WELCOME

CERN Courier – digital edition

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

We can all agree that education and outreach are vital for the future of high-energy physics, but finding the time to take part in such activities as a research scientist can be hard. Writing in this issue, president of the CERN Council, Sijbrand de Jong, leads by example. We also look at 25 years of the European School of High-Energy Physics, which has helped launch countless research careers, and get an insider's perspective on inspiring students via a visit to CERN. Hot off the heels of the award of the 2017 Nobel Prize in Physics for the discovery of gravitational waves, Barry Barish describes the status and future of gravitational-wave science, while this month's cover feature reports on progress in advanced and novel accelerators and the long-term goal of a high-energy linear collider. Also, as part of a larger research programme to understand the cosmological matter–antimatter imbalance, the ASACUSA collaboration describes new measurements of hydrogen's hyperfine structure. Finally, we bid farewell to the *Courier*'s production editor Lisa Gibson, who has been part of the team since 2013. Having produced the layouts for 45 issues and dealt with the differing demands of three *Courier* editors, we thank her for all her creative input and wish her the very best in her new career.

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CERNCOURIER

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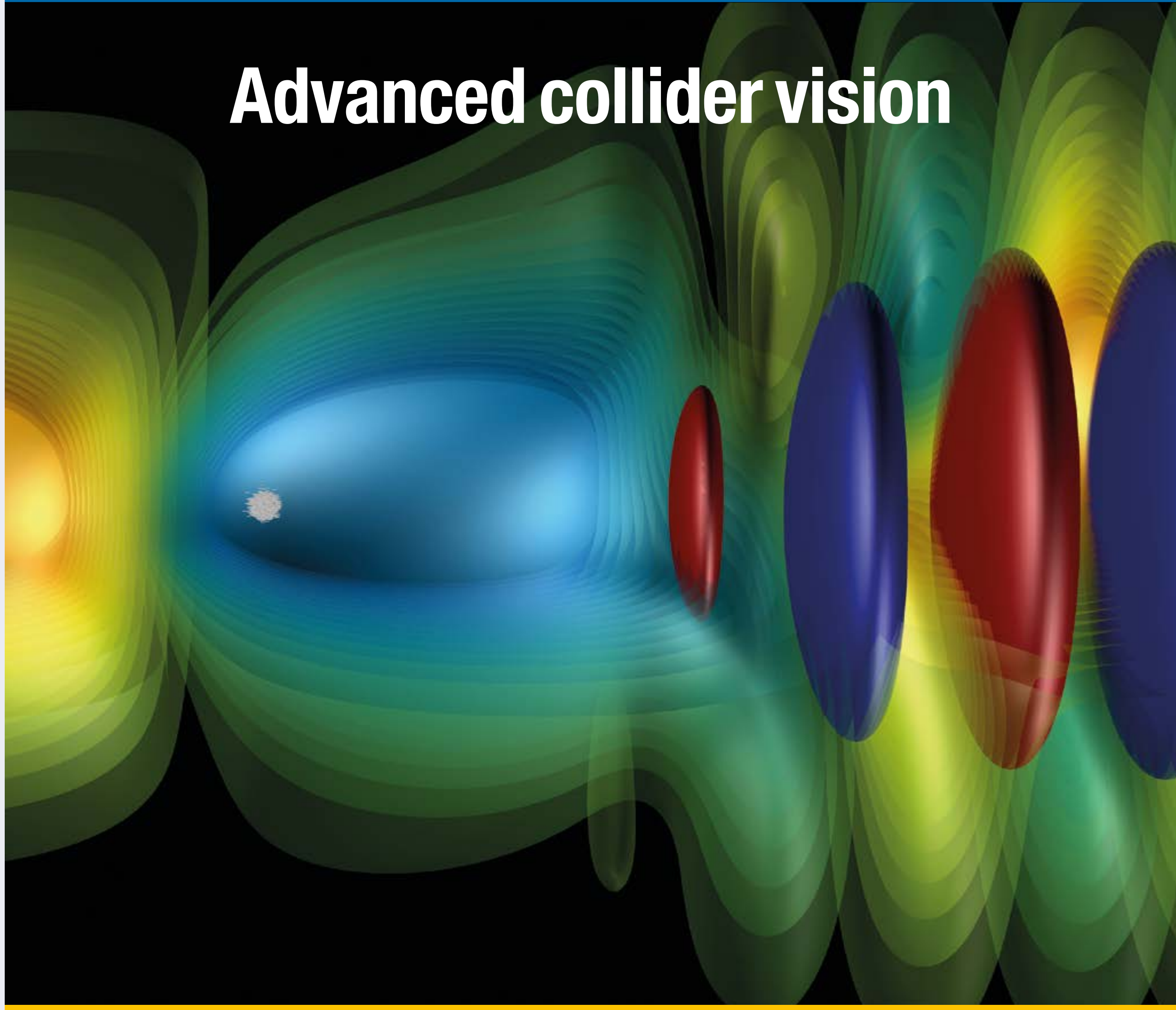
Advanced collider vision



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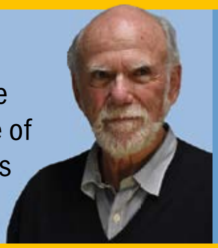

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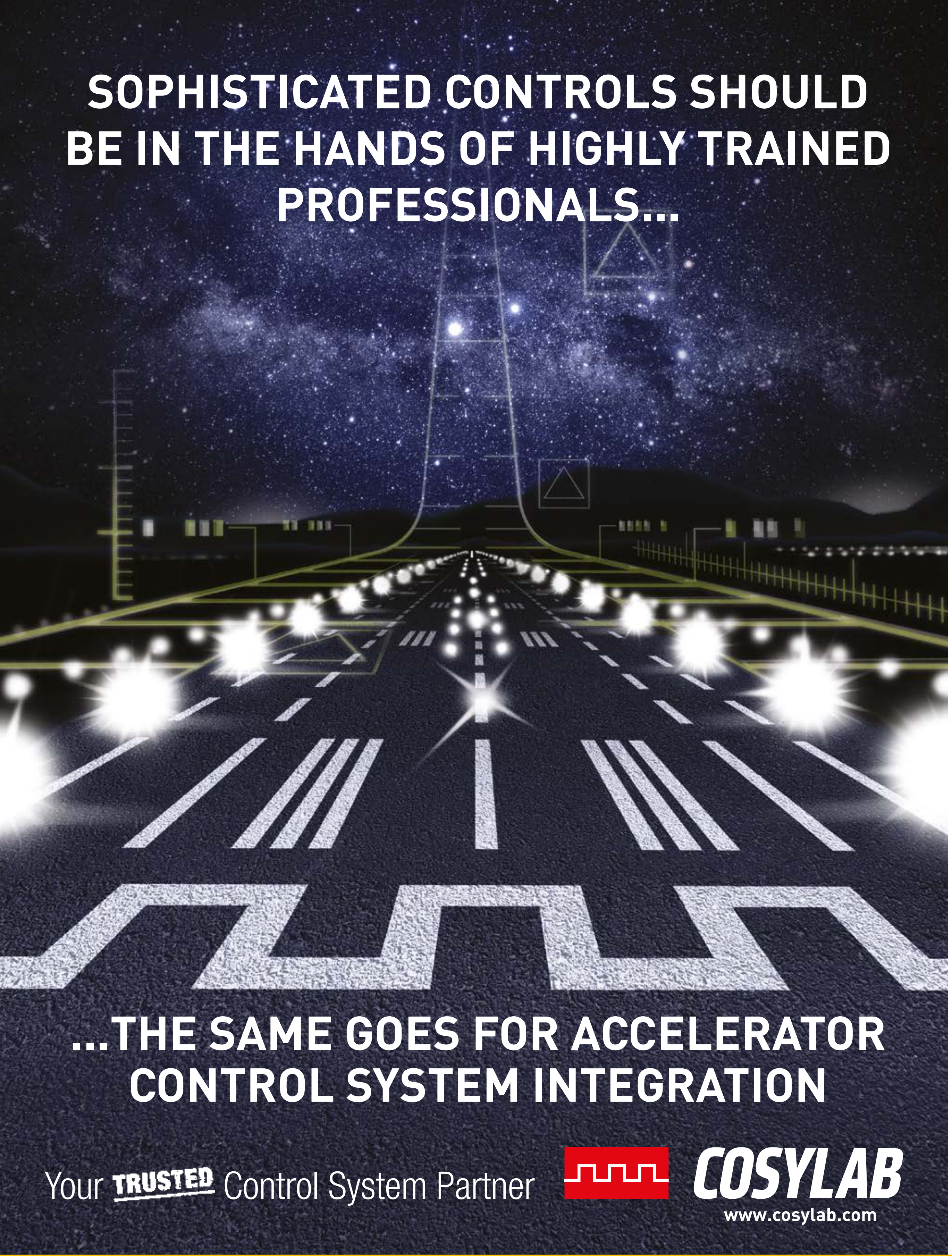

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Covering current developments in high-energy physics and related fields worldwide

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On the cover: Simulated excitation of a wakefield behind a laser driver using the WARP code. (Image credit: J-L Vay/LBNL.)

Viewpoint

So you want to communicate science?

Even the busiest physicists can find time to help inspire and educate the next generation.


W Moore

This year's graduates of a programme in the Netherlands to prepare exceptional students for undergraduate physics courses.

By Sijbrand de Jong

I returned to the Netherlands as a professor of experimental physics at Radboud University Nijmegen in 1998. After having enjoyed more than 10 years almost exclusively doing research work at CERN and elsewhere, I found (as I had strongly suspected) that I very much enjoyed teaching. Teaching first-year undergraduate physics courses, I came into contact with high-school teachers who were assisting students with the transition between secondary school and university. While successful for a broad group of students, many realised during their first year of university that studying physics was rather different from what they had imagined when they were still in school. As a result, there was a significant drop-out rate.

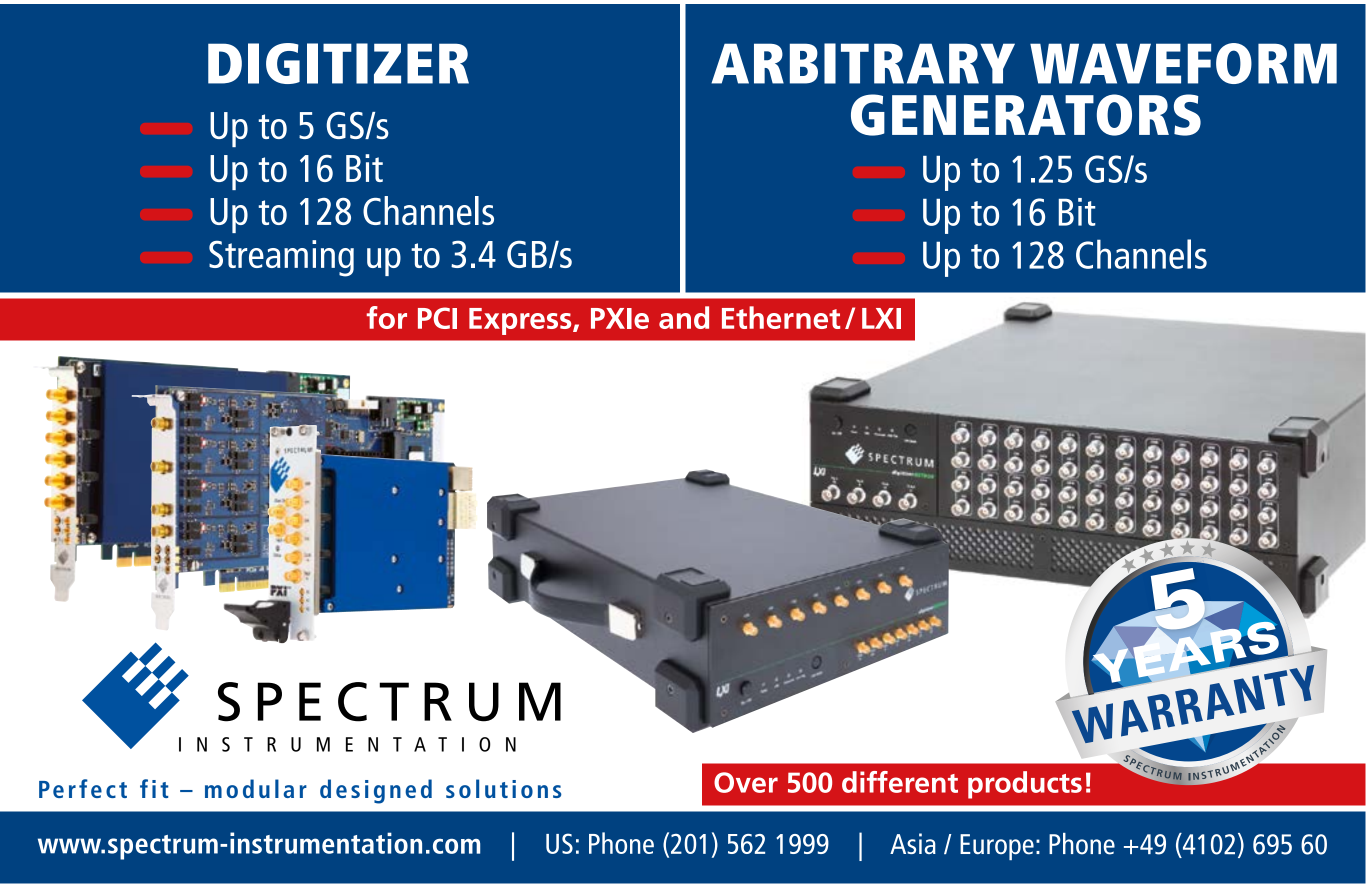
An opportunity to remedy this situation came when I read about a cosmic-ray high-school project in Canada led by experimental particle-physicist Jim Pinfold. Soon thereafter, and independently, a Nijmegen colleague, Charles Timmermans, came to me with a similar proposal for our university, and in 2000 we initiated the Nijmegen Area High School Array. Two years later, together with others, we launched the Dutch national High-School Project on Astrophysics Research with Cosmics (HiSPARC), which involved placing scintillator detectors on the roofs of high schools to form detector arrays. This is an excellent mixture of real science and educating high-school pupils in research methods. It has been a lot of fun to build the detectors with pupils, to legally walk on school roofs, and to analyse the data that arrive. Of course reality is unruly and it is sometimes hard to keep the objectives in focus: the schools can tend to be rather casual, if not careless, about the proper function of their set-up, whereas for the physics harvest it is essential to have a reliable network.

HiSPARC had an interesting side effect. While working with my group on the DØ experiment at the Tevatron, focusing on finding the Higgs boson, I was, more or less adiabatically, pulled towards the Pierre Auger Observatory (PAO) — the international cosmic-ray observatory in Argentina. The highest-energy particles in the universe are very mysterious: we don't yet know precisely where they come from, although the latest PAO results suggest we're getting close (see p15). Nor do we know how they are accelerated to energies up to 100 million TeV. My involvement as a university scientist in a high-school project has completely redirected my research career, and for the past five years I have spent all of my research time on the PAO.

Prompted by my teacher network, around 10 years ago I organised a joint effort between six nearby high schools concerning a new exam subject introduced by the Dutch ministry – "nature, life and technology", which integrates science, technology, engineering and maths (STEM) subjects. Every Friday afternoon, 350 pupils come to our faculty of science, which itself is an organisational and logistical challenge. The groups are organised during the course of the afternoon depending on the activity: a lecture for all, tutorials, and labs in biology, chemistry, physics, computer science and other subjects. Around 10 different locations in the building (and sometimes outside) are involved, and for every 20–25 pupils there is one teacher available. Following this project, in 2011 I initiated a two-year-long pre-university programme for gifted fifth and sixth graders in high school, which also takes place at the university and involves about 20 teachers and 14 university faculty members. The first cohort of pupils arrived in 2013, and one of the first graduates in the programme recently completed an internship at CERN.

Admittedly it is a lot of work. But it has been worth the effort. By thinking about how to teach particle physics to pupils with different backgrounds and experiences, I have gained more insight into the fundamentals of particle physics. Even the sometimes tedious experience of bringing school managements together and getting them to carry out projects outside of their comfort zones has prepared me well for some aspects of my present duty as president of CERN Council. Working with pupils and teachers has enriched my life, without having to compromise on research or management duties. And if I can combine such things with a research career, there seems little excuse for most scientists not to help educate and inspire the next generation.

Sijbrand de Jong is a professor of experimental physics at Radboud University Nijmegen, staff scientist at Nikhef, president of the CERN Council and a member of the Pierre Auger collaboration. (Image credit: M Brice.)



News

NEUTRINOS

Baby MIND takes first steps

In mid-October, a neutrino detector that was designed, built and tested at CERN was loaded onto four trucks to begin a month-long journey to Japan. Once safely installed at the J-PARC laboratory in Tokai, the "Baby MIND" detector will record muon neutrinos generated by beams from J-PARC and play an important role in understanding neutrino oscillations at the T2K experiment.

Weighing 75 tonnes, Baby MIND (Magnetised Iron Neutrino Detector) is bigger than its name suggests. It was initiated in 2015 as part of the CERN Neutrino Platform (*CERN Courier* July/August 2016 p21) and was originally conceived as a prototype for a 100 kt detector for a neutrino factory, specifically for muon-track reconstruction and charge-identification efficiency studies on a beamline at CERN (a task defined within the earlier AIDA project). Early in the design process, however, it was realised that Baby MIND was just the right size to be installed alongside the WAGASCI experiment located next to the near detectors for the T2K experiment, 280 m downstream from the proton target at J-PARC.

T2K studies the oscillation of muon (anti)neutrinos, especially their transformation into electron (anti)neutrinos, on their 295 km-long journey from J-PARC on the east coast of Japan to Kamioka on the other side of the island. The experiment discovered electron-neutrino appearance in a muon-neutrino beam in 2013 and earlier this year reported a two-sigma hint of CP violation by neutrinos, which will be explored further during the next eight years. Another major current target is to remove the ambiguity affecting the measurement of the neutrino mixing angle θ_{23}.

Baby MIND will help in this regard by precisely tracking and identifying muons produced when muon neutrinos from the T2K beamline interact with the WAGASCI detector. This will allow the ratio of cross-sections in water and plastic scintillator (the active material in WAGASCI) to be determined, helping researchers understand energy reconstruction biases that affect target nuclei-dependent neutrino fluxes and cross-sections. "Besides the water-to-scintillator ratio, the interest of the experiment is to measure a slightly higher-energy beam and compare the energy distribution (simply reconstructed from the muon angle and momentum, that Baby MIND measures) for the various off-axis positions relevant to the T2K and NOVA beams," says Baby MIND spokesperson Alain Blondel.


E Noah

One of several modules of the Baby MIND neutrino detector being moved into position. The detector was en route to Japan as the Courier *went to press, with installation and commissioning at J-PARC planned for the first and second quarters of 2018.*

Since its approval in December 2015, the Baby MIND collaboration – comprising CERN, the Institute for Nuclear Research of the Russian Academy of Sciences, and the universities of Geneva, Glasgow, Kyoto, Sofia, Tokyo, Uppsala, Valencia and Yokohama – has designed, prototyped, constructed and tested the Baby MIND apparatus, which includes custom designed magnet modules, electronics, scintillator sensors and support mechanics.

Significant departure

The magnet modules were the responsibility of CERN, and mark a significant departure from traditional magnetised-iron neutrino detectors, which have large coils threaded through the entire iron mass. Each of the 33 two-tonne Baby MIND iron plates is magnetised by its own aluminium coil, a feature imposed by access constraints in the shaft at J-PARC and resulting in a highly optimised magnetic field in the tracking volume. Between them, plastic scintillator slabs embedded with wavelength-shifting fibres transmit light produced by the interactions of ionising particles to silicon photomultipliers.

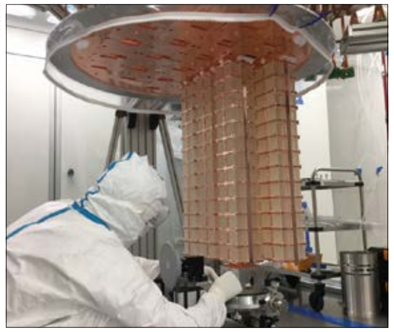
The fully assembled Baby MIND detector was qualified with cosmic rays prior to tests on a beamline at the experimental zone of CERN's Proton Synchrotron in the East Area during the summer of this year, and analyses showed the detector to be working as expected. First physics data from Baby MIND are expected in 2018. "That new systems for the Baby MIND were designed, assembled and tested on a beamline in a relatively short period of time (around two years) is a great example of people coming together and optimising the detector by using the latest design tools and benefiting from the pool of experience and infrastructures available at CERN," says Baby MIND technical co-ordinator Etam Noah.

Sommaire en français

Majorana neutrinos remain elusive

Researchers at the Cryogenic Underground Observatory for Rare Events (CUORE), located at Gran Sasso National Laboratories (LNGS) in Italy, have reported the latest results in their search for neutrinoless double beta-decay based on CUORE's first full data set. This exceedingly rare process, which is predicted to occur less than once about every 10^{26} years in a given nucleus, if it occurs at all, involves two neutrons in an atomic nucleus simultaneously decaying into two protons with the emission of two electrons and no neutrinos. This is only possible if neutrinos and antineutrinos are identical or "Majorana" particles, as posited by Ettore Majorana 80 years ago, such that the two neutrinos from the decay cancel each other out.

The discovery of neutrinoless double beta-decay (NDBD) would demonstrate that lepton number is not a symmetry of nature, perhaps playing a role in the observed matter–antimatter asymmetry in the universe, and constitute firm evidence for physics beyond the Standard Model. Following the discovery two decades ago that neutrinos have mass (a necessary condition for them to be Majorana particles), several experiments worldwide are competing to spot this exotic decay using a variety of techniques and different NDBD candidate nuclei.


INFN

Positioning one of CUORE's 19 towers of tellurium-oxide crystals beneath the cryostat.

CUORE is a tonne-scale cryogenic bolometer comprising 19 copper-framed towers that each house a matrix of 52 cube-shaped crystals of highly purified natural tellurium (containing more than 34% tellurium-130). The detector array, which has been cooled below a temperature of 10 mK and is shielded from cosmic rays by 1.4 km of rock and thick lead sheets, was designed and assembled over a 10 year period. Following initial results in 2015 from a CUORE prototype containing just one tower, the full detector with 19 towers was cooled down in the CUORE cryostat one year ago and the collaboration has now released its first publication, submitted to *Physical Review Letters*, with much higher statistics. The large volume of detector crystals greatly increases the likelihood of recording a NDBD event during the lifetime of the experiment.

Based on around seven weeks of data-taking, alternated with an intense programme of commissioning of the detector from May to September 2017 and corresponding to a total tellurium exposure of 86.3 kg per year, CUORE finds no sign of NDBD, placing a lower limit of the decay half-life of NDBD in tellurium-130 of 1.5×10^{25} years (90% C.L.). This is the most stringent limit to date on this decay, says the team, and suggests that the effective Majorana neutrino mass is less than 140–400 meV, where the large range results from the nuclear matrix-element estimates employed. "This is the first preview of what an instrument this size is able to do," says CUORE spokesperson Oliviero Cremonesi of INFN. "Already, the full detector array's sensitivity has exceeded the precision of the measurements reported in April 2015 after a successful two-year test run that enlisted one detector tower."

Over the next five years CUORE will collect around 100 times more data. Combined with search results in other isotopes, the possible hiding places of Majorana neutrinos will shrink much further.

