science* **356** 1249.

The team measured the degree to which avian eggs are symmetrical, round or bottom-heavy.

Invisible solar cells

The performance of silicon solar cells can be boosted by cloaking their metal contacts such that they are invisible to incoming light, according to a demonstration by Martin Schumann of Karlsruhe Institute of Technology and co-workers. Today's commercial solar cells lose around nine per cent of their efficiency due to light being blocked by their metallic contacts. While diffractive optical structures can help, the new scheme is based on coordinate-transformation materials that bend light around the contacts to achieve all-angle invisibility. Results showed that the short-circuit current density of the cloaked cell increases by 7.3%, while its power-conversion efficiency is enhanced by 9.3%.

● **Further reading**
M Schumann *et al.* 2017 *Adv. Opt. Mater.* 1700164.

Astrowatch

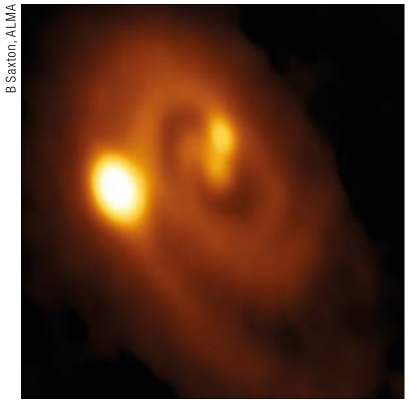
Compiled by Merlin Kole, Department of Particle Physics, University of Geneva

Evidence suggests all stars born in pairs

The reason why some stars are born in pairs while others are born singly has long puzzled astronomers. But a new study suggests that no special conditions are required: all stars start their lives as part of a binary pair. The result has implications not only in the field of star evolution but also for studies of binary neutron-star and binary black-hole formation. It also suggests that our own Sun was born together with a companion that has since disappeared.

Stars are born in dense molecular clouds measuring light-years across, within which denser regions can collapse under their own gravity to form high-density cores opaque to optical radiation, which appear as dark patches. When the densities reach the level where hydrogen fusion begins, the cores can form stars. Although young stars already emit radiation before the onset of the hydrogen-burning phase, it is absorbed in the dense clouds that surround them, making star-forming regions difficult to study. Yet, since clouds that absorb optical and infrared radiation re-emit it at much longer wavelengths, it is possible to probe them using radio telescopes.

Sarah Sadavoy of the Max Planck Institute for Astronomy in Heidelberg and Steven Stahler of the University of California at Berkeley used data from the Very Large Array (VLA) radio telescopes in New Mexico, together with micrometre-wavelength data from the James Clerk Maxwell Telescope (JCMT) in Hawaii, to study the dense gas clumps and the young stars forming in them in the Perseus cluster – a star-forming region about 600 light-years away. Data from the JCMT show the location of dense cores in the gas, while the VLA provides the location of the young stars within them.



B Saxton, ALMA

Radio image of a triple-star system forming within a dusty disc in the Perseus molecular cloud, obtained by the Atacama Large Millimeter/submillimeter Array in Chile.

Studying the multiplicity as well as the location of the young stars inside the dense regions, the researchers found a total of 19 binary systems, 45 single-star systems and five systems with a higher multiplicity. Focusing on the binary pairs, they observed that the youngest binaries typically have a large separation of 500 astronomical units (500 times the Sun–Earth distance). Furthermore, the young stars were aligned along the long axis of the elongated cloud. Older binary systems, with an age between 500,000 and one million years, were found typically to be closer together and separated around a random axis.

Subsequent to cataloguing all the young stars, the team compared the observed star multiplicity and the features seen in the binary pairs to simulations of stars being formed either as single or binary systems. The only way the model could reproduce the data was if its starting conditions contained no single stars but only stars that started out as part of wide binaries, implying that all stars are formed as part of a binary system. After formation, the stars either move closer to one another into a close binary system or move away from each other. The latter option is likely to be what happened in the case of the Sun, its companion having drifted away long ago.

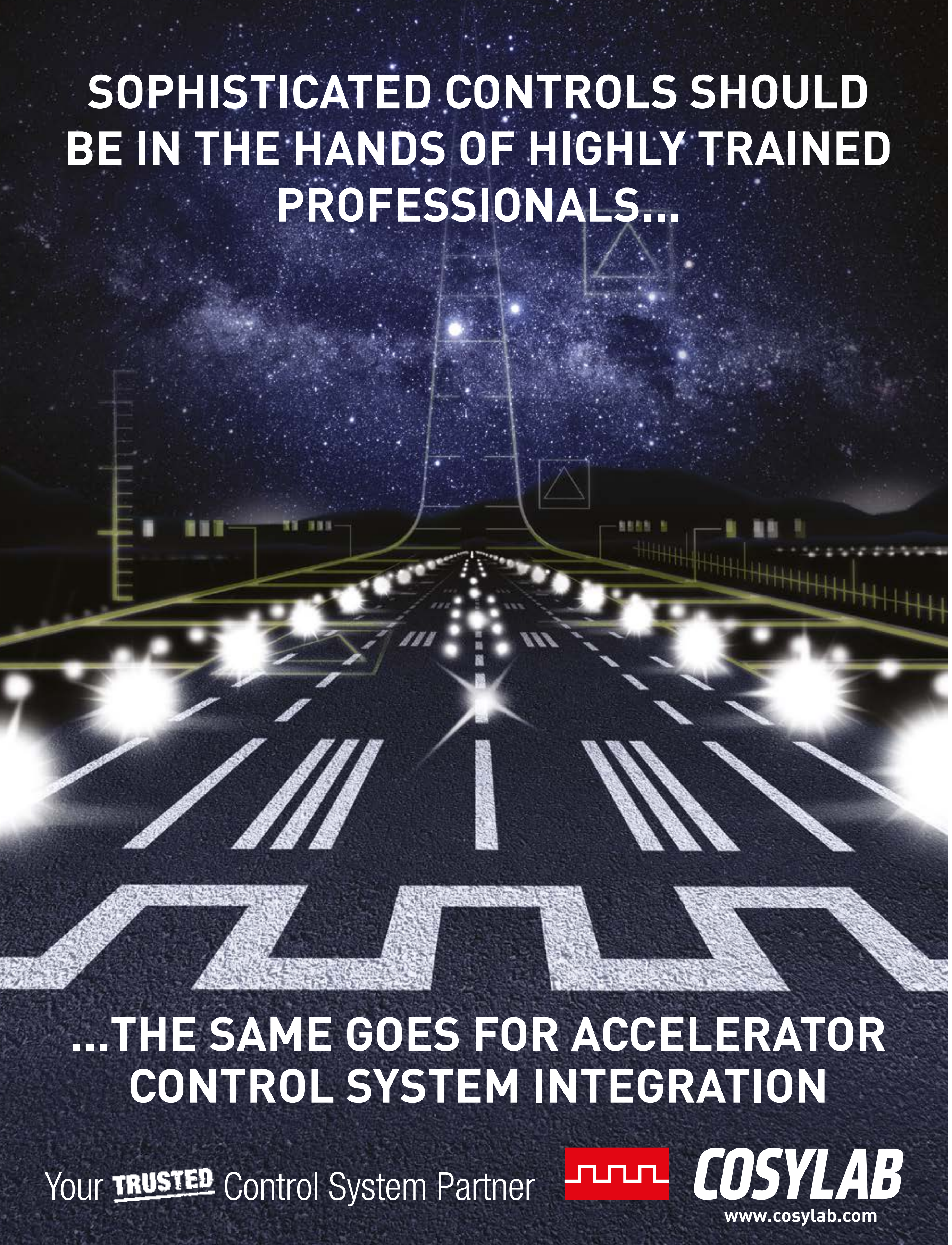
If indeed all stars are formed in pairs, it would have big implications for models of stellar birth rates in molecular clouds as well as for the formation of binary systems of compact objects. The studied nearby Perseus cluster could, however, just be a special case, and further studies of other star-forming regions are therefore required to know if the same conditions exist elsewhere in the universe.

Further reading
S Sadavoy and S Stahler 2017 *MNRAS* **469** 3881.

Picture of the month

This image from the Juno spacecraft shows the great red spot on Jupiter in beautiful detail. The Juno satellite was launched in 2011 and produced the image during a flyby on 11 July during which the satellite came as close as 3000 km to the cloud tops of Jupiter. The fast rotating storm on Jupiter is several times larger than the Earth and contains winds with speeds up to 600 km per hour. The feature is at least 150 years old, but observations of a large spot on Jupiter date back to the first astrophysical measurements from around 1600, although it is not clear if the storm observed at the time is the same that Juno captured now. The nature of the red colour is still not understood. One possibility is that it is due to chemicals that are formed as a result of cosmic-ray interactions with the ammonium hydrosulphide in Jupiter's atmosphere.

NASA/JPL-Caltech/SwRI/MSSS/Gerald Eichstädt



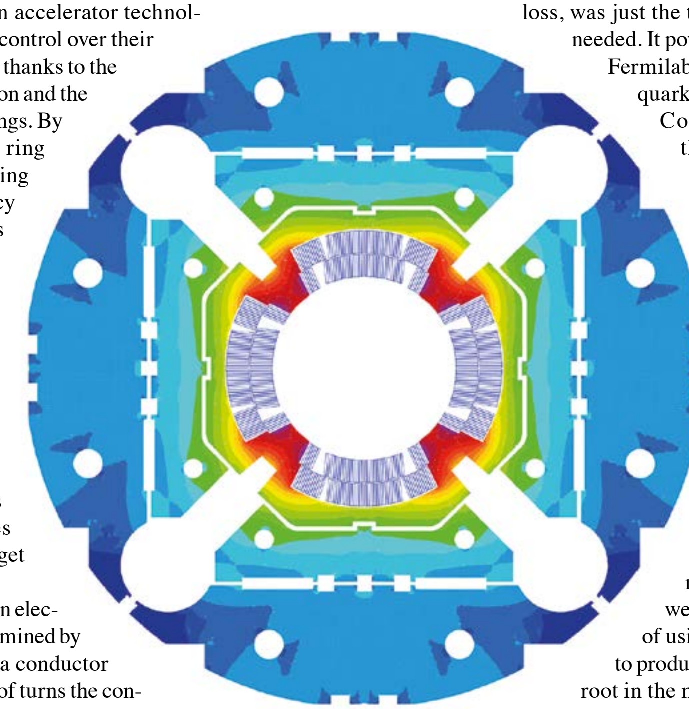
Powering the field forward

Progress in understanding the fundamental constituents of matter continues to be driven by high-field superconducting magnets such as those in the LHC and future circular colliders.

Particle physicists try to understand the environment that existed fractions of a second after the Big Bang by studying the behaviour of particles at high energies. Early studies relied on cosmic rays emanating from extraterrestrial sources, but the invention of the circular accelerator by Ernest Lawrence in 1931 revolutionised the field. Further advances in accelerator technology gave physicists more control over their experiments, in particular thanks to the invention of the synchrotron and the development of storage rings. By capturing particles via a ring of magnets and accelerating them with radio-frequency cavities, these facilities finally reached energies of a few hundred GeV. But storage rings are limited by the maximum magnetic field achievable with resistive magnets, which is around 2 T. To go further into the heart of matter, particle physicists required higher energies and a new technology to get them there.

The maximum field of an electromagnet is roughly determined by the amount of current in a conductor multiplied by the number of turns the conductor makes around its support structure. Over the years, the growing scale of accelerators and the large number of magnets needed to reach the highest energies demanded compact and affordable magnets. Conventional electromagnets, which are usually based on a copper conductor, are limited by two main factors: the amount of power required to operate them due to resistive losses and the size of the conductor. Typical conventional-magnet windings therefore tended to use conductors with a cross-sectional area of the order of a few square centimetres, which is not optimal for generating high magnetic fields.

Superconductivity, which allows certain materials at low temperatures to carry very high currents without any resistive loss, was just the transformational technology needed. It powered the Tevatron collider at Fermilab in the US to produce the top quark, and CERN's Large Hadron Collider (LHC) to unearth the Higgs boson. Advanced superconducting magnets are already being developed for future collider projects that will take physicists into a new phase of subatomic exploration beyond the LHC (figure 1 overleaf).



Magnetic design of a superconducting niobium-tin quadrupole for the High-Luminosity LHC, showing the magnetic flux density in the collars and in the yoke when the nominal current is circulating in the aperture. (Image credit: CERN/US-LARP.)

Maintaining the state

Discovered in 1911, superconductivity didn't immediately lead to broad applications, particularly not high-field accelerator magnets. As far as accelerators were concerned, the possibility of using superconducting magnets to produce higher fields started to take root in the mid-1960s. The big challenge was to maintain the superconducting state in a bulk object in which tremendous forces are at work: the slightest microscopic movement of the conductor would cause it to transition to the normal state (a "quench") and result in burn-up, unless the fault was detected quickly and the current turned off.

Early superconductors were mostly formed into high-aspect-ratio tapes measuring a few tenths of a millimetre thick and ▷

around 10 mm wide. These are not particularly useful for making magnets because precise geometry and current distribution are necessary to achieve a good field quality. Intense studies led to the development of multi-filamentary niobium-zirconium (NbZr), niobium-titanium (Nb-Ti) and niobium-tin (Nb_3Sn) wires, propelling interest in superconducting technology. In 1961, Kunzler and colleagues at Bell Labs produced a 7 T field in a solenoid, a relatively simple coil geometry compared with the dipoles or quadrupoles needed for accelerators. This swiftly led to higher-field solenoids, and a number of efforts to utilise the benefits of superconductivity for magnets began. But it was only in the early 1970s that the first prototypes of superconducting dipoles and quadrupoles demonstrated the potential of superconducting magnet technology for accelerators.

A turning point came during a six-week-long study group at Brookhaven National Laboratory (BNL) in the US in the summer of 1968, during which 200 physicists and engineers from around the world discussed the application of superconductivity to accelerators (figure 2). Considerable focus was directed towards the possibility of using superconducting beam-handling magnets (such as dipoles and quadrupoles for transporting beams from accelerators to experimental areas) for the new 200–400 GeV accelerator being constructed at Fermilab. By that time, several high-field superconducting alloys and compounds had been produced.

Hitting the mainstream

It could be argued that the unofficial kick-off for superconducting magnets in accelerators was a panel discussion at the 1971 Particle Accelerator Conference held in Chicago, although there was a clear geographical divide on key issues. The European contingent was reluctant to delve into higher-risk technology when it was clear that conventional technology could meet their needs, while the Americans argued for the substantial cost savings promised by superconducting machines: they claimed that a 100 GeV superconducting synchrotron could be built in five or six years, while the Europeans estimated a more conservative seven to 10 years.

In the US, work on furthering the development of superconducting magnets for accelerators was concentrated in a few main laboratories: Fermilab, the Lawrence Radiation Laboratory, Brookhaven National Laboratory (BNL) and Argonne National Laboratory. In Europe, a consortium of three laboratories – CEA Saclay in France, Rutherford Appleton Laboratory in the UK and the Nuclear Research Center at Karlsruhe – was formed to enable future conversion of the recently approved 300 GeV accelerator, to become CERN's Super Proton Synchrotron (SPS), to higher energies using superconducting magnets. Of particular historical note, a short paper written at this time referred to a "compacted fully transposed cable" produced at the Rutherford Lab, and the "Rutherford cable" has since become the standard conductor configuration for all accelerator magnets (figure 3 opposite).

The development of the LHC magnets offered valuable lessons for next-generation technology.

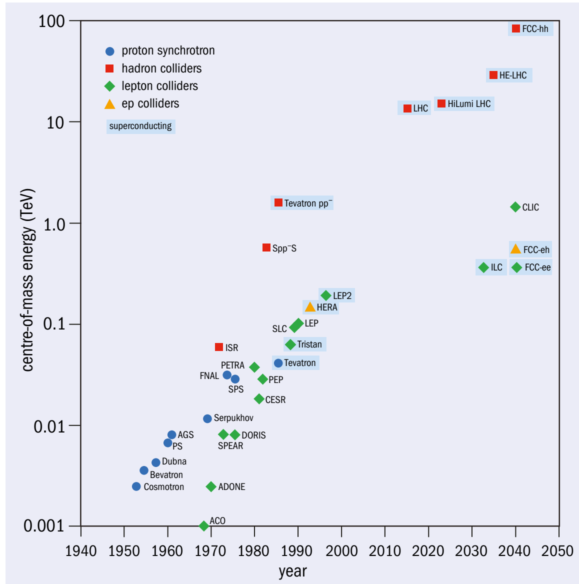


Fig. 1. Particle energy (in the centre-of-mass reference frame) as a function of time, showing various types of collider and the proposed parameters for new colliders at the energy frontier. Since the Tevatron (1983), through HERA (1991), RHIC (2000) and finally the LHC (2008), all large-scale hadron colliders have been built using superconducting magnets.

Rapid progress followed, reaching a tipping point in the 1970s with the launch of several accelerator projects based on superconducting magnets and a rapidly growing R&D community worldwide. These included: the Fermilab Energy Doubler; Interaction Region (IR) quadrupoles (used to bring particles into collision for the experiments) for the Intersecting Storage Rings at CERN; and IR quadrupoles for TRISTAN at KEK in Japan and UNK in the former USSR. The UNK magnets were ambitious for their time, with a desired operating field of 5 T, but the project was cancelled in the years following the breakup of the USSR.

Although superconducting magnet technology was one of the initial options for the SPS, it was rapidly discarded in favour of resistive magnets. This was not the case at Fermilab, which at that time was pursuing a project to upgrade its Main Ring beyond 500 GeV. The project was initially presented as an Energy Doubler, but rapidly became known by the very modern name of Energy Saver, and is now known as the Tevatron collider for protons and antiprotons, which shut down in 2011. The Tevatron arc magnets were the result of years of intense and extremely effective R&D, and it was their success that triggered the application of superconductivity for accelerators.

As superconducting technology matured during the 1980s, its applications expanded. The electron–proton collider HERA was getting under way at DESY in Germany, while ISABELLE was reborn as the Relativistic Heavy Ion Collider (RHIC) at BNL. Thanks to intensive development by high-energy physics, Nb-Ti was readily available from industry. This allowed the construction of magnets with fields in the 5 T range, while multi-filamentary conductors made from niobium-titanium-tantalum (Nb-Ti-Ta) and Nb_3Sn were being pursued for fields up to 10 T. The first papers on the proposed Superconducting Super Collider (SSC) in the US were published in the mid-1980s, with R&D for the SSC ramping up substantially by the start of the 1990s. Then, in 1991, the first papers on R&D for the LHC were presented. The LHC's 8 T Nb-Ti dipole magnets operate close to the practical limit of the conductor, and the collider now represents the largest and most sophisticated use of superconducting magnets in an accelerator.

High-field accelerator magnets

Fig. 2. A famous six-week-long study group at BNL in the summer of 1968 saw many discussions held during the coffee breaks. From left to right: W B Sampson of BNL talking with P F Smith of the Rutherford Laboratory (with back to the camera), while A D McInturff and K E Robins of BNL listen in.

The niobium-tin challenge

With the success of the LHC, the international high-energy physics community has again turned its attention to further exploration of the energy frontier. CERN has launched a Future Circular Collider (FCC) study that envisages a 100 TeV proton–proton collider as the next step for particle physics, which would require a 100 km-circumference ring of superconducting magnets with operating fields of 16 T. This will be an unprecedented challenge for the magnet community, but one that they are eager to take on. Other future machines are based on linear accelerators that do not require magnets to keep the beams on track, but demand advanced superconducting radio-frequency structures to accelerate them over short distances.

Thanks to superconducting accelerator magnets wound with strands and cables made of Cu/Nb-Ti composites, the energy reach of particle colliders has steadily increased. After nearly half a century of dominance by Nb-Ti, however, other superconducting materials are finally making their way into accelerator magnets. Quadrupoles and dipoles using Nb_3Sn will be installed as part of the high-luminosity upgrade for the LHC (the HL-LHC) in the next few years, for example, and the high-temperature superconductor $Bi_2Sr_2CaCu_2O_8$ (BSCCO), iron-based superconductors and rare-earth bismuth copper oxide (REBCO) have recently been added to the list of candidate materials. Proposals for new large circular colliders has boosted interest in high-field dipole magnets but, despite the tantalising potential for achieving dipole fields more than twice that of Nb-Ti, there are many problems that still need to be overcome.

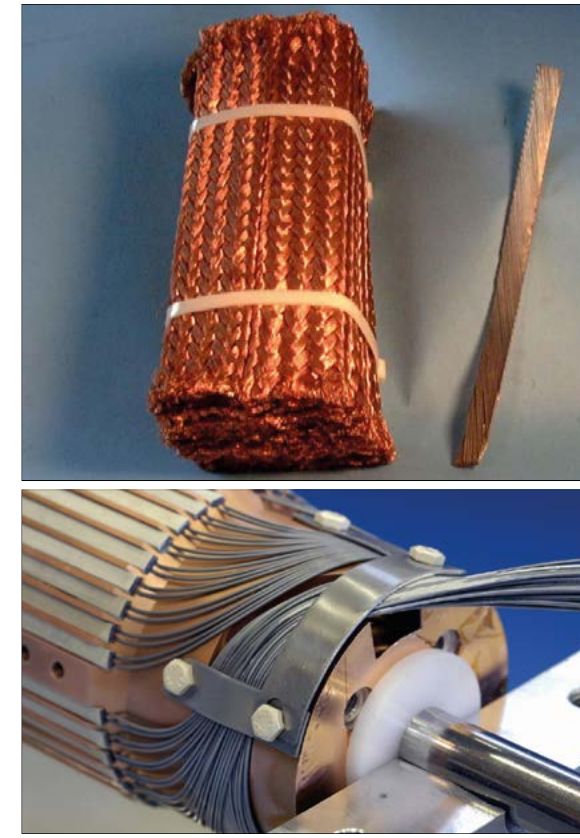


Fig. 3. When cooled to 1.9 K, the LHC's niobium-titanium cables can conduct the same current as a bundle of copper wires 11 cm high and 8 cm wide (top). The cables are made from 36 strands with a diameter of 0.825 mm, each of which comprises 6500 superconducting filaments of niobium-titanium surrounded by a 0.0005 mm layer of high-purity copper. (Above) A close-up of the lower part of a 13 kA high-temperature superconducting current lead for powering the LHC main dipole magnets, which contains the material BSCCO-2223. The technology, the first application of HTS materials in a large-scale accelerator system, allows the room-temperature power cables from the power converters to be connected to the cold Nb-Ti bus-bars of the LHC magnets.

