WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the May 2018 issue of *CERN Courier*.

Radio-frequency cavities drive accelerators across the world, their weird and wonderful metallic structures sustaining strong electromagnetic fields that shunt charged particles to higher energies. Particle physicists have pioneered the development of the most powerful superconducting cavities, and CERN is at the core of this effort. Currently installed in the Super Proton Synchrotron for their first tests in a proton beam are two superconducting "crab" cavities, named for their ability to tilt proton bunches sideways to ensure maximum collision intensity. The technology is at the heart of the high-luminosity LHC upgrade and is based on cavities made entirely from niobium. But CERN is also making huge strides with advanced niobium-coated copper cavities. Once the pinnacle of radio-frequency technology at CERN, driving the upgraded Large Electron Positron collider during the 1990s, niobium–copper cavities are back and even beginning to challenge the performance of their bulk-niobium counterparts. Such developments underpin the recent energy upgrade of the radioactive-beam facility ISOLDE and are key to next-generation accelerators at CERN and elsewhere.

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On the cover: Assembly of niobium–copper cavities for CERN's HIE-ISOLDE facility. (Image credit: M Brice/CERN.)

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IOP Publishing

News

LHC REPORT

Beams back in LHC for final phase of Run 2

M Brice, J Ordan/CERN

The LHC tunnel photographed in February.

Shortly after midday on 30 March, protons circulated in the Large Hadron Collider (LHC) for the first time in 2018. Following its annual winter shutdown for maintenance and upgrades, the machine now enters its seventh year of data taking and its fourth year operating at a centre-of-mass energy of 13 TeV.

The LHC restart, which involves numerous other links in the CERN accelerator chain, went smoothly. At the beginning of March, the first protons were injected into Linac2, and then into the Proton Synchrotron (PS) Booster. On 8 March the PS received beams, followed by the Super Proton Synchrotron (SPS) one week later. In parallel, the teams had been checking all the LHC hardware and safety installations. No fewer than 1560 electrical circuits had to be powered and about 10,000 tests performed before the LHC was deemed ready to accept protons.

The first beams circulating contain just one bunch, each of which contains 20 times fewer protons than in normal operation; the energy of the beam is also limited to the SPS injection energy of 450 GeV. Further adjustments and tests were undertaken in early April to allow the energy and density of the bunches to be increased.

Bunching up

As the *Courier* went to press, a few bunches had been injected and accelerated at full energy for optics and collimator commissioning. The first stable beams with only a few bunches are scheduled for 23 April, but could take place earlier thanks to the good progress made so far. This will be followed by a period of gradual intensity ramp-up, during which the number of bunches will be increased stepwise. Between each step, a formal check and validation will take place. The target is to fill each ring with 2556 bunches, and the experiments will be able to undertake serious data collection as soon as the number rises above 1200 bunches – which is expected in early May.

Since early December 2017, when the CERN accelerator complex entered its end of year technical stop, numerous important activities were completed on the LHC and other accelerators. Alongside standard maintenance, the LHC injectors underwent significant preparatory work for the LHC Injector Upgrade project (LIU) foreseen for 2019 and 2020 (*CERN Courier* October 2017 p32). In the LHC, an important activity was the partial warm-up of sector 1-2 to solve the so-called 16L2 issue, wherein frozen air from an accidental ingress caused beam instabilities and losses during last year's run: a total of 7 l of frozen air was removed from each beam vacuum chamber during the warm up.

The objective for the 2018 run is to accumulate more data than was collected last year, targeting an integrated luminosity of 60 fb^{-1} (as opposed to the 50 fb^{-1} recorded in 2017). While the intensity of collisions is being ramped up in the LHC, data taking is already under way at various fixed-target experiments at CERN that are served by beams from the PS Booster, PS and SPS. The first beams for physics at the n_TOF experiment and the PS East Area started on 30 March. The nuclear-physics programme at ISOLDE restarted on 9 April, followed closely by that of the SPS North Area and, later, the Antiproton Decelerator.

2018 is an important year for the main LHC experiments (ALICE, ATLAS, CMS and LHCb) because it marks the last year of Run 2. In December, the accelerator complex will be shut down for a period of two years to allow significant upgrade work for the High-Luminosity LHC, with the deployment of the LIU project and the start of civil-engineering work. Operations of the HL-LHC will begin in earnest in the mid-2020s, promising an integrated luminosity of 3000 fb^{-1} by circa 2035.

Sommaire en français

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FACILITIES

DESY sets out vision for the future

On 20 March, the DESY laboratory in Germany presented its strategy for the coming decade, outlining the areas of science and innovation it intends to focus on. DESY is a member of the Helmholtz Association, a union of 18 scientific-technical and medical-biological research centres in Germany with a workforce of 39,000 and annual budget of €4.5 billion. The laboratory's plans for the 2020s include building the world's most powerful X-ray microscope (PETRA IV), expanding the European X-ray free-electron laser (XFEL), and constructing a new centre for data and computing science.

Founded in 1959, DESY became a leading high-energy-physics laboratory and today remains among the world's top accelerator centres. Since the closure of the HERA collider in 2007, the lab's main accelerators have been used to generate synchrotron radiation for research into the structure of matter, while DESY's particle-physics division carries out experiments at other labs such as those at CERN's Large Hadron Collider.

Together with other facilities on the Hamburg campus, DESY aims to strengthen its role as a leading international centre for research into the structure, dynamics and function of matter using X rays. PETRA IV is a major upgrade to the existing light source at DESY that will allow users to study materials and other samples in 100 times more detail than currently achievable, approaching the limit of what is physically possible with X rays. A technical design report will be submitted in 2021 and first experiments could be carried out in 2026.

The DESY 2030 strategy is detailed in a 74-page brochure.

Together with the international partners and operating company of the European XFEL, DESY is planning to comprehensively expand this advanced X-ray facility (which starts at the DESY campus and extends 3.4 km northwest). This includes developing the technology to increase the number of X-ray pulses from 27,000 to one million per second (*CERN Courier* July/August 2017 p18).

As Germany's most important centre for particle physics, DESY will continue to be a key partner in international projects and to set up an attractive research and development programme. DESY's Zeuthen site, located near Berlin, is being expanded to become an international centre for astroparticle physics, focusing on gamma-ray and neutrino astronomy as well as on theoretical astroparticle physics. A key contribution to this effort is a new science data-management centre for the planned Cherenkov Telescope Array (CTA), the next-generation gamma-ray observatory. DESY is also responsible for building CTA's medium-sized telescopes and, as Europe's biggest partner in the neutrino telescope IceCube located in the Antarctic, is playing an important role in upgrades to the facility.

The centre for data and computing science will be established at the Hamburg campus to meet the increasing demands of data-intensive research. It will start working as a virtual centre this year and there are plans to accommodate up to six scientific groups by 2025. The centre is being planned together with universities to integrate computer science and applied mathematics.

Finally, the DESY 2030 report lists plans to substantially increase technology transfer to allow further start-ups in the Hamburg and Brandenburg regions. DESY will also continue to develop and test new concepts for building compact accelerators in the future, and is developing a new generation of high-resolution detector systems.

"We are developing the campus in Hamburg together with partners at all levels to become an international port for science. This could involve investments worth billions over the next 15 years, to set up new research centres and facilities," said Helmut Dosch, chairman of DESY's board of directors, at the launch event. "The Zeuthen site, which we are expanding to become an international centre for astroparticle physics, is undergoing a similarly spectacular development."

Flooded LHC data centre back in business

Following severe damage caused by flooding on 9 November, the INFN-CNAF Tier-1 data centre of the Worldwide LHC Computing Grid (WLCG) in Bologna, Italy, has been fully repaired and is back in business crunching LHC data. The incident was caused by the burst of a large water pipe at high pressure in a nearby street, which rapidly flooded the area where the data centre

INFN-CNAF

INFN-CNAF personnel working by torchlight a few days after the incident, wearing masks due to the presence of dust and mud.

is located. Although the centre was designed to be waterproof against natural events, the volume of water was overwhelming: some 500 m^3 of water and mud entered the various rooms, seriously damaging electronic appliances, computing servers, network and storage equipment. A room hosting four 1.4 MW electrical-power panels was filled first, leaving the centre without electricity.

The Bologna centre, which is one of 14 Tier-1 WLCG centres located around the world, hosts a good fraction of LHC data and associated computing resources. It is equipped with around 20,000 CPU cores, 25 PB of disk storage, and a tape library presently filled with about 50 PB of data. Offline computing activities for the LHC experiments were immediately affected. About 10% of the servers, disks, tape cartridges and computing nodes were reached by floodwater, and the mechanics of the tape library were also affected.

Despite the scale of the damage, INFN-CNAF personnel were not discouraged, quickly defining a roadmap to recovery and then attacking one by one all the affected subsystems. First, the rooms at the centre had to be dried and then meticulously cleaned to remove residual mud. Then, within a few weeks, new electrical panels were installed to allow subsystems to be turned back on.

Although all LHC disk-storage systems were reached by the water, the INFN-CNAF personnel were able to recover the data in their entirety, without losing a single bit. This was thanks in part to the available level of redundancy of the disk arrays and to their vertical layout. Wet tape cartridges hosting critical LHC data had to be sent to a specialised laboratory for data recovery.

A dedicated computing farm was set up very quickly at the nearby Cineca computing centre and connected to INFN-CNAF via a high-speed 400 Gbps link to enable the centre to reach the required LHC capacity for 2018. During March, three months since the incident, all LHC experiments were progressively put back online. Following the successful recovery, INFN is planning to move the centre to a new site in the coming years.

NA62

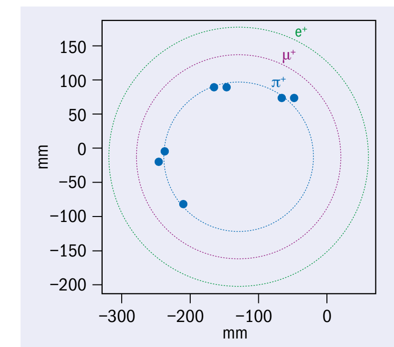
First hints of ultra-rare kaon decay

The NA62 collaboration at CERN has found a candidate event for the ultra-rare decay $K^+ \to \pi^+ \nu \bar{\nu}$, demonstrating the experiment's potential to test heavily-suppressed corners of the Standard Model (SM).

The SM prediction for the $K^+ \to \pi^+ \nu \bar{\nu}$ branching fraction is $0.84 \pm 0.03 \times 10^{-10}$. The very small value arises from the underlying coupling between s and d quarks, which only occurs in loops and is suppressed by the couplings of the quark-mixing CKM matrix. The SM prediction for this process is very clean, so finding even a small deviation would be a strong indicator of new physics.

NA62 was approved a decade ago and builds on a long tradition of kaon experiments at CERN (*CERN Courier* June 2016 p24). The experiment acts as a kaon factory, producing kaon-rich beams by firing high-energy protons from the Super Proton Synchrotron into a beryllium target and then using advanced Cherenkov and straw trackers to identify and measure the particles (see figure). Following pilot and commissioning runs in 2014 and 2015, the full NA62 detector was installed in 2016 enabling the first analysis of the $K^+ \to \pi^+ \nu \bar{\nu}$ channel.

Finding one candidate event from a sample



NA62's candidate event for the rare kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$: solid circles show hits in the RICH detector while dashed circles show predicted Cherenkov rings for a π^+, μ^+ and e^+.

of around 1.2×10^{11} events allowed the NA62 team to put an upper limit on the branching fraction of 14×10^{-10} at a confidence level of 95%. The result, first presented at Moriond in March, is thus compatible with the SM prediction, although the statistical errors are too large to probe beyond-SM physics.

Several candidate $K^+ \to \pi^+ \nu \bar{\nu}$ events have been previously reported by the E949 and E787 experiments at Brookhaven National Laboratory in the US, inferring a branching fraction of $1.73 \pm 1.1 \times 10^{-10}$ – again consistent, within large errors, with the SM prediction. Whereas the Brookhaven experiments observed kaon decays at rest in a target, however, NA62 observes them in-flight as they travel through a large vacuum tank and therefore creates a cleaner environment with less background events.

The NA62 collaboration expects to identify more events in the ongoing analysis of a 20-fold-larger dataset recorded in 2017. In mid-April the experiment began its 2018 operations with the aim of running for a record number of 218 days. If the SM prediction is correct, the experiment is expected to see about 20 events with the data collected before the end of this year.

"The $K^+ \to \pi^+ \nu \bar{\nu}$ decay is special because, within the SM, it allows one to extract the CKM element $|V_{td}|$ with a small theoretical uncertainty," explains NA62 spokesperson Augusto Ceccucci. "Developing the necessary experimental sensitivity to be able to observe this decay in-flight has involved a long R&D programme over a period of five years, and this effort is now starting to pay off."

ANTIMATTER

Antihydrogen spectroscopy enters precision era

The ALPHA collaboration at CERN's Antiproton Decelerator (AD) has reported the most precise direct measurement of antimatter ever made. The team has determined the spectral structure of the antihydrogen 1S–2S transition with a precision of 2×10^{-12}, heralding a new era of high-precision tests between matter and antimatter and marking a milestone in the AD's scientific programme (*CERN Courier* March 2018 p30).