- **Further reading**

CUORE Collaboration 2017 arXiv:1710.07988.

ACCELERATORS

EU project lights up X-band technology

Advanced linear-accelerator (linac) technology developed at CERN and elsewhere will be used to develop a new generation of compact X-ray free-electron lasers (XFELs), thanks to a €3 million project funded by the European Commission's Horizon 2020 programme. Beginning in January 2018, "CompactLight" aims to design the first hard XFEL based on 12 GHz X-band technology, which originated from research for a high-energy linear collider. A consortium of 21 leading European institutions, including CERN, PSI, KIT and INFN, in addition to seven universities and two industry partners (Kyma and VDL), are partnering to achieve this ambitious goal within the three-year duration of the recently awarded grant.


M Volpi

A CLIC X-band prototype structure built by PSI using Swiss FEL technology.

X-band technology, which provides accelerating-gradients of 100 MV/m and above in a highly compact device, is now a reality. This is the result of many years of intense R&D carried out at SLAC (US) and KEK (Japan), for the former NLC and JLC projects, and at CERN in the context of the Compact Linear Collider (CLIC). This pioneering technology also withstood validation at the Elettra and PSI laboratories.

XFELs, the latest generation of light sources based on linacs, are particularly suitable applications for high-gradient X-band technology. Following decades of growth in the use of synchrotron X-ray facilities to study materials across a wide spectrum of sciences, technologies and applications, XFELs (as opposed to circular light sources) are capable of delivering high-intensity photon beams of unprecedented brilliance and quality. This provides novel ways to probe matter and allows researchers to make "movies" of ultrafast biological processes. Currently, three XFELs are up and running in Europe – FERMI@Elettra in Italy and FLASH and FLASH II in Germany, which operate in the soft X-ray range – while two are under commissioning: SwissFEL at PSI and the European XFEL in Germany (*CERN Courier* July/August 2017 p18), which operates in the hard X-ray region. Yet, the demand for such high-quality X-rays is large, as the field still has great and largely unexplored potential for science and innovation – potential that can be unlocked if the linacs that drive the X-ray generation can be made smaller and cheaper.

This is where CompactLight steps in. While most of the existing XFELs worldwide use conventional 3 GHz S-band technology (e.g. LCLS in the US and PAL in South Korea) or superconducting 1.3 GHz structures (e.g. European XFEL and LCLS-II), others use newer designs based on 6 GHz C-band technology (e.g. SCALA in Japan), which increases the accelerating gradient while reducing the linac's length and cost. CompactLight gathers leading experts to design a hard-X-ray facility beyond today's state of the art, using the latest concepts for bright electron-photo injectors, very-high-gradient X-band structures operating at frequencies of 12 GHz, and innovative compact short-period undulators (long devices that produce an alternating magnetic field along which relativistic electrons are deflected to produce synchrotron X-rays). Compared with existing XFELs, the proposed facility will benefit from a lower electron-beam energy (due to the enhanced undulator performance), be significantly more compact (as a consequence both of the lower energy and of the high-gradient X-band structures), have lower electrical power demand and a smaller footprint.

Success for CompactLight will have a much wider impact: not just affirming X-band technology as a new standard for accelerator-based facilities, but advancing undulators to the next generation of compact photon sources. This will facilitate the widespread distribution of a new generation of compact X-band-based accelerators and light sources, with a large range of applications including medical use, and enable the development of compact cost-effective X-ray facilities at national or even university level across and beyond Europe.

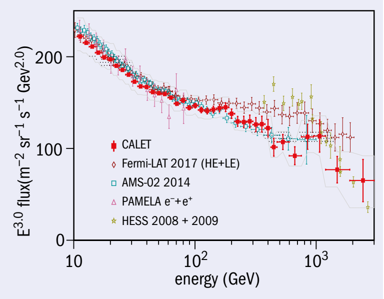
COSMIC RAYS

First cosmic-ray results from CALET on the ISS

The CALorimetric Electron Telescope (CALET), a space mission led by the Japan Aerospace Exploration Agency with participation from the Italian Space Agency (ASI) and NASA, has released its first results concerning the nature of high-energy cosmic rays.

Having docked with the International Space Station (ISS) on 25 August 2015, CALET is carrying out a full science programme with long-duration observations of high-energy charged particles and photons coming from space. It is the second high-energy experiment operating on the ISS following the deployment of AMS-02 in 2011. During the summer of 2017 a third experiment, ISS-CREAM, joined these two. Unlike AMS-02, CALET and ISS-CREAM have no magnetic spectrometer and therefore measure the inclusive electron and positron spectrum. CALET's homogeneus calorimeter is optimised to measure electrons, and one of its main science goals is to measure the detailed shape of the electron spectrum.

Due to the large radiative losses during their travel in space, high-energy cosmic electrons are expected to originate from regions relatively close to Earth (of the order of a few thousand light-years). Yet their origin is still unknown. The shape of the spectrum and the anisotropy in the arrival direction might contain crucial information as to where and how electrons are accelerated. It could also provide a clue on possible signatures of dark matter – for example, the presence of a peak in the spectrum might tell us about a possible dark-matter decay or annihilation with an electron or positron in the final state – and shed light on the intriguing electron and positron spectra reported by AMS-02 (*CERN Courier* December 2016 p26).



The cosmic-ray inclusive electron spectrum measured by CALET in the range 10 GeV to 3 TeV, where systematic errors (not including the uncertainty on the energy scale) are shown by the grey band. The present flux is reasonably consistent with the electron and positron spectrum seen by AMS-02.

To pinpoint possible spectral features on top of the overall power-law energy dependence of the spectrum, CALET was designed to measure the energy of the incident particle with very high resolution and with a large proton rejection power, well into the TeV energy region. This is provided by a thick homogeneous calorimeter preceded by a high-granularity pre-shower with imaging capabilities with a total thickness of 30 radiation length at normal incidence. The calibration of the two instruments is the key to control the energy scale and this is why CALET – a CERN-recognised experiment – performed several calibration tests at CERN.

The first data from CALET concern a measurement of the inclusive electron and positron spectrum in the energy range from 10 GeV to 3 TeV, based on about 0.7 million candidates (1.3 million in full acceptance). Above an energy of 30 GeV the spectrum can be fitted with a single power law with a spectral index of –3.152±0.016. A possible structure observed above 100 GeV requires further investigation with increased statistics and refined data analysis. Beyond 1 TeV, where a roll-off of the spectrum is expected and low statistics is an issue, electron data are now being carefully analysed to extend the measurement. CALET has been designed to measure electrons up to around 20 TeV and hadrons up to an energy of 1 PeV.

CALET is a powerful space observatory with the ability to identify cosmic nuclei from hydrogen to elements heavier than iron. It also has a dedicated gamma-ray-burst instrument (CGBM) that so far has detected bursts at an average rate of one every 10 days in the energy range of 7 KeV–20 MeV. The search for electromagnetic counterparts of gravitational waves (GWs) detected by the LIGO and Virgo observatories proceeds around the clock thanks to a special collaboration agreement with LIGO and Virgo. Upper limits on X-ray and gamma-ray counterparts of the GW151226 event were published and further research on GW follow-ups is being carried out. Space-weather studies relative to the relativistic electron precipitation (REP) from the Van Allen belts have also been released.

With more than 500 million triggers collected so far and an expected extension of the observation time on the ISS to five years, CALET is likely to produce a wealth of interesting results in the near future.

- **Further reading**

CALET Collaboration. 2017 *Phys. Rev. Lett.* **119** 181101.

LHC REPORT

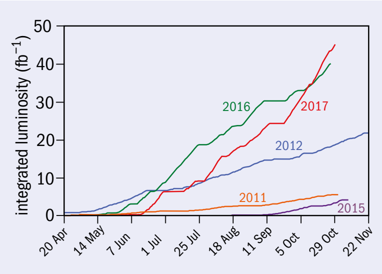
The twists and turns of a successful year for the LHC

On 11 December, the Large Hadron Collider (LHC) is scheduled to complete its 2017 proton-physics run and go into standby for its winter shutdown and maintenance programme. With the LHC having surpassed this year's integrated luminosity target of 45 fb^{-1} to both the ATLAS and CMS experiments 19 days before the end of the run, 2017 marks another successful year for the machine. September 2017 also saw the LHC's total integrated luminosity since 2010 pass the milestone of 100 fb^{-1} per high-luminosity experiment (see panel). But the year has not been without its challenges, demonstrating once again the quirks and unprecedented complexities involved in operating the world's highest-energy collider. The story of the LHC's 2017 run unfolded in three main parts.

Following a longer than usual technical stop that began at the end of 2016, the LHC was cooled to its operating temperature in April and took first beam towards the end of the month, with first stable beams declared about four weeks later. Physics got off to a great start, with an impressively efficient ramp-up reaching 2556 bunches per beam and a peak luminosity of $1.6 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ in very good time.

Careful examination

However, from the start of the run, for some unknown reason the beams were occasionally dumped with a particular signature of localised beam loss and the onset of a fast-beam instability. The cause of the premature dumps was traced to a region called 16L2, referring to the sixteenth LHC half-cell to the left of point 2 (each half-cell comprises three dipoles, one quadrupole and associated corrector magnets). The hypothesis was that the problems were caused by the presence of frozen gas in the beam pipes in this region; air had perhaps entered during the cool down and had become trapped on and around the beam screen. All available diagnostics were deployed and careful examination of the beam losses in the region revealed steady-state losses, which occasionally increased rapidly followed by a very fast beam instability. The issue appeared to respond positively to a non-zero field in a local orbit corrector, and this allowed the LHC teams to establish more-or-less steady operation by careful control of the corrector in question.



The LHC passed its 2017 integrated luminosity target of 45 fb^{-1} in late October.

To ameliorate and understand the situation better, an attempt was made to flush the gas supposedly condensed on the beam screen onto the cold mass of the magnets. To this end the beam screen around 16L2 was warmed up to around 80 K with careful monitoring of the vacuum conditions. Unfortunately, the manoeuvre was not a success: the 16L2 dumps became more frequent and many subsequent fills were lost to the problem. By this stage, electron-cloud effects had been identified as a possible co-factor in driving the instability, prompting the teams to change the bunch configuration to the so-called 8b4e scheme in which gaps are introduced into the bunch configuration. This significantly reduced the rate of 16L2 losses and allowed steady and productive running to be established by late summer.

A century of femtobarns

On 28 September, the LHC passed a high-energy proton–proton collision milestone: the accumulation of 100 fb^{-1} since its inception, equivalent to around 10^{15} collisions in each of the ATLAS and CMS experiments. The LHC started physics operations in late 2009, and by the middle of 2012 had delivered enough integrated luminosity to enabled physicists to discover the Higgs boson. After the first LHC long shutdown in 2013 and 2014, the LHC was restarted in 2015 at higher energy, paving the way for 2016, another record production year that notched up 40 fb^{-1}. Following this success, the target for 2017 and 2018 combined was raised to 90 fb^{-1}, which, despite some challenges this year, looks to be well within reach.

New heights

Performance was further improved by a reduction in the "beta-star" parameter following a technical stop in the middle of September. This move exploited the excellent aperture, collimation-system performance, stability, and optics understanding of the LHC and benefited from many years of experience operating the machine. Working with an optimised 8b4e scheme and beta-star of 30 cm resulted in CMS and ATLAS reaching their event pile-up limit, forcing the deployment of luminosity levelling as is already routine in LHCb and ALICE. The peak-levelled luminosity under these running conditions is around $1.5 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$, compared to more than $2 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ without levelling. The beam availability in the latter part of the year has been truly excellent and integrated-luminosity delivery reached new heights. One day in October was also dedicated to operation with xenon beams, taking advantage of their presence in the SPS for North Area's fixed target programme (*CERN Courier* November 2017 p7).

Following a period of machine development and some special physics runs, the winter maintenance break is due to begin on 11 December. The year-end technical stop will see the usual extensive programme of maintenance and consolidation for both the machine and experiments. It will also see sector 12 warmed up to room temperature to fully resolve the 16L2 issue. Then, in the spring of 2018, the LHC will begin a final 13 TeV run before a long shutdown of two years to make key preparations for its high-luminosity upgrade.

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

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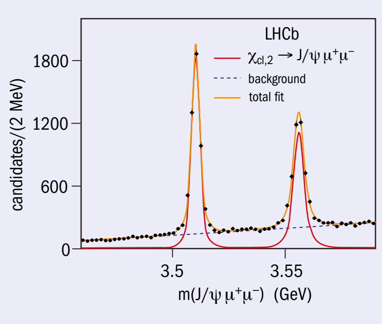
LHC EXPERIMENTS

Novel charmonium spectroscopy at LHCb

The LHCb collaboration has published the result of precision mass and width measurements of the χ_{c1} and χ_{c2} charmonium states, performed for the first time by using the newly discovered decays $\chi_{c1} \to J/\psi\,\mu^+\mu^-$ and $\chi_{c2} \to J/\psi\,\mu^+\mu^-$. Previously it has not been possible to make precision measurements for these states at a particle collider due to the absence of a fully charged final state with a large enough decay rate, allowing powerful comparisons with results from earlier fixed-target experiments.

The dominant decay mode of such charmonium states is $\chi_{c1,2} \to J/\psi\,\gamma$. However, the precision measurement of the energy of the final-state photon, γ, is experimentally very challenging, particularly in the harsh environment of a hadron collider such as the LHC. For this reason, such measurements were only possible at dedicated experiments that exploited antiproton beams annihilating into fixed hydrogen targets and forming prompt χ_{c1} states. By modulating the energy of the impinging antiprotons, it was possible to scan the invariant mass of the states with high precision. But the obvious difficulties in building such dedicated facilities has meant that precision mass measurements were only performed by two experiments: E760 and E835 at Fermilab, the latter being an upgrade of the former.



Mass distribution for selected $J/\psi\,\mu^+\mu^-$ candidates. The fit is shown by the orange curve, the χ_{c1} and χ_{c2} signal components are shown by the red curve and the background component by the dashed blue curve.

In these new Dalitz decays, $\chi_{c1,2} \to J/\psi\,\mu^+\mu^-$, where the J/ψ meson subsequently decays to another $\mu^+\mu^-$ pair, the final state is composed of four charged muons. Thus these modes can be triggered and reconstructed very efficiently by the LHCb experiment. The high precision of the LHCb spectrometer already enabled several world-best mass measurements of heavy-flavour mesons and baryons to be performed, and now it has allowed the two narrow χ_{c1} and χ_{c2} peaks to be observed in the invariant $J/\psi\,\mu^+\mu^-$ mass distribution with excellent resolution (see figure). The values of the masses of the two states, along with the natural width of the χ_{c2}, have been determined with a similar precision to, and in good agreement with, those obtained by E760 and E835.

This new measurement opens an avenue to precision studies of the properties of χ_c mesons at the LHC, more than 40 years since the discovery of the first charmonium state, the J/ψ meson. It will allow precise tests of production mechanisms of charmomium states down to zero transverse momentum, providing information hardly accessible using other experimental techniques. In addition to the charmonium system, these observations are expected to have important consequences for the wider field of hadron spectroscopy at the LHC. With larger data samples, studies of the Dalitz decays of other heavy-flavour states, such as the exotic X(3872) and bottomonium states, will become possible. In particular, measurements of the properties of the X(3872) via a Dalitz decay may help to elucidate the nature of this enigmatic particle.

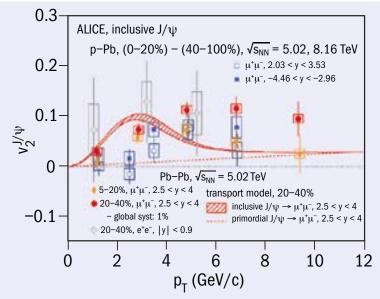
Further reading

LHCb Collaboration 2012 *Phys. Lett. B* **714** 215.
LHCb Collaboration 2013 *JHEP* **10** 115.
LHCb Collaboration 2017 LHCb-PAPER-2017-036.

The curious case of the J/ψ flow

Recently, the ALICE collaboration measured the elliptic flow of J/ψ mesons with unprecedented precision in lead–lead (Pb–Pb) collisions and, for the first time, also in proton–lead (p–Pb) collisions. While the results at low transverse momentum (p_T) in Pb–Pb collisions confirm that charm quarks flow with the quark–gluon plasma (QGP), the results at high p_T do not agree with model predictions. Furthermore, their similarity to p–Pb collisions suggest that additional J/ψ flow-generation mechanisms are still to be identified.

The elliptic flow (v_2) is the azimuthal anisotropy of the final-state particles, generated by the collective expansion of the almond-shaped interaction region of the colliding nuclei in non-central nucleus–nucleus collisions. The J/ψ meson is a bound state of charm and anti-charm quarks, which is created at early times in hard-scattering processes. Effects of the QGP on the production of J/ψ mesons are currently understood in terms of two mechanisms: suppression by dissociation due to the large surrounding colour-charge density and regeneration by recombination of de-confined charm quarks. If charm quarks thermalise in the medium, recombined states should inherit their flow.



*Inclusive J/ψ $v_2(p_T)$ at forward and mid-rapidity in Pb–Pb collisions at a nucleon–nucleon energy of 5.02 TeV and at forward and backward rapidity in p–Pb collisions at 5.02 and 8.16 TeV. Model calculations (*Nucl. Phys. A ***943*** 147) for semi-central Pb–Pb collisions are also shown as a band. The dashed line indicates the J/ψ v_2 in the absence of regeneration, which is due to the azimuthal dependence of the J/ψ suppression.*

A clear positive v_2 for J/ψ mesons at forward rapidity is observed in Pb–Pb collisions at a nucleon–nucleon energy of 5.02 TeV for different collision centralities. In semi-central collisions, the J/ψ v_2 increases with p_T up to 4–6 GeV/c and saturates or decreases thereafter. The J/ψ v_2 measurement at mid-rapidity has a larger background and is therefore less precise, but demonstrates potential for future studies at the high-luminosity LHC.

A comparison with available theoretical model calculations shows that the measured ▷

values at low p_T (below 4 GeV/c) can only be explained through a large contribution from the recombination of thermalised charm quarks. The expected v_2 without this contribution (labelled "primordial" v_2 in the figure) is much smaller than the measured values. However, the models clearly underestimate the measured azimuthal asymmetry at higher transverse momentum and do not reproduce the overall p_T dependence, suggesting that there is another mechanism to produce J/ψ v_2. The J/ψ v_2 has also been measured in p–Pb collisions at energies of 5.02 and 8.16 TeV at forward (p-travelling) and backward (Pb-travelling) rapidities. Interestingly, the J/ψ v_2 in the smaller p–Pb collision system is similar to that in central Pb–Pb collisions at high p_T. The possibly missing mechanism could therefore be the same in both collision systems.

- **Further reading**

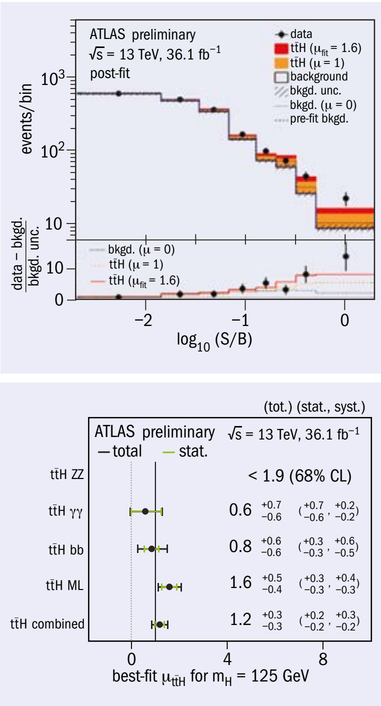
ALICE Collaboration 2017 arXiv:1709.05260.
ALICE Collaboration 2017 arXiv:1709.06807.

ATLAS reports direct evidence for Higgs–top coupling

The Higgs boson interacts more strongly with more massive particles, so the coupling between the top quark and the Higgs boson (the top-quark Yukawa coupling) is expected to be large. The coupling can be directly probed by measuring the rate of events in which a Higgs boson is produced in association with a pair of top quarks (ttH production). Using the 13 TeV LHC data set collected in 2015 and 2016, several ATLAS analyses targeting different Higgs boson decay modes were performed. The combination of their results, released in late October, provides the strongest single-experiment evidence to date for ttH production.

The H → bb decay channel offers the largest rate of ttH events, but extracting the signal is hard because of the large background of top quarks produced in association with a pair of bottom quarks. The analysis relies on the identification of b-jets and multivariate analysis techniques to reconstruct the events and determine whether candidates are more likely to arise from ttH production or from background processes.

The probability for the Higgs boson to decay to a pair of W bosons or a pair of τ leptons is smaller, but the backgrounds to ttH searches with these decays are also smaller and easier to estimate. These decays are targeted in searches for events with a pair of leptons carrying the same charge or three or more charged leptons (including electrons, muons, or hadronically decaying τ leptons). In total, seven different final states were probed in the latest ATLAS analysis.



(Top) Event yields in the multi-lepton channel as a function of the quantity $\log_{10}(S/B)$ measuring the signal-to-background ratio for data, background and a Higgs boson signal. (Below) Measurements of the ttH signal strength from individual analyses and the combined result.

Higgs boson decays to a pair of photons or to a pair of Z bosons with subsequent decays to lepton pairs (giving a four-lepton final state) are also considered. These decay channels have very small rates, but provide a high signal-to-background ratio.

In the combination of these ttH analyses, an excess with a significance of 4.2 standard deviations with respect to the "no-ttH-signal" hypothesis is observed, compared to 3.8 standard deviations expected for a Standard Model signal. This constitutes the first direct evidence for the ttH process occurring at ATLAS. A cross-section of 590^{+160}_{-150} fb is measured, in good agreement with the Standard Model prediction of 507^{+35}_{-50} fb. This measurement, when combined with other Higgs boson production and decay studies, will shed more light on the possible presence of physics beyond the Standard Model in the Higgs sector.

- **Further reading**

ATLAS Collaboration 2017 ATLAS-CONF-2017-043.
ATLAS Collaboration 2017 ATLAS-CONF-2017-045.
ATLAS Collaboration 2017 ATLAS-CONF-2017-076.
ATLAS Collaboration 2017 ATLAS-CONF-2017-077.

CMS sees Higgs boson decaying to b-quarks

The CMS experiment has added another piece to the Higgs boson puzzle, reporting evidence that the Higgs decays to a pair of b quarks.

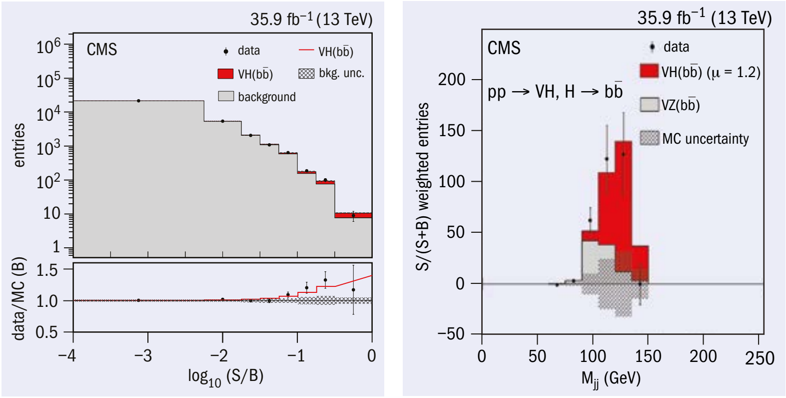
In the Standard Model (SM) the Higgs field couples to fermions, giving them their masses, through a Yukawa interaction. The recent CMS observation of the H → ττ channel provides direct evidence of this interaction. While it is clear that the Higgs boson couples to up-type quarks (based on overall agreement between the gluon–gluon fusion production channel cross-section and the SM prediction), the Higgs boson decay to bottom quark–antiquark pairs provides a unique tool to directly access the bottom-type quark couplings.