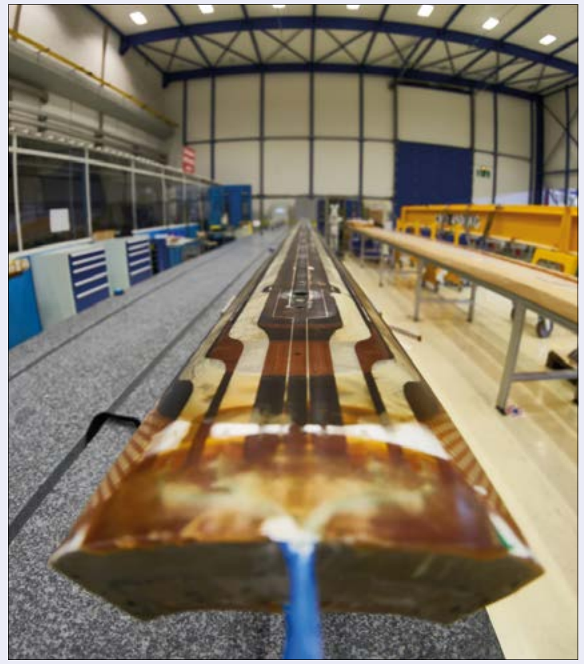
Although Nb_3Sn was one of the early candidates for high-field magnets, and has much better performance at high fields than Nb-Ti, its processing requirements, mechanical properties and costs present difficulties when building practical magnets. Nb_3Sn comes as a round wire from industry vendors, which is excellent for making multi-wire cables but requires the reaction of a copper, niobium and tin composite at 650 °C to develop the superconducting Nb_3Sn cable. Unfortunately, Nb_3Sn is a brittle ceramic, unlike Nb-Ti, which requires only modest heat treatment and drawing steps and is mechanically very strong. Years of effort worldwide have overcome these limitations and ▷

CERN breaks records with high-field magnets for High-Luminosity LHC

To keep the protons on a circular track at the record-breaking luminosities planned for the LHC upgrade (the HL-LHC) and achieve higher collision energies in future circular colliders, particle physicists need to design and demonstrate the most powerful accelerator magnets ever. The development of the niobium-titatnium LHC magnets, currently the highest-field dipole magnets used in a particle accelerator, followed a long road that offered valuable lessons. The HL-LHC is about to change this landscape by relying on niobium tin (Nb_3Sn) to build new high-field magnets for the interaction regions of the ATLAS and CMS experiments. New quadrupoles (called MQFX) and two-in-one dipoles with fields of 11 T will replace the LHC's existing 8 T dipoles in these regions. The main challenge that has prevented the use of Nb_3Sn in accelerator magnets is its brittleness, which can cause permanent degradation under very low intrinsic strain. The tremendous progress of this technology in the past decade led to the successful tests of a full-length 4.5 m-long coil that reached a record nominal field value of 13.4 T at BNL. Meanwhile at CERN, the winding of 7.15 m-long coils has begun.

Several challenges are still to be faced, however, and the next few years will be decisive for declaring production readiness of the MQFX and 11 T magnets. R&D is also ongoing for the development of a Nb_3Sn wire with an improved performance that would allow fields beyond 11 T. It is foreseen that a 14–15 T magnet with real physical aperture will be tested in the US, and this could drive technology for a 16 T magnet for a future circular collider. Based on current experience from the LHC and HL-LHC, we know that the performance requirements for Nb_3Sn for a future circular collider require a large industrial effort to make very large-scale production viable.

● *Panagiotis Charitos, CERN.*



M Brice/CERN

New long coils for the Nb_3Sn quadrupoles for the HL-LHC.

fields in the range of 16 T have recently been achieved – first in 2004 by a US R&D programme and more recently at CERN – and this is close to the practical limit for this conductor. In addition to the near-term use in the HL-LHC, and despite currently costing 10 times more than Nb-Ti, it is the material of choice for a future high-energy hadron collider, and is also being used in enormous quantities for the toroidal-field magnets and central solenoid of the ITER fusion experiment (see p34).

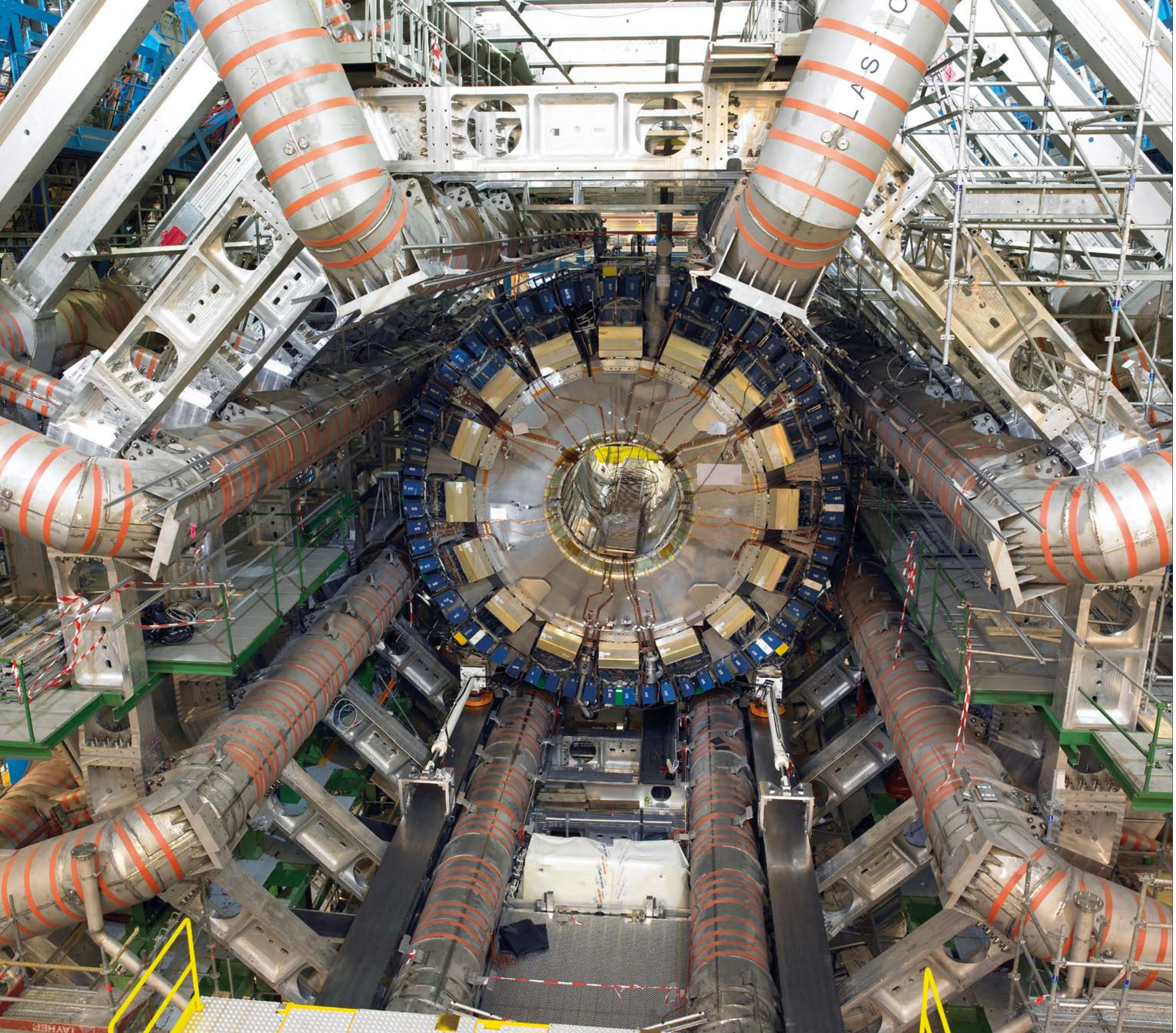
High-temperature superconductors represent a further leap in magnet performance, but they also raise major difficulties and could cost an additional factor of 10 more than Nb_3Sn. For fields above 16 T there are currently only two choices for accelerator magnets: BSCCO and REBCO. Although these materials become superconductors at a higher temperature than niobium-based materials, their maximum current density is achieved at low temperatures (in the vicinity of 4.2 K). BSCCO has the advantage of being obtainable in round wire, which is perfect for making high-current cables but requires a fairly precise heat treatment at close to 900 °C in oxygen at high pressures. This is not a simple engineering task, especially when dealing with large coils. Much progress has been made recently, however, and there is a vibrant programme in industry and academia to tackle these challenges. REBCO has excellent high-field performance, high current density and requires no heat treatment, but it only comes in tape form, presenting difficulties in winding the required coil shapes and producing acceptable field quality. Nevertheless, the performance of this high-temperature superconductor is too tantalising to abandon it, and many people are working on it. Even after half a century, progress in the development of high-field accelerator magnet R&D continues, and indeed is critical for future discoveries in particle physics.

Résumé

Des technologies pour faire avancer la connaissance

Si notre connaissance des constituants fondamentaux de la matière a progressé, c'est en partie grâce aux aimants à champ élevé des accélérateurs, qui permettent de faire entrer en collision des faisceaux de particules de haute énergie. Et sans la technologie des supraconducteurs, les progrès en physique des particules auraient été beaucoup plus lents. Les aimants supraconducteurs s'appuyant sur la technologie désormais standard des câbles en niobium-titane ont permis au Tevatron, collisionneur du Fermilab, de produire le quark top, et au Grand collisionneur de hadrons (LHC) du CERN de dévoiler le boson de Higgs. Le CERN développe à présent des aimants de pointe en niobium-étain destinés au LHC à haute luminosité et à de futurs collisionneurs circulaires, et il s'intéresse à l'utilisation de supraconducteurs à haute température.

Stephen Gourlay, Lawrence Berkeley National Laboratory.



Unique magnets

The use of superconducting magnets for detectors preceded by several years their practical application to accelerators, and each is one of a kind.

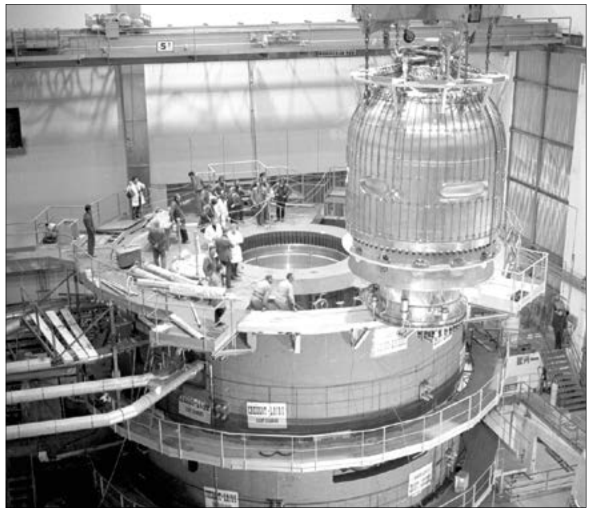
To identify particles emerging from high-energy interactions between a beam and a fixed target, or between two counter-rotating beams, experimental physicists need to measure the particle tracks with high precision. Since charged particles are deflected in a magnetic field, incorporating a magnet in the detector system serves to determine both the charge and momentum of a particle. Momentum resolution is proportional to the sagitta of the detected track, which is proportional to the magnetic field and the square of the length of the track, so larger magnets and larger fields tend to deliver better performance. While being as large and as strong as possible, however, the magnet should not get in the way of the active detector materials.

These general constraints in high-energy physics experiments point to a need for more compact superconducting devices. But additional constraints such as cost, complexity and experiment schedules can lead to the choice of a conventional "warm" magnet if sufficient field and volume can be provided for acceptable power consumption. A detector magnet is one of a kind, and a field accuracy of one part in 1000 is usually sufficient. In contrast, accelerator magnets are typically many of a kind, and are required to deliver the highest possible field with an accuracy of one part in 10,000 or better in a long and narrow aperture. This leads to substantially different technological choices.

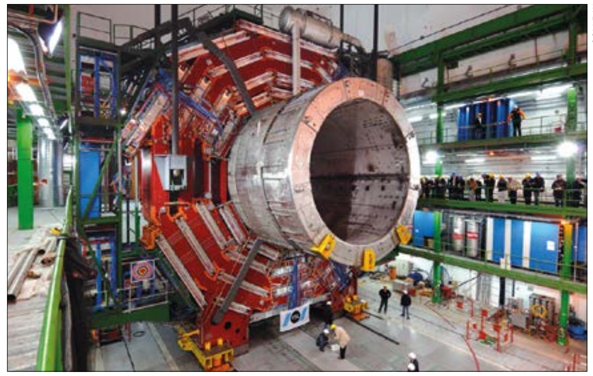
Following the discovery of superconductivity, people immediately thought of using it to produce magnetic fields. But the pure materials concerned (later to be called type-I superconductors) only worked up to a critical field of about 0.1 T. The discovery in 1961 of more practical (type-II) superconductivity in certain alloys and compounds which, unlike type-I, allow penetration of magnetic flux but exhibit critical fields of 10–20 T, immediately led to renewed ▷

The eight "racetrack" coils of the ATLAS barrel toroid, which has an outer diameter of 20.1 m, a mass of 830 tonnes and contains 56 km of superconducting niobium-titanium cable. (Image credit: M Brice, B Michel/CERN.)

Superconducting detector magnets



In the early 1970s, CERN's Big European Bubble Chamber, now an exhibit at the lab, was equipped with the largest superconducting magnet in service at the time.



M Brice

C Marcelloni

(Above) The far-from-compact CMS solenoid in position in the detector. (Left) One of the ATLAS end-cap toroids arriving at the ATLAS surface building in May 2007.

interest. Physics laboratories in Europe and the US started R&D programmes to understand how to make superconducting magnets and to explore possible applications.

The first four years were difficult: small magnets were built but it was not possible to get scaled-up versions to operate at currents anywhere close to the level obtained for short samples of the superconducting wire available at the time. A breakthrough was presented at the first Particle Accelerator Conference in 1965, in a seminal paper by Steckly and Zar on cryogenic stability. Cryogenic stability ensures that, if a superconductor becomes normal due to coil motion or a flux jump (when magnetic flux penetrates a thick type-II material leading to instability, resistance and increased temperature), it will recover its superconductivity provided enough heat can be conducted away to the coolant for the material to drop back below its critical temperature in the region where superconductivity was lost. Several laboratories immediately started to build large helium-bath-cooled bubble-chamber magnets.

The bubble chamber, invented by Donald Glaser in 1952, consists of a tank of liquid hydrogen surrounded by a pair of Helmholtz coils: particles leave tracks in the supercritical liquid and their curvatures reveal the particle's momentum. The first large (72 inch) bubble-chamber magnet at the University of California Radiation Laboratory was equipped with a 1.8 T water-cooled copper coil weighing 20 tonnes and dissipating a power of 2.5 MW. Larger magnets were desirable for improved resolution, but were clearly unrealistic with room-temperature copper coils due to the costs involved. This was therefore an obvious application for superconductivity, and the concept of cryogenic stability allowed large magnets to be built using a superconductor that was otherwise inherently unstable.

The magnets in ATLAS and CMS at the LHC occupy new territory.

Recall that this was before seminal work at the Rutherford Appleton Laboratory (RAL) had revealed the need for fine filaments and twisting to ensure stability, and before we knew that practical superconductors had to be made in that way. Indeed, it is striking to observe the audacity of high-energy physicists in the late 1960s and the early 1970s in embarking on the construction of such large and costly devices so rapidly, based on so little experience and knowledge.

Thick filaments of niobium-titanium in a copper matrix were the superconducting material of choice at the time, with coils being cooled in a bath of liquid helium. Achievements included: the 1.8 T magnet at Argonne National Laboratory for its bubble-chamber facility; a 3 T magnet for a facility at Fermilab; and the 3.5 T Big European Bubble Chamber (BEBC) magnet at CERN. The stored energy of the BEBC magnet was almost 800 MJ – a level not exceeded for a large magnet until the Large Helical Device came on stream in Japan (for fusion experiments) in the late 1990s. This use of superconducting magnets for experiments preceded by several years their practical application to accelerators.

Discoveries

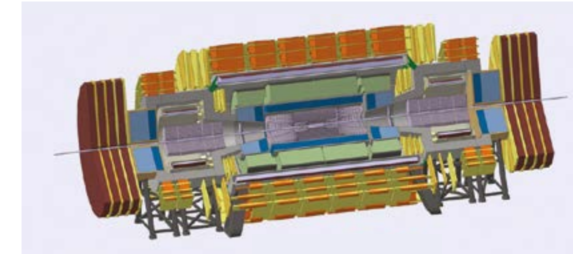
Following early experiments at CERN's Intersecting Storage Rings, which were not well equipped to observe particles having large transverse momentum, the importance of detecting all of the particles produced in beam collisions in colliders was recognised, and a need emerged for magnets covering close to a full 4π solid angle. To improve momentum resolution it was also desirable to extend the measurement of tracks beyond the magnet winding, calling for thin coils. The goal was less than one radiation length in thickness, for which a high-performance superconductor with intrinsic stability was needed. This pointed towards a design based on the type of superconducting wire that had been developed in the accelerator community and had by now become a commodity for making MRI magnets (an industry that now consumes more than 90% of the superconductors produced), with the attendant reduction in cost.

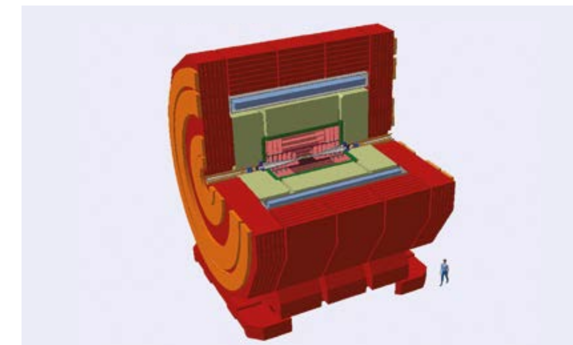
Therefore by the early 1980s the development of detector magnets had shifted to conductors made of by then standard superconducting wires consisting of twisted fine filaments in a copper matrix, single or cabled, co-extruded with ultra-pure aluminium to provide stabilization, and wound in solenoidal coils inside a hard aluminium alloy mandrel for support. Pure aluminium is an excellent conductor at low temperature, and far more transparent than the copper that had been used previously. Moreover, rather than being bath cooled, these constant field magnets were indirectly cooled to about 5 K with helium flowing in pipes in good thermal contact with the mandrel. This allowed the 1–2 T detector solenoids to become larger, without power dissipation in the winding and with a low inventory of liquid helium. In this way the coils can be made thin and relatively transparent to certain classes of particles such as muons, so that detectors can be located both inside and outside. Examples of these magnets are those used for the ALEPH and DELPHI experiments at CERN's Large Electron–Positron (LEP) collider, the D0 experiment at Fermilab and the BELLE experiment at KEK. Other prominent experiments over the years based on superconducting magnets include VENUS at KEK, ZEUS at DESY, and BaBAR at SLAC.

To the Higgs boson and beyond

While this had become the standard approach to detector magnet design, the magnets in the ATLAS and CMS experiments at the LHC occupy new territory. ATLAS uses a large toroidal coil structure surrounding a thin 2 T solenoid, and the solenoid for CMS delivers an unprecedented 3.8 T (but is not required to be very thin). While both the CMS and ATLAS solenoids use the now traditional technology based on niobium-titanium superconductor co-extruded in aluminium, to allow the structure to withstand the substantial forces the pure aluminium stabiliser is reinforced. This is done either by welding aluminium-alloy flanges to the pure aluminium (CMS) or by strengthening the pure aluminium with a precipitate that improves its strength while not increasing inordinately the resistivity of the aluminium (ATLAS solenoid).

The next generation of magnets planned for the Compact Linear Collider (CLIC), the International Linear Collider (ILC) and Future Circular Colliders (FCC) will be larger, and may require more technological development to reach the desired magnetic fields. Based on a single detector at the interaction point, a new unified detector model has been developed for CLIC and the concepts explored for this detector are also of interest to the high-luminosity, as well as for a future circular electron–positron collider. Like the LHC with ATLAS and CMS, a future circular collider requires a "general-purpose" detector. Previous studies for a detector for a 100 TeV circular hadron collider were based on a twin solenoid paired with two forward dipoles, but these have now been dropped in favour of a simpler system comprising one main solenoid enclosed by an active shielding coil. This design achieves a similar performance while being much lighter and more compact, resulting in a significant scaling down in the stored energy of the magnet from 65 GJ to 11 GJ. The total diameter of the magnet is around 18 m, and the new design could benefit from the important lessons from the construction and installation of the LHC detectors.





A detector magnet design under consideration for a future 100 TeV proton–proton collider (top image), measuring roughly 18 m in diameter and 49 m long, as part of the CERN co-ordinated Future Circular Collider project. The single-detector concept for CLIC (lower image), which measures roughly 12 m long and 13 m high.

Key to the choice of such magnets, in addition to their cost and complexity, is their ability to allow high-quality muon tracking. This is crucial for studying the properties of the Higgs boson, for example, and any additional new fundamental particles that await discovery. If the lengthy discussions surrounding the design of the ATLAS and CMS magnets many years ago are anything to go by we can look forward to intense and interesting debates about how to push these one-off magnet designs to the next level.