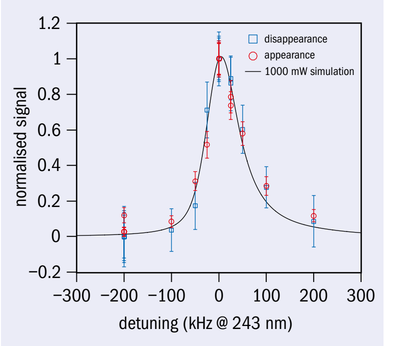
Measurements of the hydrogen atom's spectral structure agree with theoretical predictions at the level of a few parts in 10^{15}. Researchers have long sought to match this stunning level of precision for antihydrogen, offering unprecedented tests of CPT invariance and searches for physics beyond the Standard Model. Until recently, the difficulty in producing and trapping sufficient numbers of delicate antihydrogen atoms, and acquiring the necessary optical laser technology to interrogate their spectral characteristics, has kept serious antihydrogen spectroscopy out of reach. Following a major programme by the low-energy-antimatter community at CERN during the past two decades and more, these obstacles have now been overcome.

"This is real laser spectroscopy with antimatter, and the matter community will take notice," says ALPHA spokesperson Jeffrey Hangst. "We are realising the ▷

whole promise of CERN's AD facility; it's a paradigm change."

ALPHA confines antihydrogen atoms in a magnetic trap and then measures their response to a laser with a frequency corresponding to a specific spectral transition. In late 2016, the collaboration used this approach to measure the frequency of the 1S–2S transition (between the lowest-energy state and the first excited state) of antihydrogen with a precision of 2×10^{-10}, finding good agreement with the equivalent transition in hydrogen (*CERN Courier* January/February 2017 p8).

The latest result from ALPHA takes antihydrogen spectroscopy to the next level, using not just one but several detuned laser frequencies with slightly lower and higher frequencies than the 1S–2S transition frequency in hydrogen. This allowed the team to measure the spectral shape, or spread in colours, of the 1S–2S antihydrogen transition and get a more precise measurement of its frequency (see figure).



The latest ALPHA measurement involved using many laser frequencies — one matching the frequency of the 1S–2S transition in hydrogen and others detuned from it — and counting the number of atoms that dropped out of the trap as a result of interactions between the laser and the trapped atoms. Line-shape scans such as this mark the entrance of particle physics into precision spectroscopy.

The shape of the spectral line agrees very well with that expected for hydrogen, while the 1S–2S resonance frequency agrees at the level of 5 kHz out of 2.5×10^{15} Hz. This is consistent with CPT invariance at a relative precision of 2×10^{-12} and corresponds to an absolute energy sensitivity of 2×10^{-20} GeV.

Although the precision still falls short of that for ordinary hydrogen, the rapid progress made by ALPHA suggests hydrogen-like precision in antihydrogen is now within reach. The collaboration has also used its unique setup at the AD to tackle the hyperfine and other key transitions in the antihydrogen spectrum, with further seminal results expected this year. "When you look at the lineshape, you feel you have to pinch yourself – we are doing real spectroscopy with antimatter!" says Hangst.

Further reading

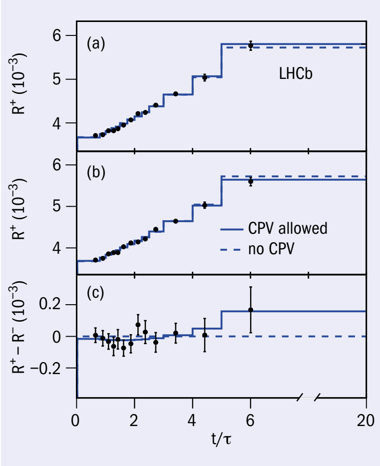
M Ahmadi *et al.* 2018 *Nature* doi:10.1038/s41586-018-0017-2.

LHC EXPERIMENTS

Charm oscillations precisely measured by LHCb

Direct searches for particles beyond the Standard Model (SM) have so far come up empty handed, but perhaps physicists can get luckier with indirect searches. Quantum mechanics allows neutral flavoured mesons to transform (or oscillate) into their anti-meson counterparts and back via weak interactions. Novel particles may contribute to the amplitude that governs such oscillations, thus altering their rate or introducing charge-parity (CP) violating rate differences between mesons and anti-mesons. Depending on the flavour structure of what lies beyond the SM, precision studies of such effects can probe energies up to 10^5 TeV – far beyond the reach of direct searches at the maximum energy currently achievable at colliders.

Oscillations, first posited in 1954 by Gell-Mann and Pais, have been measured precisely for kaons and beauty mesons. But there is room for improvement for D mesons, which contain a charm quark. Neither a nonzero value for the mass difference between mass eigenstates of neutral D mesons, nor a departure from CP symmetry, have yet been established. Charm oscillations are especially attractive because the D-meson flavour is carried by an up-type (i.e. with an electric charge of +2/3) quark. Charm-meson oscillations therefore probe phenomena complementary to those probed by strange- and beauty-meson oscillations.



Wrong-sign decay yield as a function of decay time, normalised to the D^0 lifetime, for (top) charm and (middle) anti-charm mesons in LHCb data (dots) with fit overlaid (lines). Wrong-sign decay yields are normalised to the right-sign yields to offset the exponential damping and suppress instrumental effects. The bottom panel shows the difference between charm and anti-charm wrong-to-right-sign yield ratios, which is sensitive to CP violation.

LHCb recently determined charm-oscillation parameters using 5 fb^{-1} of proton–proton collision data collected at the LHC in 2011–2016. About 5–10% of LHC collisions produce charm mesons; approximately 10,000 per second are reconstructable. Oscillations are studied by comparing production and decay flavour (i.e. whether a charm or an anti-charm is present) as a function of decay time. The charge of the pion from the strong-interaction decay $D^{*+}\to D^0\pi^+$ determines the flavour at production. The decay flavour is inferred by restricting to $K^\pm\pi^\mp$ final states because charm (anti-charm) neutral mesons predominantly decay into so-called right-sign $K^-\pi^+$ ($K^+\pi^-$) pairs. Hence, a decay-time modulation of the wrong-sign yields of $\bar{D}^0\to K^-\pi^+$ and $D^0\to K^+\pi^-$ decays indicates oscillations. In addition, differing modulations between charm or anti-charm mesons indicate CP violation. Backgrounds and instrumental effects that induce a decay-time dependence in the wrong-sign yield, or a difference between charm and anti-charm rates, may introduce harmful biases.

LHCb used track-quality, particle identification, and D^0 and D^{*+} invariant masses to isolate a prominent signal of 0.7 million wrong-sign decays overlapping a smooth background. Decays of mesons produced as charm or anti-charm were analysed independently. The wrong-sign yield as a function of decay time was fitted ▷

to determine the oscillation parameters. Statistical uncertainties dominate the precision. Systematic effects include biases from signal candidates originated from beauty hadrons, residual peaking backgrounds, and instrumental asymmetries associated with differing $K^+\pi^-$ and $K^-\pi^+$ reconstruction efficiencies. With about 10^{-4}–10^{-5} absolute (10% fractional) precision, the results are twice as precise as the previous best results (also by LHCb) and show no evidence of CP violation in charm oscillations.

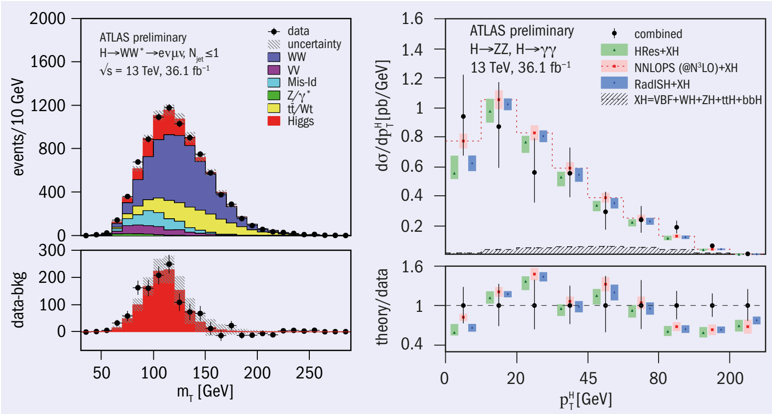
Further reading

LHCb Collaboration 2018 *Phys. Rev. D* **97** 031101.

ATLAS focuses on Higgs-boson decays to vector bosons

Decays of the Higgs boson to vector bosons (WW, ZZ, $\gamma\gamma$) provide precise measurements of the boson's coupling strength to other Standard Model (SM) particles. In new analyses, ATLAS has measured these decays for different production modes using the full 2015 and 2016 LHC datasets recorded at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 36.1 fb^{-1}.

With a predicted branching fraction of 21%, the Higgs-boson decay to two W bosons ($H \rightarrow WW$) is the second most common decay mode after its decay to two b quarks. The new analysis follows a similar strategy to the earlier ones carried out using the LHC datasets recorded at 7 and 8 TeV. It focuses on the gluon-gluon fusion (ggF) and vector-boson fusion (VBF) production modes, with the subsequent decay to an electron, a muon and two neutrinos ($H \rightarrow WW \rightarrow e\nu\mu\nu$). The main backgrounds come from SM production of W and top-quark pairs; other backgrounds involve $Z \rightarrow \tau\tau$ with leptonic τ decays and single-W production with misidentified leptons from associated jets.



Left: the transverse mass of selected events in the $H \rightarrow WW$ analysis, with red indicating the Higgs contribution (in the bottom panel, the background-subtracted data points are compared with the yield from the Higgs boson in the red histogram). Right: differential cross sections in the full phase space obtained from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ combined measurement (black points) for Higgs-boson transverse momentum p_T^H.

Events are classified according to the number of jets they contain: events with zero or one jet are used to probe ggF production, while events with two or more jets are used to target VBF production. Due to the spin-zero nature of the Higgs boson, the electron and muon are preferentially emitted in the same direction. The ggF analysis exploits this and other kinematic information via a sequence of selection requirements, while the VBF analysis combines lepton and jet variables in a boosted decision tree to separate the Higgs-boson signal from background processes.

The transverse mass of the selected events from the zero and one-jet signal regions is shown in the left figure, with red denoting the expectation from the Higgs boson and other colours representing background processes. These events are combined with those from the two-jet signal region to derive cross sections times branching fractions for ggF and VBF production of $12.3^{+2.3}_{-2.1}$ pb and $0.50^{+0.30}_{-0.29}$ pb, respectively, to be compared to the SM predictions of 10.4 ± 0.6 pb and 0.81 ± 0.02 pb.

ATLAS also performed a combination of inclusive and differential cross-section measurements using Higgs-boson decays to two photons and two Z bosons, where each Z decays to a pair of oppositely charged electrons or muons. The combination of the two channels allows the study of Higgs-boson production rates versus event properties with unprecedented precision. For example, the measurement of the Higgs-boson rapidity distribution can provide information about the underlying parton density functions. The transverse momentum distribution (figure, right) is sensitive to the coupling between the Higgs boson and light quarks at low transverse momentum, and to possible couplings to non-SM particles at high values. The measured cross sections are found to be consistent with SM predictions.

Further reading

ATLAS Collaboration 2018 ATLAS-CONF-2018-002.

ATLAS Collaboration 2018 ATLAS-CONF-2018-004.

ALICE closes in on parton energy loss

In a new publication submitted to the *Journal of High Energy Physics*, the ALICE collaboration has reported transverse momentum (p_T) spectra of charged hadrons in proton–proton (pp), proton–lead (pPb) and lead–lead (PbPb) collisions at an energy of 5.02 TeV per nucleon pair. The results shed further light on the dense quark-gluon plasma (QGP) thought to have existed shortly after the Big Bang.

At high transverse momentum, hadrons originate from the fragmentation of partons produced in hard-scattering processes. These processes are well understood in pp collisions and can be modelled using perturbative quantum chromodynamics. In PbPb collisions, the spectra are modified by the energy loss that the partons suffer when propagating in the QGP. Proton–lead collisions serve as a baseline for initial-state effects such as the modification of the gluon density of the nucleons of colliding lead nuclei.

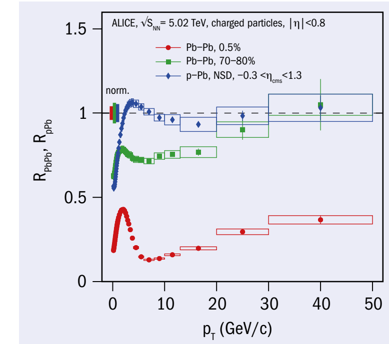
To characterise the change of spectra in nuclear collisions with respect to ▷

the expectation from pp collisions, the nuclear modification factors R_{PbPb} (R_{pPb}) are calculated by dividing the p_T spectra from PbPb (pPb) collisions by the spectra measured in pp collisions, scaled by the number of binary nucleon–nucleon collisions in the PbPb (pPb) collisions (see figure).

The nuclear modification factor in proton–lead collisions is consistent with unity at high transverse momentum. This shows that initial-state effects from the parton density in the lead nucleus are small and that the strong suppression observed in PbPb collisions is caused by final-state parton-energy loss in the QGP. The new results with higher statistics have much improved systematic uncertainties compared to the earlier publications based on Run 1 data. This is possible because of the improvements in the particle reconstruction and its description in Monte Carlo simulations, as well as data-driven corrections based on identified particles.

The suppression in PbPb collisions at 5.02 TeV is found to be similar to that at the collision energy of 2.76 TeV despite the harder spectrum at the higher energy, which indicates a stronger parton-energy loss and a larger energy density of the medium at the higher energy.

Theoretical models are able to describe the main features of the ALICE data; the improved precision of the measurements will allow researchers to constrain theoretical uncertainties further and to determine transport coefficients in the QGP. The upcoming PbPb run scheduled for November this year and the large pp reference sample collected at the end of 2017 will improve the statistical precision substantially and further extend the covered range of the transverse momentum.



Nuclear modification factor in central (0–5%) and peripheral (70–80%) lead–lead and proton–lead collisions at 5.02 TeV.

● **Further reading**

ALICE Collaboration 2018 arXiv:1802.09145.