The Higgs boson decays to a pair of b quarks 58% of the time, making it by far the most frequent decay channel. However, at the LHC the signal is overwhelmed by QCD production, which is several orders of magnitude higher. This makes the H → bb process very elusive. The most effective way to observe it is to search for associated production with an electroweak vector boson (VH, with V being a W or a Z boson). Further background reduction is achieved by requiring the Higgs boson candidates to have large transverse momentum and by exploiting the peculiar VH kinematical event properties.

The latest CMS analysis is based on LHC data collected last year at an energy of 13 TeV. To identify jets originating from b quarks, the collaboration used a novel combined multivariate b-tagging algorithm that exploits the presence of soft leptons together with information such as track impact parameters and secondary vertices. A signal region enriched in VH events was then selected, together with several control regions to test the accuracy of the Monte Carlo simulations, and a simultaneous binned-likelihood fit of the signal and control regions used to extract the Higgs boson signal.

An excess of events is observed compared to the expectation in the absence of a H → bb signal. The significance of the excess is 3.3σ, where the expectation from SM Higgs boson production is 2.8σ. The signal strength corresponding to this excess, relative to the SM expectation, is 1.2±0.4. When combined with the Run 1 measurement at a lower energy, the signal significance is 3.8σ with 3.8σ expected and a signal strength of 1.1.

To validate the analysis procedure, the same methodology was used to extract a signal for the VZ process, with Z → bb, which has a nearly identical final state but with a different invariant mass and a larger production cross-section. The observed excess of events for the combined WZ and ZZ processes has a significance of 5σ from the background-only event-yield expectation, and the corresponding signal strength is 1.0±0.2.

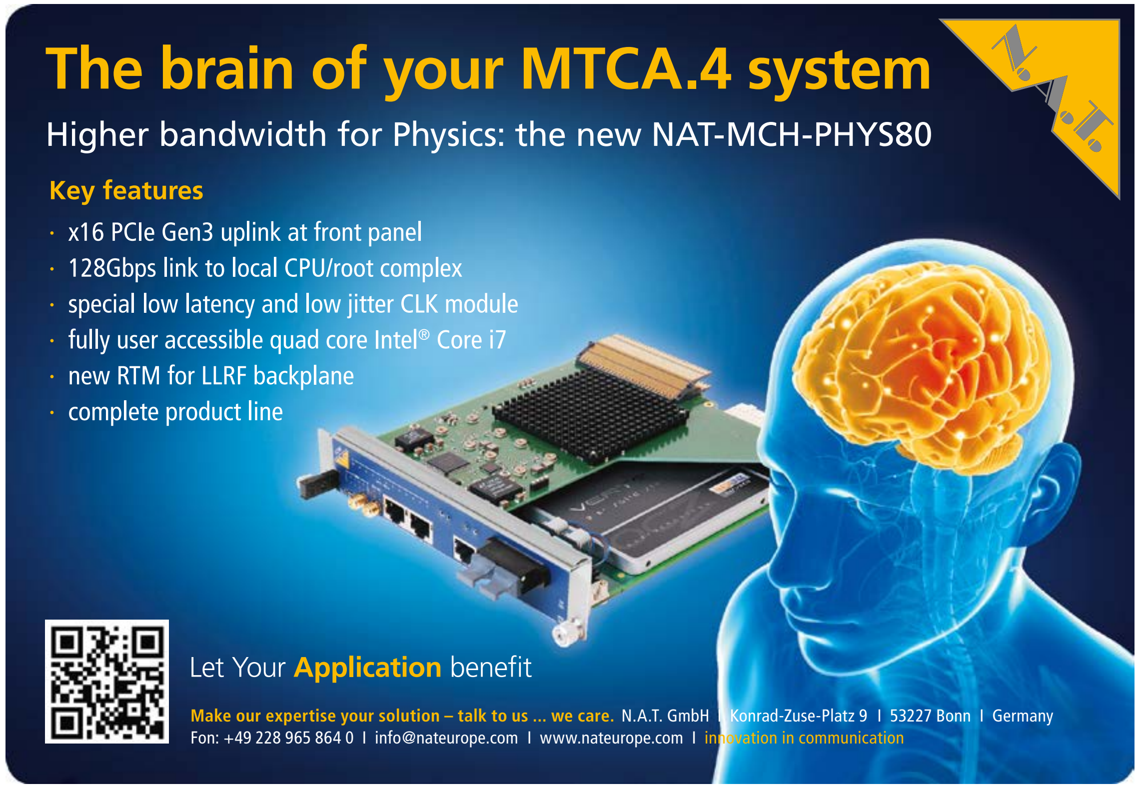


(Left) Event boosted-decision-tree (BDT) distribution sorted in bins of similar expected signal-to-background ratio (the bottom panel shows the ratio of the data to the background-only prediction). (Right) Weighted dijet invariant mass distribution comparing data with the VH and VZ processes, with all other background processes subtracted.

Thanks to the outstanding performance of the LHC, the data set will significantly increase by the end of Run 2, in 2018. This will allow a consistent reduction of the uncertainties, and a 5σ observation of the H → bb decay is expected.

- **Further reading**

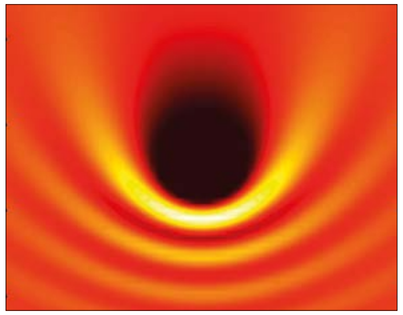
CMS Collaboration 2017 arXiv:1709.07497.



Sciencewatch

Compiled by John Swain, Northeastern University

Superfluidity at room temperature



Interference fringes in a polariton condensate as it transitions to a fluid with zero viscosity, from simulations.

Superfluidity, like superconductivity, is typically thought of as needing very low temperatures that alter the fundamental quantum-mechanical behaviour of materials. Surprisingly, Giovanni Lerario of CNR NANOTEC Institute of Nanotechnology in Italy and colleagues now report what appears to be superfluidity at room temperature. The "material" in question is a highly exotic state of bosonic quasiparticles called a polariton condensate, and the experiment comprised an optical Fabry–Pérot microcavity made from two dielectric Bragg mirrors with a thin amorphous layer of fluorescent organic material between them. A laser pulse creates a polariton flow with well-defined energy, revealing itself as a superfluid by the disappearance of scattering around an obstacle.

- **Further reading**

G Lerario *et al.* 2017 *Nature Physics* **13** 825.

Spiders and graphene

Spider silk famously has excellent mechanical properties, having both high strength (around 1.5 GPa) and toughness (around 150 J/g). Nicola Maria Pugno of the University of Trento and colleagues have now found a way to dramatically improve on these by feeding spiders aqueous dispersions of graphene or carbon nanotubes, which are then incorporated into their silk. Fracture strength went up to around 5.4 GPa and the toughness modulus to 1570 J/g. This is just a first step and opens the door to a new class of artificially modified biological material, says the team.

- **Further reading**

E Lepore *et al.* 2017 *2D Materials* **4** 031013.

Self-interacting dark matter

In explaining the diversity of rotation curves measured for spiral galaxies, the simplest cold-dark-matter (CDM) models run into difficulties. It appears, however, that self-interacting dark matter (SIDM) does better. Ayuki Kamada of the University of California at Riverside and colleagues assume only the halo concentration-mass relation predicted by CDM and a fixed value for the self-interaction cross-section. Although the specific nature or composition of the dark matter required still remains a puzzle, the team shows that the impact of baryons on the SIDM halo profile and the scatter from the assembly history of halos can explain the diverse rotation curves.

- **Further reading**

A Kamada *et al.* 2017 *Phys. Rev. Lett.* **119** 111102.

Dog voting by sneeze

African wild dogs, *Lycaon pictus*, a highly social and co-operative species, vote by sneezing, according to findings by Reena Walker of the Botswana Predator Conservation Trust and Brown University in Providence and colleagues. The team reports that when the dogs meet in social rallies before collective motions, the probability of the success of a rally is determined by the number of sneezes in the rally. The quorum was reduced if dominant individuals initiated the rally, but such dominant individuals could also be "overruled" by a consensus of enough subordinates.

- **Further reading**

R Walker *et al.* 2017 *Proc. Roy. Soc. B*
DOI: 10.1098/rspb.2017.0347.

Specific behavioural mechanisms such as sneezing may shape decision-making in a wild, socially complex animal society.

Molecular assembler

Nano machines that could put together molecules mechanically one by one, also called molecular assemblers, typically have been the stuff of futurists. Now, Salma Kassem and colleagues at the University of Manchester in the UK have demonstrated an actual example. The assembler is a single large molecule that can be switched via pH between left- and right-handed mode. It can assemble four stereoisomers of a molecule depending on the order in which switches in handedness are made, making such machines promising for future chemical synthesis and molecular manufacturing.

- **Further reading**

S Kassem *et al.* 2017 *Nature* **549** 374.

3D metal printing

Researchers have taken an important step towards 3D printing of high-strength metals. Despite the huge growth of 3D printing in recent years, the way metal grains are printed and incorporated can lead to microstructures with large columnar grains and periodic cracks. John Martin of HRL Laboratories and the University of California and colleagues have shown that adding nanoparticles to the metallic powders used as the "printer ink" results in crack-free and regularly grained printed materials with strengths comparable to wrought materials. More than 5500 alloys in use today could potentially benefit from the technique.

- **Further reading**

J Martin *et al.* 2017 *Nature* **549** 365.

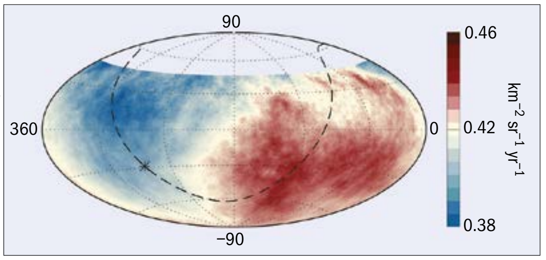
Astrowatch

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

Extreme cosmic rays reveal clues to origin

The energy spectrum of cosmic rays continuously bombarding the Earth spans many orders of magnitude, with the highest energy events topping 10^8 TeV. Where these extreme particles come from, however, has remained a mystery since their discovery more than 50 years ago. Now the Pierre Auger collaboration has published results showing that the arrival direction of ultra-high-energy cosmic rays (UHECRs) is far from uniform, giving a clue to their origins.

The discovery in 1963 at the Vulcano Ranch Experiment of cosmic rays with energies exceeding one million times the energy of the protons in the LHC raised many questions. Not only is the charge of these hadronic particles unknown, but the acceleration mechanisms required to produce UHECRs and the environments that can host these mechanisms are still being debated. Proposed origins include sources in the galactic centre, extreme supernova events, mergers of neutron stars, and extragalactic sources such as blazars. Unlike the case with photons or neutrinos, the arrival direction of charged cosmic rays does not point directly towards their origin because, despite their extreme energies, their paths are deflected by magnetic fields both inside and outside our galaxy. Since the deflection reduces as the energy goes up, however, some UHECRs with the highest energies might still contain information about their arrival direction.



Pierre Auger Collaboration

A sky map in equatorial co-ordinates showing the cosmic-ray flux above 8 EeV, revealing a clear dipole structure with a significance of 5.2σ. The galactic centre is marked with an asterisk and the galactic plane is shown by a dashed line.

At the Pierre Auger Observatory, cosmic rays are detected using a vast array of detectors spread over an area of 3000 km^2 near the town of Malargüe in western Argentina. Like the first cosmic-ray detectors in the 1960s, the array measures the air showers induced as the cosmic rays interact with the atmosphere. The arrival times of the particles, measured with GPS receivers, are used to determine the direction from which the primary particles came within approximately one degree.

The collaboration studied the arrival direction of particles with energies in the range 4–8 EeV and for particles with energies exceeding 8 EeV. In the former data set, no clear anisotropy was observed, whereas for particles with energies above 8 EeV a dipole structure was observed (see figure), indicating that more particles come from a particular part of the sky. Since the maximum of the dipole is outside the galactic plane, the measured anisotropy is consistent with an extragalactic nature. The collaboration reports that the maximum, when taking into account the deflection of magnetic fields, is consistent with a region in the sky known to have a large density of galaxies, supporting the view that UHECRs are produced in other galaxies. The lack of anisotropy at lower energies could be a result of the higher deflection of these particles in the galactic magnetic field.

The presented dipole measurement is based on a total of 30,000 cosmic rays measured by the Pierre Auger Observatory, which is currently being upgraded. Although the results indicate an extragalactic origin, the particular source responsible for accelerating these particles remains unknown. The upgraded observatory will enable more data to be acquired and allow a more detailed investigation of the currently studied energy ranges. It will also open the possibility to explore even higher energies where the magnetic-field deflections become even smaller, making it possible to study the origin of UHECRs, their acceleration mechanism and the magnetic fields that deflect them.

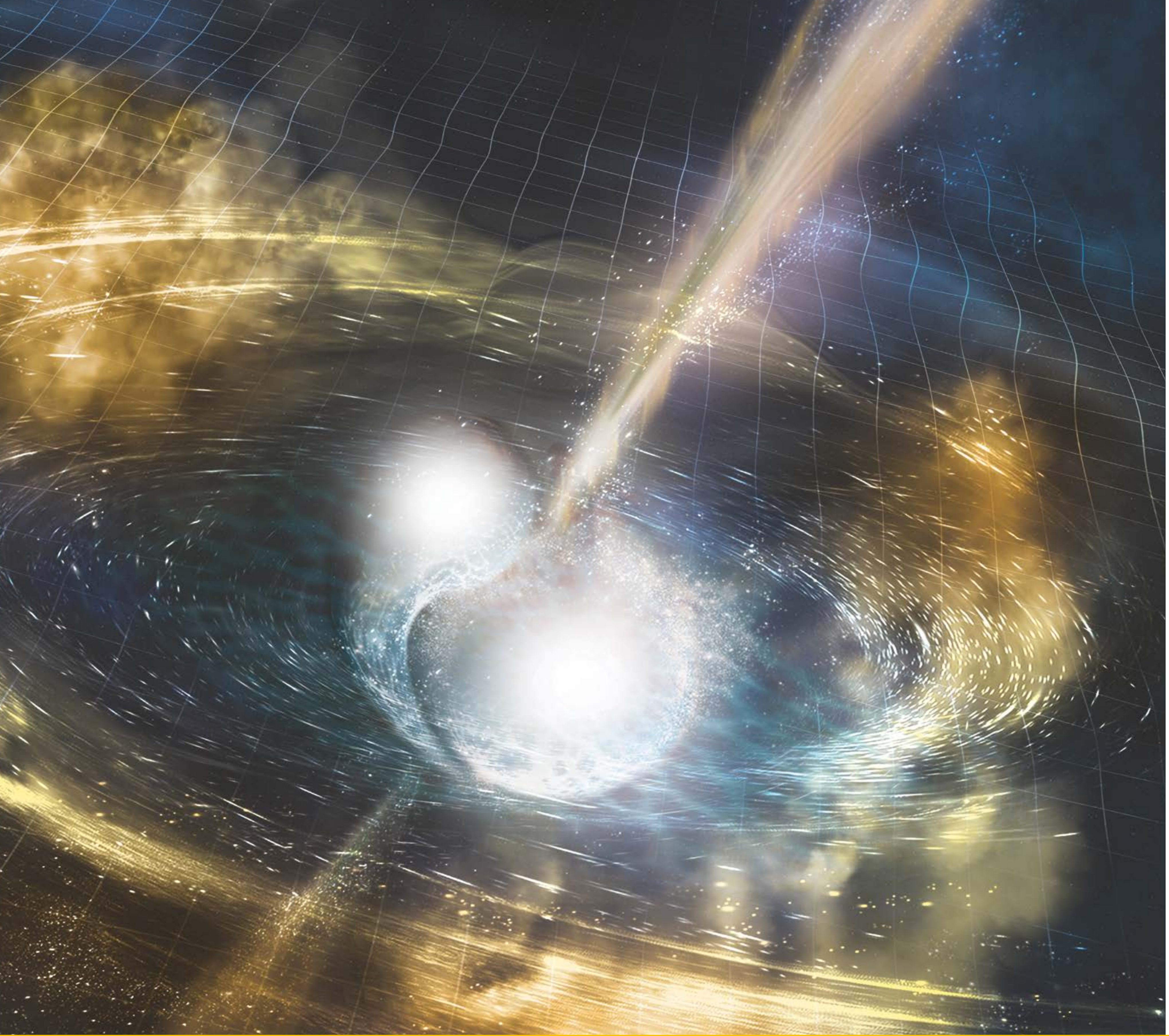
- **Further reading**

Pierre Auger Collaboration 2017 *Science* **357** 1266.

Picture of the month

This image might appear to show a large empty patch in the sky without any stars, but in reality it shows a molecular cloud in our galaxy obscuring our view. A high concentration of dust and molecular gas absorbs almost all of the visible light emitted from the stars behind it, producing the black patch. The molecular cloud shown in this image is known as Barnard 68, which is relatively nearby at about 500 light-years away and is half a light-year across. Molecular clouds are almost impenetrable for radiation in the visible part of the spectrum, but the stars behind them can be observed in the infrared. Furthermore, observations of these objects at submillimetre wavelengths can show stars forming in molecular clouds (*CERN Courier* September 2017 p15). The stars form as dense regions of the cloud collapse into themselves to form areas dense enough to initiate the burning of hydrogen.

FORS Team/8.2m VLT Antu/ESO



Gravitational waves and the birth of a new science

The recent observation of a neutron-star merger in the gravitational and electromagnetic domains opens the era of multi-messenger astronomy and calls for new gravitational-wave observatories to reveal the universe in all its colours.

On 14 September 2015, the world changed for those of us who had spent years preparing for the day when we would detect gravitational waves. Our overarching goal was to directly detect gravitational radiation, finally confirming a prediction made by Albert Einstein in 1916. A year after he had published his theory of general relativity, Einstein predicted the existence of gravitational waves in analogy to electromagnetic waves (i.e. photons) that propagate through space from accelerating electric charges. Gravitational waves are produced by astrophysical accelerations of massive objects, but travel through space as oscillations of space–time itself.

It took 40 years before the theoretical community agreed that gravitational waves are real and an integral part of general relativity. At that point, proving they exist became an experimental problem and experiments using large bars of aluminium were instrumented to detect a tiny change in shape from the passage of a gravitational wave. Following a vigorous worldwide R&D programme, a potentially more sensitive technique – suspended-mass interferometry – has superseded resonant-bar detectors. There was limited theoretical guidance regarding what sensitivity would be required to achieve detections from known astrophysical sources. But various estimates indicated that a strain ▷

An illustration of two merging neutron stars, as recently detected by LIGO–Virgo, during which bursts of gamma rays are emitted just seconds after the gravitational waves, along with swirling clouds of material including gold and other heavy metals. (Image credit: NSF/LIGO/Sonoma State University/A Simonnet.)

sensitivity $\Delta L/L$ of approximately 10^{-21} caused by the passage of a gravitational wave would be needed to detect known sources such as binary compact objects (binary black-hole mergers, binary neutron-star systems or binary black-hole neutron-star systems). That's roughly equivalent to measuring the Earth–Sun separation to a precision of the proton radius.

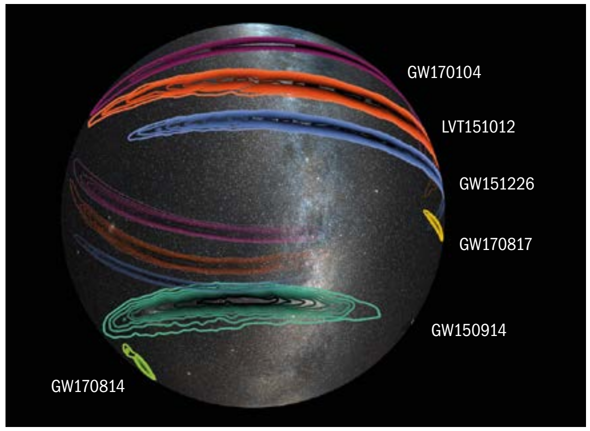
The US National Science Foundation approved the construction of the Laser Interferometer Gravitational-Wave Observatory (LIGO) in 1994 at two locations: Hanford in Washington state and Livingston in Louisiana, 3000 km away. At that time, there was a network of cryogenic resonant-bar detectors spread around the world, including one at CERN, but suspended-mass interferometers have the advantage of broadband frequency acceptance (basically the audio band, 10–10,000 Hz) and a factor-1000 longer arms, making it feasible to measure a smaller ΔL. Earth-based detectors are sensitive to the most violent events in the universe, such as the merger of compact objects, supernovae and gamma-ray bursts. The detailed interferometric concept and innovations had already been demonstrated during the 1980s and 1990s in a 30 m prototype in Garching, Germany, and a 40 m prototype at Caltech in the US. Nevertheless, these prototype interferometers were at least four orders of magnitude away from the target sensitivity.

Strategic planning

We built a flexible technical infrastructure for LIGO such that it could accommodate a future major upgrade (Advanced LIGO) without rebuilding too much infrastructure. Initial LIGO had mostly used demonstrated technologies to assure technical success, despite the large extrapolation from the prototype interferometers. After completing Initial LIGO construction in about 2000, we undertook an ambitious R&D programme for Advanced LIGO. Over a period of about 10 years, we performed six observational runs with Initial LIGO, each time searching for gravitational waves with improved sensitivity. Between each run, we made improvements, ran again, and eventually reached our Initial LIGO design sensitivity. But, unfortunately, we failed to detect gravitational waves.

We then undertook a major upgrade to Advanced LIGO, which had the goal of improving the sensitivity over Initial LIGO by at least a factor of 10 over the entire frequency range. To accomplish this, we developed a more powerful NdYAG laser system to reduce shot noise at high frequencies, a multiple suspension system and larger test masses to reduce thermal noise in the middle frequencies, and introduced active seismic isolation, which reduced seismic noise at frequencies of around 40 Hz by a factor of 100 (*CERN Courier* January/February 2017 p34). This was the key to our discovery of our first 30 solar-mass binary black-hole mergers, which are concentrated at low frequencies, two years ago. The increased sensitivity to such events had expanded the volume of the universe searched by a factor of up to 10^6, enabling a binary black-hole-merger detection coincidence within 6 ms between the Livingston and Hanford sites.

Then, on 17 August, we really hit the jackpot.



LIGO/Virgo/NASA/L Singer (Milkey Way image: Axel Mellinger)

Sky localisations of gravitational-wave signals detected by LIGO beginning in 2015 (GW150914, LVT151012, GW151226, GW170104) and, more recently, by the LIGO–Virgo network (GW170814, GW170817). The latter illustrate the improvement in localising the source thanks to the additional detector.