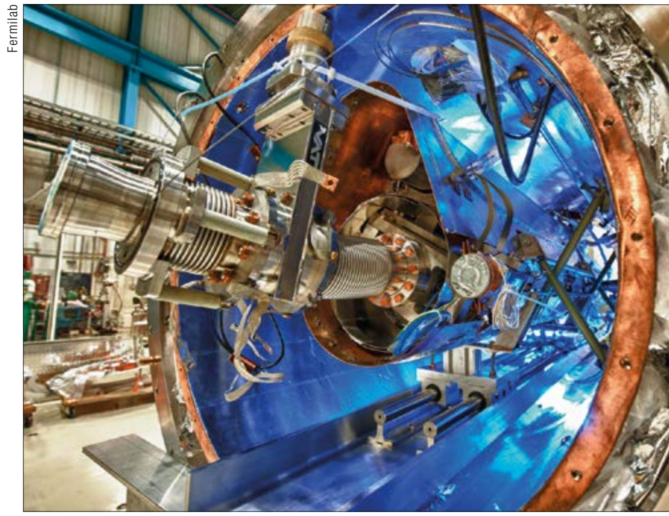
Résumé

Des aimants uniques

Les aimants supraconducteurs ont été utilisés dans des détecteurs plusieurs années avant leur utilisation dans les accélérateurs. La taille et la puissance de ces objets exceptionnels a augmenté au fil des décennies, améliorant la performance de nombreuses expériences, pour aboutir aux aimants sans précédent qui composent ATLAS et CMS. Pour ce qui est des futurs collisionneurs, la technologie des aimants des détecteurs est plus avancée que celle des aimants des accélérateurs, mais les travaux de conception des aimants destinés aux projets de la prochaine génération ont commencé, au CERN et ailleurs.

Tom Taylor, CERN.

Souped up RF



Fermilab

A superconducting RF capture cavity at Fermilab.

Superconducting radio-frequency technology has now attained a level of development similar to that reached for superconducting magnets 15 years ago, and is a key element of the LHC high-luminosity upgrade, future colliders and next-generation X-ray sources.

Behind the size, complexity and physics goals of particle accelerators such as the LHC lies a simple physics principle worked out by Maxwell more than 150 years ago: when a charged particle passes through an electric field it experiences an acceleration proportional to the electric-field strength divided by its mass. While the magnets of a circular accelerator keep the beams on track, it is this principle that shunts them to the high energies needed for particle-physics research. The first accelerators relied on electrostatic fields produced between high-voltage anodes and cathodes, but by the mid-1920s it was clear that radio technology was needed to reach the highest possible energies.

To transfer energy to a beam of charged particles, a space must be created where the beam can move along an electric field produced by high-power radio waves; the higher the field, the larger the energy gain per metre (accelerating gradient). An accelerating space, usually called a radio-frequency (RF) cavity, is a container crossed by the beam in which is stored a rotational electric field that, when the bunch of particles is passing through, is found to be properly orientated in the desired direction. Whatever geometry the cavity has, the power dissipated by the Joule effect is proportional to its surface resistance and to the square of the field inside it.

For the past 30 years, superconducting radio-frequency (SRF) cavities have been in routine operation in a variety of settings, from pushing frontier accelerators for particle physics to applications in nuclear physics and materials science. They were instrumental in pushing CERN's LEP collider to new energy regimes and in driving the newly inaugurated European X-ray Free Electron Laser. Advanced SRF "crab cavities" are now under development for the high-luminosity upgrade of the LHC.

From Stanford to LEP

It was unclear at first whether superconductivity had much value for RF technology. When a superconductor is exposed to a time-varying electromagnetic field, the electrons that are not coupled as Cooper pairs lead to energy dissipation in the shallow layer of the superconductor surface in which the electric and magnetic fields are dancing together to sustain the rotational electric field that transfers the energy to the beam. But it was soon realised that in the practical frequency range of RF accelerators, from a few hundred MHz to a few GHz, the use of SRF cavities would produce in any case a significant breakthrough due to the increase in the conversion efficiency from plug- to beam-power, cryogenics included. It was simply a question of developing the technology, and this required investment and big projects.

The High-Energy Physics Lab at Stanford University in the US was a pioneer in applying SRF to accelerators, demonstrating the first acceleration of electrons with a lead-plated single-cell resonator in 1965. Also in Europe, in the late 1960s, SRF was considered for the design of proton and ion linacs at KFK in Karlsruhe. To be superior to the competing technology of normal-conducting RF, a moderate field of a few MV/m was necessary. By the early 1970s SRF had been introduced in the design of particle accelerators, but results were still modest and a number of limiting factors needed to be understood.

The first successful test of a complete SRF cavity at high gradient and with beam was performed at Cornell's CESR facility at the end of 1984, involving a pair of 1.5 GHz, five-cell bulk niobium cavities with a gradient of 4.5 MV/m. This cavity design was then used as the basis for the CEBAF facility at Jefferson Lab. Cornell's success also triggered activities at CERN, where some visionary people were already looking at SRF as a way to double the energy of the Large Electron–Positron (LEP) collider under construction in what is now the LHC tunnel. LEP's nominal ▷

It was simply a question of developing the technology, and that required investment and big projects.

Three state-of-the-art SRF projects for the High Luminosity LHC and beyond

- **Exotic cavity geometries and ancillaries to perform specific gymnastics on the beam to significantly improve the collider luminosity.** For example, "crab cavities" (pictured right) are under development at CERN for the high-luminosity LHC with the support of a highly expert collaboration. Starting from existing advanced SRF cavities, the group developed two complementary cavity packages that will tilt the two LHC beams just before they collide, to maximise their overlap and then substantially increase the collision rate. After the collision the beam is returned to its original orbit and the challenge is to do all of this without perturbing the beam. So far, two (out a total of 16) superconducting crab cavities have been manufactured at CERN and RF tests at 2 K have been performed in a superfluid helium bath. The first cavity tests earlier this year demonstrated a maximum transverse kick voltage exceeding 5 MV, corresponding to extremely high electric and magnetic fields on the cavity surfaces. By the end of 2017, the two crab cavities will have been inserted into a specially designed cryomodule that will be installed in the Super Proton Synchrotron to undergo validation tests with proton beams.

- **Doping the very thin layer on the cavity inner surface that sustains the electromagnetic accelerating field to reduce the power dissipation at cryogenic temperatures, using a minor quantity of gas such as nitrogen.** This R&D project, led by Anna Grassellino at Fermilab, is giving very promising results and is being experimentally applied on the LCLS-II X-ray free-electron laser (XFEL) under construction at SLAC. Once the technology is stabilised, the benefit in terms of investment and operation costs will hopefully be very important for all large accelerators requiring a continuous beam, such as new circular colliders, continuous-wavelength XFELs approved or under construction, and accelerator-driven systems for new nuclear-power technology.

- **Niobium-tin (Nb_3Sn) coating of SRF cavities.** This technology has been pursued in a few laboratories for some time, with moderate success. But recent results from Cornell and Fermilab on real single-cell elliptical cavities are close to those obtained with pure niobium, and this could be the starting point for possible application of Nb_3Sn coatings in large accelerators. The coating technique, once properly developed, could have significant advantages, mainly because of the higher critical temperature and critical magnetic field of Nb_3Sn with respect to those of pure Nb.

CDRN/M Brice

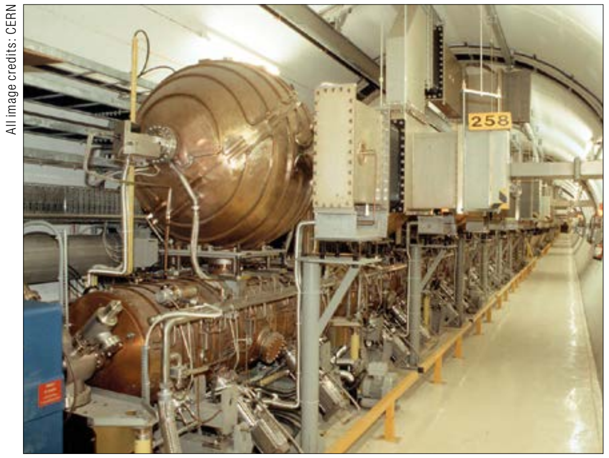
The double quarter-wave crab cavity assembled on the RF test stand for cold testing in a vertical cryostat at CERN's SM18 facility.

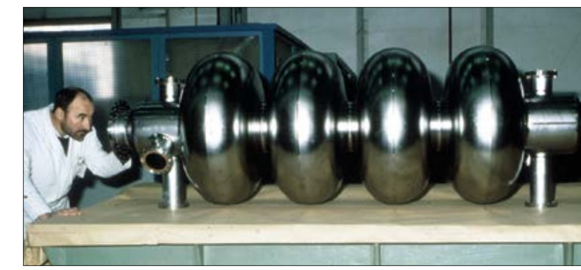
centre-of-mass energy of 90 GeV was the minimum required to produce the recently discovered Z boson, but almost double this energy was needed to test the Standard Model further: specifically, to produce pairs of W bosons.

The baseline accelerating system of LEP was already a jewel that had demanded all the knowledge and ingenuity available globally at that time. Furthermore, doubling its energy meant that researchers had to battle additional losses due to synchrotron radiation, which scales as the fourth power of the electron and positron energies. The dream was to develop an accelerating system that made use of the very low losses promised by superconductivity to deliver a factor 16 or so more energy per turn to the LEP beam, occupying more or less the same space as the machine's original copper cavities.

Developing the SRF system for "LEP II" was a great challenge and success for the accelerator community. Owing to the relatively low resonant frequency – 352 MHz – of LEP's underlying design, the superconducting cavities developed ended up being more than four times bigger than the ones successfully tested at Cornell. Since 1979, a small group at CERN had been developing the SRF technology, including all the cavity's ancillaries necessary for its eventual working, but the best niobium superconducting material produced at that time was not sufficiently performant at such scales, and the first tests cast doubt as to whether the LEP-II dream could be realised. In 1989, a pilot project of 20 niobium cavities started to evaluate the feasibility of LEP-II SC cavities. In the meantime, the niobium-copper (Nb/Cu) technology developed at CERN by

All image credits: CERN





The copper cavities used to accelerate particles in LEP (above). Replacement superconducting RF cavities installed in the LEP tunnel (above right) and their niobium accelerating structures (bottom right) allowed the collider's energy to be doubled in the late 1990s, beyond the pair-production threshold for W bosons.

Cris Benvenuti became mature enough to justify the decision to base the LEP-II programme on Nb/Cu SRF cavities. Their inherent advantages, including the possibility to replace the Nb coating by a better one in the future, were decisive in making this choice. Soon the CERN technology was transferred to industry and more than 300 2.4 m-long SRF cavities were successfully produced by three companies in France, Germany and Italy. By 2 November 2000, when LEP II was switched off to allow the LHC to be constructed, the collider's energy had topped 209 GeV. More than 17 million Z bosons were produced, and a large number of pairs of W bosons, allowing extremely precise tests of the Standard Model of particle physics. LEP missed the Higgs discovery, and we now know that a centre-of-mass energy just a few tens of GeV higher would have been sufficient to produce the fundamental particle. But this was never a realistic prospect: the machine was already pushed to its limit and any further energy increase would have eventually produced an irreparable failure.

While CERN and LEP-II were creating a valuable technology for very large SRF cavities, Jefferson Lab in the US was set to build the CEBAF accelerator. This required installing a large and complete infrastructure to develop the SRF technology based on bulk niobium, going beyond the needs of CEBAF – possibly unavoidable for the success of such a challenging project that was the first of its kind. The decision resulted in the large-scale production of 300 small cavities based on Cornell's design, but with a marginal contribution from industry mainly limited to the mechanical fabrication of the cavities with no surface treatment. The experience of CEBAF was nevertheless important for the evolution of SRF technology and some of the techniques applied became standard. Among them was the development of electron-beam welding parameters for niobium, the use of clean-room assembly and ultrapure-water rinsing, and some optimisation of the surface treatment of the active internal surface of the SRF cavities. CEBAF was also the first SRF accelerator to be cooled by superfluid helium, operating at a temperature of 2 K. The large cryogenic plant designed and built to cool CEBAF has itself been a crucial step in the development of superconducting technology, not just SRF but also for accelerator magnets such as those used in the LHC.

Concluding this important chapter in SRF development in the mid- to late-1980s are two other major high-energy-physics projects: TRISTAN at KEK in Japan and HERA at DESY in Germany. Each produced, through a big national company, state-of-the-art SRF technology involving moderate cavities, typically 500 MHz, of four to five cells, in bulk niobium. The new technologies reached an accelerating electric field of about 5 MV/m, while substantially improving the performances of HERA and TRISTAN.

Linear adventure

All of these large accelerators were still to be completed when, in July 1990, a meeting was held at Cornell, organised by Ugo Amaldi and Hasan Padamsee, to discuss the possibility of developing SRF technology for a future TeV-scale linear collider (thereby avoiding the synchrotron-radiation losses suffered by circular colliders). The proposed name of this object was TESLA and, after three days battling with various figures, we were convinced that such technology was possible. Amaldi returned to CERN to gather support and, one and half years later, over a dinner in a restaurant in Blankenese in Hamburg hosted by Bjørn Wiik, a dozen or so colleagues, including Maury Tigner, Helen Edwards and Ernst Habel, proposed that DESY should host an international collaboration with the task of developing TESLA.

The great success of TESLA in opening a new era of SRF had a number of concomitant causes, in addition to the great ▷

The European XFEL cavity family: a 1.3 GHz naked (in case) and dressed (bottom), and the smaller 3rd harmonic, 3.9 GHz cavity (top) used to linearise the longitudinal phase space.

enthusiasm, friendship and ingenuity of those involved. We had the recent experiences from LEP-II and CEBAF, for instance, plus cryogenic experience from DESY and Fermilab. The memorandum of understanding helped to inspire a pure scientific research style, with no secrets among the partner institutes and constructive competition to produce the best technology possible. Once the cavity frequency (1.3 GHz) and the number of cells per cavity (nine) had been agreed, we designed the TESLA Test Facility. This central infrastructure at DESY was to treat the active/internal surface of cavities, control and verify each step of the material and cavity production, and finally test the cavities and ancillaries in all conditions, naked and fully dressed, with and without beam. In contrast to the construction of LEP-II and CEBAF, the fabrication of the cavities themselves was handed over to industry. This turned out to be a crucial decision, leading researchers into collaboration with competing firms and taking advantage of their expertise and ingenuity. The test with beam brought about a prototype of the TESLA linac that, with the addition of some undulators, was renamed FLASH in 2003 – the harbinger of the European XFEL.

In 1996, we had the first eight-cavity cryomodule in operation with beam and a stable production of cavities performing a few times better than envisaged. The challenging objective of TESLA's mission was now very close in terms of both accelerating gradient and cost. The factor 20 improvement required to compete for the linear-collider prize was almost there. By 2000, a novel chemical process called electropolishing, developed by Kenji Saito of KEK, and a final cavity baking at moderate temperature introduced at CEA-Saclay by Bernard Visentin, took TESLA over the finish line. The success of TESLA technology was not just due to the cavity performance, but also the parallel development of power couplers, frequency tuners and other ancillaries.

The ability to accelerate very-high-power beams of protons to produce a huge flux of neutrons had major implications for neutron spallation sources like SNS in the US and the ESS under construction in Sweden, for nuclear-waste transmutation, and for accelerators for heavy ions. It took some time, but most new accelerators are in some way based on TESLA technology.

Continuing application

In 2004 the International Technology Recommendation Panel gave momentum to the newly named International Linear Collider (ILC). But it was clear that the eventual construction would not begin for at least a decade, in any case after a better definition of the physics case expected from the LHC. In the meantime, the European X-ray Free Electron Laser (XFEL), which began construction in Hamburg in 2009 and was completed this year (*CERN Courier* July/August 2017 p25), was the best opportunity for the TESLA collaboration to continue with the development of SRF technology. The realisation with industry, on budget and on time, of the advanced-SRF European XFEL has possibly been the most important recent milestone toward new frontiers for high-energy physics. Nevertheless, its 800 nine-cell cavities represent only 5% of the total number required by the ILC.

While SRF has made fantastic progress towards a linear collider and achieved a degree of maturity with the European XFEL, future circular colliders present additional R&D challenges that are similar and also complementary to the quest for very large accelerating gradient. The total power to be transferred to the beams in case of a future electron-positron collider, for example, is 100 MW continuously. This challenges the present concepts of high-power couplers, requires new ideas to minimize dynamic cryogenic losses, and has triggered R&D on new materials and fabrication techniques.

Concluding this historical summary, SRF has now reached a high level of technological development, handled by advanced industry, similar to that reached for magnets 15 years ago. As in the case of superconducting magnets, physics – and high-energy physics in particular – has been the most significant driving force. As with accelerator magnets such as those in the Tevatron, HERA and the LHC, projects such as LEP-II, CEBAF and TESLA/ILC have played a crucial role to transform, through technology transfer and industrialisation, an exotic phenomenon into a promising and useful technology. So far, the existing technology is sufficient for today's applications. But basic research always seeks the next paradigm shift, and R&D taking place in laboratories such as CERN will allow us to go beyond present limitations.

Résumé

La radiofréquence se développe

La technologie radiofréquence supraconductrice a atteint un niveau de développement semblable à celui des aimants supraconducteurs il y a 15 ans. Les cavités radiofréquence composées de niobium sont couramment utilisées dans divers domaines, qu'il s'agisse d'accélérateurs de particules repoussant les limites des hautes énergies ou d'applications en physique nucléaire et en science des matériaux. Elles ont été essentielles pour permettre au collisionneur LEP du CERN ainsi qu'à l'installation européenne XFEL, récemment inaugurée, d'atteindre de nouveaux régimes d'énergie. Les projets de ce type ont contribué, par le transfert et l'industrialisation de technologies, à transformer un phénomène exotique en une technologie prometteuse et utile ; des « cavités en crabe » supraconductrices sont d'ailleurs en développement au CERN en vue du projet LHC à haute luminosité.

Carlo Pagani, University of Milano and INFN-LASA, Italy.

Get on board with EASITrain

The new European Advanced Superconductivity Innovation and Training project, led by CERN, will help the next generation of researchers tap into superconductivity's promise.

R Hradil/RvS Media

CERN fellow Konstantina Konstantopoulou working on a new generation of MgB_2 superconductors for future colliders.

Heike Kamerlingh Onnes won his Nobel prize back in 1913 two years after the discovery of superconductivity; Georg Bednorz and Alexander Müller won theirs in 1987, just a year after discovering high-temperature superconductors. Putting these major discoveries into use, however, has been a lengthy affair, and it is only in the past 30 years or so that demand has emerged. Today, superconductors represent an annual market of around $1.5 billion, with a high growth rate, yet a plethora of opportunities remains untapped.

Developing new superconducting materials is essential for a possible successor to the LHC currently being explored by the Future Circular Collider (FCC) study, which is driving a considerable effort to improve the performance and feasibility of large-scale magnet production. Beyond fundamental research, superconducting materials are the natural choice for any application where strong magnetic fields are needed. They are used in applications as diverse as magnetic resonance imaging (MRI), the magnetic separation of minerals in the mining industry and efficient power transmission across long distances (currently being explored by the LIPA project in the US and AmpaCity in Germany).

The promise for future technologies is even greater, and overcoming our limited understanding of the fundamental principles of superconductivity and enabling large-quantity production of high-quality conductors at affordable prices will open new business opportunities. To help bring this future closer, CERN has initiated the European Advanced Superconductivity Innovation and Training project (EASITrain) to prepare the next generation of researchers, develop innovative materials and improve large-scale cryogenics (easitrain.web.cern.ch). From January next year, 15 early stage researchers will work on the project for three years, with the CERN-coordinated FCC study providing the necessary research infrastructure.

Global network

EASITrain establishes a global network of research institutes and industrial partners, transferring the latest knowledge while also equipping participants with business skills. The network will join forces with other EU projects such as ARIES, EUROTAPES (superconductors), INNWIND (a 10–20 MW wind turbine), EcoSWING (superconducting wind generator), S-PULSE (superconducting electronics) and FuSuMaTech (a working group approved in June devoted to the high-impact potential of R&D for the HL-LHC and FCC), and aims to profit from the well-established Test Infrastructure and Accelerator Research Area Preparatory Phase (TIARA) platform. EASITrain also links with the Marie Curie training networks STREAM and RADSAGA, both hosted by CERN.

Operating within the EU's H2020 framework, one of EASITrain's targets is energy sustainability. Performance and efficiency increases in the production and operation of superconductors could lead to 10–20 MW wind turbines, for example, while new efficient cryogenics could reduce the carbon footprint of industries, gas production and transport. EASITrain will also explore the use of novel superconductors, including high-temperature superconductors, in advanced materials for power-grid and medical applications, and bring together technical experts, industrial representatives and specialists in business and marketing to identify new superconductor applications. Following an extensive study, three specific application areas have been identified: uninterruptible power supplies; sorting machines for the fruit industry; and large loudspeaker systems. These will be further explored during a three-day "superconductivity hackathon" satellite event at EUCAS17, organised jointly with CERN's KT group, IdeaSquare, WU Vienna and the Fraunhofer Institute. ▷

EASITrain's application destinations

Uninterruptible power supply (UPS). UPS systems are energy-storage technologies that can take on and deliver power when necessary. Cloud-based applications are leading to soaring data volumes and an increasing need for secure storage, driving growth among large data centres and a shift towards more efficient UPS solutions that are expected to carve a slice of an almost $1 billion and growing market. Current versions are based on batteries with a maximum efficiency of 90%, but superconductor-based implementations based on flywheels will ensure a continuous and longer-lived power supply, minimising data loss and maximising server stability.

Sorting machines for the fruit industry. Tonnes of fruit have to be disposed of worldwide because current technologies based on spectroscopy are not able to determine the maturity level of fruit sufficiently accurately, with techniques also offering limited information about small-sized fruit. Superconductors would enable NMR-based scanning systems that allow producers to accurately and non-destructively determine valuable properties such as ripeness, absence of seeds and, crucially, the maturity of fruit. In 2016, sorting-machine manufacturers made profits of $360 million selling products analysing apples, pears and citrus fruit, and the market has experienced a growth of about 20% per year.