CMS observes rarest Z boson decay mode

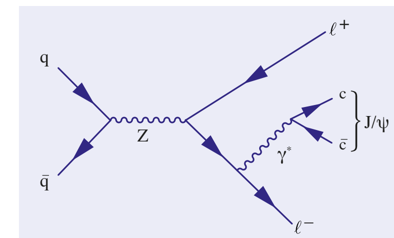
The amazing performance of the LHC provides CMS with a large sample of Z bosons. With such high statistics, the CMS collaboration can now probe rare decay channels that were not accessible to experiments at the former Large Electron Positron (LEP) collider. One of these channels, first theoretically studied in the early 1990s, is the decay of the Z boson to a J/ψ meson and two additional leptons. Theoretical calculations of this process, illustrated in the top figure, predict a branching fraction of $6.7–7.7\times10^{-7}$.

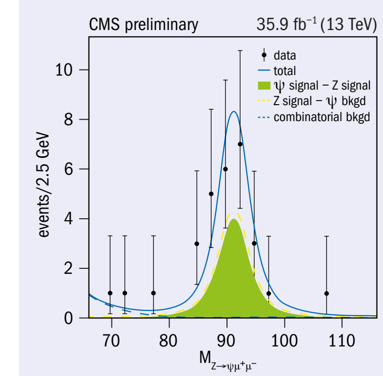
The new analysis was performed using proton–proton collision data collected during 2016, corresponding to an integrated luminosity of $35.9\,\text{fb}^{-1}$. To separate signal and background events, a 2D unbinned maximum likelihood fit was used that exploits as discriminating variables the invariant masses of the reconstructed J/ψ and Z states. Due to the limited separation sensitivity of the prompt J/ψ decays from $\psi(2S)\to J/\psi\,X$ decays, the sum of the two modes is indicated with ψ. The decay modes $Z\to\psi\,\mu^+\mu^-$ and $Z\to\psi\,e^+e^-$ were searched for, resulting in a yield of 13 and 11 reconstructed candidates in the two channels, respectively. The significance of the $Z\to\psi\,\ell^+\ell^-$ observation (where $\ell=\mu, e$) is greater than five standard deviations.

Using the $Z\to\mu^+\mu^-\mu^+\mu^-$ decay mode as a reference sample and after removing the $(\psi 2S)\to J/\psi\,X$ contribution, the branching fraction ratio $B(Z\to J/\psi\,\ell^+\ell^-)/B(Z\to\mu^+\mu^-\mu^+\mu^-)$ in the fiducial phase space of the CMS detector is measured to be 0.70 ± 0.18 (stat) $\pm\,0.05$ (syst), assuming null J/ψ polarisation.

Extrapolating from the fiducial volume to the full space and assuming that the extrapolation uncertainties of the two channels cancel in the ratio, a qualitative estimate of $B(Z\to J/\psi\,\ell^+\ell^-)$ can be extracted. The measured value of approximately 8×10^{-7} is consistent with the prediction of the Standard Model.

This is the first observation of this decay mode, and is the rarest Z-decay channel observed to date. With this analysis, CMS has started a new era of rare Z decay measurements. Looking forward, the full Run 2 data can lead to a more precise measurement of the decay's branching fraction. This is particularly important since this process is a background to the even rarer process whereby a Higgs boson decays into a J/ψ and lepton pair, and rare decays are a rich target in which to detect new physics.





Leading-order diagram of the $Z\to J/\psi\,\ell^+\ell^-$ process (top) and the invariant mass distribution of the $Z\to J/\psi\,\mu^+\mu^-$ sample.

● **Further reading**

CMS Collaboration 2018 CMS-PAS-BPH-16-001.

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

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

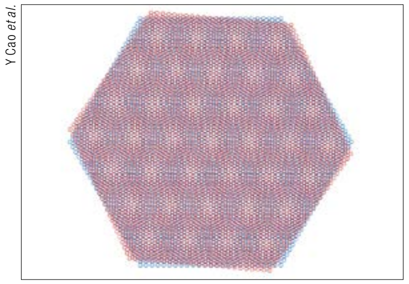
Sciencewatch

Compiled by John Swain, Northeastern University

Graphene is also a superconductor

Graphene, the one-atom-thick sheet of carbon atoms, continues to provide surprises with possibly enormous implications. Yuan Cao from MIT and colleagues show that a stack of two graphene layers can conduct electrons with zero resistance if the layers are twisted at a "magic angle" of 1.1° — a discovery that could be a step towards room-temperature superconductors. The material still needs to be cooled to 1.7 K, but the results indicate that it may superconduct in a way similar to high-temperature cuprates and point the way towards higher superconducting temperatures. Details of exactly what is taking place are being worked out.

Y Cao et al.



A stack of two graphene layers superconducts if the layers are twisted at a "magic angle".

● **Further reading**

Y Cao *et al.* 2018 *Nature* **556** 43.

Continuous-wave maser

Masers – the microwave analogues of lasers – have not seen the degree of use one might expect because they have long required cryogenics and high-vacuum systems. The development of room-temperature solid-state masers based on pentacene molecules in a *p*-terphenyl host in 2012 was a breakthrough, but the poor mechanical and thermal properties of *p*-terphenyl have restricted these masers to pulsed mode. Now, Jonathan Breeze of Imperial College London and colleagues have demonstrated the first continuous-wave room-temperature maser oscillator using optically pumped nitrogen-vacancy defect centres in diamond at 9.2 GHz. Immediate applications include radio astronomy and deep-space communications.

● **Further reading**

J D Breeze *et al.* 2018 *Nature* **555** 493.

Modifying nuclear decay rates

It is well known that the spontaneous emission rates of atoms or molecules can be modified by changing their electromagnetic environment, which is typically an optical cavity. But the same is hard to achieve for nuclear transitions because the frequency of the radiation emitted in most nuclear transitions is much larger than that of the cavity modes. Eugene Tkalya of Moscow State University now predicts that the decay rate via emission of ^{229}Th from its lowest excited nuclear state can be increased or decreased by an order of magnitude by placing the atom in a dielectric sphere or a thin film. The effect could lead to ultraprecise atomic clocks based on nuclear transitions.

● **Further reading**

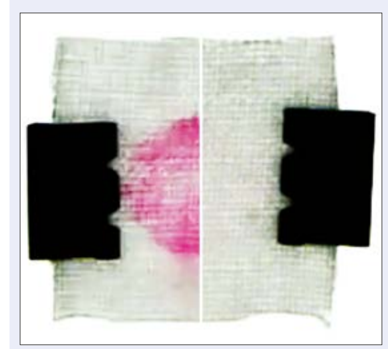
E V Tkalya 2018 *Phys. Rev. Lett.* **120** 122501.

Laundry physics

Physics usually tackles big questions, but smaller everyday ones can also be interesting. Sangwoo Shin of the University of Hawaii at Manoa and colleagues have solved a long-standing problem in laundry detergency called the stagnant core problem – figuring out how detergent gets stain particles out from between tightly wound fibres, where water flow is restricted. Shin *et al.* explain this by the migration of particles along a concentration gradient, a process that is far more effective than naive solute diffusion. This manifests as stain particles being removed from cloth far better by rinsing soapy fabric in fresh water than in detergent-filled water – an insight with potentially wide industrial applications, and perhaps something to think about the next time you do laundry.

● **Further reading**

S Shin *et al.* 2018 *Phys. Rev. Appl.* **9** 034102.



Rinsing soapy fabric in fresh water (right) gets stain particles out far better than rinsing in detergent-filled water (left).

Superionic ice

It has been suggested that water ice under high pressure, such as inside planets, would be superionic, with liquid-like hydrogen ions moving inside a solid lattice of oxygen. Now, Marius Millot of Lawrence Livermore National Laboratory and colleagues report laser-driven shock-compression of ice VII and find melting near 5000 K at 190 GPa. A variety of measurements, including optical reflectivity and absorption measurements, show a low electronic conductivity, which, together with previous measurements, provides evidence for superionic ice under planetary-interior conditions, verifying a prediction dating back 30 years.

● **Further reading**

M Millot *et al.* 2018 *Nat. Phys.* **14** 297.

Gamma-ray lasing

Gamma-ray lasers have been elusive because it's hard to produce coherent gamma rays. Now, Luca Marmugi of University College London and colleagues have identified a gamma-ray lasing mechanism in a Bose–Einstein condensate (BEC) of ^{135}Cs atoms in their isomeric state, ^{135m}Cs, that could be implemented with existing techniques. The mechanism is triggered by the spontaneous emission of one gamma photon, and relies on the transfer of the coherence of the BEC to the photon field. The ^{135m}Cs atoms can be made from proton-induced fission of actinides, followed by neutralisation, laser cooling and trapping. Standard techniques should allow trapping only of atoms in the desired state, so that a total population inversion is achieved.

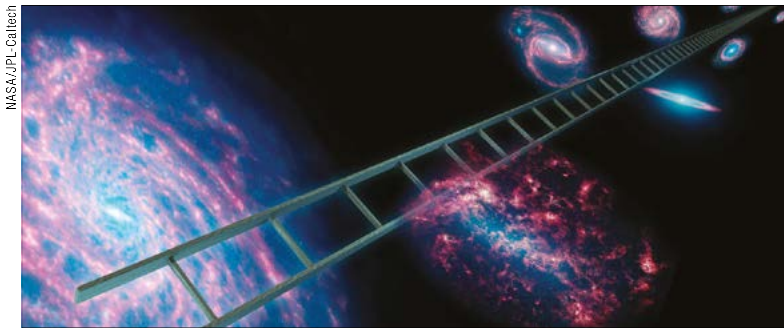
● **Further reading**

L Marmugi *et al.* 2018 *Phys. Lett. B* **777** 281.

Astrowatch

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

Hubble expansion discrepancy deepens


NASA/JPL-Caltech

An artist's concept of the distance-ladder method used by Riess and colleagues.

In the 1920s, Edwin Hubble discovered that the universe is expanding by showing that more distant galaxies recede faster from Earth than nearby ones. Hubble's measurements of the expansion rate, now called the Hubble constant, had relatively large errors, but astronomers have since found ways of measuring it with increasing precision. One way is direct and entails measuring the distance to far-away galaxies, whereas another is indirect and involves using cosmic microwave background (CMB) data. However, over the last decade a mismatch between the values derived from the two methods has become apparent. Adam Riess from the Space Telescope Science Institute in Baltimore, US, and colleagues have now made a more precise direct measurement that reinforces the mismatch and could signal new physics.

Riess and co-workers' new value relies on improved measurements of the distances to distant galaxies, and builds on previous work by the team. The measurements are based on more precise measurements of type Ia supernovae within the galaxies. Such supernovae have a known luminosity profile, so their distances from Earth can be determined from how bright they are observed to be. But their luminosity needs to be calibrated – a process that requires an exact measurement of their distance, which is typically rather large.

To calibrate their luminosity, Riess and his team used Cepheid stars, which are closer to Earth than type Ia supernovae. Cepheids have an oscillating apparent brightness, the period of which is directly related to their luminosity, and so their apparent brightness can also be used to measure their distance. Riess and colleagues measured the distance to Cepheids in the Milky Way using parallax measurements from the Hubble Space Telescope, which determine the apparent shift of the stars against the background sky as the Earth moves to the other side of the Sun. The researchers measured this minute shift for several Cepheids, giving a direct measurement of their distance. The team then used this measurement to estimate the distance to distant galaxies containing such stars, which in turn can be used to calibrate the luminosity of supernovae in those galaxies. Finally, they used this calibration to determine the distance to even more distant galaxies with supernovae. Using such a "distance ladder", the team obtained a value for the Hubble constant of $73.5 \pm 1.7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. This value is more precise than the $73.2 \pm 1.8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ value obtained by the team in 2016, and it is 3.7 sigma away from the $66.9 \pm 0.6\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ value derived from CMB observations made by the Planck satellite.

Reiss and colleagues' results therefore reinforce the discrepancy between the results obtained through the two methods. Although each method is complex and may thus be subject to error, the discrepancy is now at a level that a coincidence seems unlikely. It is difficult to imagine that systematic errors in the distance-ladder method are the root cause of the tension, says the team. Figuring out the nature of the discrepancy is pivotal because the Hubble constant is used to calculate several cosmological quantities, such as the age of the universe. If the discrepancy is not due to errors, explaining it will require new physics beyond the current standard model of cosmology. But future data could also potentially help to identify the source of the discrepancy. Upcoming Cepheid data from ESA's Gaia satellite could reduce the uncertainty in the distance-ladder value, and new measurements of the expansion rate using a third method based on observations of gravitational waves could throw new light on the problem.

Further reading

A Riess *et al.* 2018 *Astrophys. J.* **855** 136.

Picture of the month

Several nebulae make up this image, three of which form the large Seagull Nebula in the top centre, while a fourth in the bottom right is known as the Duck Nebula or Thor's Helmet. The emission from the Duck Nebula comes from hundreds of solar masses' worth of ionised gasses being pushed away and irradiated by a massive hot star thought to be on the verge of exploding as a supernova. The Seagull's head is also composed of ionised gas, although here the gas is irradiated by a binary system of two massive young stars. Finally, the large wings of the Seagull consist of a vast cloud of hydrogen gas, which is from the Milky Way's spiral arms and is lit up by young stars formed within the cloud.


Raul Villaverde Fraile

Crab kicks for brighter collisions

Advanced radio-frequency crab cavities are to be tested for the first time in a proton beam, a vital step towards the high-luminosity LHC upgrade.