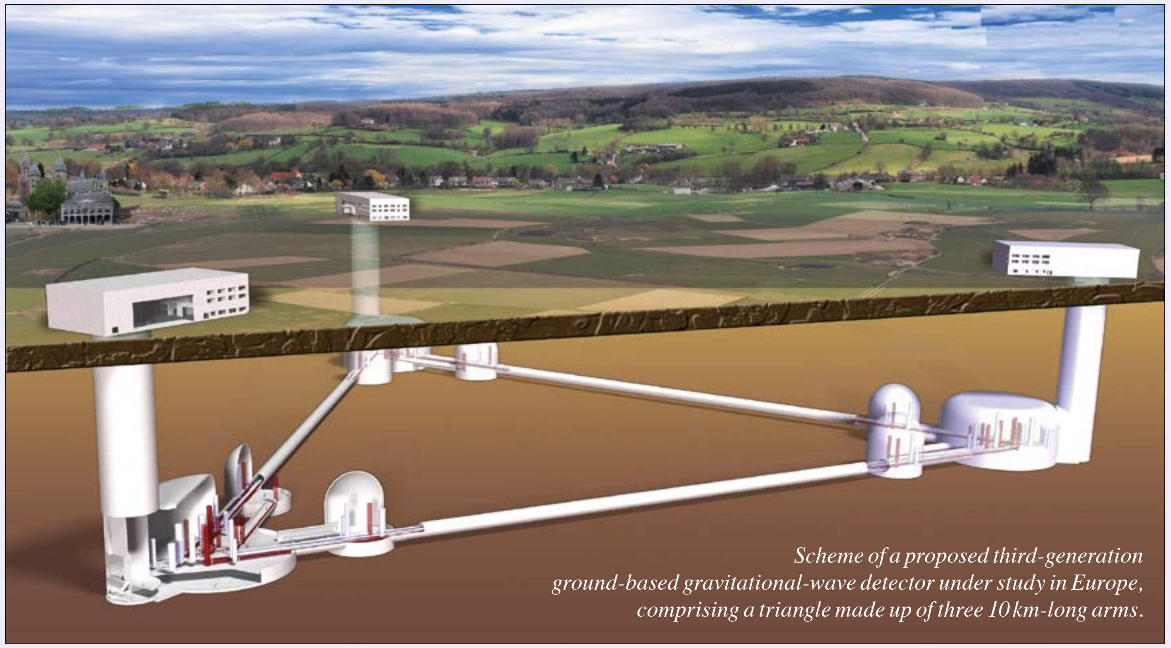
We recorded the last 0.2 seconds of this astrophysical collision: the final merger; coalescence; and "ring-down" phase, constituting the first direct observation of gravitational waves. The waveform was accurately matched by numerical-relativity calculations with a signal-to-noise ratio of 24:1 and a statistical probability easily exceeding 5σ. Beyond confirming Einstein's prediction, this event represented the first direct observation of black holes, and established that stellar black holes exist in binary systems and that they merge within the lifetime of the universe (*CERN Courier* January/February 2017 p16). Surprisingly, the two black holes were each about 30 times the mass of the Sun – much heavier than expectations from astrophysics.

Run 2 surprises

Similar to Initial LIGO, we plan to reach Advanced LIGO design sensitivity in steps. After completion of the four-month-long first data run (called O1) in January 2016, we improved the interferometer at the Livingston site from 60 Mpc to 100 Mpc for binary neutron-star mergers, but fell somewhat short in Hanford due to some technical issues, which we decided to fix after LIGO's second observational run (O2). We have now reported a total of four black-hole-merger events and are beginning to determine characteristics such as mass distributions and spin alignments that will help distinguish between the different possibilities for the origin of such heavy black holes. The leading ideas are that they originate in low-metallicity parts of the universe, were produced in dense clusters, or are primordial. They might even constitute some of the dark matter.

Advanced LIGO's O2 run ended in August this year. Although it seemed almost impossible that it could be as exciting as O1, several more black-hole binary mergers have been reported, including one after the Virgo interferometer in Italy joined O2 in August and dramatically improved our ability to locate the direction of the source. In addition, the orientation of Virgo relative to the two LIGO interferometers enabled the first information on the polarisation of ▷

CERN LIGO–Virgo meeting weighs up 3G gravitational-wave detectors



Max Planck Institute for Gravitational Physics

Scheme of a proposed third-generation ground-based gravitational-wave detector under study in Europe, comprising a triangle made up of three 10 km-long arms.

Similar to particle physicists, gravitational-wave scientists are contemplating major upgrades to present facilities and developing concepts for next-generation observatories. Present-generation (G2) gravitational-wave detectors – LIGO in Hanford, Livingston and India, Virgo in Italy, GEO600 in Germany and KAGRA in Japan – are in different stages of development and have different capabilities (see main text), but all are making technical improvements to better exploit the science potential from gravitational waves over the coming years. As the network develops, the more accurate location information will enable the long-time dream of studying the same astrophysical event with gravitational waves and their electromagnetic and neutrino counterpart signals.

The case for making future, more sensitive next-generation gravitational-wave detectors is becoming very strong, and technological R&D and design efforts for 3G gravitational detectors may have interesting overlaps with both CERN capabilities and future directions. The 3G concepts have many challenging new features, including: making longer arms; going underground; incorporating squeezed quantum states; developing lower thermal-noise coatings; developing low-noise cryogenics; implementing Newtonian noise cancellation; incorporating adaptive controls; new computing capabilities and strategies; and new data-analysis methods.

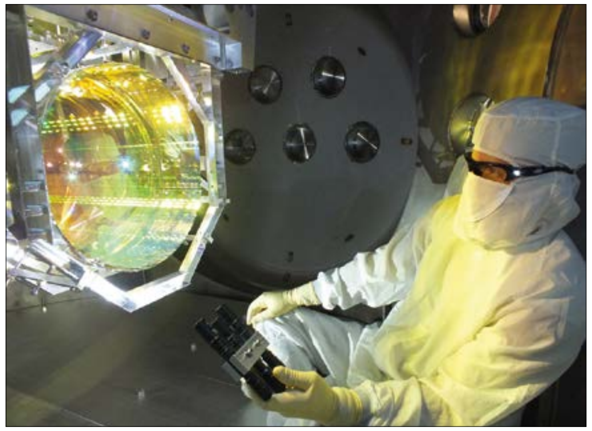
In late August, coinciding with the end of the second Advanced LIGO observational run, CERN hosted a LIGO–Virgo collaboration meeting. On the final day, a joint meeting between LIGO–Virgo and CERN explored possible synergies between the two fields. It provided strong motivation for next-generation facilities in both particle and gravitational physics and revealed intriguing overlaps between them. On a practical level, the event identified issues facing both communities, such as geology and survey, vacuum and cryogenics, control systems, computing and governance.

The time for R&D, construction and commissioning is expected to be around a decade, with problems near to intractable. It is planned to use cryogenics to bring mirrors to the temperature of a few kelvin. The mirrors themselves are coated using ion beams for deposition, to obtain a controlled reflectivity that must be uniform over areas 1 m in diameter. These mirrors work in an ultra-high vacuum, and residual gas-density fluctuations must be minimal along a vacuum cavity of several tens of kilometres, which will be the approximate footprint of the 3G scientific infrastructure.

Data storage and analysis is another challenge for both gravitational and particle physicists. Unlike the large experiments at the LHC, which count or measure energy deposition in millions of pixels at the detector level, interferometers continuously sample signals from hundreds of channels, generating a large amount of data consisting of waveforms. Data storage and analysis places major demands on the computing infrastructure, and analysis of the first gravitational events called for the GRID infrastructure.

Interferometers have to be kept on an accurately controlled working point, with mirrors used for gravitational-wave detection positioned and oriented using a feedback control system, without introducing additional noise. Sensors and actuators are different in particle accelerators but the control techniques are similar.

Comparisons of the science capabilities, costs and technical feasibility for the next generation of gravitational-wave observatories are under active discussion, as is the question of how many 3G detectors will be needed worldwide and how similar or different they need be. Finally, there were discussions of how to form and structure a worldwide collaboration for the 3G detectors and how to manage such an ambitious project – similar to the challenge of building the next big particle-physics project after the LHC.


Inspecting LIGO's optics for contaminants.

Matt Heintze/Caltech/MIT/LIGO Lab


Virgo, located near Pisa in Italy, has arms that are 3 km long and was the first detector in Europe – and the third ever – to register a passing gravitational wave.

Virgo Collaboration

the gravitational waves. Together with other measurements, this allowed us to limit the existence of an additional tensor term in general relativity and showed that the LIGO–Virgo event is consistent with the predicted two-state polarisation picture.

Then, on 17 August, we really hit the jackpot: our interferometers detected a neutron-star binary merger for the first time. We observed a coincidence signal in both LIGO and Virgo that had strikingly different properties from the black-hole binary mergers we had spotted earlier. Like those, this event entered our detector at low frequencies and propagated to higher frequencies, but lasted much longer (around 100 s) and reached much higher frequencies. This is because the masses in the binary system were much lower and, in fact, are consistent with being neutron stars. A neutron star results from the collapse of a star into a compact object of between 1.1–1.6 solar masses. We have identified our event as the merger of two neutron stars, each about the size of Geneva, but having several hundred thousand times the mass of the Earth.

As we accumulate more events and improve our ability to record their waveforms, we look forward to studying nuclear physics under these extreme conditions. This latest event was the first observed gravitational-wave transient phenomenon also to have electromagnetic counterparts, representing multi-messenger astronomy. Combining the LIGO and Virgo signals, the source of the event was narrowed down to a location in the sky of about 28 square degrees, and it was soon recognised that the Fermi satellite had detected a gamma-ray burst shortly afterwards in the same region. A large and varied number of astronomical observations followed. The combined set of observations has resulted in an impressive array of new science and papers on gamma-ray bursts, kilonovae, gravitational-wave measurements of the Hubble constant, and more. The result even supports the idea that binary neutron-star collisions are responsible for the very heavy elements, such as platinum and gold.

An ultimate goal is to use gravitational waves to study the Big Bang itself.

Going deeper

Much has happened since our first detection, and this portends well for the future of this new field. Both LIGO and Virgo entered into a 15 month shutdown at the end of August to further improve noise levels and raise their laser power. At present, Advanced LIGO is about a factor of two below its design goal (corresponding to a factor of eight in event rates). We anticipate reaching design sensitivity by about 2020, after which the KAGRA interferometer in Japan will join us. A third LIGO interferometer (LIGO-India) is also scheduled for operation in around 2025. These observatories will constitute a network offering good global coverage and will accumulate a large sample of binary merger events, achieve improved pointing accuracy for multi-messenger astronomy, and hopefully will observe other sources of gravitational waves. This will not be the end of the story. Beyond the funded programme, we are developing technologies to improve our instruments beyond Advanced LIGO, including improved optical coatings and cryogenic test masses.

In the longer range, concepts and designs already exist for next-generation interferometers, having typically 10 times better sensitivity than will be achieved in Advanced LIGO and Virgo (see panel on previous page). In Europe, a mature concept called the Einstein Telescope is an underground interferometer facility in a triangular configuration (see panel on previous page), and in the US a very long (approximately 40 km) LIGO-like interferometer is under study. The science case for such next-generation devices is being developed through the Gravitational Wave International Committee (GWIC), which is the gravitational-wave field's equivalent to the International Committee for Future Accelerators (ICFA) in particle physics. Although the science case appears very strong scientifically and technical solutions seem feasible, these are still very early days and many questions must be resolved before a new generation of detectors is proposed.

To fully exploit the new field of gravitational-wave science, we must go beyond ground-based detectors and into the pristine seismic environment of space, where different gravitational-wave sources will become accessible. As described earlier, the lowest frequencies accessible by Earth-based observatories are about 10 Hz. The Laser Interferometer Space Antenna (LISA), a European Space Agency project scheduled for launch in the early 2030s, was approved earlier this year and will cover frequencies around 10^{-1}–10^{-4} Hz. LISA will consist of three satellites separated by 2.5×10^6 km in a triangular configuration and a heliocentric orbit, with light travelling continually along each arm to monitor the satellite separations for deviations from a passing gravitational wave. A test mission, LISA Pathfinder, was recently flown and demonstrated the key performance requirements for LISA in space (*CERN Courier* January/February 2017 p37).

Meanwhile, pulsar-timing arrays are being implemented to monitor signals from millisecond pulsars, with the goal of detecting low-frequency gravitational waves by studying correlations between pulsar arrival times. The sensitivity range of this technique is 10^{-6}–10^{-9} Hz, where gravitational waves from massive black-hole binaries in the centres of merging galaxies with periods of months to years could be studied.

An ultimate goal is to study the Big Bang itself. Gravitational waves are not absorbed as they propagate and could potentially probe back to the very earliest times, while photons only take us to within 300,000 or so years after the Big Bang. However, we do not yet have detectors sensitive enough to detect early-universe signals. The imprint also of gravitational waves on the cosmic microwave background has been pursued by the Bicep2 experiment, but background issues so far mask a possible signal.

Although gravitational-wave science is clearly in its infancy, we have already learnt an enormous amount and numerous exciting opportunities lie ahead. These vary from testing general relativity in the strong-field limit to carrying out multi-messenger gravitational-wave astronomy over a wide range of frequencies – as demonstrated by the most recent and stunning observation of a neutron-star merger. Since Galileo first looked into a telescope and saw the moons of Jupiter, we have learnt a huge amount about the universe through modern-day electromagnetic astronomy. Now, we are beginning to look at the universe with a new probe and it does not seem to be much of a stretch to anticipate a rich new era of gravitational-wave science.

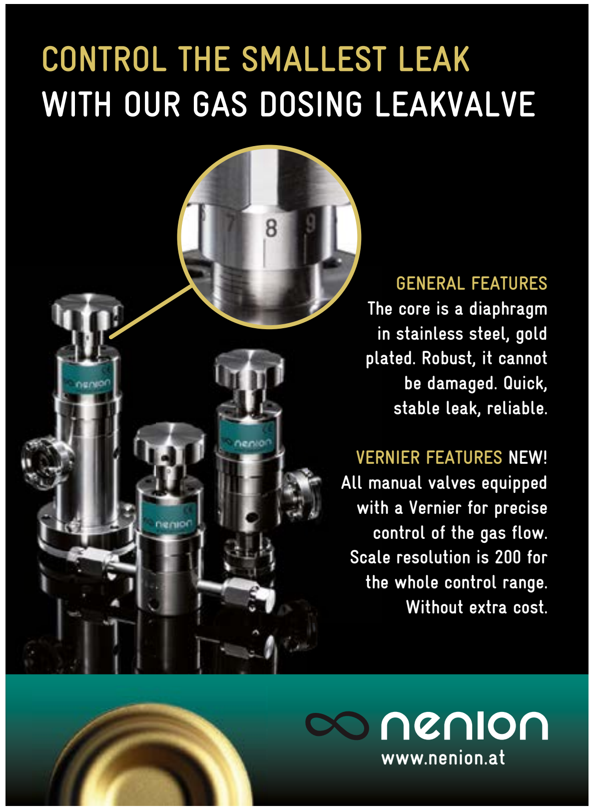
● *Barry Barish, the author of this feature, shared the 2017 Nobel Prize in Physics with Kip Thorne and Rainer Weiss for the discovery of gravitational waves* (CERN Courier *November 2017 p37).*

Résumé

Les ondes gravitationnelles et la naissance d'une nouvelle science

L'observation récente de la fusion d'étoiles à neutrons par les détecteurs d'ondes gravitationnelles LIGO et Virgo, combinée aux mesures électromagnétiques correspondantes, marque le début de l'ère de l'astronomie combinant différentes méthodes. Pour faire avancer au mieux la science des ondes gravitationnelles, de nouveaux observatoires équipés d'interféromètres sont nécessaires. En plus des extensions et des améliorations de LIGO et de Virgo, la communauté élabore des projets pour les détecteurs de la prochaine génération, à la fois sous terre et dans l'espace. Barry Barish, co-lauréat du prix Nobel de physique pour la découverte des ondes gravitationnelles, évoque dans cet article ce qui s'est passé jusqu'ici et ce qui nous attend.

Barry C Barish, LIGO Laboratory, California Institute of Technology.



Advertising feature

Tailor-made positioning solution for nanotomography: mechanical system approaches limit of technical feasibility

At the X-ray light source PETRA III at the DESY research center (German Electron Synchrotron) in Hamburg, Germany, the Helmholtz-Zentrum Geesthacht - Center for Materials and Coastal Research (HZG) operates the Imaging Beamline P05, which includes two experimental hutches, one for nanotomography and one for microtomography. In the nanotomography hutch, X-ray optics for three-dimensional micrographs with resolutions around 100 nm are used. The setup also includes microscopy optics for visible light, used for further magnification of the X-ray micrographs and their transfer to a camera.

The Z lifting stage performs the height adjustment, tilt correction, and orthogonal alignment, relative to the beam (image: PI /HZG)

With the aim to carry out as many different experiments as possible, the HZG provides two different X-ray optics configurations: An imaging setup, in which the sample is positioned in front of the objective optics , and a cone-beam setup, in which the sample is placed in the diverging beam behind the optics. In both cases, high mechanical stability and precision positioning are essential in order to obtain micrographs of high quality.

However, thanks to the close cooperation of the clients with the engineers and developers from PI (Physik Instrumente), this complex task could be solved in a practice-oriented manner.

A particular challenge was how to configure the control, which was based on an industrial controller. The challenge consisted in controlling almost 50 axes independently of one another while ensuring collision protection. The entire system was finally integrated into the TANGO interface customary for beamlines.

The Base:
Granite Platform Supported by Air Bearings

To minimize the effect of vibrations and securely fasten the individual components and stabilize them, relative to one another, a granite base 6.8 m in length forms the basis of the instrument. Another four moving granite platforms driven by linear motors are arranged on this base on air bearings. This makes it possible to position all components with high speed and precision: The sample stage, the X-ray optics, and the detector. The substructure itself, which weighs several tons, is also mounted on air bearings. This allows the entire assembly to be moved out of the X-ray beam with minimal effort when the second experimental station is to be used, while maintaining a stable position as soon as the air flow is switched off.

Complex Sequences during Sample Positioning

The basis of sample positioning is a horizontal positioning unit which moves the sample stage into the beam. It has a travel range of 20 mm, can be subjected to a load of 300 kg and works with a repeatability of 30 nm.

This displacement unit is equipped with three lifting elements which perform the height adjustment, tilt correction, and orthogonal alignment, relative to the beam. It is based on three identical, symmetrically arranged, and position-controlled stepper motors, combined with worm gears and spindle drives. Mounted on this Z stage is an air-bearing supported rotation stage. In developing this stage, the designers had to go push the limits of technical feasibility: What was required was a really "pure" rotary motion of the sample with minimal wobble, radial runout or eccentricity. Only in this case can sharp pictures over 360 degrees be made which all refer to the same volume element and can all be clearly assigned when reconstructing the picture. This is why the rotation stage, which rotates at a velocity of 36 °/s, works with flatness deviations of less than 100 nm at a resolution of 0.5 µrad. The air bearing does not produce any friction, which over time would lead to a deterioration of these values.

Parallel Kinematics for the Sample Holder and the Optics

The actual sample holder is located in the aperture of the rotation stage on the moving platform of a six-axis parallel kinematic system. The samples are positioned with six degrees of freedom. Essential features are the freely selectable pivot point of the parallel-kinematic system and its high stiffness. A six-axis parallel-kinematic system of this type is also used for the positioning of the optics. In nanotomography, which allows three-dimensional micrographs with resolutions below 100 nm, this machine is used to align compound refractive lenses (CRL) in the beam with high precision.

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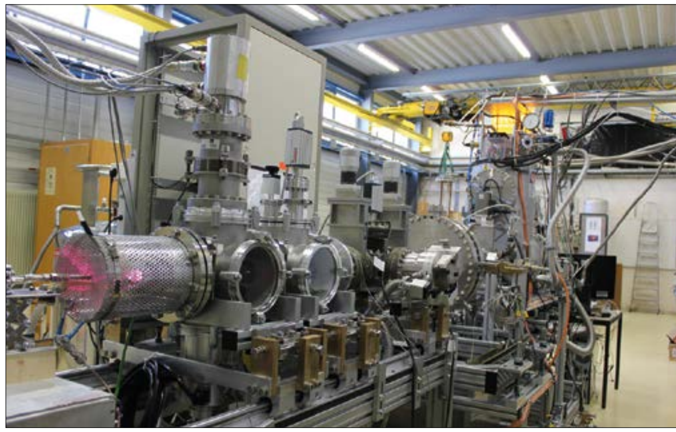
Hyperfine structure: from hydrogen to antihydrogen

Earlier this year, the ASACUSA experiment at CERN's Antiproton Decelerator published the most precise in-beam measurement of the hydrogen ground-state hyperfine splitting, and is now preparing for new measurements.



C Malbrunot

The ASACUSA experimental set-up, with the source of hydrogen visible by its characteristic pink glow.

Since the discovery of the positron in 1932 and the antiproton in 1955, physicists have striven to confront the properties of leptonic and baryonic matter and antimatter. A major advance in the story took place in 1995 when the first antihydrogen atoms were observed at CERN's LEAR facility. Then, in 2002, the ATHENA and ATRAP collaborations produced cold (trappable) antihydrogen at CERN's Antiproton Decelerator (AD), paving the way to the first measurement of antihydrogen's atomic transitions. An intense research programme at the AD has followed to compare the atomic states of antimatter with the most well-known atomic transitions in matter.

The physical properties of antimatter particles are tightly constrained within the Standard Model of particle physics (SM). For all local Lorentz-invariant quantum-field theories of point-like particles like the SM, the combination of the discrete symmetries charge-conjugation, parity and time-reversal (CPT) is conserved. An implication of the CPT theorem is that the properties of matter and antimatter are equal in absolute value. In this respect the lack of observation of primordial antimatter in the universe is tantalising, hinting that the universe has a preference for matter over antimatter despite their perfect symmetry on the microscopic scale as imposed by the SM. Although violations of CP symmetry, from which an imbalance in matter and antimatter can arise, have been observed in several systems, the effect is many orders of magnitude too small to account for the observed cosmological mismatch.

The hydrogen atom has been a source of profound theoretical developments.

In the quest for a quantitative explanation to the baryon asymmetry in the universe, one could question the validity of our formulation of the laws of physics in terms of quantum-field theory. This is additionally motivated by the notable absence of the gravitational force in the SM and would suggest that CPT symmetry (or Lorentz invariance) need not be conserved. A framework called Standard Model Extension (SME), an effective field theory that contains the SM and general relativity but also possible CPT and Lorentz violating terms, allows researchers to interpret the results of experiments designed to search for such effects.

Any measurement with antihydrogen atoms constitutes a model-independent test of CPT invariance. Given the precision at which they have been measured in hydrogen, two atomic transitions in antihydrogen are of particular interest: the 1S–2S transition and the ground-state hyperfine splitting (which corresponds to the 21 cm microwave-emission line between parallel and antiparallel antiproton and positron spins). These were determined over the past few decades in hydrogen with an absolute (relative) precision of 10 Hz (4×10^{-15}) and 2 mHz (1.4×10^{-12}), respectively. Reaching similar precision in antihydrogen, hydrogen's CPT conjugate would provide one of the most sensitive CPT tests in what was until recently a yet unprobed atomic domain. But this is a daunting challenge.