Large loudspeaker systems. The sound quality of powerful loudspeakers, particularly PA systems for music festivals and stadiums, could enter new dimensions by using superconductors. Higher electrical resistance leads to poorer sound quality, since speakers need to modify the strength of a magnetic field rapidly to adapt to different frequency ranges. Superconductivity also allows smaller magnets to be used, making them more compact and transportable. A major concern among European manufacturers has been the search for the next big step in loudspeaker evolution, to defend against competition from Asia, and the size and quality of large speakers is now a major driver of the $500 million industry.

Together with the impact that superconductors have had on fundamental research, these examples show the unexpected transformative potential of these still mysterious materials and emphasise the importance of preparing the next generation for the challenges ahead.

Résumé
Montez à bord d'EASITrain !

*Le CERN a lancé le réseau EASITrain (*European Advanced Superconductivity Innovation and Training project*), dans le but de préparer la nouvelle génération des chercheurs, de développer des matériaux innovants et d'améliorer la cryogénie à grande échelle. Quinze chercheurs en début de carrière travailleront sur ce projet pendant trois ans, et l'étude sur un futur collisionneur circulaire menée au CERN fournira l'infrastructure de test nécessaire.*

Panagiotis Charitos, CERN.

ITER

ITER's massive magnets enter production

Completion of the first toroidal-field coil for ITER, carrying 4.5 km of niobium-tin conductor, demonstrates superconductor technology on a gigantic scale.

It is 14 m high, 9 m wide and weighs 110 tonnes. Fresh off a production line at ASG in Italy, and coated in epoxy Kapton-glass panels (image top left), it is the first superconducting toroidal-field coil for the ITER fusion experiment under construction in Cadarache, Southern France. The giant D-shaped ring contains 4.5 km of niobium-tin cable (each containing around 1000 individual superconducting wires) wound into a coil that will carry a current of 68,000 A, generating a peak magnetic field of 11.8 T to confine a plasma at a temperature of 150 million degrees. The coil will soon be joined by 18 others like it, 10 manufactured in Europe and nine in Japan. After completion at ASG, the European coils will be shipped to SIMIC in Italy, where they will be cooled to 78 K, tested and welded shut in a 180 tonne stainless-steel armour. They will then be impregnated with special resin and machined using one of the largest machines in Europe, before being transported to the ITER site.

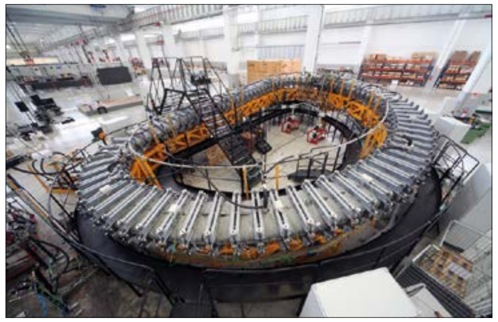
Science doesn't get much bigger than this, even by particle-physics standards. ITER's goal is to demonstrate the feasibility of fusion power by maintaining a plasma in a self-sustaining "ignition" phase, and was established by an international agreement ratified in 2007 by China, the European Union (EU), Euratom, India, Japan, Korea, Russia and the US. Following years of delay relating to the preferred site and project costs, ITER entered construction a decade ago and is scheduled to produce first plasma by December 2025. The EU contribution to ITER, corresponding to roughly half the total cost, amounts to €6.6 billion for construction up to 2020.

Fusion for energy

The scale of ITER's components is staggering. The vacuum vessel that will sit inside the field coils is 10 times bigger than anything before it, measuring 19.4 m across, 11.4 m high and requiring new welding technology to be invented. The final ITER experiment will weigh 23,000 tonnes, almost twice that of the LHC's CMS experiment. The new toroidal-field coil is the first major magnetic element of ITER to be completed. A series of six further poloidal coils, a central solenoid and a number of correction coils will complete ITER's complex magnetic configuration. The central solenoid (a 1000 tonne superconducting electromagnet in the centre of the machine) must be strong enough to contain a force of 60 MN – twice the thrust of the Space Shuttle at take-off.

Fusion for Energy (F4E), the EU organisation managing

All image credits: Fusion4Energy



Top: The encased toroidal-field coil, and winding of the conductor with millimetre precision taking place. Middle: The ITER site photographed in June 2017. Bottom: vacuum-pressure impregnation tooling, and testing the toroidal-field-coil winding packs at ASG's La Spezia facility.

Europe's contribution to ITER, has been collaborating with industrial partners such as ASG Superconductors, Iberdrola Ingeniería y Construcción, Elytt Energy, CNIM, SIMIC, ICAS consortium and Airbus CASA to deliver Europe's share of components in the field of magnets. At least 600 people from 26 companies have been involved in the toroid production and the first coil is the result of almost a decade of work. This involved, among other things, developing new ways to jacket superconducting cables based on materials that are brittle and much more difficult to handle than niobium-titanium. In total, 100,000 km of niobium-tin strands are necessary for ITER's toroidal-field magnets, increasing worldwide production by a factor 10.

Since 2008, F4E has signed ITER-related contracts reaching approximately €5 billion, with the magnets amounting to €0.5 billion. Firms that are involved, such as SIMIC where the coils will be tested and Elytt, which has developed some of the necessary tooling, have much to gain from collaborating in ITER. According to Philippe Lazare, CEO of CNIM Industrial Systems Division: "In order to manufacture our share of ITER components, we had to upgrade our industrial facilities, establish new working methods and train new talent. In return, we have become a French reference in high-precision manufacturing for large components."

CERN connection

Cooling the toroidal-field magnets requires about 5.8 tonnes of helium at a temperature of 4.5 K and a pressure of 6 bar, putting helium in a supercritical phase slightly warmer than it is in the LHC. But ITER's operating environment is totally different to an accelerator, explains head of F4E's magnets project team Alessandro Bonito-Oliva: "The magnets have to operate subject to lots of heat generated by neutron irradiation from the plasma and AC losses generated inside the cable, which has to be removed, whereas at CERN you don't have this problem. So the ITER coolant has to be fairly close to the wire – this is why we used forced-flow of helium inside the cable." A lot of ITER's superconductor technology work was driven by CERN in improving the characteristics of superconductors, says Bonito-Oliva: "High-energy physics mainly looks for very high current performance, while in fusion it is also important to minimise the AC losses, which generally brings a reduction of current performance. This is why Nb_3Sn strands for fusion and accelerators are slightly different."

CERN entered formal collaboration with ITER in March 2008 via a co-operation agreement concerning the design of ▷

Fusion4Energy

Laser welding of the toroidal field coil taking place.

high-temperature superconducting current leads and other magnet technologies, with CERN's superconducting laboratory in building 163 becoming one of the "reference" laboratories for testing ITER's superconducting strands. Niobium-tin is the same material that CERN is pursuing for the high-field magnets of the High Luminosity LHC and also a possible future circular collider, although the performance demands of accelerator magnets requires significant further R&D. Head of CERN's technology department, Jose Miguel Jimenez, who co-ordinates the collaboration between CERN and ITER, says that in addition to helping with the design of the cable, CERN played a big role in advising for high-voltage testing of the cable insulation and, in particular, with the metallurgical aspect. "Metallurgy is one of the key areas of technology transfer from CERN to ITER. Another is the HTS current leads, which CERN has helped to design in collaboration with the Chinese group working on the ITER tokamak, and in simulating the heat transfer under real conditions," he explains. "We also helped with the cryoplants, magnetic-field quality, and on central interlocks and safety systems based on our experience with the LHC."

Résumé

Les aimants d'ITER entrent en phase de production

La première bobine de champ toroïdal destinée à l'expérience sur la fusion ITER, en construction en France, est achevée. Elle mesure 14 m de haut pour 9 m de large, et pèse 110 tonnes. Elle sera bientôt rejointe par 18 autres, fabriquées en Europe et au Japon. Une fois installées, celles-ci permettront à l'installation ITER de confiner un plasma à une température de 150M degrés. La fabrication de cette bobine, qui contient 4,5 km de conducteur en niobium, représente une démonstration de l'utilisation de cette technologie supraconductrice à grande échelle.

Matthew Chalmers, CERN.

Assembly of the LHC's superconducting dipoles in 2003 at the German company Babcock-Noell, one of the three European industrial centres of production for the LHC's 1232 main dipole magnets. (Image credit: CERN.)

Superconductors and particle physics entwined

High-energy physics is one of the biggest markets for industries working in the superconducting area, with firms rising and falling with the latest projects.

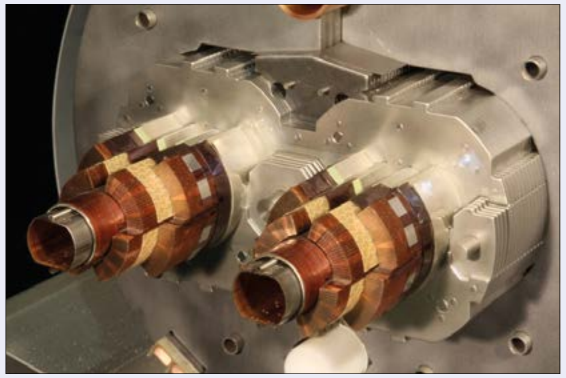
Superconductivity is a mischievous phenomenon. Countless superconducting materials were discovered following Onnes' 1911 breakthrough, but none with the right engineering properties. Even today, more than a century later, the basic underlying superconducting material from which magnet coils are made is a bespoke product that has to be developed for specific applications. This presents both a challenge and an opportunity for consumers and producers of superconducting materials.

According to trade statistics from 2013, the global market for superconducting products is dominated by the demands of magnetic resonance imaging (MRI) to the tune of approximately €3.5 bn per year, all of which is based on low-temperature superconductors such as niobium-titanium. Large laboratory facilities make up just under €1 bn of global demand, and there is a hint of a demand for high-temperature superconductors at around €0.3 bn.

Understanding the relationship between industry and big science, in particular large particle accelerators, is vital for such projects to succeed. When the first superconducting accelerator – the Tevatron proton–antiproton collider at Fermilab in the US, employing 774 dipole magnets to bend the beams and 216 quadrupoles to focus them – was constructed in the early 1980s, it is said to have consumed somewhere between 80–90% of all the niobium-titanium superconductor ever made. CERN's Large Hadron Collider (LHC), by far the largest superconducting device ever built, also had a significant impact on industry: its construction in the early 2000s ▷

CERN/Babcock Noell

Snapshot: manufacturing the LHC magnets



Industry-manufactured coils for an LHC main dipole carrying the two beam pipes, which guide protons on their circular path.

The production of the niobium-titanium conductor for the LHC's 1800 or so superconducting magnets was of the highest standard, involving hundreds of individual superconducting strands assembled into a cable that had to be shaped to accommodate the geometry of the magnet coil. Three firms manufactured the 1232 main dipole magnets (each 15 m long and weighing 35 tonnes): the French consortium Alstom MSA–Jeumont Industries; Ansaldo Superconduttori in Italy; and Babcock Noell Nuclear in Germany. For the 400 main quadrupoles, full-length prototyping was developed in the laboratory (CEA–CERN) and the tender assigned to Accel in Germany. Once LHC construction was completed, the superconductor market dropped back to meet the base demands of MRI. There has been a similar experience with the niobium-tin conductor used for the ITER fusion experiment under construction in France: more than six companies worldwide made the strands before the procurement was over, after which demand dropped back to pre-project levels.

doubled the world output of niobium-titanium for a period of five to six years. The learning curve of high-field superconducting magnet production has been one of the core drivers of progress in high-energy physics (HEP) for the past few decades, and future collider projects are going to test the HEP–industry model to its limits.

The first manufacturers

About a month after the publication of the Bell Laboratories work on high-field superconductivity at the end of January 1961 describing the properties of niobium-tin, it was realised that the experimental conductor – despite being a very small coil consisting of merely a few centimetres of wire – could, with a lot of imagination, be described as an engineering material. The discovery catalysed research into other superconducting metallic alloys and compounds. Just four years later, in 1965, Avco-Everett in co-operation with 14 other companies built a 10 foot, 4 T superconducting magnet using a niobium-zirconium conductor embedded in a copper strip.

By the end of 1966, an improved material consisting

Siemens

Siemens' MRI production site in Erlangen, Germany.

of niobium-titanium was offered at \$9 per foot bare and \$13 when insulated. That same year, RCA also announced with great fanfare its entry into commercial high-field superconducting magnet manufacture using the newly developed niobium-tin "Vapodep" ribbon at \$4.40 per metre. General Electric was not far behind, offering unvarnished "22CY030" tape at \$2.90 per foot in quantities up to 10,000 feet. Kawecki Chemical Company, now Kawecki-Berylco, advertised "superconductive columbium-tin tape in an economical, usable form" in varied widths and minimum unit lengths of 200 m, while in Europe the former French firm CSF marketed the Kawecki product. In the US, Airco claimed the "Kryoconductor" to be pioneering the development of multi-strand fine-filament superconductors for use primarily in low- or medium-field superconducting magnets. Intermagnetics General (IGC) and Supercon were the two other companies with resources adequate to fulfil reasonably sized orders, the latter in particular providing 47,800 kg of copper-clad niobium-titanium conductor for the Argonne National Laboratory's 12 foot-diameter hydrogen bubble chamber. The industrialisation of superconductor production was in full swing.

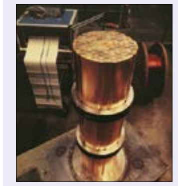
Niobium-tin in tape form was the first true engineering superconducting material, and was extensively used by the research community to build and experiment with superconducting magnets. With adequate funds, it was even possible to purchase a magnet built to one's specifications. One interesting application, which did not see the light of day until many years later, was the use of superconducting tape to exclude magnetic fields from those regions in a beamline through which particle beams had to pass undeviated. As a footnote to this exciting period, in 1962 Martin Wood and his wife founded Oxford Instruments, and four years later delivered the first nuclear magnetic resonance spectroscopy system. In November last year, the firm sold its superconducting wire business to Bruker Energy and Supercon Technologies, a subsidiary of Bruker Corporation, for \$17.5 m.

Beginning of a new industry

One might trace the beginning of the superconducting-magnet revolution to a five-week-long "summer study" at Brookhaven National Laboratory in 1968. Bringing the who's who in the

CERN

Transforming brittle conductors into high-performance coils at CERN



The manufacture of superconductors for HEP applications is in many ways a standard industrial flow process with specialised steps. The superconductor in round rod form is inserted into copper tubes, which have a round inside and a hexagonal outside perimeter (the image inset shows such a "billet" for the former HERA electron–proton collider at DESY). A number of these units are then stacked into a copper can that is vacuum sealed and extruded in a hydraulic press, and this extrusion is processed on a draw bench where it is progressively reduced in diameter. The greatly reduced product is then drawn through a series of dies until the desired wire diameter in reached, and a number of these wires are formed into cables ready for use. The overall process is highly complex and often involves several countries and dozens of specialised industries before the reel of wire or cable arrives at the magnet factory. Each step must ultimately be accounted for and any sudden change to a customer's source of funds can land the manufacturer with unsaleable stock. Superconductors are specified precisely for their intended end use, and only in rare instances is a stocked product applicable to another application.

Assembling niobium-tin Rutherford cable at CERN, with Amalia Ballarino, head of the superconductors section in CERN's technology department.

world of superconductivity together resulted not only in a burst of understanding of the many failures experienced in prior years by magnet builders, but also a deeper appreciation of the arcana of superconducting materials. Researchers at Rutherford Laboratory in the UK, in a series of seminal papers, sufficiently explained the underlying properties and proposed a collaboration with the laboratories at Karlsruhe and Saclay to develop superconducting accelerator magnets. The GESSS (Group for European Superconducting Synchrotron Studies) was to make the Super Proton Synchrotron (SPS) at CERN a superconducting machine, and this project was large enough to attract the interest of industry – in particular IMI in England. Although GESSS achieved many advances in filamentary conductors and magnet design, the SPS went ahead as a conventional warm-magnet machine. IMI stopped all wire production, but in the US the number of small wire entrepreneurs grew. Niobium-tin tape products gradually disappeared from the market as this superconductor was deemed to be unsuitable for all magnets and especially for accelerator magnet use.

In 1972 the 400 GeV synchrotron at Fermilab, constructed with standard copper-based magnets, became operational, and almost immediately there were plans for an upgrade – this time with superconducting magnets. This project changed the industrial scale, requiring a major effort from manufacturers. To work around the proprietary alloys and processing techniques developed by strand manufacturers, Fermilab settled on an Nb$_{46.5}$Ti alloy, which was an arithmetic average of existing commercial alloys. This enabled the lab to save around one year in its project schedule.

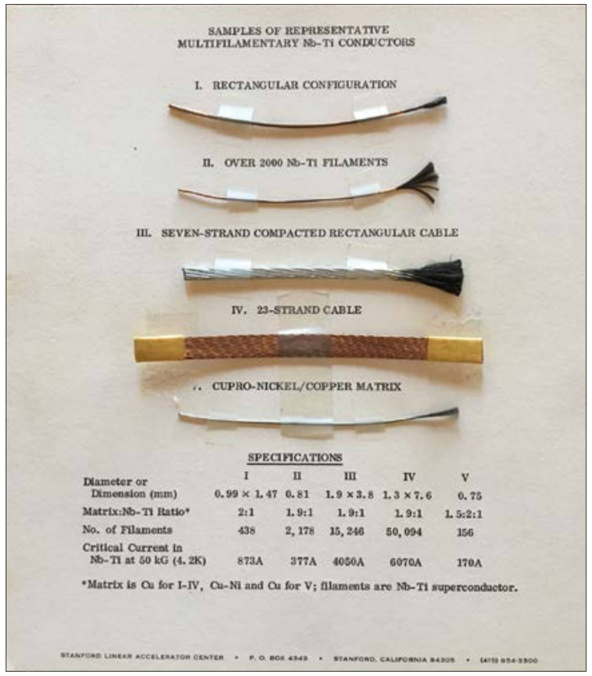
Future collider projects are going to test the HEP–industry model to its limits.

At the same time, the Stanford Linear Accelerator Center was building a large superconducting solenoid for a meson detector, while CERN was undertaking the Big European Bubble Chamber (BEBC) and the Omega Project. This gave industry a reliable view of the future. Numerous large magnets were planned by the various research arms of governments and diverse industry. For example, under the leadership of the Oak Ridge National Laboratory a consortium of six firms constructed a large-scale model of a tokamak reactor magnet assembly using six differently designed coils, each with different superconducting materials: five with niobium-titanium and one with niobium-tin. At the Lawrence Livermore National Laboratory work was in progress to develop a tokamak-like fusion device whose coils were again made from niobium-titanium conductor. The US Navy had major plans for electric ship drives, while the Department of Defense was funding the exploration of isotope separation by means of cyclotron resonance, which required superconducting solenoids of substantial size.

It appeared that there would be no dearth of succulent orders from the HEP community, with the result that even more companies around the world ventured into the manufacture of superconductors. When the Tevatron was commissioned in 1984, two manufacturers were involved: Intermagnetics General Corporation (IGC) and Magnetic Corporation of America (MCA), in an 80/20 per cent proportion. As is common in particle physics, no sooner had the machine become operational than the need for an upgrade became obvious. However, the planning for such a new larger and more complex device took considerable time, during which the superconductor manufacturers effectively made no sales and hence no profits. This led to the disappearance of less well capitalised companies, unless they had other products to market, as did Supercon and Oxford Instruments. The latter expanded ▷

Superconductor industry

Steve St. Lorant/SLAC



A selection of niobium-titanium wires in various configurations. Today, competition in the MRI market has driven down the cost of this particular superconductor.

into MRI, and its first prototype MRI magnet built in 1979 became the foundation of a current annual world production that totals around 3500 units. MRI production ramped up as the Tevatron demand declined and the correspondingly large amount of niobium-titanium conductor that it required has been stable since then.

The demise of ISABELLE, a 400 GeV proton–proton collider at Brookhaven, in 1983, and then the Superconducting Super Collider a decade later, resulted in a further retrenchment of the superconductor industry, with a number of pioneering establishments either disappearing or being bought out. The industrial involvement in the construction of the superconducting machines HERA at DESY and RHIC at BNL somewhat alleviated the situation. The discovery of high-temperature superconductivity (HTS) in 1986 also helped, although it is not clear that great profits, if any, have been made so far in the HTS arena.

A cloudy crystal ball

The superconducting wire business in the Western world has undergone significant consolidation in recent years. Niobium-titanium wire is now a commodity with a very low profit margin because it has become a standard, off-the-shelf product used primarily for MRI applications. There are now more companies than the market can support for this conductor, but for HEP and other research applications the market is shifting to its higher-performing cousin: niobium-tin.

Following the completion of the LHC in the early 2000s, the US Department of Energy looked toward the next generation of accelerator magnets. LHC technology had pushed the performance of niobium-titanium to its limits, so investment was directed towards niobium-tin. This conductor was also being developed for the fusion community ITER (p34), but HEP required a higher performance for use in accelerators. Over a period of a few years, the critical-current performance of niobium-tin almost doubled and the conductor is now a technological basis of the High Luminosity LHC (see p17). Although this major upgrade is proceeding as planned, as always all eyes are on the next step – perhaps an even larger machine based on even more innovative magnet technology. For example, a 100 TeV proton collider under consideration by the Future Circular Collider study, co-ordinated by CERN, will require global-scale procurement of niobium-tin strands and cable similar in scale to the demands of ITER.

Beyond that, the view of the superconductor industry is into a cloudy crystal ball. The current political and economic environment does not give grounds for hope, at least not in the Western world, that a major superconducting project is to be built in the near future. More generally, other than MRI, the commercial applications of superconductivity have not caught on due to customer impressions of additional complexity and risk against marginal increases in performance. We also have the consequences of the challenges that ITER has faced regarding its costs, which can attract the undeserved opinion that scientists cannot manage large projects.