Two key parameters underpin the physics reach of a particle collider: its collision energy and its luminosity, which is the number of potential collisions per unit area per unit time at the interaction point of the colliding beams. Accelerator physicists have devised numerous ways to boost the luminosity and thus scientific reach of colliders, via innovative magnet and radio-frequency (RF) technologies. One such RF innovation is the crab cavity, which is a key feature of the high-luminosity upgrade to the Large Hadron Collider (HL-LHC) now in its construction phase at CERN.

The roots of crab cavities can be traced to 1988, when Bob Palmer at Brookhaven National Laboratory proposed the crab crossing-scheme for an electron-positron linear collider. The first implementation in an accelerator was much later, in 2006, at the KEKB electron–positron collider in Japan. One crab cavity per ring operated for approximately four years and, in conjunction with other accelerator elements, helped the collider reach record luminosities. Crab-crossing was considered as one of several potential LHC upgrade paths as early as 2002 and, in 2006, the first proposal for the HL-LHC crab cavities was made. Soon afterwards, crab cavities – along with high-field niobium–tin magnets – were adopted as one of the key technologies allowing the HL-LHC to multiply the integrated luminosity of the present LHC by a factor of 10.

An extensive R&D programme followed, and the first tests of the HL-LHC crab cavities took place in spring last year (*CERN Courier* May 2017 p7). Beginning in early 2018, two cavities were installed in CERN's Super Proton Synchrotron (SPS) to study how they behave with real beam (image left). This will be the first time that a crab cavity has ever been used for manipulating protons, paving the way not just for the HL-LHC but a variety of other accelerator applications.

Cryomodule containing two crab cavities (cuboidal unit in centre) in the SPS tunnel ready for the technology's first ever tests in a proton beam. (Image credit: M Brice/CERN.)

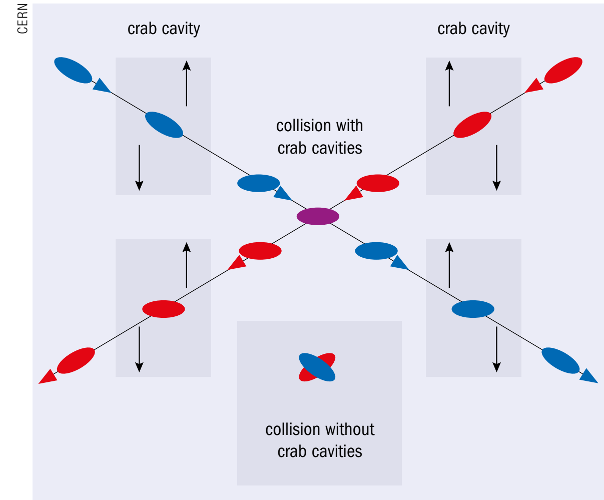


Fig. 1. In the current configuration of the LHC, the counter-propagating (red and blue) proton bunches meet with a crossing angle (bottom). To cope with the larger crossing angles at the HL-LHC, crab cavities will administer a transverse RF kick that tilts the bunches so that they appear to move sideways, causing them to collide head-on (purple) at the collision point.

Crab-wise crossings

The advanced niobium-tin "inner-triplet quadrupole" magnets for the HL-LHC (*CERN Courier* March 2017 p23 and September 2017 p17) will be placed on either side of the ATLAS and CMS experiments to squeeze the incoming proton beams into smaller transverse beam sizes at the collision point than those presently obtained at the LHC. To avoid unwanted parasitic collisions in the single beam pipe either side of the interaction points, the HL-LHC will operate with a crossing angle, which has the negative effect of reducing the luminosity with respect to that obtained with head-on collisions. Smaller beam sizes at the interaction point of the HL-LHC imply larger beams in the inner triplet magnets and, consequently, a larger crossing angle is necessary to ensure sufficient separation of the beams. At the nominal HL-LHC, the large crossing angle coupled with the small bunch dimensions would result in a luminosity reduction of around 66% if not corrected.

To recover some of this potential loss of luminosity while maintaining the necessary beam separation, an elegant crab-crossing scheme has been proposed. Independent superconducting crab cavities for each beam are positioned around 160 m upstream and downstream of a given collision point. The crab cavities provide a time-dependent transverse kick to the protons in the head and tail of a bunch. As a bunch moves towards the interaction point, the kick serves to rotate the bunch in the crossing plane so that it effectively collides head-on with its incoming counterpart (figure 1). The downstream crab cavity then reverses the kick to confine the rotation to the interaction region and leave the particle orbit in the rest of the machine untouched. A total of 16 cavities – eight (two per beam per side) near ATLAS and eight near CMS – will be required for the project.

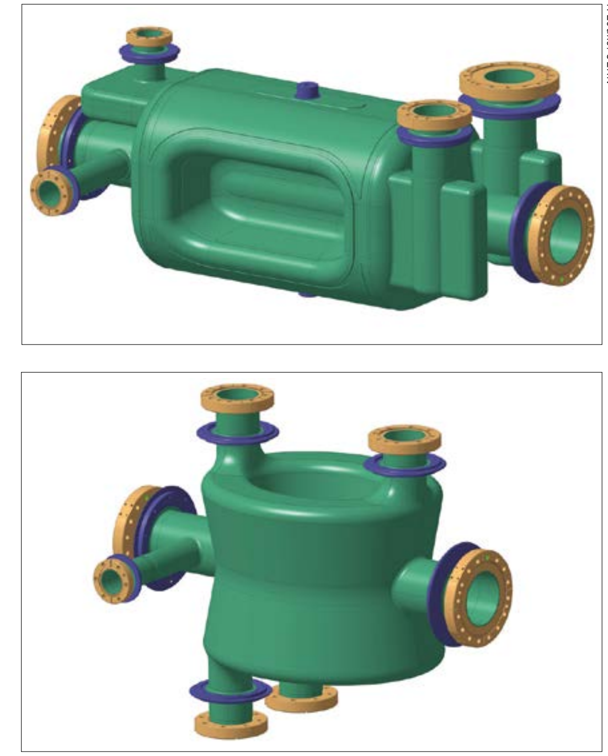


Fig. 2. Schematic view of the interfaces of two cavities under development: RFD (top) and DQW (bottom).

The tight spatial constraints of the HL-LHC upgrade meant a long journey of technological challenges. The large crossing angle (implying a large transverse kick) between the HL-LHC beams required a radically new RF concept for particle deflection with a novel shape and significantly smaller cavities than those used in other accelerators. In less than two years, more than 10 concurrent designs from RF experts across three continents were being discussed as potential options. By 2013, three designs stemming from a worldwide collaboration between CERN, the US and the UK were considered to be most adapted to the HL-LHC: double quarter wave (DQW), RF dipole (RFD) and four rod (4R). The results of RF tests of these designs were highly promising and, in 2014, an international panel recommended that efforts be focused on the first two (figure 2) with the aim of making a full validation with real proton beams. Both designs will be used, one around ATLAS and the other around CMS.

The cavities are made from sheets of high-purity niobium, a type II superconductor commonly used for very high-field superconductors. A sheet thickness of 4 mm is necessary to cope with the strict mechanical constraints; advanced shaping, machining and ultra-precise electron-beam welding are required to produce the complex shapes with mechanical tolerances well below 1 mm. Once "dressed", each cavity is equipped with: a helium tank, an internal magnetic shield, a precision frequency tuning system, a fundamental RF power coupler, a field probe and two or three

T Capelli/CERN

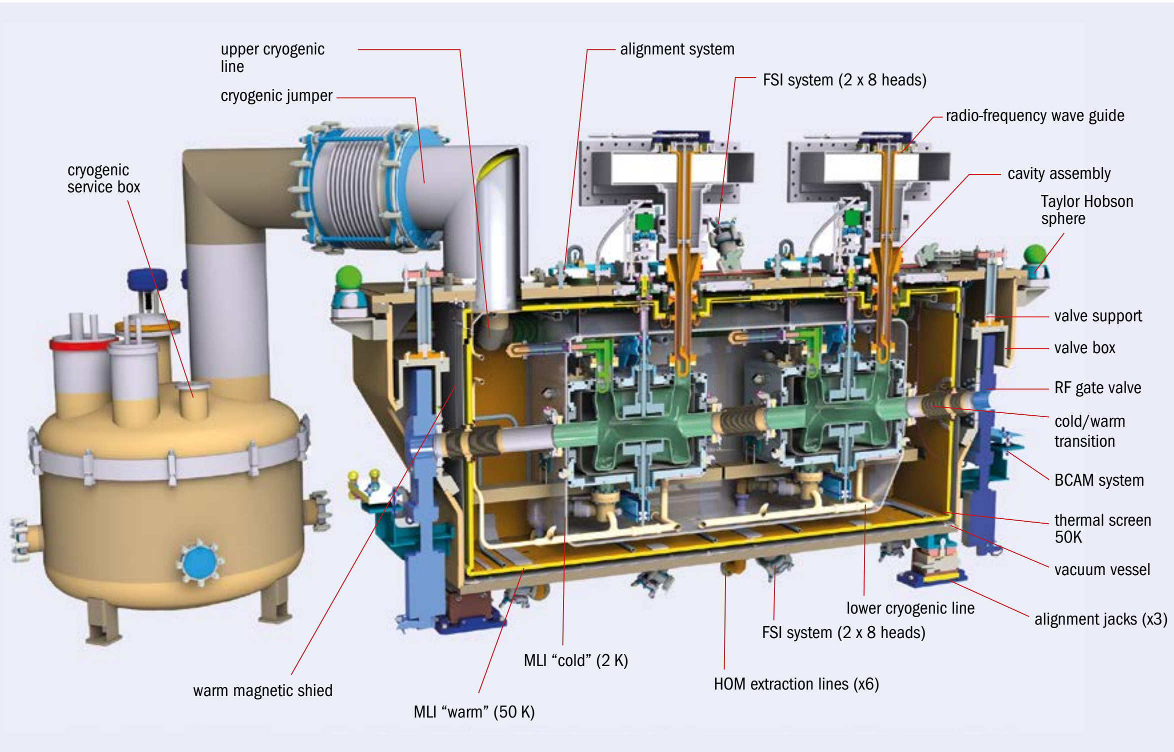


Fig. 3. Cross section of the DQW cryomodule showing two dressed cavities, the vacuum vessel, support and alignment systems, magnetic and thermal shields, RF internal lines, cryogenic lines, and many other features.

higher-order mode couplers (figure 3).

The helium tank serves as an enclosing body to cool the cavity surface with saturated superfluid helium at 2 K and its geometry was chosen to limit the maximum stress on the cavity. Owing to the unconventional geometries of the crab cavities, titanium was selected because it has nearly the same thermal contraction as niobium. An active frequency tuning system structurally integrated with the tank with a resolution of a few nanometres allows the cavity frequency to be precisely synchronised to the beam. Two identical cavities are inserted into a special cryomodule that serves as a high-performance thermos flask under high vacuum, thus reducing the heat load and stray magnetic fields from the outside environment and keeping the cavities stable at 2 K. This is made feasible with different layers of materials all properly thermalised in a staged fashion and under high vacuum conditions to minimise the total footprint. The most external layer of the cryomodule is the vacuum vessel. A complex cryogenic circuit with staged temperatures also allows the passage of the cold helium (2 K and 50 K) to cool the cavity ancillaries such as higher-order mode couplers and RF lines. The cryomodule also serves as the support structure and keeps the two cavities precisely aligned.

Successful operation of the crab cavities depends on their correct position and orientation, and the HL-LHC places tight constraints on the cavity alignment; in particular, the transverse displacement of one cavity with respect to another should not exceed 500 μm. To determine the cavity alignment relative to targets positioned outside the cryostat, a position monitoring system five to ten times more precise is needed. Frequency scanning interferometry was chosen for this task, whereby a laser beam is sent inside the cryomodule and reflected off several reflectors placed on the cavity interfaces to track their movements. The optical path of the measurement beam is then compared with a beam from a reference interferometer, offering absolute interferometric distance measurements with sub-micrometre precision.

Early last year, two superconducting prototype DQW-type crab cavities manufactured at CERN underwent RF tests in a superfluid helium bath at a temperature of 2 K. These first cavity tests demonstrated a maximum transverse-kick voltage exceeding 5 MV, surpassing the nominal operational voltage of 3.4 MV. The corresponding electric and magnetic fields on the cavity surfaces were 57 MV/m and 104 mT, respectively (for comparison, the KEKB cavities reached a maximum of 2.5 MV kick voltage in similar tests). Prototypes of the DQW and the RFD cavities were built in the US and reached even higher fields than the CERN prototypes, demonstrating the robustness of the RF design.

By the end of 2017, the two crab cavities were assembled at CERN into a special cryomodule to allow operation in an accelerator environment. Its design was a joint effort between CERN and the UK. The module was successfully RF-tested at 2 K in December at CERN's SM18 facility (figure 4, lower right), validating the mechanical, cryogenic and RF functioning prior to its installation in the SPS for beam tests. The complete installation of the cryomodule and support infrastructure, requiring a new high-power RF and cryogenic system, had to be finished in a period of eight weeks during the year-end technical stop of the SPS. The rush was dictated by the operation schedule of the CERN accelerator complex: after 2018, all the accelerators of the injector complex will be stopped for two years, to undergo a major upgrade in preparation for the HL-LHC.