Status and prospects

Measurements of the hyperfine splitting of hydrogen reached their apogee in the 1970s. It is only recently that interest in such measurements has been revived, motivated by the possibility to further ▷

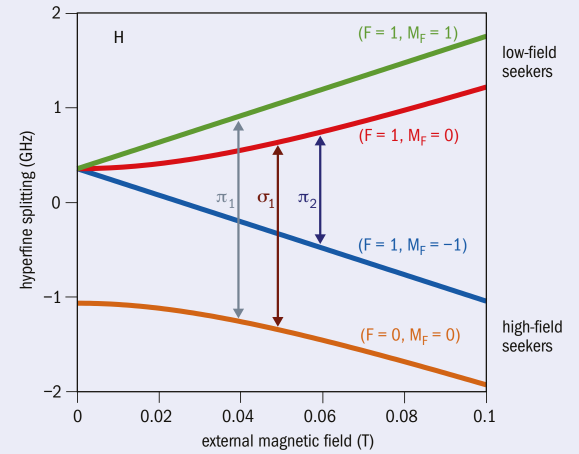


Fig. 1. The Breit–Rabi diagram shows the energy levels in ground-state hydrogen as a function of the strength of an external magnetic field. The states with a positive or negative slope are named low- and high-field seekers (lfs or hfs), respectively, and three possible hyperfine transitions between lfs and hfs are denoted by arrows.

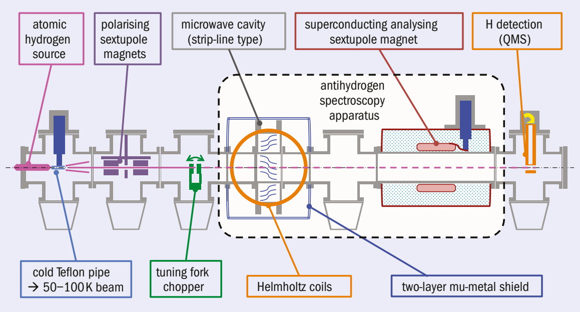


Fig. 2. Schematic of the experimental set-up for ASACUSA's hydrogen hyperfine splitting measurement. The cavity and sextupole are identical to those that will be used in the planned antihydrogen experiment.

develop methods that can be applied to antihydrogen. Hydrogen's hyperfine splitting was originally measured using a maser to interrogate atoms held in a Teflon-coated storage bulb, but this technique is not transferable to antihydrogen because unavoidable interactions between the antiatoms and the walls would lead to annihilations.

A precision of a few Hz can, however, be envisioned using the "beam-resonance" method of Rabi. This technique involves a polarised beam, microwave fields to drive spin flips, magnetic-field gradients to select a spin state, and a detector to measure the flux of atoms as a function of the microwave frequency. While less precise than the maser technique, the in-beam method can be directly applied to antihydrogen with a foreseen initial precision of a few kHz (10^{-6} relative precision). The leading order of the hyperfine splitting can be calculated from the known properties of the antiproton and positron, but a 10^{-6} level measurement would be sensitive to the antiproton magnetic and electric form factors that are so far unknown.

Earlier this year, the ALPHA experiment at CERN's AD measured the hyperfine splitting of trapped antihydrogen. Following a long campaign that saw ALPHA determine antihydrogen's 1S–2S transition in 2016 (*CERN Courier* January/February 2017 p8), the collaboration achieved a precision of 4×10^{-4} (0.5 MHz) on the hyperfine measurement. Ultimately the precision of in-trap measurements will be limited by the presence of strong magnetic-field gradients, however. The in-beam technique, by contrast, probes the hyperfine transition far away from the strong inhomogeneous magnetic trapping fields. In the 1950s this technique enabled hydrogen's hyperfine structure to be determined to a precision of 50 Hz. The recent measurement of this transition by the ASACUSA experiment using a similar technique has now improved on this precision by more than an order of magnitude.

The ASACUSA collaboration was formed in 1997 to investigate antiprotonic atoms and collisions involving slow antiprotons. Its antihydrogen programme started in 2005 at the AD and in recent years the collaboration has focused on two topics. One is laser spectroscopy of antiprotonic helium, which allows the determination of the antiproton mass (*CERN Courier* September 2011 p7) and the antiproton magnetic moment. The latter value was recently measured to higher precision in Penning traps first by the ATRAP experiment (*CERN Courier* May 2013 p6) and, as announced in October, further improved by more than three orders of magnitude by the BASE experiment, both also located at the AD.

The second focus of ASACUSA, led by the CUSP group, is to measure the hyperfine structure of antihydrogen in a polarised beam. ASACUSA employs a multi-trap set-up to produce an antihydrogen beam (*CERN Courier* March 2014 p5) for Rabi-type spectroscopy on the hyperfine transition. The spectroscopy apparatus was designed to match the expected properties of an antihydrogen beam and called for a test of the apparatus with a hydrogen beam of similar characteristics.

Hydrogen first

The spectroscopy technique relies on the dependency of the atomic energy levels on a magnetic field, also known as the Zeeman effect (figure 1). In the presence of a magnetic field, the degeneracy of the hyperfine triplet states is lifted. Two of the states, called low-field seekers (lfs), have a rising energy with rising magnetic field, while the third state of the triplet and the singlet state decrease their energies with rising magnetic field (they are called high-field seekers, hfs). These distinguishing properties are used to first polarise the beam by means of a magnetic-field gradient (figure 2), which leads to opposite forces on lfs and hfs. As a result, only lfs arrive at the interaction region, where a microwave cavity provides an oscillating magnetic field. This field can then induce state conversions from lfs to hfs if tuned to the right frequency. Atoms in hfs states are subsequently removed from the beam by a second section of magnetic-field gradients, thus leading to a reduced count rate at the detector when the transition is induced.

The hyperfine transitions would provide yet unknown information on the internal structure of the antiproton.

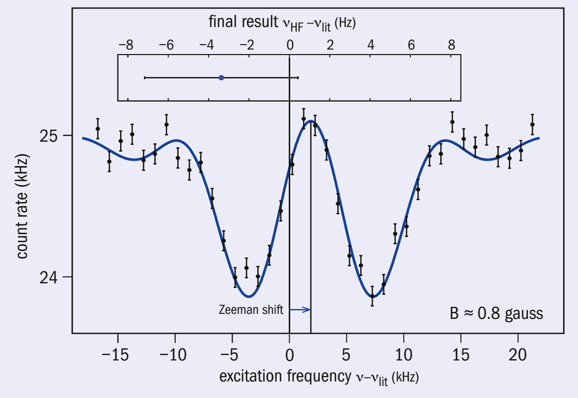


Fig. 3. Example of a hyperfine resonance spectrum in an external static magnetic field of around 80 µT. The "double-dip" structure is due to the particular shape of the RF field in the cavity leading to a field changing sign at the centre. The line at 0 represents the known zero-field value from established maser measurements. More than 500 such spectra have been recorded under changing experimental conditions to extrapolate to the zero-field hyper-fine splitting value, with ASACUSA's final result shown in the inset (note the different scales).

In the apparatus design chosen, large geometrical openings compensate for the low antihydrogen flux and a superconducting magnet is used to generate sufficiently selective magnetic-field gradients over such a large area. The oscillating microwave field needed to drive the hyperfine transition must be homogenous over the large geometrical opening, which dictated the design of the cavity leading to a particular resonance spectrum (figure 3). The functionality of the spectroscopy apparatus and other technical developments were tested by coupling a cold and polarised hydrogen source and a quadrupole mass spectrometer as hydrogen detector to the spectroscopy apparatus envisioned for the antihydrogen experiment (figure 2).

The measurement led to the determination of the hydrogen's so-called σ_1 hyperfine transition (figure 1), the transition frequency of which was measured as a function of the externally applied magnetic field. From a set of frequency determinations, the zero-field value could be extracted and such measurements were repeated under 10 distinct conditions to investigate systematic effects. In total more than 500 resonances (an example is shown in figure 3) were acquired to extract the zero-field hydrogen ground-state hyperfine splitting. Numerical methods developed to assist the analysis of the transition line shape contributed to the improvement by more than an order of magnitude, leading to a precision of 3.8 Hz and a value consistent with the more precise maser result.

A measurement of hydrogen's hyperfine splitting at the Hz level implies an absolute precision of 10^{-15} eV. Given the scarcity of antihydrogen and the yet unprobed properties (namely velocity and atomic states) of the antihydrogen beam, a measurement at this level of precision on antihydrogen is not possible in the short-term. However, the analysis of ASACUSA data collected with hydrogen enabled the collaboration to assess the necessary number of antiatoms to reach a 10^{-6} sensitivity, assuming plausible beam properties. The conclusion is that a measurement at the peV level (kHz precision) should be possible if 8000 antiatoms can be detected after the spectrometer. That would require at least an order-of-magnitude increase in the antihydrogen flux.

The Rabi-type spectroscopy approach chosen by ASACUSA has the capability to test individual transitions in hydrogen and antihydrogen under well-controlled external conditions and, if successful, will immediately result in a precision of 10^{-6} or better. At this level, the hyperfine transitions would provide yet unknown information on the internal structure of the antiproton. However, much work remains to be done for the ASACUSA experiment to gather the needed number of antihydrogen atoms in a reasonable time.

Until then, more measurements can be performed with the hydrogen set-up. The apparatus has recently been modified to allow for the simultaneous measurement of σ_1 and π_1 transitions (figure 1). Within the SME, the latter transition could reveal CPT and Lorentz violations while the σ_1 transition is insensitive to these effects and would serve as a monitor of potential systematic errors. This would give access to a number of so-far-unconstrained SME parameters that can be probed by hydrogen alone. While the antihydrogen experiment focuses on increasing the cold, ground-state antihydrogen flux, the hydrogen experiment is about to start a new measurement campaign for which results are expected in the next 18–24 months. The hydrogen atom has been a source of profound theoretical developments for some time, and history has shown that it is well worth the effort to study it ever more closely.

● Further reading

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Résumé

Structure hyperfine : de l'hydrogène à l'antihydrogène

En début d'année, l'expérience ASACUSA basée auprès du décélérateur d'antiprotons du CERN a publié la mesure la plus précise faite sur un faisceau d'une transition hyperfine de l'état fondamental de l'hydrogène. La collaboration prépare à présent de nouvelles mesures sur cet atome, le plus simple de tous, avec l'objectif final d'appliquer la même technique de mesure à l'antihydrogène. Les comparaisons entre l'hydrogène et son équivalent dans l'antimatière constituent en effet un test précis de la symétrie CPT et de l'invariance de Lorentz.

Chloé Malbrunot, CERN; **Martin Simon** and **Eberhard Widmann**, Stefan Meyer Institute, Vienna.

Reaching out from the European school

The CERN–JINR European School of High-Energy Physics marks 25 years of teaching advanced topics in particle physics to young experimentalists and, since 2014, training them in communication and outreach skills.

Training and education have been among CERN's core activities since the laboratory was founded. The CERN Convention of 1954 stated that these activities might include "promotion of contacts between, and interchange of, scientists…and the provision of advanced training for research workers". It was in this spirit that the first residential schools of physics were organised by CERN in the early 1960s. Initially held in Switzerland, with a duration of one week, the schools soon evolved into two-week events that took place annually and rotated among CERN Member States.

Following discussions between the Directors-General of CERN and the Joint Institute for Nuclear Research (JINR) in Russia, it was agreed that CERN should organise the 1970 school in collaboration with JINR. The event was held in Finland, which at that time was not a Member State of either institution, and the CERN–JINR collaboration evolved into today's annual CERN–JINR European Schools of High-Energy Physics (HEP). The European schools that began in 1993 (*CERN Courier* June 2013 p27) are held in a CERN Member State three years out of four, and in a JINR Member State one year out of four.

The target audience of the European schools is advanced PhD students in experimental HEP, preparing them for a career as research physicists. Around 100 students attend each event following a rigorous selection process. Those attending the 2017 school – the 25th in the series, held from 6 to 19 September in Évora, Portugal – were selected from more than 230 candidates, taking into account their potential to pursue a research career in experimental particle physics. The 100 successful students included 33 different nationalities and, reflecting an increasing trend over the past quarter century of the European schools, about a third were women.

The core programme of the schools continues to be particle-physics theory and phenomenology, including general topics such as the Standard Model, quantum chromodynamics and flavour physics, complemented by more specialised aspects such as heavy-ion physics, Higgs physics, neutrino physics and physics beyond the Standard Model. A course on practical statistics reflects the importance of this topic in modern HEP data analysis. The school also includes classes on cosmology, in light of the strong link between particle physics and astrophysical dark-matter research. Students are taught about the latest developments and prospects at CERN's Large Hadron Collider (LHC). They also hear from the Director-General of CERN and the director of JINR about the programmes and plans of the two organisations, which have links going back more than half a century. Thus, in addition to studying a wide spectrum of physics topics, the students are given a broad overview and outlook on particle-physics facilities and related issues.

Posters from all 25 schools to date, taking place in: Évora, Portugal; Skeikampen, Norway; Bansko, Bulgaria; Garderen, the Netherlands; Parádfürdö, Hungary; Anjou, France; Cheile Gradistei, Romania; Raseborg, Finland; Bautzen, Germany; Herbeumont-sur-Semois, Belgium; Třešť, Czech Republic; Aronsborg, Sweden; Kitzbühel, Austria; Sant Feliu de Guíxols, Spain; Tsakhkadzor, Armenia; Pylos, Greece; Beatenberg, Switzerland; Caramulo, Portugal; Častá - Papiernička, Slovakia; St Andrews, Scotland, UK; Menstrup, Denmark; Carry-le-Rouet, France; Dubna, Russia; Sorrento, Italy; and Zakopane, Poland.

The two-week residential programme includes a total of more than 30 plenary lectures of 90 minutes each, complemented by parallel discussion sessions involving six groups of about 17 students. Each group remains with the same discussion leader for the duration of the school, providing an environment where the students are comfortable to ask questions about the lectures and explore topics of interest in greater depth. The students are encouraged to discuss their own research work with each other and with the staff of the school during an after-dinner poster session. The lecturers are highly experienced experts in their fields, coming from many different countries in Europe and beyond, while the discussion leaders are highly active, but sometimes less-senior physicists.

New ingredient

A new ingredient in the school's programme since 2014 is training in outreach for the general public. Making use of two 90 minute teaching slots, the students learn about communicating science to a general audience from two professional trainers who have a background in journalism with the BBC. The compulsory training sessions are complemented by optional one-on-one exercises that are very popular with the students. The exercises involve acting out a radio interview about a discovery of new physics at the LHC based on a fictitious scenario.

Building on what they have learnt in the science-communication training, the students from each discussion group collaborate in their "free time" to prepare an eight-minute talk on a particle-physics topic at a level understandable to the public. This is an exercise in teamwork as well as in outreach. The group needs to identify the specific aspects of the topic that they are going to address, develop a plan to make it interesting and relevant to a general audience, share the work of preparing the presentation between the team members, and agree who will give the talk on their behalf. ▷

N Ellis/CERN

Ruben Conceição/LIP

University of Evora

Ricardo Goncalo, LIP

Clockwise from top left: CERN's Director-General Fabiola Gianotti talking with students at the 2017 European school during a coffee break. A student at the 2017 European school practices a radio interview with a trainer. The winners of the collaborative outreach project at the 2017 European school. The audience at the public outreach event, including (from right) in the front row: Victor Matveev, director of JINR, Gaspar Barreira, director of LIP, Manuel Heitor, Portuguese minister for science, technology and higher education, Ana Costa Freitas, rector of the University of Évora, and Mário Pimenta, president of LIP.

The results of the collaborative group projects are presented in an after-dinner session that is video recorded. A jury made up of experienced science communicators judges the projects and gives feedback to each group. The topics addressed in the projects at the 2017 school in Portugal included the Standard Model, neutrinos, extra dimensions, and cosmology, with the prize for the best team effort going to a presentation on the Higgs boson illustrated with a "cookie-eating grandmother" field.

Equipping young researchers with good science-communication skills is considered important by the management of both CERN and JINR, and outreach training is greatly appreciated by most of the European school's students. As a follow up, students are encouraged to make contact with the people responsible for outreach in their experimental collaborations or home institutes, with a view to participating in science-communication activities.

All these schools are important ingredients in delivering CERN's mission in education and outreach.

In addition to the outreach training, important public events are often held in the host country at the time of the school – benefitting from the presence of the leading scientists who are lecturing. This is well illustrated by the 2017 edition, at which a public event at Évora University coincided with visits to the school by CERN Director-General Fabiola Gianotti, who gave a talk entitled "The Higgs particle and our life", and JINR director Victor Matveev. The event was attended by numerous high-level representatives of Portuguese scientific institutes and universities, and also by the Portuguese minister of science, technology and higher education, Manuel Heitor. There was an audience of about 300, including high-school teachers, pupils and university students, with more following a live webcast.

Branching out

In addition to the annual schools that take place in Europe, CERN is involved in organising schools of HEP in Latin America (in odd-numbered years since 2001) and in the Asia-Pacific region (in even-numbered years since 2012). These schools have a similar core programme to the European ones, but with more emphasis on instrumentation and experimental techniques. This reflects the fact that there are fewer opportunities in some of the countries concerned for advanced training in these areas.

Although there is so far no specific teaching at the schools in Latin America and the Asia-Pacific region on communicating science to a general audience, education and outreach activities are often arranged in the host country around the time of the schools. For example, an important education and outreach programme was organised to coincide with the 2017 CERN–Latin-American School held from 8 to 21 March in Querétaro, Mexico. Here, several teachers from the CERN school gave short lecture courses or seminars to undergraduate students from Universidad Autónoma de Querétaro and the Juriquilla campus of Universidad Nacional Autónoma de México.

A highlight of the outreach programme in Mexico was a large public event on 8 March, the arrivals day for students at the CERN school and, by coincidence, International Women's Day. This included introductory talks by Fabiola Gianotti (recorded in advance and subtitled in Spanish) and by Julia Tagüeña Parga (in person), deputy director for scientific development in the Mexican national science and technology agency, CONACyT. These were followed by a lecture entitled "Einstein, black holes and gravitational waves" by Gabriela Gonzalez, spokesperson of the LIGO collaboration, attracting a capacity audience of about 400 people.

As is evident, the European schools of HEP have a long history and continue their primary mission of teaching HEP and related topics to young researchers. However, the programme continues to evolve, and it now includes some training in science communication that is becoming increasingly important in the CERN and JINR Member States. The success of the schools can be judged by an anonymous evaluation questionnaire in which the overall assessment is overwhelmingly positive, with about 60% of students in 2014–2017 giving the highest ranking of "excellent".

In total, more than 3000 students have attended the schools, including the Latin-American schools since 2001 and the Asia–Europe–Pacific schools since 2012, as well as the European schools since 1993. All these schools are important ingredients in delivering CERN's mission in education and outreach, and in supporting its policies of international co-operation and being open to geographical enlargement within and beyond Europe. They bring together participants and teachers of many different nationalities, and each school requires close collaboration between CERN, co-organisers such as JINR for the European schools, and colleagues from the host country. The schools may also link in with other aspects of CERN's international relations. For example, the 2015 Latin-American school in Ecuador helped to pave the way for formal membership of Ecuadorian universities in the CMS experiment. Similarly, the 2011 European school and associated outreach activities in Bucharest marked steps towards Romania becoming a Member State of CERN.

The next European school will be held in Maratea, Italy, from 20 June to 3 July 2018, followed by an Asia–Europe–Pacific school in Quy Nhon, Vietnam, from 12 to 25 September 2018.

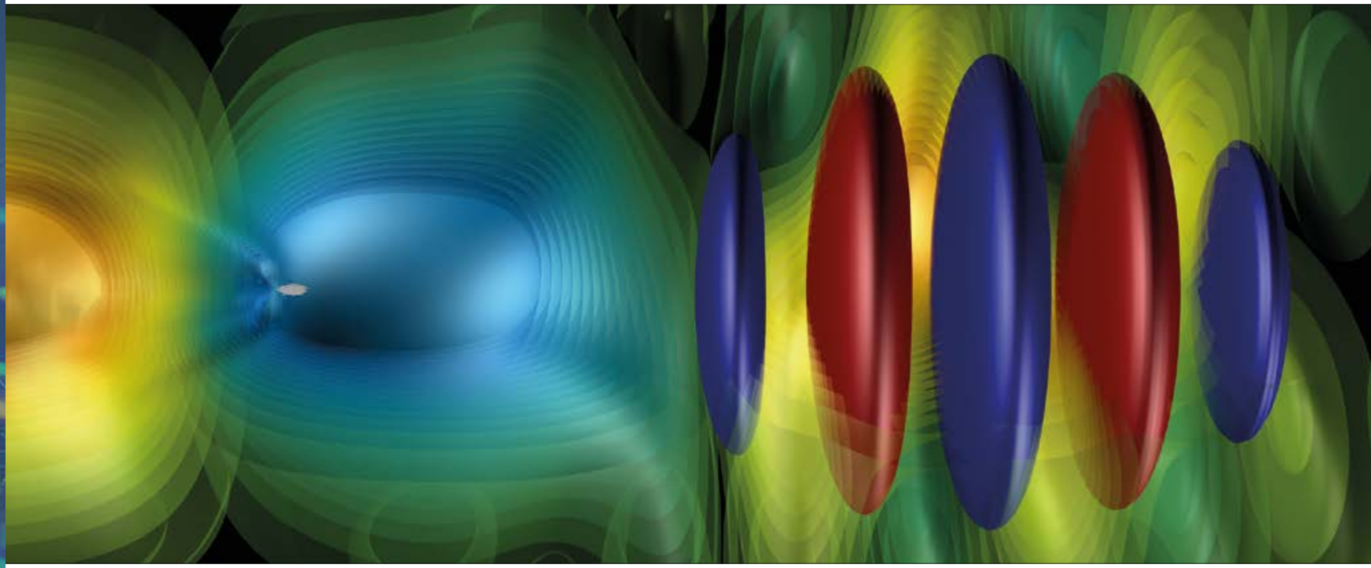
Résumé

La communication grand public au menu des écoles européennes

Cela fait 25 ans que l'école européenne CERN-JINR de physique des hautes énergies dispense à de jeunes expérimentateurs un enseignement sur des sujets avancés en physique des particules, afin de les préparer à une carrière dans la recherche. Après un processus de sélection rigoureux, une centaine d'étudiants participe à chaque école. Depuis 2014, un nouvel élément a été introduit dans ces écoles : une formation à la communication grand public. La formation et l'éducation font en effet partie des missions centrales du CERN depuis sa fondation, et le Laboratoire participe aussi à l'organisation d'écoles en Amérique latine et dans la région Asie-Pacifique.

Nick Ellis and **Martijn Mulders**, CERN.

Charting a course for advanced accelerators


Simulated excitation of a wakefield behind a laser driver using the WARP code, with the laser pulse depicted in alternating dark-blue and dark-red spheroids. Yellow/white areas have more plasma electrons, blue/green more plasma ions. (Image credit: J-L Vay/LBNL.)

Applying next-generation plasma acceleration techniques to high-energy physics requires a global effort by the accelerator community.

Progress in experimental particle physics is driven by advances in accelerators. The conversion of storage rings into colliders in the 1970s is one example, another is the use of superconducting magnets and RF structures that allow higher energies to be reached. CERN's Large Hadron Collider (LHC) is halfway through its second run at an energy of 13 TeV, and its high-luminosity upgrade is expected to operate until the mid-2030s. Several machines are under consideration for the post-LHC era and many will be weighed up during the European Strategy for Particle Physics beginning in 2019. All are large facilities based on advanced but essentially existing accelerator technologies.