One facet of the superconductor industry that seems to be thriving is small-venture establishments, sometimes university departments, which carry out superconductor R&D quasi-independently of major industrial concerns. These establishments maintain themselves under various government-sponsored support, such as the SBIR and STTR programmes in the US, and stepwise and without much fanfare they are responsible for the improvement of current superconductors, be they low- or high-temperature. As long as such arrangements are maintained, healthy progress in the science is assured, and these results feed directly to industry. And as far as HEP is concerned, as long as there are beams to guide, bend and focus, we will continue to need manufacturers to make the wires and fabricate the superconducting magnet coils.

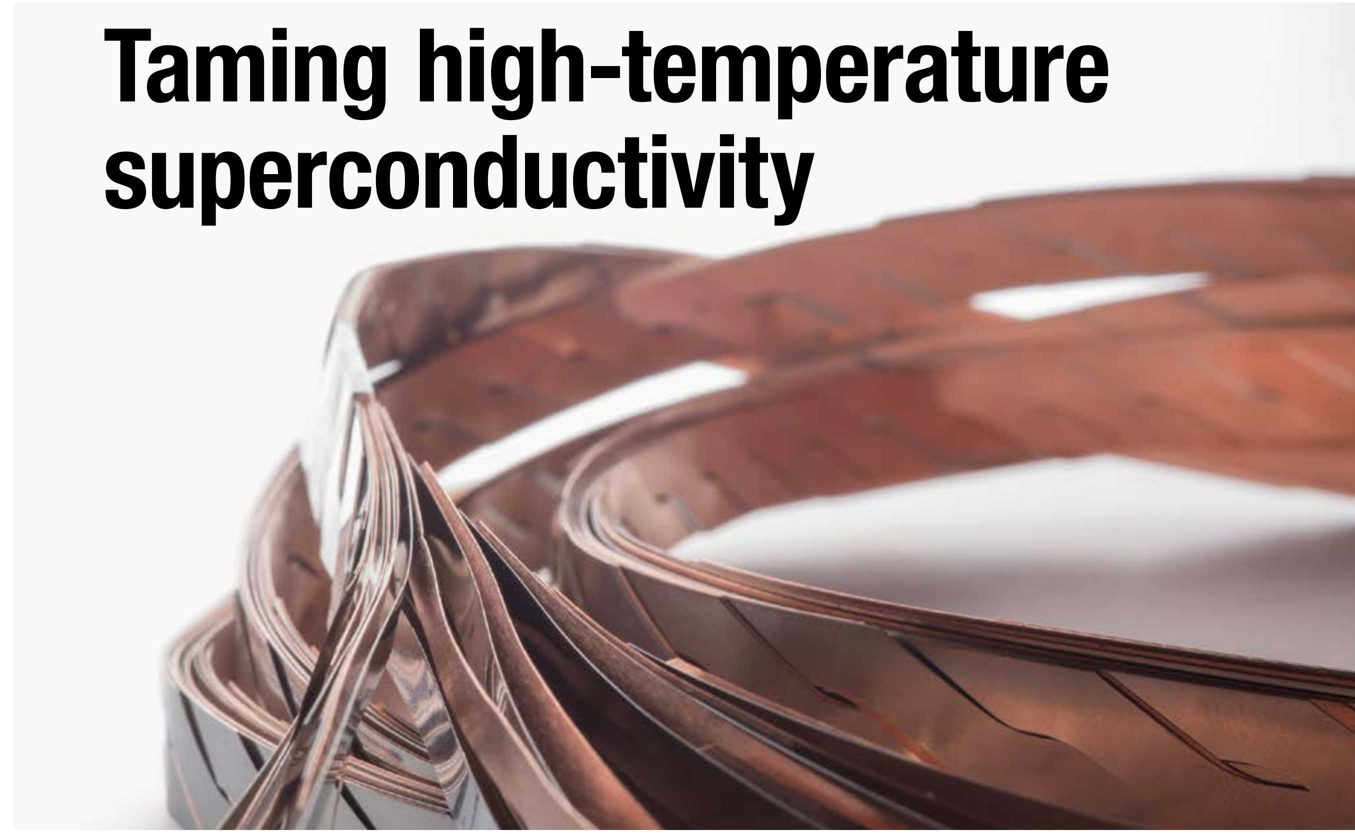
Résumé

Les liens entre supraconducteurs et physique des particules

La physique des hautes énergies est l'un des plus grands marchés pour les industries du domaine des supraconducteurs, et les entreprises peuvent ainsi croître ou décliner en fonction des grands projets scientifiques en cours. La construction des dipôles du LHC, par exemple, a fait doubler la production mondiale de niobium-titane pendant 5 à 6 ans. Le CERN construit à présent la technologie destinée au LHC à haute luminosité et étudie des modèles pour un futur collisionneur circulaire. Le supraconducteur choisi est le niobium-étain, et le modèle de fonctionnement de l'industrie liée à la physique des hautes énergies sera ainsi à nouveau poussé dans ses limites.

Bruce Strauss, US Department of Energy and IEEE Council on Superconductivity, and **Steve St Lorant**, SLAC National Accelerator Laboratory and Stanford University.

Taming high-temperature superconductivity



Prototype "Roebel" cable based on the high-temperature superconductor REBCO (rare-earth barium-copper oxide) is being used to wind a demonstration accelerator dipole at CERN as part of the EuCARD-2 project. (Image credit: H Barnard/CERN.)

Understanding the mechanism behind high-temperature superconductivity, discovered three decades ago, is a major theoretical challenge that has the potential to impact other fields including particle physics.

Superconductivity is perhaps the most remarkable manifestation of quantum physics on the macroscopic scale. Discovered in 1911 by Kamerlingh Onnes, it preoccupied the most prominent physicists of the 20th century and remains at the forefront of condensed-matter physics today. The interest is partly driven by potential applications – superconductivity at room temperature would surely revolutionise technology – but to a large extent it reflects an intellectual fascination. Many ideas that emerged from the study of superconductivity, such as the generation of a photon mass in a superconductor, were later extended to other fields of physics, famously serving as paradigms to explain the generation of a Higgs mass of the electroweak W and Z gauge bosons in particle physics.

Put simply, superconductivity is the ability of a system of fermions to carry electric current without dissipation. Normally, fermions such as electrons scatter off any obstacle, including each other. But if they find a way to form bound pairs, these pairs may condense into a macroscopic state with a non-dissipative current. Quantum mechanics is the only way to explain this phenomenon, but it took 46 years after the discovery of superconductivity for Bardeen, Cooper and Schrieffer (BCS) to develop a verifiable theory. Winning the 1972 Nobel Prize in Physics for their efforts, they figured out that the exchange of phonons leads to an effective attraction between pairs of electrons of opposite momentum if the electron energy is less than the characteristic phonon energy (figure 1, overleaf). Although electrons still repel each other, the effective Coulomb interaction becomes smaller at such frequencies (in a manner opposite to asymptotic freedom in high-energy physics). If the reduction is strong enough, the phonon-induced electron–electron attraction wins over Coulomb repulsion and the total interaction becomes attractive. There is no threshold for the magnitude of the attraction because low-energy fermions live at the boundary of the Fermi sea, in which case an arbitrary weak attraction is enough to create bound states of fermions at some critical temperature, T_c. ▷

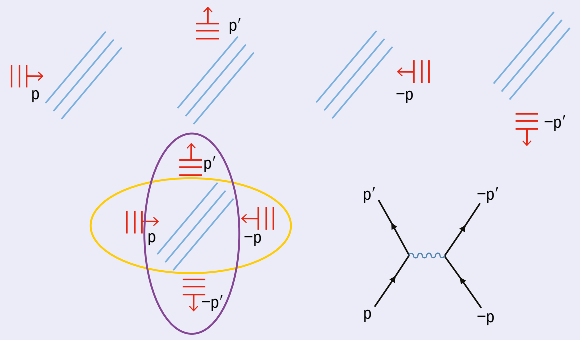
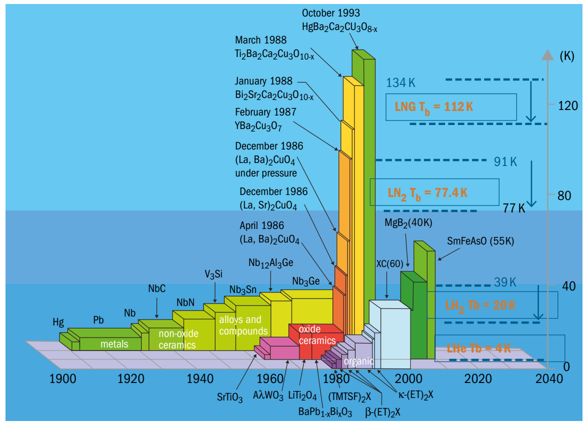


Fig. 1. Pairing in a conventional superconductor involves an electron (red) with momentum p scattering off a virtual phonon (blue) to the state p′. The virtual phonon is extremely slow compared with the electron, so another electron of momentum −p can scatter off the same phonon to state −p′. The net effect (bottom line) is that two pairs of electrons with zero total momentum have scattered off one another and, since the electrons were not at the same place at the same time, they can avoid the direct Coulomb repulsion.



B Glowacki

Fig. 2. Materials with record superconducting transition temperatures as a function of time, showing BCS superconductors, iron-based superconductors and high-temperature cuprate superconductors. The current record holder is a BCS-type superconductor, hydrogen sulphide, under a gigantic pressure of 155 GPa (not shown).

The formation of bound states, called Cooper pairs, is one necessary ingredient for superconductivity. The other is for the pairs to condense, or more specifically to acquire a common phase corresponding to a single macroscopic wave function. Within BCS theory, pair formation and locking of the phases of the pairs occur simultaneously at the same T_c, while in more recent strong-coupling theories bound pairs exist above this temperature. The common phase of the pairs can have an arbitrary value, and the fact that the system chooses a particular one below T_c is a manifestation of spontaneous symmetry breaking. The phase coherence throughout the sample is the most important physical aspect of the superconducting state below T_c, as it can give rise to a "supercurrent" that flows without resistance. Superconductivity can also be viewed as an emergent phenomenon.

While BCS theory was a big success, it is a mean-field theory, which neglects fluctuations. To really trust that the electron–phonon mechanism was correct, it was necessary to develop theoretical tools based on Green functions and field-theory methods, and to move beyond weak coupling. The BCS electron–phonon mechanism of superconductivity has since been successfully applied to explain pairing in a large variety of materials (figure 2), from simple mercury and aluminium to the niobium-titanium and niobium-tin alloys used in the magnets for the Large Hadron Collider (LHC), in addition to the recently discovered sulphur hydrides, which become superconductors at a temperature of around 200 K under high pressure. But the discovery of high-temperature superconductors drove condensed-matter theorists to explore new explanations for the superconducting state.

The observation of d-wave symmetry in the cuprates was extremely surprising.

Unconventional superconductors

In the early 1980s, when the record critical temperature for superconductors was of the order 20 K, the dream of a superconductor that works at liquid-nitrogen temperatures (77 K) seemed far off. In 1986, however, Bednorz and Müller made the breakthrough discovery of superconductivity in $La_{1-x}Ba_xCuO_4$ with T_c of around 40 K. Shortly after, a material with a similar copper-oxide-based structure with T_c of 92 K was discovered. These copper-based superconductors, known as cuprates, have a distinctive structure comprising weakly coupled layers made of copper and oxygen. In all the cuprates, the building blocks for superconductivity are the CuO_2 planes, with the other atoms providing a charge reservoir that either supplies additional electrons to the layers or takes electrons out to leave additional hole states (figure 3).

From a theoretical perspective, the high T_c of the cuprates is only one important aspect of their behaviour. More intriguing is what mechanism binds the fermions into pairs. The vast majority of researchers working in this area think that, unlike low-temperature superconductors, phonons are not responsible. The most compelling reason is that the cuprates possess "unconventional" symmetry of the pair wave function. Namely, in all known phonon-mediated superconductors, the pair wave function has s-wave symmetry, or in other words, its angular dependence is isotropic. For the cuprates, it was proven in the early 1990s that the pair wave function changes sign under rotation by 90°, leading to an excitation spectrum that has zeros at particular points on the Fermi surface. Such symmetry is often called "d-wave". This is the first symmetry beyond s-wave that is allowed by the antisymmetric nature of the electron wave functions when the total spin of the pair is zero. The observation of a d-wave symmetry in the cuprates was extremely surprising because, unlike s-wave pairs, d-wave Cooper pairs can potentially be broken by impurities.

Woodstock physics

P Schewe & P Grant

Participants at a special session of the 1987 March meeting of the American Physical Society in New York devoted to the newly discovered high-temperature superconductors. The hastily organised session, which later became known as the "Woodstock of Physics" lasted from the early evening to 3.30 a.m. the following morning, with 51 presenters and more than 1800 physicists in attendance. Bednorz and Müller received the Nobel prize in December 1987, one year after the discovery, which was the fastest award in the Nobel's history.

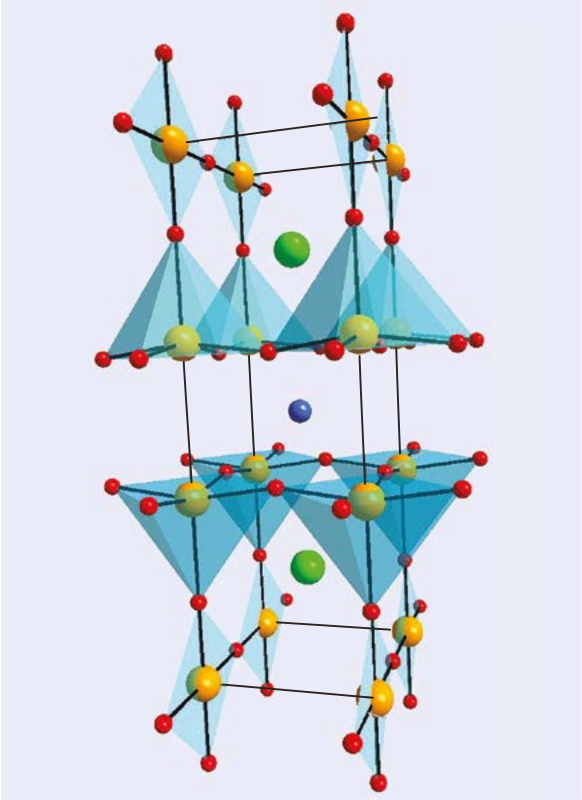


Fig. 3. Atomic structure of one of the best-known high-temperature superconductors, $YBa_2Cu_3O_7$, showing the position of copper (orange), oxygen (red), barium (green) and yttrium (blue) atoms. The material is highly anisotropic and pairing occurs in the CuO_2 planes. By removing oxygen far from the planes, one can change the average number of conduction electrons.

The cuprates hold the record for the highest T_c for materials with an unconventional pair wave-function symmetry: 133 K in mercury-based $HgBa_2Ca_2Cu_3O_8$ at ambient pressure. They were not, however, the first materials of this kind: a "heavy fermion" superconductor $CeCu_2Si_2$ discovered in 1979 by Steglich, and an organic superconductor discovered by Jerome the following year, also had an unconventional pair symmetry. After the discovery of cuprates, a set of unconventional iron-based superconductors was discovered with T_c up to 60 K in bulk systems, followed by the discovery of superconductivity with an even higher T_c in a monolayer of FeSe. But even low-T_c, unconventional materials can be interesting. For example, some experiments suggest that Cooper pairs in Sr_2RuO_4 have total spin-one and p-wave symmetry, leading to the intriguing possibility that they can support edge modes that are Majorana particles, which have potential applications in quantum computing.

If phonon-mediated electron–electron interactions are ineffective for the pairing in unconventional superconductors, then what binds fermions together? The only other possibility is a nominally repulsive electron–electron interaction, but for this to allow pairing, the electrons must screen their own Coulomb repulsion to make it effectively attractive in at least one pairing channel (e.g. d-wave). Interestingly, quantum mechanics actually allows such schizophrenic behaviour of electrons: a d-wave component of a screened Coulomb interaction becomes attractive in certain cases.

Cuprate conundrums

There are several families of high-temperature cuprate superconductors. Some, like LaSrCuO, YBaCuO and BSCCO, show superconductivity upon hole doping; others, like NdCeCuO, show superconductivity upon electron doping. The phase diagram of a representative cuprate contains regions of superconductivity, regions of magnetic order, and a region (called the pseudogap) where T_c decreases but the system's behaviour above T_c is qualitatively different from that in an ordinary metal (figure 4, overleaf). At zero doping, standard solid-state physics says that the system should be a metal, but experiments show that it is an insulator. This is taken as an indication that the effective interaction between electrons is large, and such an interaction-driven insulator is called a Mott insulator. Upon doping, some states become empty and the system eventually recovers metallic behaviour. A Mott insulator at zero doping has another interesting property: spins of localised electrons order antiferromagnetically. Upon doping, the long-range antiferromagnetic order quickly disappears, while short-range magnetic correlations survive.

Since the superconducting region of the phase diagram is sandwiched between the Mott and metallic regimes, there are two ways to think about HTS: either it emerges upon doping of a Mott insulator (if one departs from zero doping), or it emerges from a metal with increased antiferromagnetic correlations if one departs from larger dopings. Even though it was known before the discovery of high-temperature superconductors that antiferromagnetically mediated interaction is attractive in the d-wave channel, it took time to ▷

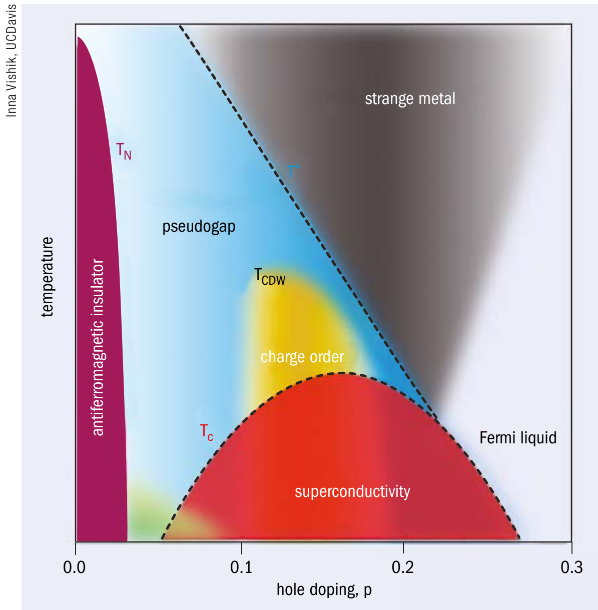


Fig. 4. The phase diagram of a typical cuprate superconductor. When plotted as a function of temperature and hole-doping, p (where p = 0 means one conduction electron per copper atom), many different phases appear: the most prominent are antiferromagnetism near p = 0 and a superconductivity dome at larger doping. In the "pseudogap" region, states disappear at low energy, while above this line the metallic state is different from an ordinary metal and is called a strange metal.

develop various computational approaches, and today the computed value of T_c is in the range consistent with experiments. At smaller dopings, a more reliable approach is to start from a Mott insulator. This approach also gives d-wave superconductivity, with the value of T_c most likely determined by phase fluctuations and decreasing as a function of decreased doping. Because both approaches give d-wave superconductivity with comparable values of T_c, the majority of researchers believe that the mechanism of superconductivity in the cuprates is understood, at least qualitatively.

A more subtle issue is how to explain the so-called pseudogap phase in hole-doped cuprates (figure 4). Here, the system is neither magnetic nor superconducting, yet it displays properties that clearly distinguish it from a normal, even strongly correlated metal. One natural idea, pioneered by Philip Anderson, is that the pseudogap phase is a precursor to a Mott insulator that contains a soup of local singlet pairs of fermions: superconductivity arises if the phases of all singlet pairs are ordered, whereas antiferromagnetism arises if the system develops a mixture of spin singlets and spin triplets. Several theoretical approaches, most notably dynamical mean-field theory, have been developed to quantitatively describe the precursors to a Mott insulator.

The understanding of the pseudogap as the phase where electron states progressively get localised, leading to a reduction of T_c, is accepted by many in the HTS community. Yet, new experimental results show that the pseudogap phase in hole-doped cuprates may actually be a state with a broken symmetry, or at least becomes unstable to such a state at a lower temperature. Evidence has been reported for the breaking of time-reversal, inversion and lattice rotational symmetry. Improved instrumentation in recent years also led to the discovery of a charge-density wave and pair-density wave order in the phase diagram and perhaps even loop-current order. Many of us believe that the additional orders observed in the pseudogap phase are relevant to the understanding of the full phase diagram, but that these do not change the two key pillars of our understanding: superconductivity is mediated by short-range magnetic excitations, and the reduction of T_c at smaller dopings is due the existence of a Mott insulator near zero doping.

Why cuprates still matter

The cuprates have motivated incredible advances in instrumentation and experimental techniques, with 1000-fold increases in accuracy in many cases. On the theoretical side, they have also led to the development of new methods to deal with strong interactions – dynamical mean-field theory and various metallic quantum-critical theories are examples. These experimental and theoretical methods have found their way into the study of other materials and are adding new chapters to standard solid-state physics books. Some of them may even one day find their way into other fields, such as strongly interacting quark–gluon matter. We can now theoretically understand a host of the phenomena in high-temperature superconductors, but there are still some important points to clarify, such as the mysterious linear temperature dependence of the resistivity.

The community is coming together to solve these remaining issues. Yet, the cynical view of the cuprate problem is that it lacks an obvious small parameter, and hence a universally accepted theory – the analogue of BCS – will never be developed. While it is true that serendipity will always have its place in science, we believe that the key criterion for "the theory" of the cuprates should not be a perfect quantitative agreement with experiments (even though this is still a desirable objective). Rather, a theory of cuprates should be judged by its ability to explain both superconductivity and a host of concomitant phenomena, such as the pseudogap, and its ability to provide design principles for new superconductors. Indeed, this is precisely the approach that allowed the recent discovery of the highest-T_c superconductor to date: hydrogen sulphide. At present, powerful algorithms and supercomputers allow us to predict quite accurately the properties of materials before they are synthesised. For strongly correlated materials such as the cuprates, these calculations profit from physical insight and vice versa.