J Ordan/CERN J Ordan and M Brice/CERN J Ordan/CERN A Macpherson/CERN

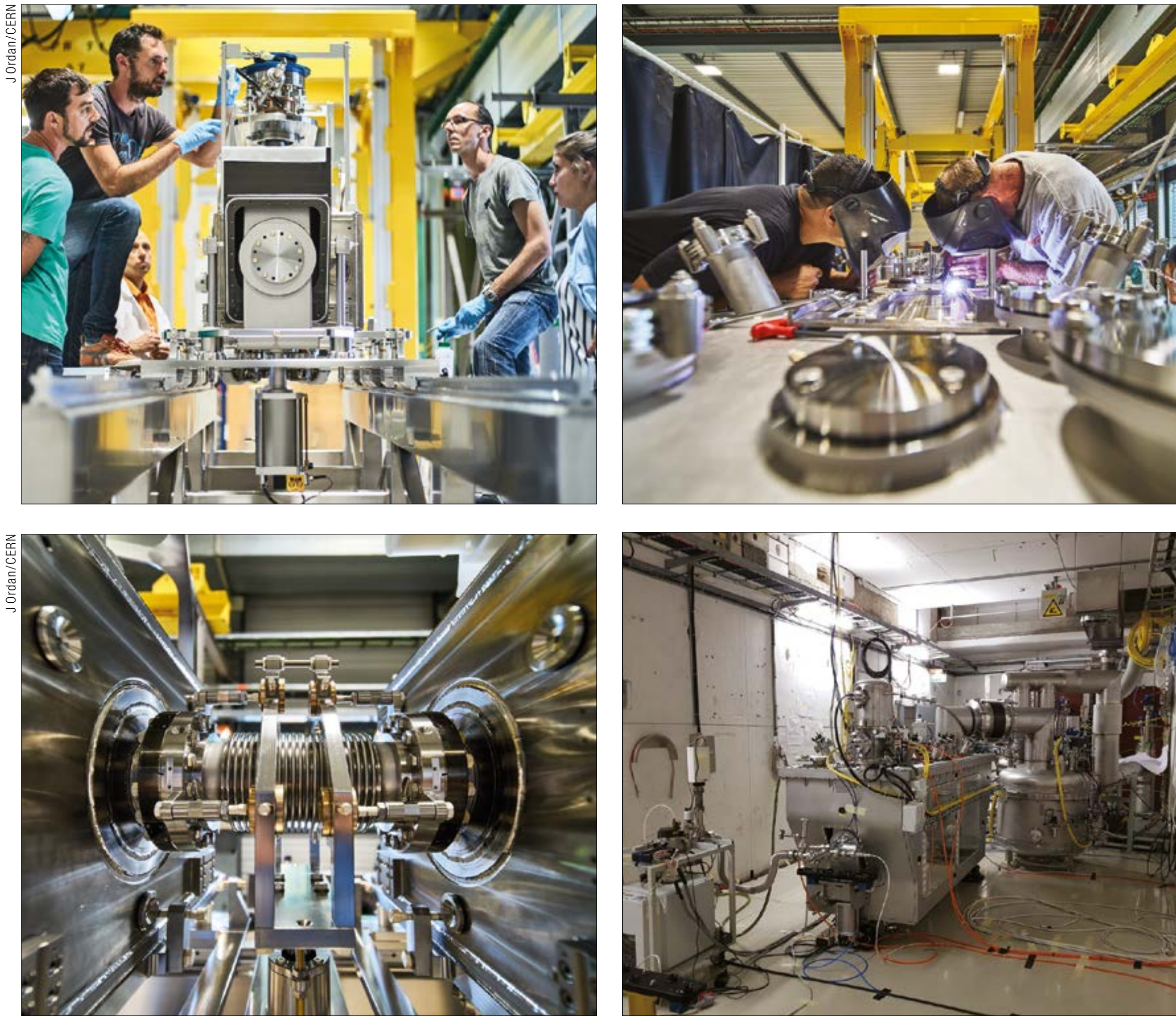


Fig. 4. Checking the RF interfaces (top left), welding (top right) and interconnecting bellows (bottom left) of a string of two prototype crab cavities in the SM18 test facility. Validation tests of the fully assembled unit took place in December (bottom right).

Ready for beam

Proton beam tests of the compact crab cavities in the SPS are considered a prerequisite before installation into the LHC itself. The aim is to demonstrate the operational performance of the cavity and transparency throughout the energy cycle and to study long-term effects on proton beams and failure modes.

A 15 m long section of the SPS ring was identified as suitable for installation of the in-beam crab-cavity test stand. The beam line was equipped with two articulated, Y-shaped vacuum chambers to provide a bypass to the circulating beam, with highly flexible bellows allowing for a lateral displacement of approximately 51 cm (figure 5, middle). Via this articulated continuous connection of the vacuum beam pipe, the crab-cavity test module can remain parked out of the beamline during regular operation of the SPS and be transferred back into the beamline during periods dedicated to crab-cavity testing. This is essential because the entrance diameter of the crab cavities is smaller than what is needed for beam extraction to the LHC, plus there is an inherent operational risk associated with having a prototype element inserted in the beamline of the main injector to the LHC. The motorised trans-

M Brice/CERN
M Brice/CERN
J Ordan/CERN

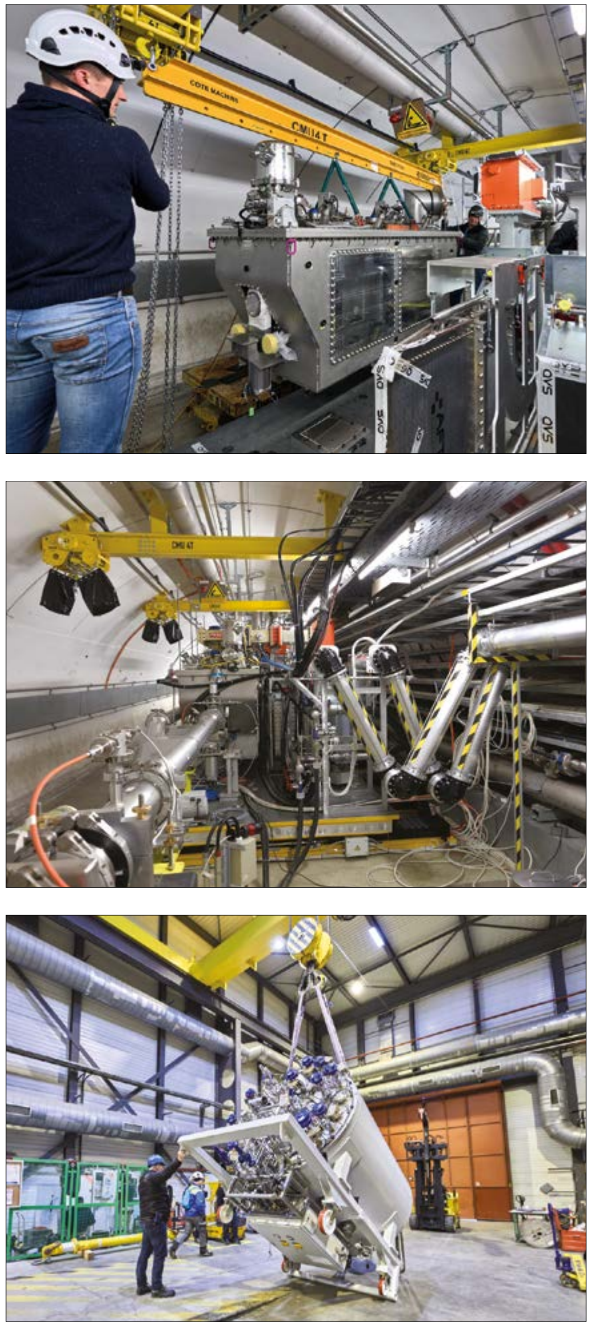


Fig. 5. *Top: installing the cryomodule in the SPS tunnel; middle: Y-shaped vacuum chambers provide a bypass to the circulating SPS beam, with articulated waveguides delivering RF power to the cavity as it moved in and out of the beam by a motorized transfer table; bottom: the cold-box, produced by Linde Kryotechnik, for the SPS crab-cavity test stand for the HL-LHC on its arrival at CERN.*

fer table, produced by Added Value Solutions (Spain), also supports the Y-chambers, the two RF circulators and passive loads, and a cryogenic valve box – corresponding to a total load of about 15 tonnes, which is moved in and out of the beam with a positioning precision of a few micrometres.

Due to limited space and accessibility in the underground areas of the SPS, the RF amplifiers required to power the cavities were placed in a surface building and RF power routed via coaxial lines to the cryomodule. The cold box for the cryogenic refrigeration system, by contrast, was installed underground because transporting liquid helium along a vertical pipeline increases losses by evaporation. Helium is liquefied in the cold-box and routed to the cryomodule via a 110 m long cryogenic distribution line. A comprehensive beam-test programme is now under preparation. In parallel to the installation of the prototype cryomodule in the SPS, an effort has started to fabricate at CERN two RFD prototype cavities. They will then be assembled at Daresbury (UK) into a cryomodule that will be tested in the SPS after the second LHC long shutdown. An industrial contract for the production of DQW cavities for the full crab-cavity system for the HL-LHC was finalised in December 2017 with Research Instruments in Germany, and the industrial production of the RFD cavities, which is now under the responsibility of a collaboration with the US, is also ramping up.

Superconducting crab cavities and RF deflectors have a wide range of applications other than high-energy physics. The significant contribution of the HL-LHC developments to ultra-compact and very high-field cavities are already influencing new proposals for luminosity improvements similar to the HL-LHC for electron–hadron colliders, bunch compression in light sources to produce sub-picosecond photon pulses, and ultrafast particle separators in proton linacs as a means to separate bunches of secondary particles for different experiments.

It is now also evident that crab cavities are useful beyond the HL-LHC for even higher energy colliders. In the proton-proton version of the Future Circular Collider (FCC) study, the bunches would be squeezed at the collision point by a factor of 2–4 compared with that of the HL-LHC. Without crab cavities to compensate, only 20% of the available peak luminosity would be exploited by the machine. It is clear that this advanced RF technology, taken further than before by its adaption to the HL-LHC, has an extremely bright future for high-energy physics and beyond.

Résumé

Des cavités en crabe pour des collisions plus brillantes

Les spécialistes des accélérateurs ont imaginé divers moyens d'accroître la luminosité, et donc le potentiel scientifique des collisionneurs, au moyen de technologies innovantes concernant les cavités radiofréquence. L'un de ces moyens est la cavité en crabe, ainsi appelée parce qu'elle permet de dévier les faisceaux dans la direction transversale ; c'est l'une des bases de la conception du LHC à haute luminosité. Dans cette perspective, des cavités en crabe perfectionnées ont été installées dans le Supersynchrotron à protons en vue de réaliser un premier essai sur un faisceau de protons.

Rama Calaga, **Ofelia Capatina** and **Giovanna Vandoni**, CERN.

The long march of niobium on copper

Niobium–copper accelerating cavities, once the pinnacle of radio-frequency technology at CERN, are back in business and beginning to challenge the performance of their bulk-niobium counterparts.

Superconductors are poor thermal conductors. Whenever a superconducting state is established in a given material, a large fraction of the conduction electrons are frozen in Cooper pairs and become unavailable for heat transport. This can have serious practical implications: at low temperatures, even a small amount of localised heating can drive the material into a normal conducting state, triggering an avalanche process (or quench) that destroys superconductivity in the whole device. It is therefore good practice in applied superconductivity to stabilise superconductors with a high-thermal-conductivity metal. The superconducting niobium–titanium filaments in strands used for accelerator magnets such as those in the LHC, for example, are usually embedded in a copper matrix to spread out any small fluctuation in temperature.

In the world of superconducting radio-frequency (SRF) cavities, which are used to accelerate charged particles in accelerators around the globe, this technique is the exception rather than the rule. Today, mainstream SRF technology makes use of bulk niobium sheets to build the entire resonator structure, circumventing the problem of poor thermal conductivity by using material of very high purity. In the past 40 years, great leaps forward have brought bulk-niobium cavity performances close to what is considered the intrinsic limit of the material, with accelerating fields of the order 50 MV/m in elliptical structures.

However, things were not always this way. In the 1960s, lead (which is a type-I superconductor) was electroplated on copper RF resonators used for beam acceleration at several high-energy physics facilities around the world. As the RF currents only penetrate a few tens of nanometres in the cavity wall, a few-micron-thin superconducting layer on a high-thermal-conductivity copper substrate provided an elegant solution to the problem of thermal stabilisation, in perfect analogy to what happens in superconducting strands for magnets.

Coated RF cavities (figure 1, p28) offered another advantage: they allowed the function of producing high electric fields to be easily decoupled from that of giving enough mechanical stability, which is required to control the field amplitude and phase sufficiently for beam acceleration. The main drawback of lead-plated cavities was their relatively low accelerating field, limited by the critical magnetic field of lead. A natural step forwards was to use niobium, whose critical field is about 2.5 times higher. Unfortunately, the synthesis of good-quality niobium films on copper was much more difficult, and in the 1970s the research quickly turned to using bulk niobium as a cavity material.

Niobium-coated cavities

In 1984, Cristoforo Benvenuti, Nadia Circelli and Max Hauer from CERN (figure 2, p29) published a seminal paper on niobium films for superconducting accelerating cavities. These films were deposited on copper cavity substrates by sputtering, which was reported to give encouraging results on real cavities. It was the start of a successful development, which in only a few years led to the greatest achievement of niobium–copper technology: the SRF system of the upgraded Large Electron Positron collider (LEP), which operated at CERN in the mid- to late-1990s. This consisted of 288 four-cell elliptical cavities working at a frequency of 352 MHz, the vast majority of which were produced with niobium–copper technology in three European industries. During the early times of LEP, niobium–copper cavities could outperform their bulk niobium counterparts at LEP's nominal fields. Besides being cheaper and free from quenches, they also revealed unexpected insensitivity to trapped magnetic flux. This is a peculiar problem of superconducting cavities that can spoil their performance unless great care is used to shield the cavity from any magnetic fields when it undergoes the superconducting transition. The need for magnetic shielding added to the cost of the bulk niobium systems, whereas LEP's niobium–copper cavities could operate without shielding.