A completely different breed of accelerator based on novel accelerating technologies is also under intense study. Capable of operating with an accelerating gradient larger than 1 GV/m, advanced and novel accelerators (ANAs) could reach energies in the 1–10 TeV range in much more compact and efficient ways. The technological challenge is huge and the timescales are long, but the eventual goal is to have a linear electron–positron or an electron–proton collider at the energy frontier. Such a machine would have a smaller footprint than conventional collider designs and promises energies that otherwise are technologically extremely difficult and expensive to reach.

The first Advanced and Novel Accelerators for High Energy Physics Roadmap (ANAR) workshop took place at CERN in April, focusing on the application of ANAs to high-energy physics (*CERN Courier* June 2017 p7). The workshop was organised under the umbrella of the International Committee for Future Accelerators as a step towards an international ANA scientific roadmap for an advanced linear collider, with the aim of delivering a technical design report by 2035. The first task towards this goal is to take stock of the scientific landscape by outlining global priorities and identifying necessary facilities and existing programmes.

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The ANA landscape

The first idea to accelerate particles in a plasma came as long ago as 1979, with a seminal publication by Tajima and Dawson. It involved the use of wakefields – accelerating longitudinal electric fields generated in a plasma in the wake of a driving laser pulse or a particle bunch – to accelerate and focus a relativistic bunch of particles. In ANAs using plasma as a medium, the wakefields are sustained by a charge separation in the plasma driven by a laser pulse or a particle beam. Large energy gains over short distances can also be reached in ANAs using dielectric material structures that can sustain maximum accelerating fields larger than is possible in metallic structures. These ANAs can accelerate electrons as well as positrons and can also be driven by laser pulses or particle bunches.

Initial experiments took place with electrons at SLAC and elsewhere in the 1990s, demonstrating the principles of the technique, but the advent of high-power lasers as wakefield drivers led to increased activity. After the first demonstration of peaked electron spectra in millimetre-scale plasmas in 2004, GeV electron beams were obtained with 40 TW laser pulses in 2006 and subsequently electron beams with multi-GeV energies have been reported with PW-class laser systems and few-centimetre-long plasmas. Advanced and novel technologies for accelerators have made remarkable progress over the past two decades. They are now capable of bringing electrons to energies of a few GeV over a distance of a few centimetres, compared to 0.1 MeV per centimetre for the Large Electron–Positron (LEP) collider. Reaching such energies with ANAs has therefore sparked interest for high-energy physics applications, in addition to their potential for industry, security or health sectors.

Several challenges must be addressed before proposing a technical design for an advanced linear collider (ALC), requiring the sustained efforts of a diverse community that currently includes more than 62 laboratories in more than 20 countries. The key challenges are either related to fundamental components of ANAs – such as the injectors, accelerating structures, staging of components and their reliability – or to beam dynamics at high energy and the preservation of energy spread, emittance and efficiency.

A major component necessary for the application of an ANA to high-energy physics is a wakefield driver. In practice, this could be an efficient and reliable laser pulse with a peak power topping 100 TW, or a particle bunch with an energy higher than 1 GeV. In both cases, however, the duration of the pulse must be shorter than 100 fs.

The plasma medium, separated into successive stages, is another key component. Assuming accelerating gradients in the region 10–50 GeV/m and energy gains of 10–20 GeV per stage, plasma media 20–200 cm long are required. The main challenges for the plasma medium are the reproducibility, density uniformity, density ramps at their entrance and exit, and the high repetition rate required for collider operation. Tailoring the density ramps is important to mitigate the usually large mismatch between the small transverse size of the accelerated beam inside the plasma and the relatively large beam size that interstage optics must handle between plasma modules.

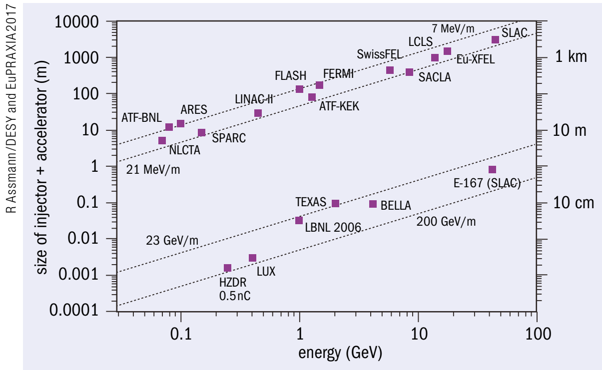
ANA technology could potentially define particle physics into the 22nd century.


M Brice/CERN


Lawrence Berkeley National Laboratory

(Top) The AWAKE experiment at CERN, which is exploring high-gradient accelerators by driving a 10 m-long plasma with a high-energy bunch of protons from the SPS. (Above) The BELLA experiment at Lawrence Berkeley National Laboratory recently demonstrated laser-driven acceleration across two stages – an important step towards particle-physics applications.

Staging successive accelerator modules is a further challenge in itself. Staging is necessary because the energy carried by most drivers is much smaller than the final energy desired for the accelerated bunch, e.g. 1.6 kJ for 2×10^{10} electrons or positrons at an energy of 500 GeV. Since state-of-the-art femtosecond laser pulses and relativistic electron bunches carry less than 100 J, multiple drivers and multiple stages are needed. Staging has to achieve, in a compact way, coupling of the accelerated bunch out of one plasma module into the next one, while preserving all bunch properties, and evacuating the exhausted driver and bringing the fresh driver before entering the next stage. Staging has been demonstrated, although with low-energy beams (< 200 MeV), in a number of schemes, the most recent being the one performed at the BELLA Center at LBNL. Injection of electrons from a laser plasma injector into a plasma module providing acceleration to 5–10 GeV is one of the goals of the French APOLLON CILEX laser facility starting operation in 2018, and of the baseline explored in the design study EuPRAXIA (see panel on right). The AWAKE experiment at CERN, meanwhile, aims to use protons to drive a plasma wakefield in a single plasma section with the long-term goal of accelerating electrons to TeV energies.


R Assmann/DESY and EuPRAXIA2017

Comparison of selected linear accelerators, showing size as a function of energy, putting the challenge of developing a wakefield-driven accelerator in context with the current landscape. The dashed lines show the expected scaling with a certain energy gain per distance.

Stability, reproducibility and reliability are trademarks of accelerators used for particle physics. Results obtained with ANAs often appear of lower stability and reproducibility than those obtained with conventional accelerators. However, it is important to note that these ANAs are run mostly as experiments and research tools, with limited resources put towards feedback and control systems – which are one of the major features of conventional accelerators. A strong effort therefore has to be put into developing proper tools and devices, for instance by exploiting synergies with the RF-accelerator community to develop more reliable technologies.

Testing the components for an eventual ALC requires major facilities, most likely located at national or international laboratories. ANA technology might be more compact than that of conventional accelerators, but the environment for producing even 10–100 GeV range prototypes is beyond the capability of university labs, requiring multiple engineering skills to demonstrate reliable operation in a safe environment. The size and cost of these facilities are better justified in a collaborative environment, in line with the development of accelerators relevant for high-energy physics.

Four-phase roadmap

Co-ordination of the advanced accelerators field is at different levels of advancement around the world. In the US, roadmaps were drawn up in 2016 for plasma- and structure-based ANAs with application to high-energy physics and the construction of a linear collider in the 2040s. One outcome of the ANAR workshop this year was a first attempt at an international scientific roadmap. Arranged into four distinct phases, the roadmap describes the stages deemed scientifically necessary to elaborate a design for a multi-TeV linear collider.

The first is a five-year-long period in which to develop injectors and accelerating structures with controlled parameters, such as an injector–accelerator unit producing GeV-range electron and positron beams with high-quality bunches, low emittance and low relative energy spread. A second five-year phase will lead to ▷

EAAC workshop showcases advanced accelerator progress


V Tullio/INFN

Participants of the September EAAC event in Italy.

The 3rd European Advanced Accelerator Concept (EAAC) workshop, held every two years, took place from 24 to 30 September on the Island of Elba, Italy. Around 300 scientists attended, with advanced linear colliders at the centre of discussions. Specialists from accelerator physics, RF technology, plasma physics, instrumentation and the laser field discussed ideas and directions towards a new generation of ultra-compact and cost-effective accelerators with novel applications in science, medicine and industry.

Among the many outstanding presentations at EAAC 2017, at which 70 PhD students presented their work, were reports on: laser-driven kHz generation of MeV beams at LOA/TU Vienna; dielectric acceleration results from PSI/DESY/Cockcroft; first results from the AWAKE experiment at CERN; 7 GeV electrons in laser plasma acceleration from LBNL; 0.5 nC electron bunches from HZDR; new R&D directions towards high-power lasers at LLNL; controllable electron beams from Osaka and LLNL; undulator X-ray generation after laser plasma accelerators from DESY/University of Hamburg/SOLEIL/LOA; important progress in hadron beams from plasma accelerators from Belfast/HZDR/GSI; and future collider plans from CERN.

A special session was devoted to the Horizon2020 design study EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications). EuPRAXIA is a consortium of 38 institutes, co-ordinated by DESY, which aims to design a European plasma accelerator facility. This future research infrastructure will deliver high-brightness electron beams of up to 5 GeV for pilot users interested in free-electron laser applications, tabletop test beams for high-energy physics, medical imaging and other applications. This study, conceived at the EAAC meeting in 2013, is strongly supported by the European laser industry.

The EAAC was founded by the European Network for Novel Accelerators in 2013 and has grown in its third edition into a meeting with worldwide visibility, rapidly catching up with the long tradition of the Advanced Accelerator Concepts workshop (AAC) in the US. The EAAC2017 workshop was supported by the EuroNNAc3 network through the EU project ARIES, INFN as the host organisation, DESY and the Helmholtz association, CERN and the industrial sponsors Amplitude, Vacuum FAB and Laser Optronic.

● *Ralph Assmann, DESY, Massimo Ferrario, INFN and Edda Gschwendtner, CERN.*

Advanced and novel accelerators

improved bunch quality at higher energy, with the staging of two accelerating structures and first proposals of conceptual ALC designs. The third phase, also lasting five years, will focus on the reliability of the acceleration process, while the fourth phase will be dedicated to technical design reports for an ALC by 2035, following selection of the most promising options.

Community effort

Many very important challenges remain, such as improving the quality, stability and efficiency of the accelerated beams with ANAs, but no show-stopper has been identified to date. However, the proposed time frame is achievable only if there is an intensive and co-ordinated R&D effort supported by sufficient funding for ANA technology with particle-physics applications. The preparation of an eventual technical design report for an ALC at the energy frontier should therefore be undertaken by the ANA community with significant contributions from the whole accelerator community.

From the current state of wakefield acceleration in plasmas and dielectrics, it is clear that advanced concepts offer several promising options for energy frontier electron–positron and electron–proton colliders. In view of the significant cost of intense R&D for an ALC, an international programme, with some level of international co-ordination, is more suitable than a regional approach. Following the April ANAR workshop, a study group towards advanced linear colliders, named ALEGRO for Advanced LinEar collider study GROup, has been set up to co-ordinate the preparation of a proposal for an ALC in the multi-TeV energy range. ALEGRO consists of scientists with expertise in advanced accelerator concepts or accelerator physics and technology, drawn from national institutions or universities in Asia, Europe and the US. The group will organise a series of workshops on relevant topics to engage the scientific community. Its first objective is to prepare and deliver, by the end of 2018, a document detailing the international roadmap and strategy of ANAs with clear priorities as input for the European Strategy Group. Another objective for ALEGRO is to provide a framework to amplify international co-ordination on this topic at the scientific level and to foster worldwide collaboration towards an ALC, and possibly broaden the community. After all, ANA technology represents the next-generation of colliders and could potentially define particle physics into the 22nd century.

Résumé

Ouvrir la voie pour les accélérateurs du futur

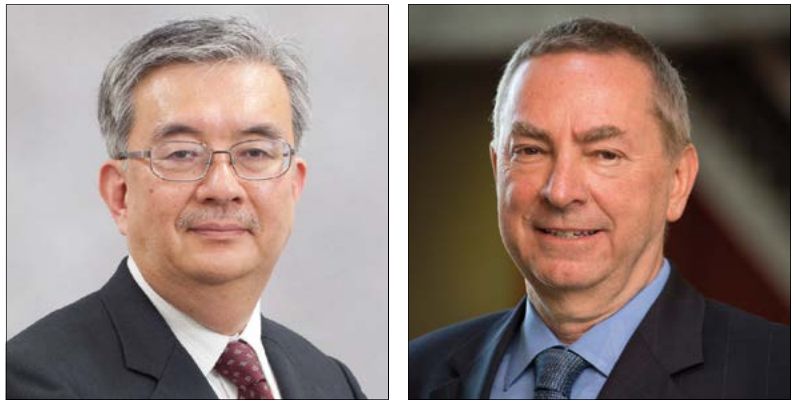
Des accélérateurs innovants, utilisant des techniques d'accélération par plasma et capables de fonctionner avec un gradient d'accélération supérieur à 1 GV/m, pourraient atteindre des énergies de l'ordre de 1 à 10 TeV, de façon plus compacte et efficace que ceux basés sur les conceptions conventionnelles. Les défis technologiques sont énormes et l'échelle de temps pour y parvenir longue, et la communauté internationale travaillant sur les accélérateurs est encouragée à collaborer au développement de collisionneurs linéaires électron-positon ou électron-proton à la frontière des énergies accessibles.

Brigitte Cros, CNRS, and **Patric Muggli**, MPP/CERN.

Faces & Places

APPOINTMENTS

KEK and Fermilab directors reappointed


KEK/FNAL

Masanori Yamauchi (left) and Nigel Lockyer remain in post.

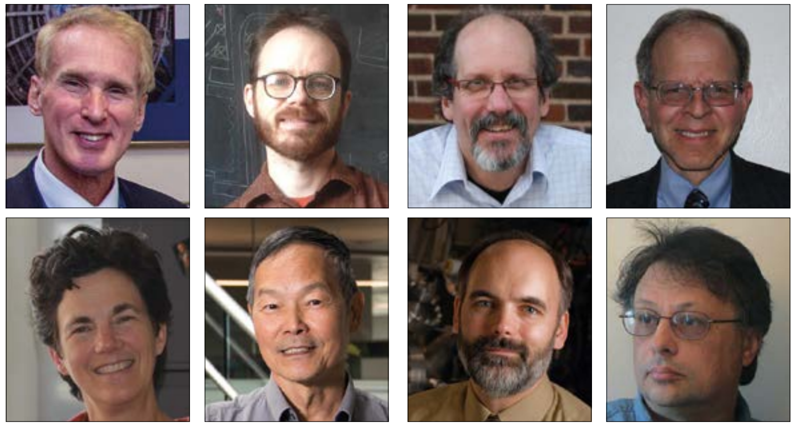
The leaders of two of the world's foremost high-energy physics laboratories have been reappointed for second terms. Director general of the KEK laboratory in Japan, Masanori Yamauchi, has been granted a second three-year term lasting until 2021, while, independently, director of Fermilab in the US, Nigel Lockyer, has been appointed for a second five-year term.

Since April 2015, Yamauchi has overseen KEK's accelerator upgrades for various facilities including the transformation of KEKB into SuperKEKB (*CERN Courier* September 2016 p32). Neutrinos have been another focus of his directorship, in particular improving the precision of neutrino-mixing measurements at the T2K experiment and supporting the next generation of long-baseline neutrino experiments. The search committee cited Yamauchi's "high international scientific rating, his ability to co-ordinate relationships both inside and outside KEK, and his vision for meeting KEK's medium-term goals" among the reasons for the appointment.

Nigel Lockyer has been at the helm of Fermilab since 2013, before which he was director of Canada's TRIUMF laboratory. His second term, which begins on 3 September 2018, comes as Fermilab begins building its flagship Long-Baseline Neutrino Facility (LBNF), which will send neutrinos underground from Illinois to South Dakota for the international DUNE project. During his first term, Lockyer helped to position the US as a world leader in neutrino research, in addition to Fermilab's strong role in the Large Hadron Collider and the CMS experiment at CERN, and continuing particle-astrophysics programme.

AWARDS

APS announces 2018 prizes and awards


(Left to right) Lawrence Sulak, Eric Dahl, Keith Olive, Michael Dine, Ann Nelson, Alexander Wu Chao, Bradley Sherrill, Edward Shuryak, who received key awards in particle and nuclear physics. The annual American Physical Society (APS) awards take into account "scores of outstanding nominees across the spectrum of physics disciplines", recognising the most accomplished, promising and respected scientists and leaders.

The American Physical Society (APS) has announced the winners of its spring 2018 prizes and awards, several of which recognise contributions to high-energy particle and nuclear physics.

The W K H Panofsky Prize in Experimental Particle Physics went to Lawrence Sulak of Boston University "for novel contributions to detection techniques, including pioneering developments for massive water Cherenkov detectors that led to major advances in nucleon decay and neutrino oscillation physics". Sulak helped design and build the first massive liquid-scintillator calorimeter and large-area drift chambers, and also the forward calorimeter for the CMS detector at the LHC. Also in the experimental arena, the Henry Primakoff Award for Early-Career Particle Physics was granted to Eric Dahl of Northwestern University and Fermilab, citing his fundamental contributions to the development of

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new techniques for the direct detection of dark matter, including the use of bubble chambers and xenon time projection chambers.

The Robert R Wilson Prize for Achievement in the Physics of Particle Accelerators goes to Alexander Wu Chao of SLAC National Accelerator Laboratory "for insightful, fundamental and broad-ranging contributions to accelerator physics, including polarisation, beam–beam effects, non-linear dynamics, and collective instabilities, for tireless community leadership and for inspiring and educating generations of accelerator physicists".

Theorist Keith Olive of the University of Minnesota has won the Hans A Bethe Prize "for outstanding contributions across a broad spectrum of fields including nuclear physics, particle physics, theoretical and observational astrophysics, and cosmology, especially Big Bang nucleosynthesis and the properties of dark matter". The J J Sakurai Prize for theoretical particle physics is shared between Michael Dine of the University of California in Santa Cruz and Ann Nelson of the University of Washington. The citation noted the pair's groundbreaking explorations of physics beyond the Standard Model, including their seminal joint work on dynamical supersymmetry breaking, and for their innovative contributions to a broad range of topics – including new models of electroweak symmetry breaking, baryogenesis and solutions to the strong charge-parity problem.

In the nuclear-physics area, Bradley Sherrill of the National Superconducting Cyclotron Laboratory, located on the campus of Michigan State University (MSU), won the Tom W Bonner Prize in Nuclear Physics for his scientific leadership in the development and utilisation of instruments and techniques for discovery and exploration of exotic nuclei. The citation also recognised his role in advancing the Facility for Rare Isotope Beams, which is currently under construction at MSU. The Herman Feshbach Prize in Theoretical Nuclear Physics, meanwhile, went to Edward Shuryak of Stony Brook University "for his pioneering contributions to the understanding of strongly interacting matter under extreme conditions, and for establishing the foundations of the theory of quark–gluon plasma and its hydrodynamical behaviour".

A further 30 prizes and awards were announced by the APS, including the Dannie Heineman Prize for Mathematical Physics awarded to Barry Simon of Caltech and IBM "for his fundamental contributions to the mathematical physics of quantum mechanics, quantum field theory, and statistical mechanics, including spectral theory, phase transitions, and geometric phases, and his many books and monographs that have deeply influenced generations of researchers". With a few exceptions, APS prizes and awards are open to all members of the scientific community in the US and abroad.

Wang, Kim and Nishikawa awarded Pontecorvo Prize

The 2017 Bruno Pontecorvo Prize, awarded by the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, has been awarded to Yifang Wang of the Institute of High Energy Physics in Beijing, Soo-Bong Kim of Seoul National University in Korea and Koichiro Nishikawa of the KEK laboratory in Japan. The prize recognises the trio's outstanding contributions to the study of neutrino-oscillation phenomena and in particular to the measurement of the θ_{13} mixing angle in the Daya Bay, RENO and T2K experiments. The Pontecorvo Prize was established in 1995 to commemorate Bruno Pontecorvo, once assistant of Enrico Fermi and often called the father of neutrino physics.


JINR

The prize ceremony at JINR on 19 September with (left to right) Koichiro Nishikawa, Soo-Bong-Kim, Yifang Wang and JINR director Viktor Matveev.

ANNIVERSARIES

ISOLDE marks 50 years of physics with exotic nuclei

On 16 October, researchers working on the ISOLDE Radioactive Ion Beam facility at CERN celebrated 50 years since it received its first beam of radioactive exotic isotopes. ISOLDE initially took protons from the oldest CERN accelerator, the synchrocyclotron, and these first ISOLDE experiments focused on studying the fundamental properties of exotic nuclei.

After the shutdown of the synchrocyclotron in 1990, a new ISOLDE experimental hall was connected to the PS Booster. Since 1992, more than 1000 different exotic beams have been produced and accelerated for the more than 500 users that now come to ISOLDE each year to perform experiments in the fields of nuclear structure, nuclear astrophysics, fundamental interactions and materials research, and recently also for biochemistry and medical-applications research.


CERN

The first test of the unique ISOLDE installation at the 600 MeV synchrocyclotron in October 1967.

Diamond anniversary


Diamond Light Source

Inaugurating Diamond Light Source 10 years ago (from left): The Queen, former Diamond CEO Gerd Materlik, the Duke of Edinburgh, and former Diamond chairman David Cooksey.

On 19 October, the UK's third-generation synchrotron X-ray facility, Diamond Light Source, marked 10 years since its official opening. For the past decade, Diamond's scientific output has exceeded expectations, with 6000 peer-reviewed journal articles based on user experiments across a range of disciplines published so far. Academic and industrial user visits now exceed 9000 per year, in addition to around 60,000 visitors ranging from undergraduates to members of the public. "With these achievements in mind, all I can say is that I am humbled and proud to be at the head of such a great project, made possible by the dedication of our current and former staff, contractors and user community from academia and industry," said Diamond CEO Andrew Harrison.


S Bennett/CERN

On 10–11 October, the Germany Federal Ministry of Education and Research (BMBF) together with CERN held the 13th edition of the popular industry event Germany at CERN. During the two days, 37 German companies showcased their latest products and services for scientists, engineers, technicians and buyers at CERN. The annual meeting, like similar events with other Member States, allows firms to make connections and establish leads for future contracts. Pictured on the left are CERN Director-General Fabiola Gianotti and Karl Eugen Huthmacher, director-general of BMBF's Provision for the Future – Basic and Sustainability Research department, speaking with an exhibitor.

MEETINGS

Crete workshop takes stock of hadron therapy

Understanding the fundamental laws of nature is the dream of physicists and the mandate of research institutions such as CERN. Many of us, however, are often faced with the question: "Why is this useful?" Motivated by the need to enhance awareness of the benefits of fundamental research to society and to facilitate future progress, a workshop and public event titled Ions for Cancer Therapy, Space Research and Material Science took place on 28–30 August in Chania, Crete.


G Feofilov

Around 50 people took part in the Crete meeting on hadron therapy.

Participants received a comprehensive overview of the current status of particle therapy for cancer. The number of working clinical facilities, mainly using protons, is rising rapidly. Nearly all new clinics use active beam scanning to provide more conformal doses and also the possibility to modulate fields for enhanced sparing of critical healthy tissue. Experts from several of the leading European centres – including the National Centre of Oncological Hadron therapy (CNAO) in Italy, the Heidelberg Ion-Beam Therapy Center (HIT) in Germany and the Paul Scherrer Institute (PSI) in Switzerland – summarised their clinical and research activities. All centres are engaged in clinical trials to provide evidence on the efficacy for different tumour entities.