From a broader perspective, studies of HTS have led to renewed thinking about perturbative and non-perturbative approaches to physics. Physicists like to understand particles or waves and how they interact with each other, like we do in classical mechanics, and perturbation theory is the tool that takes us there – QED is a great example that works because the fine-structure constant is small. In a single-band solid where interactions are not too strong, it is natural to think of superconductivity as being mediated by, for example, the exchange of antiferromagnetic spin fluctuations. When interactions are so strong that the wave functions become extremely entangled,

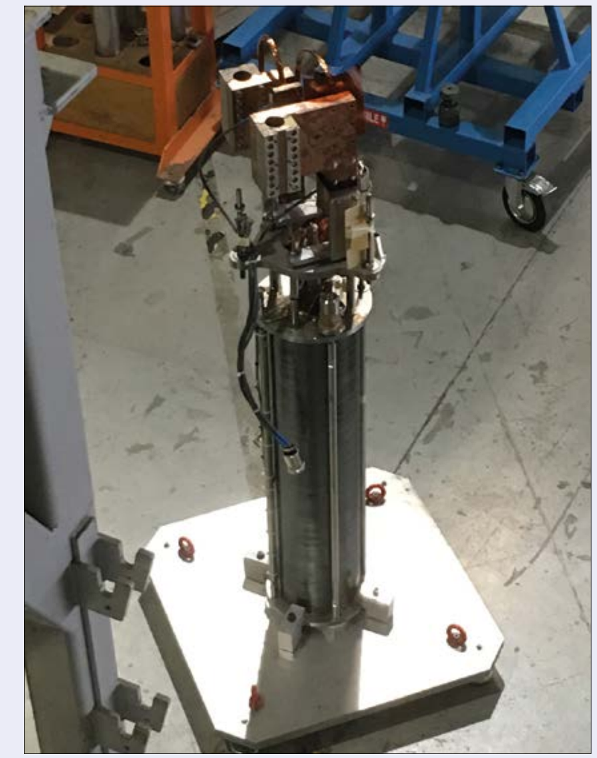
CERN puts high-temperature superconductors to use

A few years ago, triggered by conceptual studies for a post-LHC collider, CERN launched a collaboration to explore the use of high-temperature superconductors (HTS) for accelerator magnets. In 2013 CERN partnered with a European particle accelerator R&D project called EuCARD-2 to develop a HTS insert for a 20 T magnet. The project came to an end in April this year, with CERN having built an HTS demonstration magnet based on an "aligned-block" concept for which coil-winding and quench-detection technology had to be developed. Called Feather2, the magnet has a field of 3 T based on low-performance REBCO (rare-earth barium-copper-oxide) tape. The next magnet, based on high-performance REBCO tape, will approach a stand-alone field of 8 T. Then, once it is placed inside the aperture of the 13 T "Fresca2" magnet, the field should go beyond 20 T.

Now the collaborative European spirit of EuCARD-2 lives on in the ARIES project (Accelerator Research and Innovation for European Science and Society), which kicked off at CERN in May. ARIES brings together 41 participants from 18 European countries, including seven industrial partners, to help bring down the cost of the conductor, and is co-funded via a contribution of €10 million from the European Commission.

In addition, CERN is developing HTS-based transfer lines to feed the new superconducting magnets of the High Luminosity LHC based on magnesium diboride (MgB_2), which can be operated in helium gas at temperatures of up to around 30 K and must be flexible enough to allow the power converters to be installed hundreds of metres away from the accelerator. The relatively low cost of MgB_2 led CERN's Amalia Ballarino to enter a collaboration with industry, which resulted in a method to produce MgB_2 in wire form for the first time. The team has since achieved record currents that reached 20 kA at a temperature above 20 K, thereby proving that MgB_2 technology is a viable solution for long-distance power transmission. The new superconducting lines could also find applications in the Future Circular Collider initiative.

● *Matthew Chalmers, CERN.*



The Feather2 HTS demonstration magnet pictured in CERN's SM18 facility in July.

it still makes sense to look at the internal dynamics of a Cooper pair to check whether one can detect traces of spin, charge or even orbital fluctuations. At the same time, perturbation theory in the usual sense does not work. Instead, we have to rely more heavily on large-scale computer calculations, variational approaches and effective theories. The question of what "binds" fermions into a Cooper pair still makes sense in this new paradigm, but the answer is often more nuanced than in a weak coupling limit.

Many challenges are left in the HTS field, but progress is rapid and there is much more consensus now than there was even a few years ago. Finally, after 30 years, it seems we are closing in on a theoretical understanding of this both useful and fascinating macroscopic quantum state.

● Further reading

PW Anderson 1963 *Phys. Rev.* **130** 439.
PW Anderson 1987 *Science* **235** 1196.
J Bardeen *et al.* 1957 *Phys. Rev.* **108** 1175.
D M Basov and A Chubukov 2011 *Nature Physics* **7** 272
J Bednorz and K Mueller 1986 *Zeitschrift für Physik B* **64** 189.
A Drozdov *et al.* 2015 *Nature* **525** 73.
A-M Tremblay 2013 "Strongly correlated superconductivity" in *Emergent Phenomena in Correlated Matter Modeling and Simulation, Vol. 3* Verlag des Forschungszentrum Jülich.
F Wilczek 2000 *Nucl. Phys. A* **663** 257.

Résumé

Dompter la supraconductivité à haute température

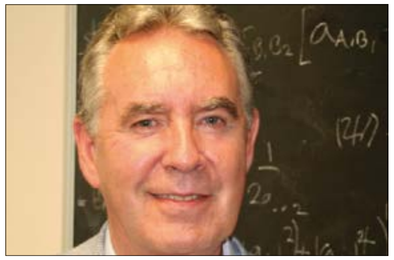
Il y a 30 ans, Johannes Bednorz et Karl Müller recevaient le prix Nobel de physique pour la découverte de matériaux céramiques devenant supraconducteurs à des températures relativement élevées. D'autres types de supraconducteurs à haute température, présentant des températures de transition encore plus élevées, ont depuis été découverts, laissant entrevoir des perspectives attrayantes pour des applications à température ambiante. Le mécanisme gouvernant la supraconductivité à haute température s'est révélé difficile à comprendre, mais les théoriciens approchent à présent d'une théorie pratique de cet état quantique macroscopique.

André-Marie Tremblay, Institut quantique, Université de Sherbrooke, and **Andrey Chubukov**, University of Minnesota, Minneapolis.

Faces & Places

AWARDS

IOP awards for 2017 announced


Researchers working in high-energy physics were awarded five prizes from the UK Institute of Physics (clockwise from top left): David Charlton, Michael Duff, Guy Wilkinson, Nigel Glover and Ceri Brenner.

Each year, the UK's Institute of Physics (IOP) recognises outstanding and exceptional contributions to physics. 2017 sees five awards go to those working in high-energy physics.

David Charlton of the University of Birmingham in the UK received the Richard Glazebrook Medal and Prize (an IOP gold medal) for his leadership in experimental work on the electroweak standard model, beginning with the study of Z-boson decays at LEP and culminating in the discovery of the Higgs boson at the LHC. He worked on OPAL from 1989 to the end of data taking at LEP, and on ATLAS where he was spokesperson from 2013–2017. Fellow gold medalist, winning the Dirac medal and Prize, is Michael Duff of Imperial College London and Oxford University, for his "sustained groundbreaking contributions to theoretical physics including the discovery of Weyl anomalies, for having pioneered Kaluza–Klein supergravity, and for recognising that superstrings in 10 dimensions are merely a special case of membranes in an 11-dimensional M-theory".

Former LHCb spokesperson, Guy Wilkinson of the University of Oxford, has won the James Chadwick Medal and Prize, for his "outstanding contributions to the experimental study of heavy quarks and CP violation, most especially for his leadership of, and his decisive contributions to, the LHCb experiment". Nigel Glover of Durham University also won a subject medal – the John William Strutt, Lord Rayleigh Medal and Prize – for pioneering new methods for the application of perturbative quantum chromodynamics to high-energy processes involving energetic jets, leading to sophisticated simulation codes that are being used to describe LHC data.

Finally, the Clifford Patterson Medal and Prize, awarded for exceptional early career contributions to the application of physics in an industrial or commercial context, went to Ceri Brenner of the UK Science and Technology Facilities Council, for "driving the development of laser-driven accelerators for applications and for leading collaborative partnerships between academia and industry vital for the transfer of this technology to tackle global challenges". The awards will be presented at a ceremony in London in November.

Flerov prize for superheavy elements


JINR

Witold Nazarewicz.

The 2017 Joint Institute for Nuclear Research (JINR) Flerov Prize has been awarded to Witold Nazarewicz of Michigan State University in the US for his contribution to the theoretical understanding of the properties of the heaviest elements. Nazarewicz's research focuses on rare isotopes, including superheavy nuclei and the heaviest elements that lie at the current borders of the chart of nuclides, and his calculations have helped to clarify the unusual properties of these elements.

A special Flerov prize for experimental research of heavy nuclei and synthesis of elements with atomic numbers 115 (moscovium) and 117 (tennessine) was also awarded to James Roberto of Oak Ridge National Laboratory, Alexander Shushkin (Elektrokhimpribor, Russia) and Vladimir Utyonkov (JINR, Dubna). Over the last two decades, collaboration between JINR and US labs has changed our understanding of the upper regions of the period table.

Events

DUNE breaks ground underground

On 21 July, scientists and dignitaries broke ground 1.5 km beneath the surface of South Dakota, US, to celebrate the start of the construction of the international Long-Baseline Neutrino Facility (LBNF). LBNF will host the international Deep Underground Neutrino Experiment (DUNE), involving around 1000 scientists from more than 160 institutions in 30 countries. The US$1 billion-plus LBNF/DUNE project will send an intense neutrino beam through 1300 km of rock from Fermilab in Illinois to the DUNE detectors deep underground at the Sanford Underground Research Facility in Lead, South Dakota. More than 800,000 tonnes of rock will be excavated to create the four huge chambers that will host the DUNE detectors.

The DUNE collaboration has begun the process of identifying the scientific institutions that will help build the components for the full-sized detectors. The cryostats and time projection chambers at the heart of the four DUNE detectors will hold almost 70,000 tonnes of liquid argon to detect neutrinos from Fermilab and supernova and search for new subatomic phenomena such as proton decay.

Large prototype detectors for DUNE based on liquid-argon technology are already currently under construction at CERN, which is a major partner in the project (*CERN Courier* March 2017 p19). The CERN neutrino platform was established in 2013 to strengthen European participation in neutrino experiments worldwide. Earlier this summer, CERN completed the refurbishment of part of the ICARUS detector, which was recently shipped to Fermilab's short-baseline neutrino facility, and a CERN team is currently testing a detector called Baby MIND for the WAGASCI experiment in Japan.

R Hahn/Fermilab

Representatives from US Congress, the US Department of Energy, the president's office, South Dakota state, CERN, INFN, STFC, and other project partners participated in the ceremony.

Langevin-Joliot travels back in time

Physicist Hélène Langevin-Joliot – emeritus research director in fundamental nuclear physics at the CNRS in Orsay, granddaughter of Pierre and Marie Curie, and daughter of Frédéric Joliot and Irène Curie – came to CERN in early July, bringing to life a little-known piece of local history. On 25 July 1930, the International Commission for Intellectual Cooperation (an advisory body to the League of Nations), which included Marie Curie and Albert Einstein, visited a restaurant called Hotel Leger in Thoiry, a small village close to CERN that was often the site of highbrow discussions (image, bottom). On invitation from CMS physicist Chiara Mariotti, Langevin-Joliot, who is 89, retraced the steps of her eminent ancestry during a visit to the local area and CERN. Alongside her academic career, she has campaigned against the deployment of nuclear weapons and championed access to scientific careers for women and others.

J Ordan/CERN

Marie-Pierre Soulard Lége

(Above) Marie Curie's granddaughter Hélène Langevin-Joliot at the Globe talking about her exceptional family and the current status of women in science. (Left) Marie Curie (seated, far left) at Hotel Leger, with Einstein seated third from the left. Curie was the first female to win a Nobel prize and remains the only person to have won it in two different sciences.

Anniversaries

10th anniversary of the ERC

J Ordan/CERN

Reinhilde Veugelers of the ERC Scientific Council speaking at an event held in the Globe on 6 July to mark 10 years of the European Research Council.

On 6 July, the Globe of Science and Innovation hosted an event celebrating the 10th anniversary of the European Research Council (ERC). The ERC awards significant grants to scientists to allow them to carry out cutting-edge research in institutes in the European Union or in associated countries such as Switzerland. For the seven-year period of Europe's Horizon 2020 programme, the ERC's budget is €13.1 billion, 39% of which is directed at physical sciences and engineering, and its advanced grants are highly sought after. The ERC held its plenary meeting at CERN from 4 to 7 July, and the Globe event saw CERN Director-General Fabiola Gianotti join other high-profile figures for a round-table discussion about the role of the ERC and fundamental research in Europe.

Brookhaven marks seven rich decades

BNL

Brookhaven site office manager Frank Crescenzo (left) and the lab's director Doon Gibbs kick off celebrations earlier this year.

Brookhaven National Laboratory in the US is marking two anniversaries occurring this year. It is 70 years since Brookhaven lab was founded in 1947 and 100 years since the founding of Camp Upton, the former US Army base where the lab operates today. Brookhaven has been at the forefront of high-energy physics research since its early days, with the Alternating Gradient Synchrotron (AGS) leading to the discovery of CP violation, the Ω^- and charmed baryons, the J/ψ meson and the muon neutrino. Today the lab is home to the Relativistic Heavy Ion Collider (RHIC), which has changed our view of the quark–gluon plasma, and the National Synchrotron Light Source II (NSLS-II).

CONFERENCES

Venice EPS event showcases the best of HEP

C Checchia

The Venice conference was attended by more than 1000 physicists from 50 countries.

Major scientific gatherings such as the European Physical Society (EPS) biennial international conference on High Energy Physics offer a valuable opportunity to reflect on the immense work and progress taking place in our field, including the growing connections between particle physics and the universe at large. This year's EPS conference, held in Venice, Italy, from 5–12 July, was also the first large conference where the results from the 2015 and 2016 runs of the Large Hadron Collider (LHC) at 13 TeV were presented.

Setting the bar just a day into the Venice event, LHCb announced the discovery of a new doubly charmed baryon from precision measurements of B decays, with heavy-flavour analyses continuing to offer a rich seam of understanding. LHCb also presented the intriguing anomalies being seen in the ratios of certain Standard Model decays that hint at deviations from lepton universality, with further data from LHC Run 2 hotly anticipated.

The LHC is firmly in the precision business these days. In the last two years, the machine has delivered large amounts of collision data to the experiments and striking progress has been made in analysis techniques. These have enabled measurements of rare electroweak processes such as the associated production of a top quark, a Z boson and a quark (tZq) by ATLAS, for example, and the definitive observation of WW scattering by CMS. Top physics is another booming topic, with new top-mass and single-top production measurements and many other results, including "legacy" measurements from the Tevatron experiments, on show.

At the core of the LHC's analysis programme is the exploration of the Higgs boson, which now enters its sixth year. Particularly relevant is how the Higgs interacts with other particles, since this could be altered by physics beyond the Standard Model. While the Higgs was first spotted decaying into other bosons (W, Z, γ), ATLAS reported the first evidence for the decay of the Higgs boson to a pair of bottom quarks, with a significance of 3.6σ, while CMS presented the first observation by a single experiment of the decay to a pair of τ leptons, with a significance of 5.9σ. The Higgs mass is also narrowing to 125 GeV, while the fundamental scalar nature of the new particle continues to raise hope that it will lead to new insights.

The lack of direct signs of new physics at the LHC is an increasing topic of discussion, and underlies the importance of precision measurements. Direct searches are pushing the mass limits for new particles well into the TeV range, but new physics could be hiding in small and subtle effects. It is clear that there is physics beyond the Standard Model, just not what it is, and one issue is how to communicate this scientifically fascinating but non-headline-worthy aspect of today's particle-physics landscape.

High precision is also being attained in studies of the strong interaction. ALICE, for example, reported an increase in strangeness production with charged multiplicity that seems to connect smoothly the regimes seen in pp, pPb and PbPb collisions. Overall, and increasingly with complementary results from the other LHC experiments, ALICE is closing in on the evolution of the quark–gluon plasma, and thus on understanding the very early universe.

Particle physics, astrophysics and cosmology are closer today than ever, as several sessions at the Venice event demonstrated. One clear area of interplay is dark matter: if dark matter interacts only through gravity, then finding it will be very difficult for accelerator-based studies, but if it has a residual interaction with some known particles, then accelerators will be leading the hunt for direct detection. Cosmology's transformation to a precision science continues with the recent detection of gravitational waves, with LIGO's results already placing the first limits on the mass of the graviton at less than 7.7×10^{-23} eV/c^2. There were also updates from dark-energy studies, and about precision CMB explorers beyond Planck.

Neutrino physics is also an extremely vibrant field, with neutrino oscillations continuing to offer chances for discovery. The various neutrino-mixing angles are starting to be well measured and Nova and T2K are zooming in on the value of the CP-violating phase, which seems to be large, given tantalising hints from T2K. The hunt for sterile neutrinos continues, and for neutrinoless double beta decay, with several searches ongoing worldwide.

In summary, the 2017 EPS-HEP conference clearly demonstrated how we are progressing towards a full understanding both of the vastness of the universe and of the tiniest constituents of matter. There are many more results to look forward to, many of which will be ready for the next EPS-HEP event in Ghent, Belgium, in 2019. As summed up by the conference highlights: the field is advancing on all fronts – and it's impressive.

A quarter century of DIS workshops

DIS17

Participants at the DIS17 meeting at the University of Birmingham campus.

With a total of 304 talks, Deep Inelastic Scattering 2017 (DIS17) demonstrated how deep inelastic scattering (DIS) and related topics permeate most aspects of high-energy physics and how we still have a huge amount to learn about strong interactions. Held at the University of Birmingham in the UK from 3–7 April, more than 300 participants from 41 countries enjoyed a week of lively scientific discussion and largely unanticipated sunshine.

The first of this series of annual international workshops on DIS and related topics took place in Durham, UK, in the Spring of 1993, when the first results from the world's only lepton-hadron collider, HERA at DESY, were discussed by around 80 participants. A quarter of a century later, the workshop series has toured the globe, digested data from the full lifetime of HERA and numerous fixed-target DIS experiments, as well as playing a major role in the development and understanding of hadron-collider physics.

The dominant theme of DIS17 this year was the relevance of strong interactions, parton densities (PDFs) and DIS to the LHC. But a wide and eclectic range of other topics was included, notably new results from experiments at the Relativistic Heavy Ion Collider (RHIC), JLab and HERA, as well as theoretical advances and future plans for the field.

Following plenary review talks covering the latest news from the field, there followed two and a half days during which seven working groups operated in up to six simultaneous parallel sessions, covering: PDFs; low proton momentum fraction (Bjorken-x) physics; Higgs and beyond-the-Standard Model (BSM) studies in hadron collisions; hadronic, electroweak and heavy-flavour observables; spin and 3D hadron structure; and future facilities. The Birmingham event included a topical lecture on probing ultra-low-x QCD with cosmic neutrinos at IceCube and Auger, and a special session was devoted to the status and scientific opportunities offered by future proposed DIS facilities at CERN such as the Large Hadron electron Collider, LHeC) and at BNL or JLab in the US (the Electron Ion Collider, EIC).

All aspects of proton–proton collisions at the LHC featured during this year's DIS event, from the role of parton densities and perturbative QCD dynamics in beyond-the Standard Model searches and Higgs boson studies, through the measurement and interpretation of processes that are sensitive to parton densities (such as electroweak gauge boson production), to topics that challenge our understanding of strong-interaction dynamics in the semi- and non-perturbative regimes. Ten years after HERA completed data-taking, the collider still featured strongly. The final round of combined inclusive DIS data published in 2016 by the H1 and ZEUS experiments have been integrated into global PDF fits, and also for a handful of new measurements and combinations. Heavy-ion collision results from RHIC and the LHC were also well represented, as were insights into 3D proton structure and hadron spin from semi-inclusive DIS and polarised proton–proton collisions at COMPASS, JLab and RHIC, and current and future DIS measurements with neutrinos.

Data from HERA and the LHC have brought a new level of precision to the parton densities of the proton, with associated theoretical advances including the push towards higher order (next-to-next-to-next-to leading order) descriptions. Taming the "pathological" rise of the proton gluon density at low-x in the perturbative domain remains a major topic, which is now being addressed experimentally in ultra-peripheral collisions and forward measurements at the LHC, as well as through theoretical modelling of low-x, low-Q^2 HERA data with nonlinear parton dynamics and resummation techniques. The related topic of diffractive electron–proton scattering and the heavily gluon-dominated diffractive PDFs is benefiting from the full HERA statistics. New insights into elastic and total cross-sections, such as TOTEM's observation of a non-exponential term in the four-momentum transfer dependence of the elastic cross-section, are emerging from the LHC data. Uncertainties in PDFs remain large at high x, and intense work is ongoing to understand LHC observables such as top-quark pair production, which are sensitive in this region. New data and theoretical work are revealing the transverse structure of the proton for the first time in terms of transverse-momentum-dependent parton densities. The LHC's proton–lead collision data are also constraining nuclear PDFs in an unprecedented low-x kinematic region.