In the meantime, as coated-cavity technology took off at CERN, bulk niobium technology was progressing fast: all over the world in national laboratories and in industry, the SRF community removed all of the obstacles one after the other in the quest for higher accelerating fields and lower power dissipation (expressed by the unloaded quality factor, Q). Nowadays, state-of-the-art bulk niobium cavities are cutting-edge technology objects made from high residual-resistivity-ratio (RRR) niobium sheets that are shaped and electron-beam welded with the utmost precision. They must be assembled according to high cleanliness standards borrowed from the semiconductor industry to prevent electron-field emission. They need to

Assembly of the HIE-ISOLDE niobium–copper cavities in a cleanroom at CERN's SM18 facility. (Image credit: M Brice/CERN.)

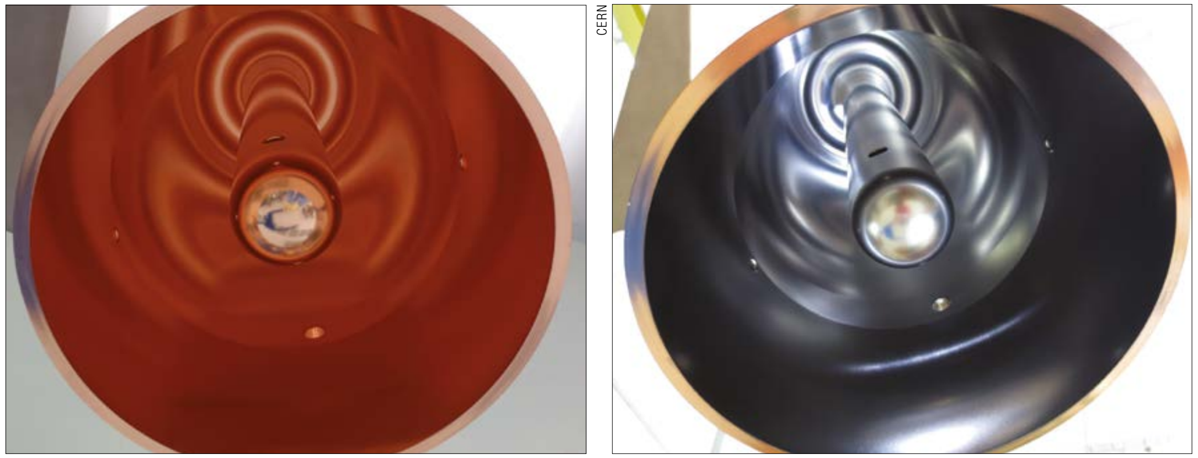


Fig. 1. Seamless quarter-wave resonator for HIE-ISOLDE before (left) and after (right) coating.

be carefully shielded from the Earth's and other parasitic magnetic fields, operated in superfluid helium, and employ complex feedback systems and high installed RF power to combat the effects of microphonics (vibrations that detune the cavities). The result is outstanding in terms of accelerating field and Q, now approaching the theoretical limits. Bulk niobium cavities can be produced in industry and are operating reliably in accelerators at several facilities worldwide, such as the European X-ray free electron laser (XFEL) in Hamburg (*CERN Courier* July/August 2017 p25).

In contrast, niobium–copper cavities suffered from a problem that had been present since the start: at high accelerating fields, the cavity Q value decreased faster than it did in the case of bulk niobium. This phenomenon is still not fully explained today. During and after the LEP era, a great deal of research was carried out at CERN on 1.5 GHz niobium–copper cavities to tackle the issue. Despite significant progress in understanding and remarkable cavity results, the gap in performance compared with bulk niobium was not bridged. This prevented niobium-coated copper cavities from being considered for the high-energy linear colliders under study at the time – namely TESLA, the technology of which has since morphed into that underpinning the European XFEL and the International Linear Collider proposal (*CERN Courier* September 2017 p27).

At medium accelerating fields, like those required for circular hadron machines and many other applications, the drop in Q was not a showstopper. For the LHC, the niobium–copper technology was applied to build the 16 single-cell 400.8 MHz elliptical cavities required in the machine's accelerating sections. The LHC cavities, like their LEP ancestors, also work at a temperature of 4.5 K – the cryogenics for which is cheaper and more robust than that used for bulk niobium devices.

CERN invested in rebuilding its SRF infrastructure and expertise.

In the 1990s, niobium–copper cavities of another shape, adapted for heavy-ion acceleration, were employed for the ALPI linac in INFN Legnaro, Italy. Here, Vincenzo Palmieri and collaborators developed niobium-sputtered quarter-wave resonators (QWRs) on copper substrates. A total of 58 niobium–copper cavities are operational today in ALPI, replacing old lead-plated cavities and considerably extending the energy reach of the machine.

Revival at ISOLDE

During the construction of the LHC in the early 2000s, the SRF activities and infrastructures at CERN were down-sized as resources were focused on the production of the LHC's superconducting magnets. However, the need for a new SRF system came back in a CERN project in 2009, when a proposal was approved for a high-energy upgrade of the ISOLDE facility using a superconducting linac booster for the radioactive ion beams. For this application, niobium–copper technology was considered particularly well suited because the absence of beam loading allows the stiff, niobium-coated copper cavities to be operated at very narrow RF bandwidths, leading to significant savings in installed RF power. To support the high-energy HIE-ISOLDE upgrade, CERN invested in rebuilding its SRF infrastructure and expertise.

Today, thanks to the collective effort of several CERN teams, the high-beta section of the HIE-ISOLDE linac is complete (figure 3). The work for HIE ISOLDE also offered an opportunity to advance understanding of the limitations to niobium–copper cavity performance. One particular issue was the frequent appearance of defects on the copper substrate, especially close to the electron-beam weld. To overcome this problem, towards the end of the production, a new design for the RF cavity was proposed, which made possible machining the whole resonator out of a copper billet and thus avoided any weld (figure 1). The results of the change were very encouraging.

The first two cavities, manufactured with this technique in industry and coated at CERN, were tested at the end of 2017. Their RF performance scored top of a series of 20 units. Even more strikingly, when cooled down close to superfluid helium temperatures with active shielding of the ambient field, a cavity reached unprecedented peak fields for niobium–copper technology (figure 4). Incredibly, the RF performance of this cavity is comparable to bulk niobium cavities with the same shape, at least as far as the Q-slope is concerned. This result is now the basis of exploring new possible applications, notably for the acceleration of higher-beta beams like those required in spallation sources for accelerator-driven systems.

At about the same time, another excellent result was achieved in the context of the LHC spare-cavities programme. Newly coated cavities are giving results that lie on an upward learning curve, and have already surpassed the LHC specifications. Achieving such good RF performances is only possible if high quality standards are maintained along the whole production chain, from manufacturing of the copper substrate, to chemical polishing, ultra-pure water rinsing, cleanroom assembly and coating, to the final RF test at cryogenic temperatures. This requires a close collaboration of various teams of specialists, and CERN is an ideal place for that.

These two recent achievements are proof that the potential of niobium–copper technology is not exhausted, and that these cavities could be as high performing as their bulk niobium counterparts. Indeed, this technology is already being considered within the Future Circular Collider study, led by CERN to explore the feasibility of a 100 km-circumference machine. Clearly, the long march of niobium on copper is far from over.

Fig. 2. The first prototype niobium–copper superconducting cavity, pictured in December 1983 with Nadia Circelli, Cristoforo Benvenuti, Jacques Genest and Max Hauer.

Fig. 3. The HIE-ISOLDE linac, which was completed this year and comprises 20 niobium–copper sputtered cavities hosted in four cryomodules operating at 101.28 MHz and 4.5 K.

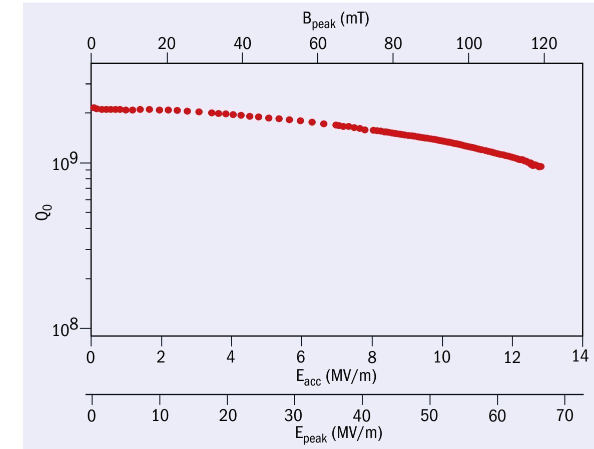


Fig. 4. Quality factor versus energy for a seamless niobium-coated copper QWR cavity, showing outstanding RF performance.

Further reading

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Résumé

Niobium et cuivre : le retour

Les cavités supraconductrices constituées de cuivre à revêtement niobium, qui étaient autrefois le nec plus ultra de la technologie des cavités radiofréquence au CERN, font un retour remarqué. Les évolutions observées au CERN ces dernières années font apparaître que le potentiel de la technologie niobium-cuivre est loin d'être épuisé, et que ces cavités pourraient être tout aussi performantes que les cavités en niobium massif. Cette technologie a déjà été installée dans la version à haute énergie d'ISOLDE. Elle est envisagée dans le cadre de l'étude sur un futur collisionneur circulaire, et pourrait avoir d'autres applications, notamment les sources de spallation pour les systèmes entraînés par accélérateur.

Walter Venturini Delsolaro, **Guillaume Rosaz** and **Alban Sublet**, CERN.

TRIUMF's staff posing on the cyclotron magnet in 1972.

All image credits: TRIUMF

Tales of TRIUMF

Founded 50 years ago to meet research needs that no single university could provide, Canada's premier accelerator laboratory continues to drive discoveries.

The TRIUMF laboratory's 50-year legacy is imprinted on its 13-acre campus in Vancouver; decades-old buildings of cinder-block and corrugated steel sit alongside new facilities housing state-of-the-art equipment. With each new facility, the lab continues its half-century journey from a regional tri-university meson facility (from where the acronym TRIUMF comes) to a national and international hub for science.

At the laboratory's centre is the original 520 MeV cyclotron, a negative-hydrogen-ion accelerator so well engineered when it was first built that it continues to function (albeit with updated controls and electronics) as TRIUMF's heart. Over the past 50 years, the TRIUMF cyclotron has spurred the growth of a diverse and multidisciplinary community whose ideas continue to coax new uses from the decades-old accelerator. These new applications serve to continuously redefine TRIUMF as an institution: a superconducting linear accelerator that complements the original cyclotron; 17 universities and counting that have joined the original trio; and an expanding network of collaborators that now spans the globe.

TRIUMF, which began with a daring idea and a simple patch of rainforest on the University of British Columbia's (UBC) south campus, is this year reflecting on its rich past, its vibrant present and the promise of a bright future.

The tri-university meson facility

The first inklings for the tri-university meson facility were themselves a product of three separate elements: a trio of Canadian universities, a novel accelerator concept and an appetite for collaboration within the field of nuclear physics in the early 1960s. And the researchers involved were well positioned to develop such a proposal. John Warren, at that time head of the nuclear-physics group at UBC, had established a team of remarkable graduate students while constructing a 3 MeV Van de Graaff accelerator. Erich Vogt had just transitioned to the UBC physics faculty from an illustrious career as a theoretical nuclear physicist at the Chalk River Laboratory in Ontario. And finally, J Reginald Richardson, a Canadian-born physicist at the University of California in Los Angeles (UCLA), who had finalised a concept for a sector-focused, spiral-ridge negative-hydrogen-ion cyclotron – many of the ideas for which came while holidaying at his cottage on Galiano Island on the West Coast of British Columbia. In the years that followed, all three of them would go on to become a director of TRIUMF.

At the time, the world was ready to dig deeper into nuclear structure and explore other hadronic mysteries using powerful meson beams. This push for "meson factories" led to LAMPF in the US, SIN (now PSI) in Switzerland and, eventually, TRIUMF in Vancouver.

In 1964, a young physicist named Michael Craddock (who would become a long-time *CERN Courier* contributor) completed his PhD in nuclear physics at the University of Oxford in the UK before joining the UBC physics faculty. In June 1965, Craddock attended a meeting between representatives of UBC, the University of Victoria and Simon Fraser University, and wrote a summary of the proceedings: an agreement to develop a proposal for a tri-university meson facility based on the Richardson negative-hydrogen-ion cyclotron. Not three years later, in April 1968, the group received $19 million CDN in federal funding and construction began.

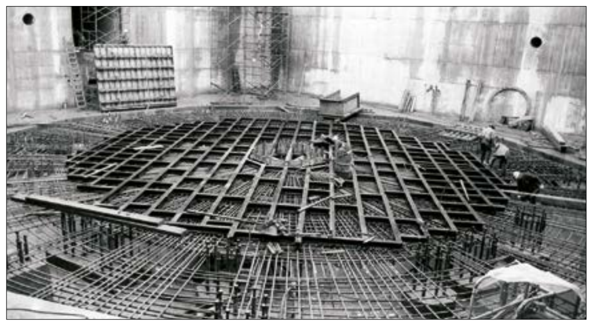
Warren presided as TRIUMF's first director, and many of the accelerator's build team came from his Van de Graaff graduate students. The initial organisation consisted of a university faculty member directing the engineers and consultants responsible for each of the main components of the cyclotron: its ion source, radio-frequency, magnet and vacuum systems. Joop Burgerjon, the engineer for the construction of the 50 MeV negative-hydrogen-ion cyclotron at the University of Manitoba, which was itself a copy of the 50 MeV UCLA cyclotron, became the chief engineer for TRIUMF.