The history of particle therapy is a prime example of society benefiting from basic research, as was illustrated from the perspectives of CERN and the GSI centre in Germany as early drivers of the technology. GSI pioneered carbon therapy in Europe in the 1990s with a pilot study that eventually included 440 patients. Subsequently, a number of clinical centres were opened, the HIT in Heidelberg being the first. CERN

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provided valuable input with its Proton-Ion Medical Machine Study (PIMMS), which was later realised in the clinical centres of CNAO and also MedAustron in Austria.

Major issues remaining in scanned particle therapy are range uncertainty, i.e. the knowledge of the exact position of Bragg peaks within the patient, and the treatment of moving targets such as in the thorax or abdomen. Both topics were addressed in detail, showing ways to assess and safely deliver doses to lung cancer as already performed, for example, at NIRS in Japan. Several methods were presented to use particle beams for imaging. This would enable clinicians to directly image tissue stopping power instead of converting X-ray attenuation from computed tomography (CT) scans, which is one of the major sources of uncertainty. Particle imaging could also be performed online during therapy to assess both the location of the target and to estimate range from projection images.

Proposals for future projects in Europe, Russia and the US were also presented, underlining the need for diagnostic methods together with therapy, followed by discussions about related applications for space research and dosimetry. Specific developments of detectors routinely used for physics research were also presented, highlighting projects such as Medipix and Timepix based on silicon-detector technologies (*CERN Courier* October 2017 p17). The workshop was complemented by presentations of research activities at the nearby Technical University of Crete (TUC) related to "science for health" and details on medical applications and transfer of knowledge via companies resulting from its research projects. In addition, with the goal of bringing local universities into closer contact with international organisations planning new facilities, a special session was hosted at TUC.

Strong co-operation

On the final day of the Crete meeting, a specific session was dedicated to developments of accelerators for medical and industry purposes. These included a report from the TERA foundation and the start-up firm ADAM SA in the UK, making the case for a multi-ion research facility in parallel with new compact single-ion accelerator designs for treatment.

The benefits of strong co-operation and the best use of expertise and resources were repeatedly highlighted during presentations of the future BIOMAT projects planned at GSI/FAIR (*CERN Courier* July/August 2017 p41) and JINR for biophysics and material research. The BIOMAT facility will use heavy ions for its biophysics research programme, focusing mainly on space-radiation effects and for materials research, while NICA at JINR will offer a radiobiology and materials-science programme.

The workshop facilitated a healthy flow of information and strengthened co-operation on relevant activities in the large research centres, with valuable input from existing therapy centres and proposals for future projects. The scientific workshop was preceded by a weekend of well-received public events in the old city of Chania and concluded with an open discussion. This clearly conveyed the message that, despite the main aims of large research institutes such as CERN and GSI being fundamental research, important spin-offs have a direct impact on everyday life.

- indico.cern.ch/e/ions2017

Madagascar physics in focus


Association Gasy Miara-Mandroso

Participants at the 9th HEPMAD event.

The 9th High-Energy Physics Madagascar International Conference (HEPMAD17) was held on 21–26 September at the Malagasy National Academy in Madagascar, involving around 50 participants including 10 invited speakers from abroad. The HEPMAD conference series is unique in sub-Saharan Africa and Indian Ocean countries, and the event alternates with the QCD-Montpellier series (*CERN Courier* November 2017 p39). It is part of a programme to promote high-energy physics in Madagascar, where the iHEPMAD research institute was founded in 2002 offering masters and PhD courses, and is complemented by popular seminars delivered at different Madagascan high-schools.

This year, results from experiments at the LHC were the focus of experimental talks, covering tests of the Standard Model and searches for new physics by ATLAS and CMS and the production of heavy quarks by ALICE. From the theory side, iHEPMAD members presented recent results on the estimate of heavy molecules and four-quark states using the QCD spectral sum-rule approach, with preliminary results on the extraction of QCD parameters such as the coupling constant and running quark masses from the masses of the $\eta_{c,b}$ mesons. These presentations were accompanied by talks from national researchers covering climatology, technology for sustainable energies and radioprotection. The conference was also an opportunity for foreign participants to discover the natural richness and traditions, as well as the social poverty, of Madagascar. HEPMAD18 will be held in Antananarivo from 20 to 26 September 2018.

Precision electroweak discussions in Orsay

A special electroweak workshop took place in Orsay on 2–6 October with the help of the Paris-Saclay University and in co-ordination with the LHC Physics Centre (LPCC) at CERN.

With the LHC entering a new phase of precision physics studies, about 30 participants (theorists and experimentalists) were involved in lively discussions to see how uncertainties on measurements (of the W-boson mass and the Weinberg angle, for instance) could be reduced. The effort will continue within the electroweak working group of the LPCC.


L Fayard

Participants at the electroweak workshop at Orsay.

CAS course in advanced accelerator physics

The CERN Accelerator School (CAS) and Royal Holloway University of London (RHUL) organised a course on advanced accelerator physics held at the RHUL campus on 3–15 September. The course followed an established format with lectures in the mornings and practical courses in the afternoons. The lecture programme consisted of 38 talks, while the practical courses provided hands-on experience in beam instrumentation and diagnostics, RF-measurement techniques, and optics design and corrections. Participants selected one of the three courses and followed their chosen topic throughout the school.


S Aiden

A total of 70 students of 24 nationalities attended the course, with most participants coming from European counties, but also from Canada, China, Mexico and Russia.

Forthcoming CAS courses in 2018 will be on: beam dynamics and technologies for future colliders (Zurich, Switzerland, 21 February–6 March); beam instrumentation (Tuusula, Finland, 2–15 June); computing and simulation (Greece, November); and an introduction to accelerator physics (Romania, early autumn).

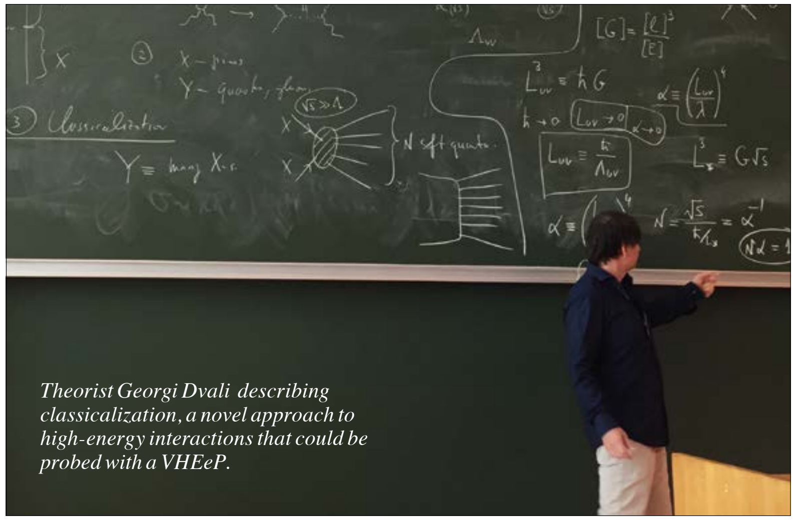
- cern.ch/schools/CAS

Exploring the physics case for a very-high-energy electron–proton collider

Rapid progress is being made in novel acceleration techniques (see p31). An example is the AWAKE experiment at CERN (*CERN Courier* January/February 2017 p8), which is currently in the middle of its first run demonstrating proton-driven plasma wakefield acceleration. This has inspired researchers to propose further applications of this novel acceleration scheme, among them a very-high-energy electron–proton (VHEeP) collider.

Simulations show that electrons can be accelerated up to energies in the TeV region over a length of only a kilometre using the AWAKE scheme. The VHEeP collider would use one of the LHC proton beams to drive a wakefield and accelerate electrons to an energy of 3 TeV over a distance less than 4 km, then collide the electron beam with the LHC's other proton beam to yield electron–proton collisions at a centre-of-mass energy of 9 TeV – 30 times higher than the only other electron–proton collider, HERA at DESY. Other applications of the AWAKE scheme with electron beams up to 100 GeV are being considered as part of the Physics Beyond Colliders study at CERN (*CERN Courier* November 2016 p28).

Of course, it's very early days for AWAKE. Currently the scheme offers instantaneous luminosities for VHEeP of just 10^{28} – 10^{29} cm^{-2} s^{-1}, mainly due to the need to refill the proton bunches in the LHC once they have been used as wakefield drivers. Various schemes are being considered to increase the luminosity, but for now the physics case of a VHEeP collider with very high energy but moderate luminosities is being considered. Motivated by these ideas, a workshop called Prospects for a very high energy ep and eA collider took place on 1–2 June at the Max Planck Institute for Physics in Munich to discuss the VHEeP physics case.


A Caldwell

Theorist Georgi Dvali describing classicalization, a novel approach to high-energy interactions that could be probed with a VHEeP.

Electron–proton scattering can be characterised by the variables Q^2 (the squared four-momentum of the exchanged boson) and x (the fraction of the proton's momentum carried by the struck parton), the reaches of which are extended by a factor 1000 to high Q^2 and to low x. The energy dependence of hadronic cross-sections at high energies, such as the total photon–proton cross-section, which has synergy with cosmic-ray physics, can be measured and QCD and the structure of matter better understood in a region where the effects are completely unknown. With values of x down to 10^{-8} expected for $Q^2 \gtrsim 1$ GeV^2, effects of saturation of the structure of the proton will be observed and searches at high Q^2 for physics beyond the Standard Model will be possible, most significantly the increased sensitivity to the production of leptoquarks.

Deepening knowledge

A major theme of the workshop and physics focus for VHEeP is a deeper understanding of QCD and hadronic cross-sections at the highest energies and lowest values of x. Theoretical expectations show that saturation of the structure of the proton will be observed at VHEeP and will also be at a scale where QCD calculations are perturbative. This is particularly true in eA collisions with a higher density of gluons, where a saturation scale of around 20 GeV^2 is expected – a value where the cross-section at VHEeP is also expected to be large.

The physics at low x is also important for understanding cosmic-ray production at high energies where the rate of production of neutrinos at the TeV scale and above strongly depends on the gluon density down to values of x as low as 10^{-9}, as well as the total charm-production cross-section. The complementary nature of low-x physics and total cross-sections also has links to our understanding of gravity, for instance via the AdS/CFT duality and novel theories that VHEeP could probe. The needs of polarisation and eA physics were discussed, as was HERA data at low x and the status of Monte Carlo simulations for ep and eA physics.

Overall the workshop highlighted how the extra energy reach at VHEeP would deepen our knowledge of the fundamental structure of matter and lead to a new way of understanding QCD. It could also help address big questions in physics such as the confinement of quarks and understanding black holes or new theories that attempt to explain all particle interactions.

The workshop ended with a discussion on how VHEeP could fit in to the global particle-physics landscape, specifically with current planned and possible ep and eA physics experiments. The proposed Electron Ion Collider in the US, LHeC at CERN and VHEeP have much in common, but also significant differences. There is much complementarity between the low-energy, high-luminosity polarised physics, such as the 3D mapping of the proton, and the physics at high energy, such as saturation. The different communities should therefore work to put forward a roadmap outlining a rich physics programme of electron–proton and electron–ion interactions, which will then serve as strong input to the European Strategy for Particle Physics in the next couple of years.

VISITS


S Bennett/CERN

Cong Tac Pham, deputy minister for science and technology, Socialist Republic of Vietnam, visited CERN on 3 October, during which he passed by the ISOLDE experimental hall and ATLAS experiment and signed the guestbook.


S Bennett/CERN

On 19 October, **Toril Nagelhus Hernes**, pro-rector for innovation at the Norwegian University of Science and Technology (NTNU), signed a collaboration agreement with CERN director for accelerators and technology Frédérick Bordry (pictured). NTNU and CERN have worked closely together for many years, and the new agreement will bring collaboration between the two institutions closer.


J Ordan/CERN

Blaženka Divjak, minister of science and education, Republic of Croatia, visited CERN on 24 October. She took in the CERN Control Centre, ALICE and S'Cool LAB, and discussed Croatia's application for associate membership of CERN. She is pictured signing the guestbook with director of international relations Charlotte Warakaulle and Director-General Fabiola Gianotti.


J Ordan/CERN

On 26 October representatives of the Austrian, Swiss and German Science Foundations came to CERN, in part to discuss opportunities for future projects. Pictured left to right (with CERN director for research and computing Eckhard Elsen second from left) are the current presidents of the Austrian, Swiss and German foundations: **Klement Tockner**, **Matthias Egger** and **Peter Strohschneider**, respectively.

OBITUARIES

Henri Desportes 1933–2017

It is with great sadness that we announce the death of Henri Desportes, at the age of 84, on 24 September in the village of Gif sur Yvette, France. He was the head of the CEA Saclay department STCM until his retirement in the mid 1990s. Since the 1960s he was a pioneer of applied superconductivity and rapidly became an internationally recognised expert in the development of numerous accelerator and detector magnet systems for high-energy physics.

In particular, Desportes contributed to the creation of the first superconducting magnets for many experimental programmes, including: polarised targets (HERA, installed at CERN and then in Protvino); the 15 foot bubble chamber at Argonne National Laboratory in the US; the magnet of the CERN hybrid spectrometer bubble chamber in 1972; the first thin-walled solenoid, CELLO, in 1978 at DESY; and the solenoid for the ALEPH experiment at LEP in 1986. His early participation in the genesis and design of the large magnets for the CMS and ATLAS detectors for the LHC should also not be forgotten.


G Desportes

Desportes was an expert in magnets for experiments.

Desportes supervised numerous work at Saclay on the development of innovative superconducting magnets with a wide range of scientific, technical and medical applications. He was the main initiator of new techniques using helium indirect cooling, the stabilisation of superconductor by aluminium co-extrusion and externally supported coils. Henri worked on all of these subjects with some of the great names in physics. It is partly thanks to him that Saclay has been involved in most of the magnets for large detectors built in Europe since the early 1970s. For this work he received a prestigious IEEE Council on Superconductivity Award in 2002.

We will remember his courtesy, his humour and his unfailing involvement in these flagship projects that have contributed greatly to physics experiments and to several fundamental discoveries.

● *Antoine Daël.*

Patrick Fleury 1935–2017

Experimental particle physicist Patrick Fleury passed away on 14 September. After graduating from France's prestigious Ecole Polytechnique, he first encountered particle physics during a traineeship at Berkeley. On his return, he quickly became a prominent figure in the field of bubble chambers. Appointed by Bernard Gregory, he operated the DBC 81 chamber at CERN, which was built at Saclay in collaboration with the Polytechnique and Orsay. He studied the use of deuterium in the chamber, which received beam from the Proton Synchrotron (PS), and led a study group concerning the f_0 spin and the "g" meson. He was also in charge of the construction of CERN's separated M5 beam, a high-quality beam from the PS.

Quite rightly, Fleury always underlined the crucial role played by the Polytechnique and its leading bubble-chamber experts, first and foremost Louis Leprince-Ringuet, in the development of particle physics at CERN, from its inception to the modern day. Due to Bernard Gregory's involvement at CERN, Fleury effectively ran Polytechnique's laboratory (LPNHE-X) from 1973 to 1975, before taking on the role officially until 1984, a period that included its move to Palaiseau. On the new site, he and Charles Gregory built up a technical group capable of building large-scale facilities, and established a strong electronics team and an IT team. Fleury also set up the "solar unit" that would later become a major laboratory, the PICM.


H Fleury

Fleury transitioned to astroparticle physics during his career.

Over the years, Fleury played a major and often pioneering role in several fields of physics at IN2P3 with the support of its director, the late Jean Yoccoz (*CERN Courier* April 2017 p43), as well as in very-large-scale integration (VLSI) and massive computation, founding the Centre de Calcul Vectoriel pour la Recherche in Palaiseau and installing a CRAY supercomputer there. Fleury then steered his laboratory towards the use of electronic detectors and, from 1968 onwards, oversaw their introduction at CERN, working with Arne Lundby's group (with Pierre Lehmann) and then becoming involved in the physics of the Omega spectrometer, and later in the DELPHI experiment at LEP.

Following his time at the head of LPNHE-X and a stint at Stanford, he led experiments at Saclay's Saturne accelerator, before deciding to take his career in a different direction, moving towards what would later be known as astroparticle physics, where he contributed to the establishment of major areas of study. Before Stanford, he had already helped found the Fréjus underground laboratory, on the suggestion of André Rousset, before IN2P3 and the CEA took it over.

Above all, Fleury played a fundamental role in the emergence of ground-based gamma-ray astronomy, both in France and internationally, through the ARTEMIS, CAT, CELESTE and HESS projects, as well as in IN2P3's involvement in NASA's FERMI gamma-ray satellite. Alongside Eric Paré, he designed CAT, France's first Cherenkov imaging telescope and a prototype for the international HESS project. From 1992 onwards, Fleury, a true visionary, launched a series of colloquia on gamma-ray astronomy, which ultimately united all the teams working in the field, including those of MAGIC (La Palma) and VERITAS (Arizona), around the Cherenkov Telescope Array observatory.

Finally, as chair of the scientific-evaluation committee of Virgo, he played a key role in IN2P3's involvement in the field of gravitational waves. The committee's report was presented in 1990, the result of hard work and many visits to the international laboratories and agencies involved. Its favourable verdict was a deciding factor in the minister Hubert Curien's approval of the project in France.

Patrick Fleury was an exceptional scientist, a clear-sighted, passionate and visionary project developer with immense intellectual and moral strength and profound humanity, who always strove to support and instil confidence in his colleagues.

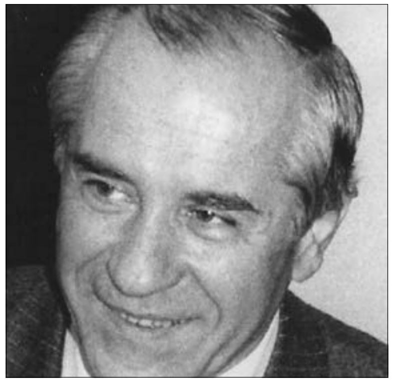
● *His colleagues and friends.*

Sergei Matinyan 1931–2017

Renowned Armenian theorist Sergei Matinyan died on 8 September in Durham, North Carolina, aged 86. He was noted for founding now well-known scientific centres: the first high-energy theoretical physics laboratory in Georgia, and a broad-coverage theory laboratory in Yerevan.

Born in Tbilisi, Georgia, and graduating from Tbilisi University in 1954, Matinyan started his scientific career at the Institute of Theoretical and Experimental Physics, Moscow, working on helium superfluidity under Lev Landau. His work on K-meson oscillations carried out later in Tbilisi was an essential step in the field. In the 1960s Matinyan studied strong interactions via complex momentum (Regge) theory, and developed the asymptotic theory of interaction of hadrons with nuclei at very high energies.

An essential phase of his career began in 1970 when he moved to Yerevan, Armenia, to become the deputy of Artem Alikhanian, the founder and then director of the Yerevan Physics Institute. There he went on to head the department of theoretical physics and lectured in Yerevan State University on quantum electrodynamics and the weak interactions. Important work around that time, in 1977, was the investigation of the ground state in non-Abelian Yang–Mills theory, where the presence of a gauge field condensate was demonstrated for the first time.


Armenian theoretical physicist Sergei Matinyan.

In the 1990s while at Duke University he summarised his research in the monograph *Chaos and Gauge Field Theory*, 1994, with Biro and Muller. He was elected to the National Academy of Sciences of Armenia in 1990.

Matinyan was an outstanding mentor and was particularly efficient in attracting gifted students. He supervised more than 30 PhD students in Georgia and Armenia, and his seminars were known for their depth in science and democracy of spirit. Matinyan was instrumental in organising the Soviet–US workshops on gauge theories in Yerevan held in 1983 and 1988, attended by a number of major figures. These conferences were essential events under the conditions of the Iron Curtain.

Sergei Matinyan's outstanding legacy will be remembered by his former students and colleagues.

● *Ara Ioannisian.*

Gary Steigman 1941–2017

Gary Steigman played a pivotal role in the development of modern cosmology, particularly the application of particle physics and nuclear physics to cosmological questions. He died on 9 April of complications following a fall.

Born on 23 February 1941, Gary grew up in the Bronx, New York. He received his undergraduate degree from the City University of New York in 1961 and his PhD in 1968 from New York University under the supervision of Mal Ruderman. He joined the Institute of Theoretical Astronomy (now the Institute of Astronomy) in Cambridge as a visiting fellow in 1968 and became a research fellow at Caltech in 1970. Gary joined the faculty of Yale University in 1972, leaving Yale for the Bartol Institute at the University of Delaware in 1978 and was then recruited to Ohio State in 1986.


Steigman helped bring cosmology and particle physics closer.

Gary was ubiquitous on the cosmology conference circuit, so much so that he often referred to himself as the "TWA professor of physics". Beginning in 1972, Gary spent 23 summers at the Aspen Center for Physics, where he served as a trustee (1978–1983), a member of the Advisory Board (1983–1998), and a long-time organiser of astrophysics workshops. Visitors to Aspen will remember Holly, Gary's Great Pyrenees dog (pictured) and a fixture on Gary's travels.

Gary's contributions to cosmology span nearly half a century, beginning with his 1968 PhD dissertation, in which he showed that

▷

matter–antimatter symmetric cosmologies were untenable: the universe must have an excess of baryons over antibaryons. This work was published in *Nature*, and Gary followed up with an influential article in the *Annual Review of Astronomy and Astrophysics* in 1976. While this conclusion seems obvious now, it was certainly not obvious in the late 1960s; at that time a symmetric universe could have been considered more natural. The origin of the observed baryon excess remains undetermined to this day, but Gary's results subsequently underpinned the research field of baryogenesis.

This work was followed in 1977 by Gary's influential primordial nucleosynthesis limit on the number of neutrino species, in collaboration with Jim Gunn and David Schramm. At the time this paper was written there were only weak experimental limits on the number of generations in the Standard Model; Gary's work demonstrated that this number must be less than or equal to seven, a result later confirmed by SLC and LEP measurements of the Z width. This paper represents one of the first attempts to use cosmology to constrain particle physics, an area that blossomed in the 1980s following Gary's pioneering work.

Gary received first prize in the 1980 Gravity Research Foundation essay competition for his paper with David Schramm exploring a universe dominated by massive neutrinos, one of the earliest proposals for a nonbaryonic universe. Later, Gary's 1984 paper with Mike Turner and Lawrence Krauss raised the possibility of a cosmological constant to allow for a flat universe.

He went on to pursue his most significant area of research: primordial nucleosynthesis. Following early work by Peebles and Wagoner, Fowler and Hoyle in the 1960s, an improved understanding of chemical evolution and better observational limits allowed primordial nucleosynthesis to become the first true area of precision cosmology in the 1980s. With long-time collaborators David Schramm, Mike Turner, Keith Olive and Terry Walker, Gary's work in this field followed two major thrusts: deriving accurate estimates of the baryon density of the universe, and constraining particle properties. A series of major papers in the 1980s and 1990s provided the gold standard for the prediction of the baryon density of the universe, a prediction spectacularly confirmed by later CMB measurements.

More recently, Gary renewed an earlier interest in relic particle abundances. Among his later papers were a series of improved calculations of these abundances, along with new constraints on fractionally charged relic particles and several important papers on dark radiation.