Concerning the future of DIS, potential revolutions in our understanding could be made with polarised proton and heavy-ion targets and with step changes in energy and luminosity becoming abundantly clear. The EIC offers 3D hadron tomography and an unprecedented window on the spin and flavour structure of protons and ions. Its eA scattering programme would probe low-x parton dynamics in a region where collective effects ultimately leading to gluon saturation are expected to become important. The LHeC offers a standalone Higgs production programme complementary to that of the LHC, as well as a new level in precision in PDFs that could be applied to extend the sensitivity to new physics at the LHC. The ep and eA scattering programme also would probe low-x parton dynamics in the region where gluon saturation is expected to be firmly established. Together, the proposed facilities open up an exciting set of new windows on hadronic matter with relevance to major questions such as quark confinement and hadronic mass generation.

The next instalment of DIS in April 2018, to be held in Kobe, Japan, is eagerly awaited.

HEPTech helps transform ideas into innovations

G Otto/GSI

2017 HEPTech Symposium participants at Darmstadt.

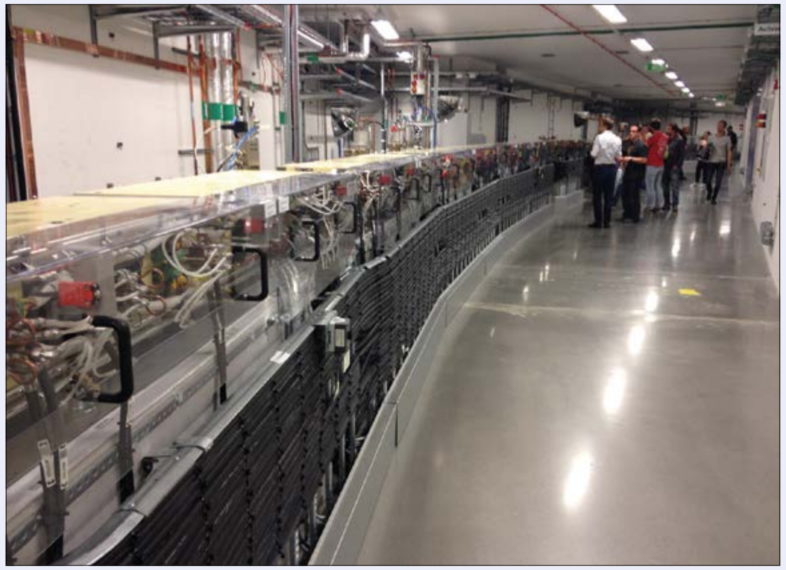
For a fourth consecutive year, the High-Energy Physics Technology Transfer Network (HEPTech), initiated by CERN in 2006, brought together early stage researchers in high-energy physics and related scientific domains to help them transform their research ideas into marketable innovations. The symposium was hosted by the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany, from 19–23 June.

Twenty participants from 11 European countries met with entrepreneurs and experienced scientists, learning about technology-push, design-thinking technology characterisation and value proposition. Prominent speakers introduced delegates to the specifics of collaborations in physics, the management of large research projects and decision-making, in a scientific environment. By exploring real cases, the long road from an innovation to a patent or licence and how to deal with intellectual-property rights, was made clear. Basic requirements for public funding and some funding opportunities for start-ups were presented, in addition to tips about how to avoid unexpected traps entrepreneurs might face.

Within the week-long event, the secrets of successful project management were discussed, and the importance of appropriate staffing and negotiation techniques.

The entrepreneurship success story of Raspberry Pi revealed how developments in research are transformed into successful marketable products and how to develop a commercially sustainable product in a competitive environment. A great challenge for the early stage researchers was to prepare short pitches presenting their research projects to an expert panel, with the aim of attracting investor attention.

All topics were presented by experienced professionals, entrepreneurs and technology-transfer experts, and participants enjoyed the networking opportunities on offer. The next HEPTech symposium will be held in June 2018 at the extreme light source ELI-ALPS in Szeged, Hungary.



R Bailey

The CERN Accelerator School (CAS) and MAX IV Laboratory jointly organised a specialised course on vacuum for particle accelerators in Glumslov, Sweden from 6–16 June. The course attracted 80 participants of 27 nationalities, comprising 30 hours of lectures and 17 hours of practical tutorial work. Lectures covered material properties, impedance and instabilities, gauges and pumps, surface properties and treatments, beam-induced effects, computational techniques and controls, manufacturing and acceptance, and a look to the future. The practical work included hands-on experience of impedance calculations, residual gas analysis and leak-detection techniques. An advanced accelerator-physics course will be held in the UK in late summer and a joint accelerator school on radio-frequency technologies will be held in Kanagawa, Japan, from 16–26 October. Pictured are CAS participants touring the new MAX IV storage ring.

Visits

All image credits: S Bennett

Prime minister of Montenegro **Duško Marković** came to CERN on 7 July. He visited the underground area at CMS, during which he signed a memorandum of understanding between Montenegro and CERN with CERN director for research and computing Eckhard Elsen (pictured right).

On 14 July, **Monique T G van Daalen**, ambassador of the Netherlands to the United Nations Office, visited CERN. Before signing the guestbook with CERN Director-General Fabiola Gianotti and president of the CERN Council Sijbrand de Jong (pictured), she visited the Antiproton Decelerator and ATLAS.

Mukhtar Ahmed, chairman higher education commission of Pakistan, pictured with Christoph Schäfer of CERN after signing the guestbook. During the 17 July visit, he took in the synchrocyclotron, ALICE, IdeaSquare, S'Cool LAB and CMS.

Monsieur **Henri-Michel Comet**, préfet de la région Auvergne-Rhône-Alpes, France, was at CERN on 20 July, during which he visited the synchrocyclotron and CMS, and signed the guestbook in the presence of CERN Director-General Fabiola Gianotti.

Obituaries

Vinod Chohan 1949–2017

Vinod "Nick" Chohan came to CERN in 1975 as a fellow, then went to SIN (today PSI) near Zürich. In 1980 he returned to CERN as a machine-supervisor in the PS division. At that time, the construction of the Antiproton Accumulator (AA, the world's first machine to produce, accumulate and store antiprotons) was just finished and the team was busy running it in. The purpose of the AA was to supply antiprotons to the SPS to allow it to function as a proton–antiproton collider, and Nick became a prominent member of the AA operations team that made this possible. His speciality was the controls aspects of the highly complicated processes within the AA and for the transfer of the antiprotons to the SPS. Simon van der Meer, inventor of stochastic cooling, on which the AA was based, had written practically all of the software himself, in his own highly sophisticated style. Nick became the only one to fully understand it, and later extend it to the Antiproton Collector (AC) and convert it for integration into the PS controls system.

Nick Chohan's charisma will be missed

When, in 1991, the PS Beam Diagnostics (BD) Group was founded, Nick was the natural choice to become the section leader for systems integration with the PS controls. In 1996, when the high-energy collider part of CERN's antiproton programme was terminated, Nick took on the additional responsibility of PS divisional safety officer. Then, in 2002, he became heavily involved in the LHC project. Nick moved to the Accelerator Technology (AT) Division, where he led a team that first tested an LHC prototype-sector and then all of the 1706 superconducting bending magnets. CERN manpower was insufficient, but a collaboration with India, managed by Nick, made it possible.

Once the LHC became operational, Nick returned to his old affinity with antiprotons, now at the low-energy end of the programme, as editor of the ELENA design report. In 2014, the 65 year bell rang in his retirement. But for Nick, that was not a reason to stop work at CERN. He joined the CERN scientific information service and provided highly welcome help on accelerator physics literature, photographic documentation and articles for Wikipedia.

Throughout his years at CERN, we all knew Nick as friendly and easy-going, always helpful and dedicated in his typical competent manner. We are deeply moved by his sudden disappearance and shall hold on to the memory of the many good moments and years of collaboration and friendship that we shared with him.

● *His friends and colleagues.*

Satoshi Ozaki 1929–2017

World-renowned physicist Satoshi Ozaki, who helped design and build accelerators for scientific research across two continents including two of the flagship facilities at Brookhaven National Laboratory (BNL), died on 22 July aged 88. He was a senior scientist emeritus at BNL and a key driver of international collaborations in high-energy and nuclear physics.

Ozaki joined Brookhaven Lab in 1959 with a master's degree in physics from Osaka University, Japan, and a PhD in physics from the Massachusetts Institute of Technology. He worked in a group he eventually co-led with Samuel Lindenbaum on experiments at Brookhaven's Alternating Gradient Synchrotron (AGS), developing state-of-the-art electronic detectors and an online data facility for monitoring detector performance by reconstructing subsets of data in real time. This was the first system of its kind and is now a routine component of data-acquisition systems for complex electronic detectors. The Ozaki–Lindenbaum group also developed a multiparticle spectrometer at the AGS that served many

BNL

Satoshi Ozaki, builder of accelerators and scientific collaborations across continents.

experimental groups at Brookhaven and collaborating universities. In addition, Ozaki led the development of detectors for ISABELLE, the first design for a dual-ring superconducting collider at Brookhaven.

Ozaki's work in large-scale detector development led to an invitation in 1981 from KEK to direct the construction of TRISTAN, the first major high-energy particle collider in Japan. Under Ozaki, this $500 million project was completed on time and within budget to start operations in 1987, accelerating and storing beams of electrons and positrons at 30 GeV – the highest energy in the world at the time. In 1989, Ozaki returned to Brookhaven to head the Relativistic Heavy Ion Collider (RHIC) project, which achieved first collisions in 2000 and is now the highest energy collider in the US, with many important discoveries about the quark–gluon plasma under its belt. Ozaki was also essential in securing Japanese support for RHIC-related projects.

In 2005, Ozaki joined the National Synchrotron Light Source II (NSLS-II) project. As the initial head of the NSLS-II accelerator division, Ozaki built up the group and remained with the project as a senior advisor even after formally retiring at the end of 2012. He took on the major task of procuring the storage-ring magnets, and attended the formal dedication of the completed facility in February 2015. Ozaki was also involved in the Facility for Rare Isotope Beams (FRIB) currently under construction at Michigan State University.

Ozaki's accomplishments have been recognised with numerous prestigious awards, including the 2007 IEEE Nuclear and Plasma Sciences Society Accelerator Science and Technology Award and the 2009 Robert R Wilson Prize of the American Physical Society, and in 2013 he was recognised with Japan's prestigious Order of the Sacred Treasure.

Ozaki was predeceased by his wife, Yoko, and is survived by their two children, Keiko Simon and Tsuyoshi Ozaki, their spouses, and four grandchildren.

● *Brookhaven National Laboratory.*

Faces & Places

Yassen Stanislavov Stanev 1962–2017

Yassen Stanev of the Bulgarian school of theoretical physics and INFN at the University of Rome "Tor Vergata", passed away on 9 June after a short illness. He was born in Sofia, Bulgaria, on 4 July 1962. After graduating in physics at the University of Sofia, he worked in its theoretical-physics department before joining the Institute for Nuclear Research and Nuclear Energy of the Bulgarian Academy of Sciences in 1992. Stanev defended his PhD thesis on conformally invariant quantum-field theory models in 1994 under the guidance of Ivan Todorov, who has long been a distinguished Bulgarian visitor of the CERN theory department. Since 2004, he had been working at the University of Rome.

Stanev had a wide range of scientific interests, including super-conformal field

Stanev was an expert in conformal field theories

theories (CFTs), quantum groups, string theory and gauge theories. His work on the structure of the conformally invariant three-point correlation of the stress-energy tensor, published while he was a PhD student in his 20s, is still influential today. His pioneering work in the mid 1990s with his Italian colleagues unveiled the general completeness relations for 2D CFT's in the presence of boundaries and cross-caps, and his related results on open strings (which include the first chiral type-I superstring model in four dimensions) are well known among string theorists. After the advent of the AdS/CFT correspondence, he worked extensively on N = 4 SYM and its conformal deformations. His last research, on two-point correlators in N = 2 gauge theories, involved an international team of colleagues and appeared a month before his premature death.

Stanev was also a gifted teacher and, during the last few years, he was a member of the INFN theoretical-physics committee. We will miss his wit, humour, critical views and his friendship.

● *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.

Imagine taking part in one of the largest scientific experiments in the world.

People at CERN are driven by a shared goal, a single purpose. They want to achieve the impossible, to do what's never been done before. Everyone here strives to be the best they can be, true specialists and industry "firsts" are created regularly – not just in the world of physics. The engineering and technical skills needed to make the experiments succeed are as world-class as the science behind them.

If you're a student, a graduate, just starting your career or an experienced professional; if you're interested in joining our technical or support teams or if you're an engineer or professional in any area from mechanics to accounting, this is more than an opportunity to start or develop your career: it's an opportunity to develop knowledge and science on a global scale.

In fact, it's an opportunity like nowhere else on Earth.
cern.ch/jobs. Take part!

CERN | HR Human Resources

Imperial College London

Department of Materials, Faculty of Engineering

Reader or Chair in Functional Thin Film Growth

Competitive Salary

We are seeking a new colleague to lead a world-class hub in functional thin film growth for device structures by establishing an internationally recognised experimental research programme. As an exceptional academic with a track record of the highest quality research in the area of the physical deposition of thin films, you are invited to apply.

This post is associated with the Atoms to Devices core research area of the Henry Royce Institute (HRI) for Advanced Materials at Imperial College London. You will be supported with purpose-built laboratory space at Imperial's new White City Campus and a generous capital equipment budget to expand our current shared facility.

You will be joining a vibrant and exciting department that enjoys an ethos of collaboration and is recognised as world-leading with strong international links.

You will be expected to:

- attract and supervise high-quality PhD students and supervise postdoctoral research staff
- publish papers in leading peer-reviewed journals
- disseminate research findings at international conferences
- seek and obtain external research funding
- contribute to the Department's outstanding teaching programmes
- interact with scientists and engineers from other departments across Imperial and the HRI, as well as to develop external collaborations both nationally and internationally.

You will possess a PhD degree (or equivalent) in physical sciences, engineering or a related discipline. You will be able to provide evidence of an international reputation including an outstanding publication record, a track record of securing major research funding and experience of teaching undergraduate students. Ability to lead a shared facility, or evidence of potential to do so through success in setting up a substantial experimental laboratory are also essential.

For more information and how to apply please visit www.imperial.ac.uk/job-applicants/.

Closing Date: 30 September 2017

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 future colliders (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.

Futher informations and a link to the submission system for your application and the references can be found here:

http://particle-physics.desy.de/education__career/fellowship/index_eng.html

Please note that it is the applicants responsibility that all material, including letter of references, reach DESY before the deadline for the application to be considered.

Salary and benefits are commensurate with those of public service organisations in Germany. Classification is based upon qualifications and assigned duties. Handicapped persons will be given preference to other equally qualified applicants. DESY operates flexible work schemes. DESY is an equal opportunity, affirmative action employer and encourages applications from women. Vacant positions at DESY are in general open to part-time-work. During each application procedure DESY will assess whether the post can be filled with part-time employees. 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: FHFE003/2017
Notkestraße 85 | 22607 Hamburg | Germany | Phone: +49 40 8998-3392
Email: recruitment@desy.de
Deadline for applications: 30 September 2017
www.desy.de

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

HELMHOLTZ | ASSOCIATION

Accelerators | Photon Science | Particle Physics
Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

DESY

PARTICLE PHYSICS.

DESY, Hamburg location, is seeking:
Scientist (f/m) ATLAS

DESY

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

The particle physics programme of DESY consists of strong contributions to the LHC experiments ATLAS and CMS, the Belle and Belle-2 Experiments at KEK and to the preparation of future experiments. The experimental programme is enhanced by collaboration with a strong theory group. DESY is searching an experienced experimental physicist (f/m), who will take a leading role in the physics analysis of ATLAS data and in the operational and upgrade aspects of the ATLAS experiment.

The position

- Active role in the ATLAS experiment
- Leading role in ATLAS data analysis
- Strong participation in ATLAS detector operation or upgrade (hardware and/or software)
- Participation in the supervision of students and postdocs

Requirements

- PhD in experimental Particle Physics
- Experience in data analysis
- Experience in detector operations and/or development
- Experience in software development
- Outstanding teamwork abilities and excellent communication skills and knowledge of English

For further information please contact Prof. Dr. Beate Heinemann (beate.heinemann@desy.de).

Please submit your application including a motivation letter, research interests, curriculum vitae and copies of University degrees to the DESY human resources department. Make sure that you indicate the position identifier on all communications (FHMA037/2017).

Please arrange for two letters of reference to be sent to the DESY human resource department (recruitment@desy.de), clearly stating your name and the position identifier (FHMA037/2017).

Salary and benefits are commensurate with those of public service organisations in Germany. Classification is based upon qualifications and assigned duties. Handicapped persons will be given preference to other equally qualified applicants. DESY operates flexible work schemes. DESY is an equal opportunity, affirmative action employer and encourages applications from women. Vacant positions at DESY are in general open to part-time-work. During each application procedure DESY will assess whether the post can be filled with part-time employees. 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: FHMA037/2017
Notkestraße 85 | 22607 Hamburg | Germany | Phone: +49 40 8998-3392
Email: recruitment@desy.de
Deadline for applications: 30 September 2017
www.desy.de

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

HELMHOLTZ | ASSOCIATION

CERN Courier September 2017

KIT

Karlsruhe Institute of Technology

Karlsruhe Institute of Technology (KIT) pools its three core tasks of research, higher education, and innovation in a mission. With about 9,400 employees and 25,000 students, KIT is one of the big institutions of research and higher education in natural sciences and engineering in Europe.

In Division V, Physics and Mathematics, the Department of Physics at KIT invites applications for a

Professorship (W3) in Experimental Astroparticle Physics

(succession of Prof. J. Blümer). The position is based at the Institute for Experimental Particle Physics (ETP) and holds, in addition, the directorship of the Institute for Nuclear Physics (IKP).

Both institutes play a leading role in large international experiments, like KATRIN and the Pierre Auger Observatory as well as at CERN and KEK. Further activities include contributions to IceCube and the search for Dark Matter. We expect an active development of research in experimental Astroparticle Physics and a leading participation in the Helmholtz programs **Matter and the Universe and Matter and Technology**.

We are seeking an outstanding scientist with background in one or more of the following areas: search for Dark Matter, high-energy astroparticle physics, and neutrino physics. The institutes provide excellent infrastructure with workshops, laboratories and clean rooms. Furthermore, the Grid Computing Centre Karlsruhe (GridKa) hosts extensive computing resources for data processing and analysis. The institutes are embedded in the KIT Centre for Elementary Particle and Astroparticle Physics (KCETA), with its Graduate School KSETA, which connects the experimental, theoretical, and technological activities surrounding the professorship.

You are also expected to take part in teaching activities of the Department of Physics at the undergraduate and graduate levels, and in service typical for a faculty member. Applicants should have obtained the degree of **Habilitation** or an equivalent scientific qualification, and are required to have experience in teaching. The appointed professor is expected to teach in German after a reasonable amount of time.

KIT is pursuing a gender equality policy. We would therefore particularly encourage qualified women to apply. If qualified, handicapped applicants will be preferred. The requirements for employment listed in § 47 Landeshochschulgesetz (LHG) apply.

Applications with the usual resume (including a curriculum vitae, a research plan, a summary of the teaching experience, and the five most important publications), should be sent by **October 2, 2017** to: **Dekan der KIT-Fakultät für Physik, Karlsruher Institut für Technologie (KIT), 76128 Karlsruhe, Germany**, preferably via e-mail to **dekanat@physik.kit.edu**. For questions related to research and the institutes please contact Prof. Th. Müller, e-mail: thomas.muller@kit.edu or Prof. G. Drexlin, e-mail: guido.drexlin@kit.edu.

Since 2010, the KIT has been certified as a family-friendly university.

KIT – The Research University in the Helmholtz Association

SCIENTIFIC MAGNETICS

World Leaders in Cryogen-free Superconducting Magnets

Scientific Magnetics is a leading manufacturer of superconducting magnets and helium-free cryogenic systems, based in Abingdon, Oxfordshire. In line with our exciting expansion plans, we are hiring across a number of business-critical functions. To compliment and reinforce our existing team of highly experienced engineers, technicians and support staff, we would be interested in hearing from candidates to fulfil our

Senior Physicist/Magnet Engineer role

Reporting to the Technical Director

Position: Full Time

Key Responsibilities:

Modelling of magnetic (mainly superconducting) systems using industry standard tools including OPERA, COMSOL Multiphysics and other analytical tools.

Design and development of cryogenic and cryogen-free superconducting magnet systems.

Generation of line-up information for the drawing office; checking and approving of detailed drawings.

Generation of working instructions and procedures in accordance with the Company's ISO9001 Quality Assurance policy.

Project management of projects and parts of major projects.

Specifying and conducting tests in the workshop; recording and interpreting results in accordance with quality and health & safety policies.

Liaison with partners and suppliers in all parts of the world as required.

Generation of technical reports for internal use and external publication.

Fostering relationships and links with existing customers and suppliers, and with potential new customers in academia and industry.

Dealing with queries from customers and collaborators, supplying information in the relevant format in a concise and timely manner.

Keeping up to date with relevant technology and disseminating information within the Company.

Qualifications / Experience:

Degree qualified in physics or a physical science course, possibly to PhD level.

Expertise and knowledge of a subset of the following:

- Superconducting magnet design
- OPERA 2D / 3D –Static magnetic and transient analysis
- COMSOL Multiphysics simulation software package
- Superconducting joint design
- Quench protection design
- Persistent switch design
- Impregnation techniques for magnet designs
- Cryogenic vessel heat load calculations

To apply, please email your CV to **jobs@scientificmagnetics.co.uk**

www.scientificmagnetics.co.uk

Scientific Magnetics Ltd is part of Avingtrans PLC

Announcement of CERN's 2018 Beamline for Schools competition

CERN is pleased to announce the 5th edition of the Beamline for Schools competition. Once again, in 2018, a fully equipped beamline will be made available at CERN for high-school students from around the world. What better way to learn about physics?

As in previous years, two teams will be invited to CERN to run their proposed experiments. The competition is open to teams of at least 5 students aged 16 and up with at least one adult supervisor.