Ewart Blackmore (one of this article's authors) was one of Warren's graduate students who was brought back to work on the accelerator design and construction. In 1968, while working as a postdoctoral fellow at what is now the Rutherford Appleton Laboratory, in the UK, Blackmore and another postdoctoral fellow, David Axen (also a former UBC graduate student) received a call to coordinate an experiment to measure the dissociation rate of negative hydrogen ions in a magnetic field. This is an important parameter for setting the maximum magnetic field of the cyclotron. The measurement used the proton linear accelerator at the Rutherford laboratory and resulted in a higher dissociation rate than expected from earlier experiments, increasing the size of the cyclotron by 4%.

Upon his return to Vancouver, Blackmore shouldered the responsibility for the cyclotron's injection, beam diagnostics and extraction systems. All of these components and more were put to the test with a full-scale model of the cyclotron's centre core, which achieved first beam in 1972. Finally, despite a six-month delay to reshape the magnetic field produced by the 4000 tonne magnet, the TRIUMF team of about 160 physicists, engineers and technical staff coaxed a beam of protons from the cyclotron on 15 December 1974. TRIUMF's scientific programme began the following year with an initial complement of experimental beamlines: proton, neutron, pion and muon. In the end, the project was on budget and very near the original schedule. The machine reached its design current of 100 μA in 1977, with Blackmore coordinating the first five years of commissioning and operations. He recalls that it was a remarkable experience to witness the moment first beam was achieved from the cyclotron. "At the start of it all, most of us had little understanding of cyclotrons and related technologies, but we had the valuable experience we had gained as graduate students."

ARIEL will triple the output of the rare-isotope programme.

Site group, before the construction of the cyclotron.



Building the cyclotron.

International physics hub

The story of TRIUMF quickly developed, the lab reinventing itself time and again to keep up with the fast pace at which the field was evolving. By the early 1980s, TRIUMF was a well-established accelerator laboratory that operated the world's largest cyclotron. In those days, TRIUMF utilised proton and neutron beams to drive a powerful research programme in nucleon–nucleon/nucleus interaction studies, muon beams for muon-spin-rotation experiments in material sciences, pion beams for nuclear-structure studies, and meson beams for precision electroweak experiments.

However, as the field advanced, new discoveries in meson science were changing the landscape. TRIUMF responded by proposing an even-larger accelerator system, the 30 GeV KAON (Kaons, Antiprotons, Other hadrons and Neutrinos) complex. When fully complete, KAON would have allowed cutting-edge high-energy-physics experiments at the intensity frontier. It was a bold proposal that garnered substantial national and international interest but ultimately did not find enough political support to be funded. Nevertheless, the concept itself was considered visionary, and the science that TRIUMF wanted to enact was taken up decades later in modified forms at the J-PARC complex in Japan and the upcoming FAIR facility in Germany (*CERN Courier* July/August 2017 p41).

J Reginald Richardson tuning up the cyclotron to 500 MeV for the first time in 1974.

TRIUMF's control room today.

The loss of KAON forced an existential crisis on TRIUMF, and the laboratory responded in two parallel directions. Firstly, TRIUMF expanded Canada's contributions to international physics collaborations. During the decade-long campaign to design KAON, TRIUMF had developed an impressive array of scientific and engineering talent and capabilities in the design of accelerators, production targets and detectors. This enabled the Canadian physics community – supported by TRIUMF – to contribute to CERN's Large Hadron Collider (LHC) and join the ATLAS collaboration, building components such as the warm twin-aperture quadrupoles for the LHC and the hadronic endcap calorimeter for ATLAS. This positioned TRIUMF as Canada's gateway to international subatomic physics and paved the way for Canada's contributions to other major physics collaborations like T2K in Japan.

The laboratory's second response to the loss of KAON was the development at TRIUMF of a new scientific programme centred on rare isotopes. By the 1980s, the field of rare isotopes had become of burgeoning interest, opening new avenues of research for TRIUMF into nuclear astrophysics, fundamental nuclear physics and low-energy precision probes of subatomic symmetries. TRIUMF had recognised the worldwide shortage of isotope production facilities and understood the role it could play in rectifying the situation. The lab already possessed expertise in beam and target physics, design and engineering — and, since its inception, a high-powered 520 MeV cyclotron that could act as a beam driver for producing exotic isotopes.

Rare-isotope beams at TRIUMF started during the KAON era with the small TISOL (Test facility of Isotope Separation On-Line) project in 1987, which used an isotope-separation concept developed at CERN's ISOLDE facility. Experience at TISOL gave its proponents confidence that a much-larger-scale rare-isotope-beams facility could be built at TRIUMF. And so the Isotope Separator and Accelerator (ISAC) era was born at TRIUMF. Today, TRIUMF's ISAC boasts the highest production power of any ISOL-type facility and some of the highest rates of rare-isotope production in the world. ISAC enables TRIUMF to produce isotopes for a variety of research areas, including studies of the formation of the heavy chemical elements in the universe, exploration of phenomena beyond the Standard Model of particle physics and inquiry into the deepest secrets of the atomic nucleus. In addition, spin-polarised beta-emitting isotopes produced at TRIUMF make possible detailed probes for surface and interface studies in complex quantum materials or novel batteries, benefiting the molecular- and materials-science communities.

TRIUMF is continuing to build on its expertise and capabilities in isotope science by adding new rare-isotope production facilities to supply the laboratory's existing experimental stations. A new project, ARIEL (the Advanced Rare Isotope Laboratory), will add two rare-isotope production stations driven by a new proton beamline from the cyclotron and a new electron beamline from a new superconducting linear accelerator (designed and built in Canada). ARIEL will triple the output of the science programme based on rare-isotope beams, creating new opportunities for innovation and allowing the lab to branch off into promising new areas, even outside of subatomic physics, materials science and nuclear astrophysics. Although ARIEL's completion date is set for 2023, the facility's multi-stage installation will allow the TRIUMF community to begin scientific operations as early as 2019.

An innovation lab

TRIUMF's history is defined not only by a drive to push the frontiers of science and discovery, but also those of innovation. The flexibility of the iconic cyclotron at the heart of TRIUMF's scientific programme has allowed the lab to venture into areas that few could have imagined at the time of its original proposal. Standing on the shoulders of its founders, TRIUMF's community now turns to the next half-century and beyond, and asks: how can TRIUMF increase its impact on our everyday lives?

While fundamental research remains core to TRIUMF's mission, the laboratory has long appreciated the necessity and opportunity for translating its technologies to the benefit of society. TRIUMF Innovations, the lab's commercialisation arm, actively targets and develops new opportunities for collaboration and company creation surrounding the physics-based technologies that emerge from the TRIUMF network.

Perhaps the most long-standing of these collaborations is TRIUMF's more than 30-year partnership with the global health-science company Nordion. A team of TRIUMF scientists, engineers and technicians works with Nordion to operate TRIUMF cyclotrons to produce commercial medical isotopes that are used in diagnosing cancer and cardiac conditions. During the course of this partnership, more than 50 million patient doses of medical isotopes have been produced at TRIUMF and delivered to patients around the world.

Another outcome of TRIUMF Innovations is ARTMS Products

Facilities

ARIEL, the Advanced Rare Isotope Laboratory.

TRIUMF's staff at the time of the visit of Canada's governor general in March 2018.

Inc, which produces cyclotron-target technology enabling cleaner and greener manufacturing of medical isotopes within local hospitals. ARTMS has already secured venture-capital funding and multiple successful installations are under way around the world. Its technology for producing the most commonly used medical isotope, technetium-99, will help stabilise the global isotope supply chain in the wake of the shutdown of the Chalk River reactor facility.

TRIUMF Innovations will play a key role in fostering industry relationships enabled by the future Institute for Advanced Medical Isotopes (IAMI), a critical piece of infrastructure that will advance nuclear medicine in Canada. Supported by TRIUMF's life sciences division, IAMI will provide infrastructure and expertise towards developing new diagnostics and radiotherapies. IAMI will also provide industry partners with facilities to study and test new isotopes and radiopharmaceuticals that hold great promise for improving the health of patients in Canada and around the world.

Similarly, TRIUMF and TRIUMF Innovations are also working to support the emerging field of targeted alpha-emitting therapeutics — radiotherapy medicines that hold new promise for patients who have been diagnosed with advanced and life-threatening metastasised cancers. Multiple new companies are currently developing novel treatments, but all are hampered by a global shortage of actinium-225 (^{225}Ac), a hard-to-produce isotope at the core of many of these therapies. The TRIUMF cyclotron is unmatched in ^{225}Ac production capacity, and the laboratory is working with researchers and industry partners to bring this production online and to speed up the development of new therapies with the potential to offer new hope to patients with cancers that are currently deemed incurable.

Beyond these developments, TRIUMF Innovations manages a portfolio of TRIUMF products and services that range from providing irradiation services for stress-testing communications and aerospace technologies to improving the efficacy and safety of mining exploration using muon detectors to help geologists estimate the size and location of ore deposits.

In the coming years, TRIUMF Innovations will continue to advance commercialisation both within TRIUMF and through TRIUMF's networks. For example, TRIUMF is now seeking to develop a new data-science hub to connect its 20 member universities and global research partners to private-sector training opportunities and new quantum-computing tools. Drawing on data-science acumen developed through the ATLAS collaboration, TRIUMF is building industry partnerships that train academic researchers to use their data-science skills in the private sector and connect them with new research and career opportunities.

It is clear that TRIUMF's sustained focus on commercialisation and collaboration will ensure that the lab continues to bring the benefits of accelerator-based science into society and to pursue world-leading science with impact.

The quest continues

Fifty years in, TRIUMF's narrative is a continuous work in progress, a story unfolding beneath the mossy boughs of the same fir and alder trees that looked down on the first shovel strike, the first sheet of concrete, the first summer barbecue. In the coming years, the lab will continue to welcome fresh faces, to upgrade and add new facilities, to broach new frontiers, and to confront new challenges. It is difficult to predict exactly where the next era of TRIUMF will lead, but if there is one thing we can be sure of, it is that TRIUMF's community of discoverers and innovators will be exploring ideas and seeking out new frontiers for years to come.

• Further reading

TRIUMF50.com.

Résumé

Les succès de TRIUMF

Fondé il y a 50 ans pour répondre à des besoins de recherche dépassant les possibilités d'une seule université, TRIUMF, le plus important des laboratoires d'accélérateurs au Canada, continue à produire des découvertes dans les domaines de la physique fondamentale, de la médecine nucléaire et de la science des matériaux. Son cyclotron de 520 MeV, présent depuis les origines, reste au cœur des activités du laboratoire, qui a permis le développement d'une communauté scientifique diverse et multidisciplinaire. Aujourd'hui, 17 universités participent à TRIUMF, constituant un réseau dynamique et mondial de collaborateurs, dont beaucoup travaillent avec des expériences du CERN.

Stuart Shepherd, **Ewart Blackmore**, **Jens Dilling** and **Kathryn Hayashi**, TRIUMF

Faces & Places

APPOINTMENTS

New leader at Fermilab's next accelerator

On 1 March, accelerator physicist Lia Merminga was appointed project director for Fermilab's PIP II (Proton Improvement Plan II) and its new superconducting linear accelerator. Along with improvements to Fermilab's Main Injector and Recycler accelerators, PIP II will provide high-intensity proton beams for future experiments including the flagship Long-Baseline Neutrino Facility and the Deep Underground Neutrino Experiment. The new 800 MeV machine will double the energy of the existing linac at Fermilab and is the first particle accelerator to be built in the US with significant contributions from international partners. Merminga, previously associate laboratory director for accelerators at SLAC National Accelerator Laboratory, succeeds Fermilab's Stephen Holmes. She has more than 25 years' experience in accelerator and superconducting radio-frequency technology, and served as director of the Center for Advanced Studies of Accelerators at Jefferson Lab and as head of the accelerator division at Canada's TRIUMF laboratory.

FNAL

Lia Merminga will lead the superconducting linac PIP II, serving neutrino experiments.

Change of chairs for antimatter community

Experimentalists Stefan Ulmer of RIKEN and Chloé Malbrunot of CERN have been elected chairperson and deputy chairperson, respectively, of the Antiproton Decelerator (AD) user community. The roles involve representing the interests of the antimatter community to CERN management, requiring regular contact with the spokespersons of approved AD experiments and organising beam time. The AD is a unique global research facility hosting the AEgIS, ALPHA, ASACUSA, ATRAP, BASE and GBAR experiments. Ulmer is founder and spokesperson of the BASE collaboration, while Malbrunot is involved with ASACUSA and AEgIS. For the past 17 years the AD user community has been represented by Walter Oelert and, since 2012, Horst Breuker.

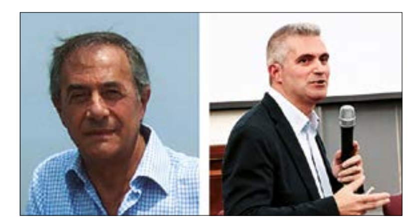
M Brice/CERN

Left to right: Walter Oelert, Chloé Malbrunot, Stefan Ulmer and Horst Breuker.

AWARDS

Pontecorvo award to Fogli and Lisi

The 2017 Bruno Pontecorvo Prize, which is given by the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, has been awarded to Gianluigi Fogli and Eligio Lisi of the University of Bari and INFN in Italy for their pioneering contributions to the development of the global analysis of neutrino oscillation data from different experiments. The announcement followed the approval of an international jury's recommendations by the JINR scientific council at its 123rd session on 22–23 February.



Gianluigi Fogli (left) and Eligio Lisi.

The work of Fogli, Lisi and the Bari neutrino group on the theory and phenomenology of neutrino and astroparticle physics has led to a detailed understanding of oscillation searches with solar, atmospheric, accelerator and reactor neutrinos, and of their interplay with non-oscillatory searches. The two laureates will report on their achievements at an awards ceremony at the next session of the JINR council on 20–21 September. The Pontecorvo Prize was established in 1995 to commemorate Bruno Pontecorvo, once Enrico Fermi's collaborator and often deemed the father of neutrino physics.