In 1986, Gary came to Ohio State University to develop a research centre in cosmology that spanned both the physics and astronomy departments. His efforts yielded what is today the Ohio State Center for Cosmology and AstroParticle Physics, encompassing almost 30 faculty members in both departments and more than 15 postdocs.

Gary was a collaborator, a mentor and a good friend. He found his true companion in Sueli Viegas, his wife and fellow astronomer. Gary deserves much of the credit for bringing together the fields of cosmology and nuclear/particle physics, an area of work that became enormously productive in the years following Gary's pioneering efforts. Gary blazed a trail for others to follow, and he will be missed by all of us.

● *Robert Scherrer, John Beacom, Keith Olive, Michael Turner and Terry Walker.*

Beamline for Schools: a successful story continues

You haven't heard of Beamline for Schools lately? Probably because we have been very busy in September. The winners of this year's edition have been at CERN to conduct their experiments.

The winning team from Italy has tested its self-designed and self-constructed Cherenkov detector while the Canadian team was looking for hypothetical exotic particles carrying a fractional charge. Have a look at http://cern.ch/go/Cg6P if you want to know more and get inspired for BL4S edition 2018!

Get even more inspired by two videos that have been produced by members of the Canadian team:
https://www.youtube.com/watch?v=gI3ay1EgGt8
https://www.youtube.com/watch?v=gF3BES_fy0Q&t

Winning BL4S has been an incredible experience for both the students and their teachers. Both teams have been received by the officials of their home town and have given interviews on national TV and radio stations. When we asked them how they would describe their experience the two words that were used by most of them were "life changing".

BL4S 2018 is in the starting blocks. Do not miss your life changing experience by participating in the competition. Pre-register now and submit your proposal by 31 March 2018!

Join the adventure here: cern.ch/bl4s

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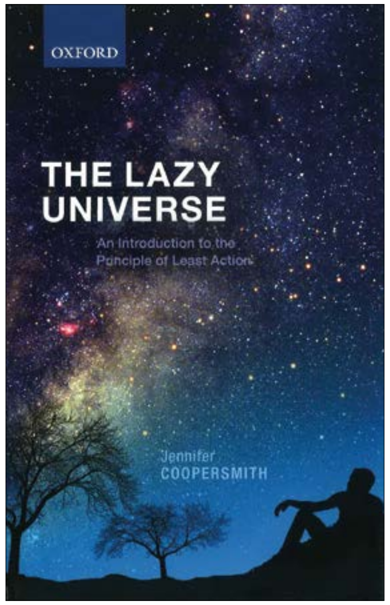
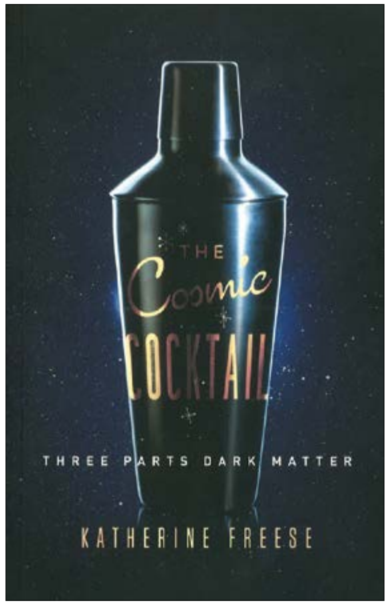
Bookshelf

Compiled by Virginia Greco, CERN





The Lazy Universe: An Introduction to the Principle of Least Action

By Jennifer Coopersmith

Oxford University Press

With contagious enthusiasm and a sense of humour unusual in this kind of literature, this book by Jennifer Coopersmith deals with the principle of least action or, to be more rigorous, of stationary action. As the author states, this principle defines the tendency of any physical system to seek out the "flattest" region of "space" – with appropriate definitions of the concepts of flatness and space. This is certainly not among the best-known laws of nature, despite its ubiquity in physics and having survived the advent of several scientific revolutions, including special and general relativity and quantum mechanics. The author makes a convincing case for D'Alembert's principle (as it is often called) as a more insightful and conceptually fertile basis to understand classical mechanics than Newton's laws. As she points out, Newton and D'Alembert asked very different questions, and in many cases variational mechanics, inspired by the latter, is more natural and insightful than working in Newton's absolute space, but it can also feel like using a sledgehammer to crack a peanut.

The book starts with a general and very accessible introduction to the principle of least action. Then follows a long and interesting description of the developments that led to the principle as we know it today. The second half of the book delves into Lagrangian and Hamiltonian mechanics, while the final chapter illustrates the relevance of the principle for modern (non-classical) physics, although this theme is also touched upon several times in the preceding chapters.

An important caveat is that this is not a textbook: it should be seen as complementary to, rather than a replacement for, a standard introduction to the topic. For example, the Euler–Lagrange equation is presented but not derived and, in general, mathematical formulae are kept to a bare minimum in the main text. Coopersmith compensates for this with several thorough appendices, which range from classical textbook-like examples to original derivations. She makes a convincing critique of a famous argument by Landau and Lifshitz to demonstrate the dependence of kinetic energy on the square of the speed, and in one of the appendices she develops an interesting alternative explanation.

Although the author pays a lot of credit to *The Variational Principles of Mechanics* by Cornelius Lanczos (written in 1949 and re-edited in 1970), hers is a very different kind of book aimed at a different public. Moreover, the author has developed several original and insightful analogies. For example, she remarks upon how smartphones know their orientation: instead of measuring positions and angles with respect to external (absolute) space, three accelerometers in the phone measure tiny motions in three directions of the local gravity field. This is reminiscent of the methods of variational mechanics.

Notations are coherent throughout the book and clearly explained, and footnotes are used wisely. With an unusual convention that is never made explicit, the author graphically warns the reader when a footnote is witty or humorous, or potentially perceived as far-fetched, by putting the text in parenthesis.

My main criticism concerns the frequent references to distant chapters, which entangle the logical flow. This is a book made for re-reading and, as a result, it might be difficult to follow for readers with little previous knowledge of the topic. Moreover, I was rather baffled by the author's confession (repeated twice) that she was unable to find a quote by Feynman that she is sure to have read in his *Lectures*. Nevertheless, these minor flaws do not diminish my general appreciation for Coopersmith's very useful and well-written book.

The first part is excellent reading for anybody with an interest in the history and philosophy of science. I also recommend the book to students in physics and mathematics who are willing to dig deeper into this subject after taking classes in analytical mechanics, and I believe that it is accessible to any student in STEM disciplines. Practitioners in physics from any sub-discipline will enjoy a refresh and a different point of view that puts their tools of the trade in a broader context.

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

The Cosmic Cocktail: Three Parts Dark Matter

By Katherine Freese

Princeton University Press

Also available at the CERN bookshop

This book by Katherine Freese, now out in paperback, is aimed at non-professionals interested in dark matter. The hypothesis that the matter in galaxy clusters is dominated by a non-luminous component, and hence is dark, goes back to a paper published in 1933 by the Swiss astronomer Fritz Zwicky, who also coined the term "dark matter". But it has only been during the last 20 years or so that we have realised that the matter in the universe is dominated by dark matter and that most of it is non-baryonic, i.e. not made of the stuff that makes up all the other matter we know. ▷

The author explains the observational evidence for dark matter and its relevance for cosmology and particle physics, both in a formal scientific context and also based on her personal adventures as a researcher in this field. I especially enjoyed her detailed, well-informed discussion and evaluation of present dark-matter searches.

The book is structured in nine chapters. The first is a personal introduction, followed by a historical account of the growing evidence for dark matter. Chapter 3 discusses our present understanding of the expanding universe, explaining how much of what we know is due to the very accurate observations of the cosmic microwave background. This is followed by a chapter on Big Bang nucleosynthesis, describing how the first elements beyond hydrogen (deuterium, helium-3, lithium and especially helium-4) were formed in the early universe. In the fifth chapter, the plethora of dark-matter candidates – ranging from axions to WIMPS and primordial black holes – are presented. Chapter 6 is devoted to the LHC at CERN: its four experiments are briefly described and the discovery of the Higgs is recounted. Chapters 6 and 7 are at the heart of the author's own research (the author is a dark-matter theorist and not heavily involved in any particular dark-matter experiments). They discuss the experiments that can be undertaken to detect dark matter, either directly or indirectly or via accelerator experiments. An insightful and impartial discussion of present experiments with tentative positive detections is presented in chapter 8. The final chapter is devoted to dark energy, responsible for the accelerated expansion of the universe. Is it a cosmological constant or vacuum energy with a value that is many orders of magnitude smaller than what we would expect from quantum field theory? Is it a dynamical field or does the beautiful theory of general relativity break down at very large distances?

Even though in some places inaccuracies have slipped in, most explanations are rigorous yet non-technical. In addition to the fascinating subject, the book contains a lot of interesting personal and historical remarks (many of them from the first- or second-hand experience of the author), which are presented in an enthusiastic and funny style. They are one of the characteristics that make this book not only an interesting source of information but also a very enjoyable read.

As a female scientist myself, I appreciated the way the author acknowledges the work of women in science. She presents a picture of a field of research that has been shaped by many brilliant female scientists, starting from Vera Rubin's investigations of galaxy rotation curves and ending with Elena Aprile's and Laura Baudis' lead in the most advanced direct dark-matter searches. It seems to need a woman to do justice to our outstanding female colleagues.

The fact that less than three years after the first publication of the book some cosmological parameters have shifted and some information about recent experiments is already outdated only tells us that dark matter is a hot topic of very active research. I sincerely hope that the author's gut feeling is correct and the discovery of dark matter is just around the corner.

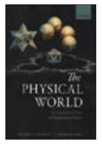
- *Ruth Durrer, University of Geneva, Switzerland.*

Books received

The Physical World: An Inspirational Tour of Fundamental Physics

By Nicholas Manton and Nicholas Mee

Oxford University Press



Ranging from classical to quantum mechanics, from nuclear to particle physics and cosmology, this book aims to provide an overview of various branches of physics in both a comprehensive and concise fashion. As the authors state, their objective is to offer an inspirational tour of fundamental physics that is accessible to readers with a high-school background in physics and mathematics, and to motivate them to delve deeper into the topics covered.

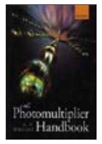
Key equations are presented and their solutions derived, ensuring that each step is clear. Emphasis is also placed on the use of variational principles in physics.

After introducing some basic ideas and tools in the first chapter, the book presents Newtonian dynamics and the application of Newton's law of gravitation to the motion of bodies in the solar system. Chapter 3 deals with the electromagnetic field and Maxwell's equations. From classical physics, the authors jump to Einstein's revolutionary theory of special relativity and the concept of space–time. Chapters 5 and 6 are devoted to curved space, general relativity and its consequences, including the existence of black holes. The other revolutionary idea of the 20th century, quantum mechanics, is discussed in chapters 7 and 8, while chapter 9 applies this theory to the structure and properties of materials, and explains the fundamental principles of chemistry and solid-state physics. Chapter 10 covers thermodynamics, built on the concepts of temperature and entropy, and gives special attention to the analysis of black-body radiation. After an overview of nuclear physics (chapter 11), chapter 12 presents particle physics, including a short description of quantum field theory, the Standard Model with the Higgs mechanism and the recent discovery of its related boson. Chapters 13 and 14 are about astrophysics and cosmology, while the final chapter discusses some of the fundamental problems that remain open.

The Photomultiplier Handbook

By A G Wright

Oxford University Press



This volume is a comprehensive handbook aimed primarily at those who use, design or build vacuum photomultipliers. Drawing on his 40 years of experience as a user and manufacturer, the author wrote it to fill perceived gaps in the existing literature.

Photomultiplier tubes (PMTs) are extremely sensitive light detectors, which multiply the current produced by incident photons by up to 100 million times. Since their invention in the 1930s they have seen huge developments that have increased their performance significantly. PMTs have been and still are extensively applied in physics experiments and their evolution has been shaped by the requirements of the scientific community.

The first group of chapters sets the scene, introducing light-detection techniques and discussing in detail photocathodes – important components of PMTs – and optical interfaces. Since light generation and detection are statistical processes, detectors providing electron multiplication are also considered statistical in their operation. As a consequence, a chapter is dedicated to some theory of statistical processes, which is important to choose, use or design PMTs. The second part of the book deals with all of the important parameters that determine the performance of a PMT, each analysed thoroughly: gain, noise, background, collection and counting efficiency, dynamic range and timing. The effects of environmental conditions on performance are also discussed. The last part is devoted to instrumentation, in particular voltage dividers and electronics for PMTs.

Each chapter concludes with a summary and a comprehensive set of references. Three appendices provide additional useful information.

The book could become a valuable reference for researchers and engineers, and for students working with light sensors and, in particular, photomultipliers.

Unleashing the physicist within

A well-organised school trip to a laboratory like CERN can change a young person's life.


A Galloni

The author (far right) with UK students at CERN in September, organised by the University of Liverpool.

When I was 17, it was a very good year – a very good year for inspiration to enter the wonderful world of high-energy physics research. At that point I knew I wanted to study physics at undergraduate level, but after a four-week-long placement at the University of Liverpool – hunting for Higgs signals in simulated data sets, making histograms, writing reports and designing posters – I was hooked on becoming a researcher.

That was in 2010. I am now a third-year PhD student at the same university, working in the electroweak group at the LHC's LHCb experiment. This summer I had the opportunity to provide 18 students at that same point of study with a similar experience to the one that set me on the road to where I am today.

Each year the University of Liverpool organises a week-long summer school for high-school students in several UK schools. The school has grown year by year and the most recent edition was mine to organise. One of the things that has been included since the very beginning is a ROOT workshop in which the students spend half a day getting stuck into coding, producing histograms and developing selection criteria to isolate a simulated $K_S \to \pi^+\pi^-$ signal. Helping them to understand the code for the first time reminds me of exactly where I've come from.

But there's more to the school than C++. With help from some other postgraduate students, a lecture course is always included with talks on the Standard Model, the LHC experiments and searches for new physics. We teach the students about how particle detectors work, how antimatter is produced and trapped, and the way neutrinos are produced and studied at experiments around the world. There are trips to the ATLAS visitor centre and LHCb surface area, as well as to Microcosm and the Globe. This year we were also lucky to be taken to the CERN Control Centre and to the CMS experiment. I was excited to see some of these places now, so I can't imagine what the geeky little 17-year-old me would've been like!

This year I was amazed to hear 17 year olds eagerly explaining how they planned to use Lagrange points.

All of this is then applied to a challenge for the students to design their own particle-physics experiments, which are assessed at the end of the week for their physics accuracy, creativity and feasibility. This year I was amazed to hear 17 year olds eagerly explaining how they planned to use Lagrange points to position dark-matter detectors in space.

But the school isn't all academic. As an initial welcome, we hosted a quiz of both physicsy and not-so-physicsy questions (anybody know whether "adamantium" is stronger than "vibranium"?) and some time to chat with PhD students about life, the universe and everything (or, to see that physicists are really just like everybody else). We finished the week with the traditional end-of-school meal, so the students know what to expect when they present their own groundbreaking discoveries at future conferences.

I'm made up that I was able to give so many young people an experience like the one that led me on my career path as a research scientist. Hearing stories of students from past years who were inspired to go on to study and work in physics is even greater thanks than the card and presents my gang gave me on our last day.

These things take effort, of course, and often rely on the good nature of colleagues to give up some of their time. But I would encourage any student or researcher in high-energy physics to get involved with such activities, either via their home institutions or official CERN channels. Not only might it inspire a young person to follow a science, technology, engineering and mathematics career, but, if my experience is anything to go by, it brings valuable perspective to your career too.

- *Heather Wark, University of Liverpool.*

CERN Courier Archive: 1974

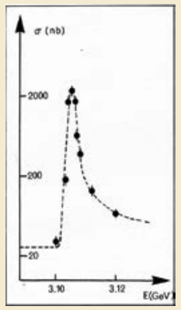
A LOOK BACK TO CERN COURIER VOL. 14, DECEMBER 1974, COMPILED BY PEGGIE RIMMER

NEWS

The new particles


CERN 118.11.74

Sam Ting telling the new particle story to an enthusiastic audience in the CERN auditorium on 21 November.



The dramatic signal of the 3.1 GeV particle at SPEAR. The vertical axis shows the cross-section (probability) in nanobarns for an interaction between an electron and positron to produce strongly interacting hadrons. Along the horizontal axis the probability is seen jumping a hundred times at 3.1 GeV.

1974 has been one of the most fascinating years ever experienced in high-energy physics. Anyone in touch will be well aware of the ferment created by the recent news from Brookhaven and Stanford, followed by Frascati and DESY, of the existence of new particles. Why the excitement? A brief answer is that the particles have been found in a mass region where they were completely unexpected with stability properties which, at this stage, are inexplicable.

Since spring, a MIT/Brookhaven team, led by Sam Ting, has been looking at collisions between protons which yield an electron–positron pair. They use a slow ejected 28.5 GeV proton beam from the Brookhaven 33 GeV synchrotron to bombard beryllium. The probability that collisions will yield such a pair is very low and the detection system has to be capable of picking out an event from a million or more.

From about August, the system was totting up an unusually large number of events with a combined electron–positron energy of 3.1 GeV. They were on to something important – a resonance, an unstable particle which breaks up too quickly to be seen, its mass identified by the combined energy of more stable particles emerging from its decay. By the end of October, they had collected about 500 events but were soon prodded into print by dramatic news from the other coast of America.

In June, a Berkeley/Stanford team at the Stanford Linear Accelerator Center electron–positron storage ring SPEAR had seen some "funny" readings at collision energies between 3.1 and 3.2 GeV. While meditating during the summer transformation of SPEAR I into SPEAR II, the suspicion grew that a resonance could lie at these energies. Following the upgrade, the team went into action and on the weekend of 9–10 November the hunt began, changing the beam energies in 0.5 MeV steps. By 11.00 a.m. Sunday morning the new particle had been unequivocally found. A jump in cross-section from 20 to 200 nanobarns soared to 2000 nanobarns as the data were refined. It was nothing short of shattering. Burt Richter described it as "the most exciting and frantic week-end in particle physics I have ever been through".

Within hours of the SPEAR measurements, telephone wires across the Atlantic were humming as enquiries and rumours were exchanged. As soon as it became clear what had happened, European Laboratories looked to see how they could contribute to the excitement. Obvious candidates to be in on the act quickly were the electron–positron storage rings at Frascati and DESY.

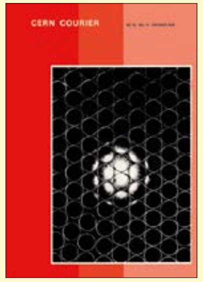
From 13 November, three experimental teams on the ADONE storage ring at Frascati began to search in the same energy region and on 15 November the new particle was seen by all three. At DESY, the DORIS storage ring was brought into action with the PLUTO and DASP detection systems. During the weekend of 23–24 November, a clear signal at about 3.1 GeV energy was seen in both systems.

For the past year, something has been expected in the hadron–lepton relationship. Are the new particles behind this and if so, how? Do they carry a new quantum number? Theorists have recently invoked two new properties that could influence which interactions can take place – colour and charm. Colour is suggested as a 3-valued property of quarks, the constituents of hadrons, to make sense of the statistics used to calculate the consequences of their existence. Charm is a property suggested to explain some observations concerning neutral current interactions.

Still reeling from the 1973 discovery of neutral currents, 1974 began with the SPEAR hadron production mystery, continued with new high-energy information from Fermilab and the CERN ISR, including the high lepton production rate, and finished with the discovery of new particles. All against a background of feverish theoretical activity trying to keep pace with what the accelerators and storage rings have been uncovering.

● Compiled from texts on pp415–419.

Compiler's Note



As noted in last month's *Courier* (p50), charm was the property attributed to the 1974 particles. The J/ψ – J at BNL, ψ at SLAC, earning the 1976 Nobel Prize in Physics for Ting and Richter – was declared to be a charmed quark–antiquark meson, completing a second family of matter particles. Though not known at the time, one and only one family remained to be discovered. The bottom quark, with a mass around 4 GeV, was found at Fermilab in 1977 (*CERN Courier* June 2017 p18), compelling physicists to search for its partner. But the top didn't materialise until 1995, when Fermilab's Tevatron energies were sufficient to create this astonishingly heavy quark. Weighing in around 173 GeV, its mass resembles that of a gold nucleus containing 197 protons and neutrons.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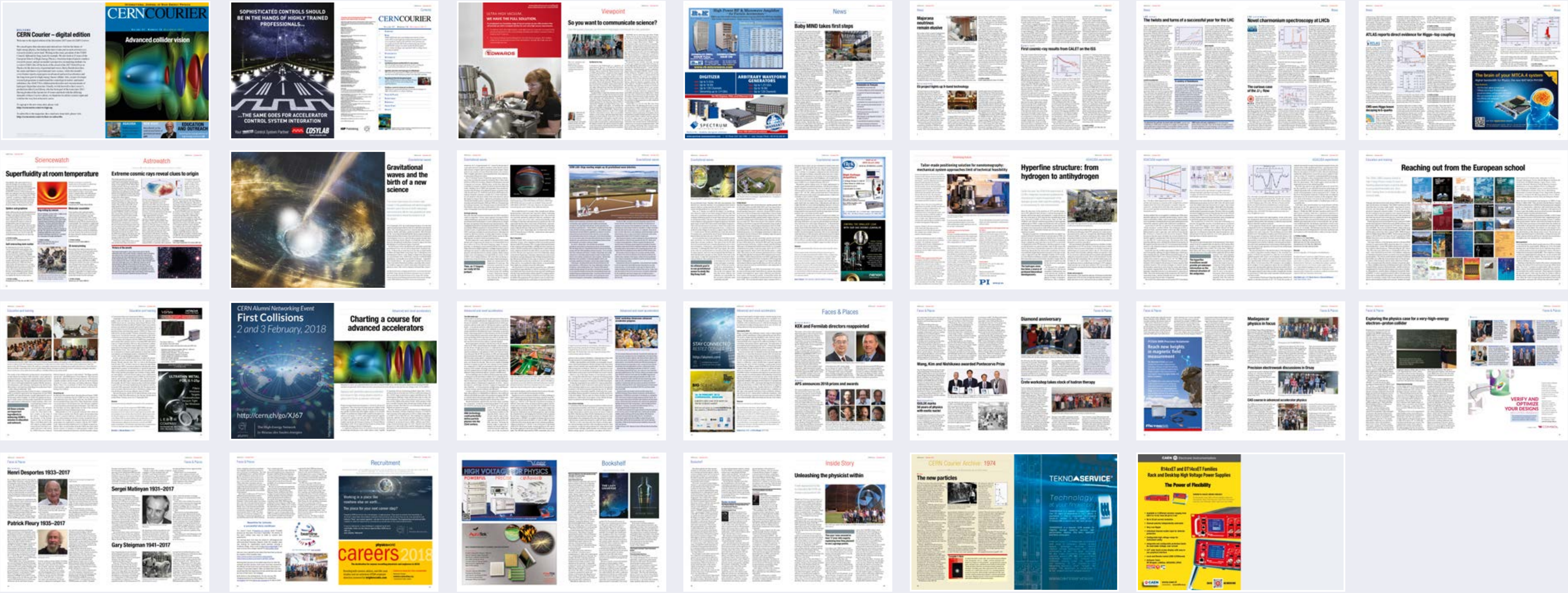

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