BL4S is a unique science competition that can be used by teachers to complement or extend the physics classes. Our experience shows that it triggers a high level of motivation among students. Please help us to spread the word.

The deadline for proposals is the 31 March 2018. The winners will be announced in June and are expected to come to CERN in September 2018. Short-listed teams are offered smaller prizes. All participants will receive a certificate.

Dive into the fascinating world of particle physics and register already for 2018: http://beamline-for-schools.web.cern.ch/pre-registration-2018

beamline for schools

cern.ch/bl4s

powered by CERN

Join the adventure here: cern.ch/bl4s

eli beamlines

Institute of Physics ASCR, v. v. i., Na Slovance 2, 182 21 Praha 8

info@eli-beams.eu | www.eli-beams.eu

The ELI (Extreme Light Infrastructure) Project is an integral part of the European plan to build the next generation of large user and research facilities. ELI-Beamlines, as a cutting edge facility, is currently being constructed in Prague, Czech Republic. ELI will provide for both fundamental and applied research sources (beamlines) of energetic photons and charged particles accelerated or generated in laser-driven plasma under extremely high intensities of electromagnetic fields.

The theory and simulation group wants to reinforce their activities in the field of macroscopic laser-plasma interaction and its simulation. This is of importance to pre-pulse physics for high- power laser-matter interaction as well as for inertial confinement fusion.

The work is supposed to prepare and accompany experiments planned at international high- intensity laser facilities and help to define the research program for ELI-Beamlines.

In our team we therefore have the following position available:

Junior scientist for macroscopic laser-plasma interaction

Job description:

- Macroscopic simulations of laser-plasma interaction are essential for a detailed understanding of the underlying physics on macroscopic spatial scales and temporal scales
- This requires the development of accurate models for transport processes of particles and photons, correct laser absorption models and accounting for possible backscattering.
- The work will require to develop these new models in collaboration with other groups locally and internationally and to incorporate them in numerical simulation tools.

Requirements:

- PhD in theory/simulation of hot plasmas
- Experience with simulation work and code development
- Good analytical skills
- Very good working knowledge of English
- Previous experience in laser-plasma interaction studies would be a plus
- Experience with one or more programming languages (C, C++, Fortran)

Job conditions:

- The opportunity to participate in this unique scientific project
- Career growth, professional education
- Competitive and motivating salary
- 5 weeks of holiday and other employee benefits

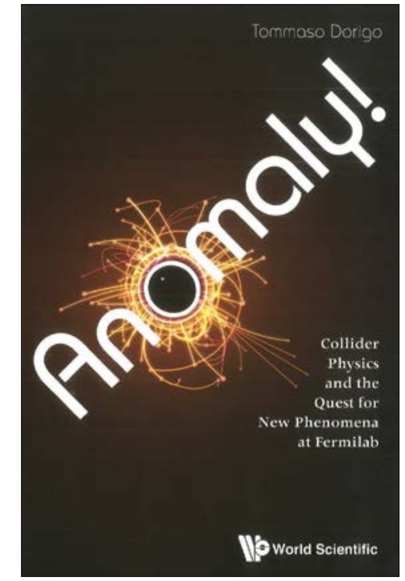
Applications, containing CV, cover letter, contacts of references, and any other material the candidate considers relevant, should be sent to Mrs. Jana Ženišková, HR specialist (jana.zeniskova@eli-beams.eu, +420 - 601560322). Please include the following text in your cover letter, to allow us to process your personal details:

I agree that, according to the decree 101/2000 coll. (Czech Republic), my personal details sent to FZU AV CR, v.v.i., Na Slovance 2, 18221 Praha 8, Czech Republic can be used for the purpose of obtaining employment and management of database of employment candidates. This permission is given for the period of one year and can be at any time withdrawn by giving a notice in writing.

Bookshelf

Compiled by Virginia Greco, CERN

Anomaly! Collider Physics and the Quest for New Phenomena at Fermilab
By Tommaso Dorigo
World Scientific
Also available at the CERN bookshop



Anomaly! is a captivating story of supposed discoveries that turned out not to be. The book provides an honest and not always flattering description of how large high-energy physics collaborations work, what makes experimental physicists excited, and of the occasional interference between scientific goals and personal factors such as ambition, career issues, personality clashes and fear of being scooped. Dorigo, who complements his recollections with many interviews and archival searches, proves to be a highly skilled communicator of science to the general public, as already known to the readers of his often controversial blog *A Quantum Diaries Survivor*. Thanks to well-chosen alternation of narration and explanation, several sections of the book read like a novel.

The main theme, as indicated by the title, is the anomalies (or outliers) that tantalised members of the CDF collaboration at Fermilab – and sometimes the external world – but ultimately turned out to be red herrings. The author uses these stories to show how cautious experimental particle physicists have to be when applying statistics in their data analysis. He also makes a point about the arbitrariness of the conventional 3σ and 5σ thresholds for claiming "evidence" and "discovery" of a new phenomenon.

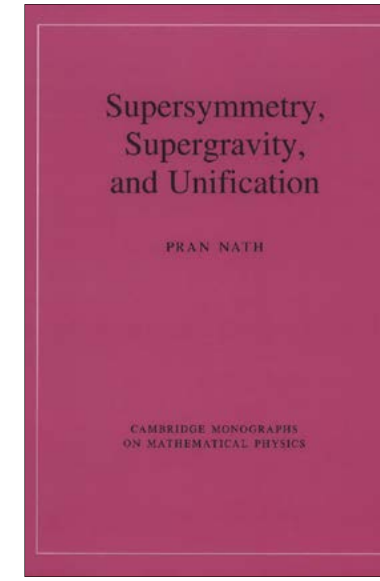
Slightly off topic, given the title of the book, three chapters are devoted to the ultimately successful search for the top quark, the first evidence of which was very far from being an "anomaly": its existence was expected in the mainstream and the "global fits" of other collider data were already pointing at the right mass range. Here Dorigo is interested in the opposite lesson: the conventional thresholds on p-values, originally motivated by the principle "extraordinary claims demand extraordinary proofs", are hard to justify when a discovery is actually a confirmation of the dominant paradigm. (The author explicitly comments on the similarity with the Higgs boson discovery two decades later.) The saga of the top-quark hunt, which contains many funny and even heroic moments, is also an occasion for the author to elaborate on what he describes as over-conservative attitudes dominating in large teams when stakes are high.

In general, the book's topics have clearly been chosen more by the importance of the lesson they teach than by their ultimate impact on science. Almost an entire chapter is devoted to a measurement of the Z boson mass at Fermilab, which was already known in advance to be doomed to obsolescence very soon, as the experiments at the upcoming LEP accelerator were more suited to that kind of measurement. Still, the chapter turns out to be an enthralling story, ending with a mysterious attempt by an unsporting competitor from another US laboratory to sabotage the first CDF report of this measurement at an international conference. In some other cases, the choice of topics is driven by their entertainment value, as in the case of the episode of the "Sacred Sword", a radioactive-contamination incident that luckily ended well for its protagonists.

The author's role in the book is at the same time that of an insider and of a neutral observer, attending crucial meetings and observing events unfold as a collaboration member among many others, with the remarkable exception of the final story where he plays the role of internal reviewer of one of the eponymous anomalies. In spirit and form, *Anomaly!* reminds me of Gary Taubes' celebrated *Nobel Dreams*, but with more humour and explicit subjectivity. Although far from being scholarly, *Anomaly!* may also appeal to readers interested in the sociology of science or in the epistemological problem of how a scientific community finally settles on a single consensus, in the vein of Andrew Pickering's *Constructing Quarks*, Peter Galison's *How Experiments End* and Kent Staley's *The Evidence for the Top Quark: Objectivity and Bias in Collaborative Experimentation*. The latter, in particular, is interesting to compare with the chapters of *Anomaly!* that narrate the same story.

● *Andrea Giammanco, UCLouvain, Louvain-la-Neuve, Belgium.*

Supersymmetry, Supergravity, and Unification
By Pran Nath
Cambridge



This book discusses the role played by supersymmetry, and especially supergravity, in the quest for a unified theory of fundamental interactions. These are vast subjects, which not only embrace particle physics but also have ramifications in many other fields, such as modern mathematics, statistical physics and condensed-matter systems.

The author focuses on a rather specific subject: supergravity as a plausible scenario (perhaps more convincing than supersymmetry itself) for physics beyond the Standard Model. This justifies the way the author has chosen to distribute the material over the 24 chapters, for a total of 500 pages.

The first seven chapters introduce the ▷

Bookshelf

field theories and symmetry principles on which a framework for the unification of particle forces would be based. After a short history of force unification, the author covers general relativity, Yang–Mills theories, spontaneous symmetry breaking, the basics of the Standard Model, the theory of gauge anomalies, effective Lagrangians and current algebra.

Supersymmetry is introduced next, with a short mathematical formulation including the concepts of graded lie algebras, superfields and the basic tools needed to construct (rigid) supersymmetric field theories, their multiplets and invariant Lagrangians. Non-supersymmetric grand unified theories and their supersymmetric extensions are also reviewed, investigating in particular the potential role they play in gauge coupling unification. It is surprising that the author does not discuss the original motivation for advocating supersymmetry in this context, which is related to the hierarchy problem and to the issue of naturalness of scales. No such discussion occurs in this chapter nor in the following one, devoted to the minimal supersymmetric Standard Model. The theory of supergravity and its mathematical structure, including matter couplings, is briefly exposed as well.

The second half of the book includes five chapters dedicated to the phenomenology of supergravity, covering in detail supergravity unification, CP violation, proton decay and supergravity in cosmology and astroparticle physics. In particular, supergravity inflation and supersymmetric candidates for dark matter are discussed at length. Further theories of supergravity and their connection to string theories in diverse dimensions are only briefly touched upon.

The last part of the book provides some tools, such as anti-commuting variables and spinor formalism, which are needed to write supersymmetric Lagrangians and to extract physical consequences. Notations, conventions and other miscellaneous arguments including further references conclude the volume.

The book can be considered as a valuable and updated addition to Steven Weinberg's third volume on supersymmetry in *The Quantum Theory of Fields* series (2000, Cambridge University Press).

The author is a world expert on supersymmetry and supergravity phenomenology, who has contributed to the field with many original and outstanding works.

Certainly useful to graduate students in physics, the book could also prove to be a resource for advanced graduate courses in experimental high-energy physics.

● *Sergio Ferrara, CERN.*

Books received

The Meaning of the Wave Function: In Search of the Ontology of Quantum Mechanics

By Shan Gao

Cambridge University Press

Does the wave function directly represent a state of reality, or merely a state of (incomplete) knowledge of it, or something else? This question is the starting point of this book, in which the author – a professor of philosophy – aims to make sense of the wave function in quantum mechanics and investigate the ontological content of the theory. A very powerful mathematical object, the wave function has always been the focus of a debate that goes beyond physics and mathematics to the philosophy of science.

The first part of the book (chapters 1–5) deals with the nature of the wave function and provides a critical review of its competing interpretations. In the second part (chapters 6 and 7), the author focuses on the ontological meaning of the wave function and proposes his view, which is that the wave function in quantum mechanics is real and represents the state of random discontinuous motion of particles in 3D space. He offers two main arguments supporting this new interpretation. The third part (chapters 8 and 9) is devoted to investigating possible implications. In particular, the author discusses whether the quantum ontology described by the wave function is enough to account for our definite experience, or whether additional elements, such as many worlds or hidden variables, are needed.

Aimed at readers familiar with the basics of quantum mechanics, the book could also appeal to students and researchers interested in the philosophical aspects of modern science theories.

Problem Solving in Quantum Mechanics: From Basics to Real-World Applications for Materials Scientists, Applied Physicists, and Device Engineers

By Marc Cahay and Supriyo Bandyopadhyay

Wiley

With the rapid development of nanoscience and nano-engineering, quantum mechanics can no longer be considered exclusively the interest of physicists. Indeed, a fundamental understanding of physical phenomena at the nanoscale will require future electronic engineers, condensed-matter physicists and material scientists to master the fundamental principles of quantum theory.

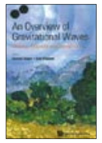
Noticing that many textbooks on quantum mechanics are not meant for a wide audience of scientists, in particular those interested in practical applications and technologies at the nanoscale, the authors decided to fill this gap. In particular, they focus on the solution of problems that students and researchers working on state-of-the-art material and device applications might have to face. The problems are grouped by theme in 13 chapters, each completed by a section of further readings.

An ideal resource for graduate students, the book is also of value to professionals who need to update their knowledge or to refocus their expertise towards nanotechnologies.

An Overview of Gravitational Waves: Theory, Sources and Detection

By Gerard Auger and Eric Plagnol (eds)

World Scientific



In 2016, the first direct detection of gravitational waves – produced more than a billion years ago during the coalescence of two black holes of stellar origin – by the two detectors of the LIGO experiment was a tremendous milestone in the history of science. This timely book provides an overview of the field, presenting the basics of the theory and the main detection techniques.

The discovery of gravitational radiation is extraordinarily important, not only for confirming the key predictions of Einstein's general relativity, but also for its implications. A new window on the universe is opening up, with more experiments – already built or in the planning stage – joining the effort to perform precise measurements of gravitational waves.

The book, composed of eight chapters, collects the contributions of many experts in the field. It first introduces the theoretical basics needed to follow the discussion on gravitational waves, so that no prior knowledge of general relativity is required. A long chapter dedicated to the sources of such radiation accessible to present and future observations follows. A section is then devoted to the principles of gravitational-wave detection and to the description of present and future Earth- and space-based detectors. Finally, an alternative detection technique based on cold atom interferometry is presented.

CERN Courier Archive: 1974

A look back to CERN Courier vol. 14, September 1974, compiled by Peggie Rimmer

Labs

Fermi National Accelerator Laboratory

The Fermi National Accelerator Laboratory has rapidly established itself among the finest research centres in high-energy physics. It is operating the world's highest energy, highest intensity proton accelerator and, until it is joined by the CERN SPS, has a monopoly on some almost completely unexplored regions of physics.

Something about the atmosphere of the Laboratory is different from any of the established high-energy physics research centres. Aesthetically, a spectacular site has emerged from the cornfields of Illinois. Managerially, a way of operating not in line with practices elsewhere has been implemented. Behind these features is Director R R Wilson, who set very ambitious goals and reached them with his own distinctive style.

A special effort has been made to establish a framework of equal employment opportunity to encourage the recruitment and training of staff from minority groups. The Laboratory Policy Statement says categorically "in any conflict between technical expediency and human rights, we shall stand firmly on the side of human rights."

The spectacular site is also being used to preserve features of the region or to re-establish a lost environment. A herd of buffalo enjoys one field, a herd of Angus cattle another. The centre of the ring is being given over to a ten-year project to restore an area of prairie to its pre-urbanization state. It will be the biggest nature reserve of its type in the world.

● Compiled from texts on pp283, 285 & 292.

The Meson hall houses the bulk of the detection systems for experiments on secondary beams with energies up to 300 GeV. The beams, emerging from a single target, enter from the left and "fingers" to accommodate additional detectors protrude behind the building on the right.

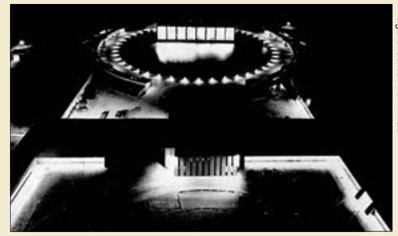


Image credits: Fermilab

A night view from the top of Hi-Rise which again illustrates the architectural attractiveness of the site. It shows the 8 GeV booster with its central cooling pond and services building. In front of it is the cross-gallery, housing the control room, and on each side are the symmetric arms of the linac (on the right) and the link to the main ring (on the left).

Argonne

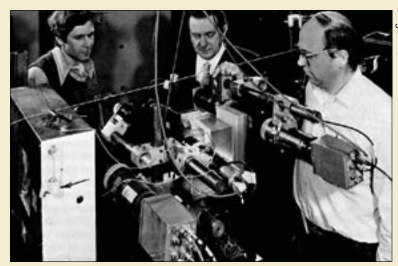
Proton radiography

A particularly lively topic at Argonne is the development of practical methods of using proton beams to take medical radiographs. A small group has been working on this in collaboration with members of the medical faculty of the University of Chicago. The group is very enthusiastic about the eventual value of proton radiography in medical applications, as an example of unexpected benefits from high-energy physics research.

The great attractiveness of the technique comes from the fact that the number of transmitted protons varies very rapidly near the end of their range so that slight density variations in the material traversed can cause dramatic changes in the number of emerging protons. This is in contrast to X-rays which are exponentially attenuated while traversing matter. Tumours and other abnormalities in human tissue are characterized by changes in density of a few percent or less from that of healthy tissue, so proton radiography could make the detection of tumours more reliable at an earlier stage of development than is possible at present and with a significantly smaller radiation dose.

When the project was first discussed at Argonne about a year ago, it was realized that, to become a common diagnostic tool, appropriate proton beams would be necessary at hospitals. R L Martin produced a conceptual design for a reliable and inexpensive 200 MeV proton diagnostic accelerator (PDA) which most hospitals could afford and operate. Ron Martin expressed it in his usual pungent style by saying that "anyone who wants to shut down accelerators […] should have their heads examined and in another year Argonne will have just the tool to do it with."

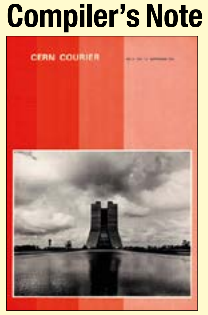
● Compiled from text on pp303–304.



Argonne

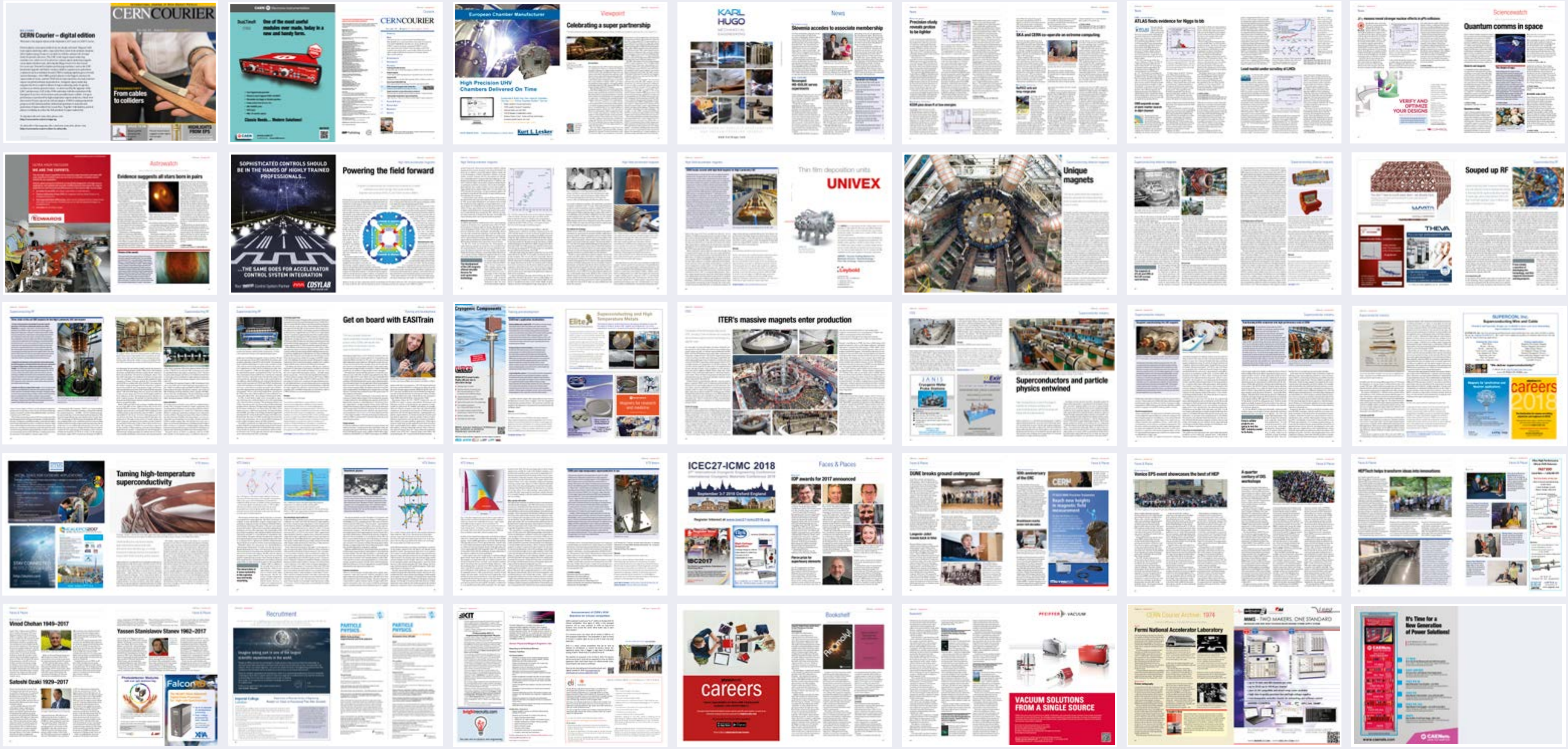
Tests on proton radiography using a beam from the 200 MeV booster at Argonne and a brain specimen in a water-filled box.

Compiler's Note



Robert Rathbun Wilson's influence on the look and feel of Fermilab is legendary. A 20th century polymath, Wilson left another memorable legacy. Having worked on the Manhattan Project, he fought unceasingly for the peaceful use of atomic energy. A seminal contribution was his paper "Radiological Use of Fast Protons", published in 1946, which established the fundamental tenets and techniques of proton therapy.

In 2000, Wilson was fittingly laid to rest in the Pioneer Cemetery, an early settlers' burial ground dating from 1839 that became enclosed within the 6800 acre Fermilab site. In 2006, his wife Jane was buried alongside him.



CERNCOURIER

Volume 57 Number 7 September 2017

Contents