Gold medal for extreme nuclei

The 2017 Lomonosov Gold Medal, the highest accolade of the Russian Academy of Sciences, has been awarded to Yuri Oganessian of the Joint Institute for Nuclear Research (JINR) in Russia and Björn Jonson of Chalmers University of Technology in Sweden. The pair has extended our knowledge on nuclei at the extremes of existence in opposite ends of the nuclear chart. Oganessian has made fundamental contributions to the study of superheavy elements, also acknowledged in 2016 when element 118 was named Oganesson (Og), while Jonson, who has also played key roles in CERN's ISOLDE facility, has focused on the nuclear structure and stability at the boundaries of the nuclear chart for the lightest elements. The award ceremony took place in Moscow on 30 March.

E Puzynina/JINR

Björn Jonson (left) and Yuri Oganessian have extended the boundaries of the nuclear chart.

Winners of the 2018 Collide awards revealed

Arts at CERN, a project started in 2001, allows artists from all over the world to spend time at CERN and work alongside particle physicists and engineers. On 22 March the winners of the 2018 Collide International and Collide Geneva awards, organised in collaboration with Arts at CERN, were announced. London-based Polish artist Suzanne Treister won the Collide International award, a three-month artist residency in collaboration with the Foundation for Art and Creative Technology in the UK that will begin in May.


A Henchoz and J Lang

A previous work titled Archipelago and Tempo *by Collide Geneva winners Sylvie Henchoz and Julie Lang.*

Her investigation, titled *Holographic Universe*, aims to "explore the artists' motivations and intentions through the history of art, from cave painting to modernism and global contemporary art". The Collide Geneva award, a partnership between Arts at CERN and local authorities, was won by Anne Sylvie Henchoz and Julie Lang. The pair will spend three months at CERN during the autumn, further developing their project *Space Time Energy*, exploring potential analogies between the human body and particles.

Meetings

Defining technology for tomorrow's experiments

The scale and technological sophistication of the detectors at the LHC experiments is almost incomprehensible. In addition to several subdetector systems, they contain millions of detecting elements and support a research programme for an international community of thousands of scientists. The volume of data that will be produced during the high-luminosity upgrade of the LHC (HL-LHC) and by future colliders calls for even more sophisticated technologies.

In November 2017, CERN launched a process to define its R&D programme on new experiment technologies from 2020 onwards. The programme covers detector upgrades beyond the HL-LHC phase and includes concepts developed for the Compact Linear Collider (CLIC) and the Future Circular Collider (FCC) study. The first workshop took place at CERN on 16 March and more than 450 physicists and engineers took part.


A Ricci

The CERN workshop discussed new experimental technologies for the 2020s.

Beyond the HL-LHC, explained organiser Christian Joram, the landscape of experiments is only vaguely defined and may evolve in different directions. Therefore, the aim is to launch an R&D programme that concentrates on advancing key technologies rather than developing specialised applications.

It has been shown before that developments in detectors for high-energy physics also benefit many other sectors, from healthcare and medical imaging to industry and quality monitoring. As noted by workshop co-organiser and head of CERN's experimental physics department Manfred Krammer, it is timely to think how industry can be involved in joint R&D efforts.

Detector improvements envisioned for the 2020s and beyond include better electronic readout, modelling and simulation tools, and better computational techniques for reconstructing the recorded information. Increased timing accuracy to mitigate event pile-up in very high-luminosity environments will almost certainly impact the development of all classes of detectors, whether silicon, gas or photodetectors. The challenges of the HL-LHC and future colliders also places tough requirements on readout electronics and fast data links, while advances in data processing and storage are equally important.

Participants also discussed the special facilities and infrastructures needed to test chips under realistic conditions – presenting an impressive number of options on advanced materials, design tools and production technologies, which could change the way we build detectors and boost their performance. R&D into magnet design for future colliders also demands progress in superconducting materials and cables to meet strict strength and cost requirements.

The talks at the March workshop covered a variety of topics reflecting CERN's diversity and strong collaboration with commercial and academic partners worldwide. They demonstrated that new concepts, manufacturing tools and materials, combined with the development of simulation tools and software, can open a new era in detector technologies.

A second workshop will take place this autumn to review progress.

● *Panos Charitos, CERN.*

Standard Model gets annual check up at Moriond

The 2018 Moriond sessions took place in La Thuile, Italy, from 10 to 24 March. The annual conference is an opportunity to review the progress taking place over the breadth of particle physics, from B physics to gravitational waves and from advances in electroweak precision tests to exploratory searches for dark matter. The quest for new particles covers an impressive 40 orders of magnitude, from the 10^{-22} eV region explored via neutron-spin precession to the 13 TeV energy of the LHC and the highest-energy phenomena in cosmic rays.


V Varanda

Participants during a talk at the 2018 Moriond conference in Italy.

Anomalies in the decays of beauty quarks found by the LHCb and B-factory experiments continue to entice theorists to look for explanations for these possible hints of lepton non-universalities, and experimental updates are eagerly awaited (*CERN Courier* April 2018 p23). Progress continues in the field of CP violation in B and D mesons, while quantitative tests of the CKM matrix are being helped by precise calculations in lattice QCD. Progress on leptonic and semi-leptonic D-meson decays was reported from BES-III, while Belle showed hints of the decay $B^+ \to \mu^+ \nu$ and evidence of isospin violation. In the classic field of rare kaon decays, the CERN SPS experiment NA62 showed its first results, presenting one candidate event for the elusive decay $K^+ \to \pi^+ \nu \bar{\nu}$ obtained using a novel in-flight technique (see p7).

Fundamental parameters of the Standard Model (SM), such as the masses of the top quark and W boson, are being measured with increasing precision. The SM is in very good shape, apart from the long-standing exception of forward–backward asymmetries. These asymmetries are also being studied at the LHC, and precise results continue to be produced at the Tevatron.

Results on top-quark production and properties are constantly being improved, while hadron spectroscopy is as lively as ever, both in the light meson sector (BESIII) and in heavy quarks (BaBar, Belle and LHCb). Data from HERA are still providing new inputs into structure functions, with c and b quarks now being included. Heavy-ion collisions at LHC and RHIC continue to explore the behaviour of the hot, dense quark–gluon plasma, while proton–ion collisions at fixed-target experiments (LHCb) provide useful inputs to constrain Monte Carlo event generators.

The news on the Brout–Englert–Higgs mechanism is good, with progress on many fronts. The amount of new results presented by ATLAS and CMS, including evidence of ttH production, and global combinations of production and decay channels shows that the precision on the couplings between the Higgs and other particles is improving fast. The study of rare decays of the Higgs boson is advancing rapidly, with the $H \to \mu^+\mu^-$ decay within reach.

The search for heavy resonances is continuing at full speed, with CMS presenting one Z' analysis employing the full, available LHC data set (77.3 fb^{-1}), including 2017 data. Is supersymmetry hiding somewhere? Several analyses at ATLAS and CMS are now being recast to include more elusive signatures with various amounts of R-parity violation and degenerate spectra, and there is an emerging interest in performing searches beyond narrow-width approximations.

The search for dark matter is on, with WIMP direct searches maturing rapidly (XENON1T) and including novel experiments like DARKSIDE which, with just 20 l of very pure liquid argon, presented a new best limit at low masses. This field shows that, with ingenuity, there is still room to have an impact. Bounds on extremely light axion-like particles were presented by ADMX for QCD axions, and for neutron electric dipole moments. The interplay between these dedicated experiments and the search for directly produced dark matter at the LHC are highly complementary.

The field of neutrinos continues to offer steady progress with new and old puzzles being addressed. The latest results from T2K disfavour CP-conservation at the level of two sigma, while NOvA disfavours the inverted hierarchy at a similar level. A revival of decay-at-rest techniques and the measurement of coherent elastic neutrino–nucleus scattering by COHERENT (*CERN Courier* October 2017 p8) were noticeable. The search for heavy neutral leptons is taking place at both fixed-target and collider experiments, while reactor experiments (like DAYA BAY and STEREO) are meant to clarify the reactor antineutrino anomaly. The puzzle of sterile neutrinos is not yet completely clarified after 20 years. Deep-sea (ANTARES) and South Pole (IceCube) experiments are now mature, with ANTARES showing, among other things, searches for point-like sources. IceCube presented a brand new analysis looking for tau-neutrino appearance that is competitive with existing results. Neutrinoless double-beta decay experiments are now biting into the sensitivity of the inverted mass hierarchy (CUORE and EXO-200), with promising developments in the pipeline (CUPID).

Completing the programme of the electroweak session was a glimpse into the physics of cosmic rays and gravitation. The sensitivity of AUGER is now such that mapping the origin of the cosmic rays on the sky becomes feasible. With the observation of a binary neutron-star collapse by LIGO and VIRGO, 2017 saw the birth of multi-messenger astronomy.

On the theory side, one continues to learn from the abundance of experimental results, and there is still so much to be learned by the study of the Higgs and further high-energy exploration. SM computations are breaking records in terms of the numbers of loops and legs involved. Electroweak and flavour physics can indicate the way to new physics scales and extend the motivation to search for dark matter at very low energies. The case to study neutrinos remains as compelling as ever, with many outstanding questions still waiting for answers.

● *Augusto Ceccucci, CERN.*

Industry rises to FCC conductor challenge

A Koufidou

The first Future Circular Collider conductor-development workshop at CERN in March.

Superconductivity underpins large particle accelerators such as the LHC. It is also a key enabling technology for a future circular proton–proton collider reaching energies of 100 TeV, as is currently being explored by the Future Circular Collider (FCC) study. To address the considerable challenges of this project, a conductor development workshop was held at CERN on 5 and 6 March to create momentum for the FCC study and bring together industrial and academic partners.

The alloy niobium tin is the most successful practical superconductor to date, and has been used in all superconducting particle accelerators and detectors. But the higher magnetic fields required for the high-luminosity LHC (11 T) and FCC (16 T) call for new materials. A potential superconducting technology suitable for accelerator magnets beyond fields of 10 T is the compound niobium tin (Nb_3Sn), which is the workhorse of the 16 T magnet-development programme at CERN.

The FCC conductor programme aims to develop Nb_3Sn multi-filamentary wires with a critical current-density performance of at least 1500 A/mm^2 at 16 T and at a temperature of 4.2 K. This is 30 to 50% higher than the conductor for the HL-LHC, and a significant R&D effort – including fundamental research on superconductors – is needed to meet the magnet requirements of future higher-energy accelerators. The FCC magnets will also require thousands of tonnes of superconductor, calling for a wire design suitable for industrial-scale production at a considerably lower cost than current high-field conductors.

CERN is engaged in collaborative conductor development activities with a number of industrial and academic partners to achieve these challenging targets, and the initial phase of the programme will last for four years. Representatives from five research institutes and seven companies from the US, Japan, Korea, Russia, China and Europe attended the March meeting to discuss progress and opportunities. Firms already producing Nb_3Sn superconducting wire for the FCC programme are Kiswire Advanced Technology (KAT); the TVEL Fuel Company working with the Bochvar Institute (JSC VNIINM); and, from Japan, Furukawa Electric and Japan Superconductor Technology (JASTEC), both coordinated by the KEK laboratory. Columbus Superconductor SpA is participating in the programme for other superconducting materials, while two additional companies – Luvata and Western Superconducting Technologies (WST) – expressed their interest in the CERN conductor programme and attended the workshop.

The early involvement of industry is crucial and the event provided an environment in which industrial partners were free to discuss their proposed technical solutions openly. In the past, most companies produced a bronze-route Nb_3Sn superconductor, which has no potential to reach the target for FCC. Thanks to their commitment to the programme, and with CERN's support, companies are now investing in a transition to internal tin processes. Innovative approaches for characterising superconducting wires are also coming out of academia. Developments include the correlation of microstructures, compositional variations and superconducting properties at TU Wien, research into promising internal-oxidation routes at the University of Geneva, phase transformation studies at TU Bergakademie Freiberg and research of novel superconductors for high-fields at SPIN in Genova.

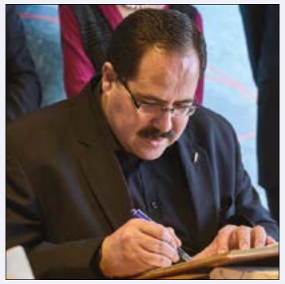
The FCC initiative is similar to the process that took place during the R&D period for niobium titanium for the LHC. Participants agreed that this could result in a new class of high-performance Nb_3Sn material suitable not only for accelerator magnets, but also for other large-scale applications such as high-field NMR and laboratory solenoids.

● *Panos Charitos, CERN.*

J Ordan/CERN

On 27 March, seven L'Oréal-UNESCO For Women in Science "international rising talents" visited CERN, following the 20th edition of the international award at a ceremony in Paris. Left to right: Selene Lizbeth Fernandez Valverde from Mexico; Areej Abuhammad from Jordan; Anna Kudryavtseva from Russia; CERN Director-General Fabiola Gianotti; Ibtissem Guefrachi from Tunisia; Yukiko Ogawa from Japan; Danielle Twilley from South Africa; and Hiep Nguyen from Vietnam.

Visits



J Ordan/CERN

Sabri Saidam, minister of education and higher education, Palestine, came to CERN on 21 March. He toured the ATLAS visitor centre and CERN Data Centre.

J Ordan/CERN

Olga Nachtmannová, state secretary for Slovakia's ministry of education, science, research and sport, came to CERN on 22 and 23 March. She visited ALICE and met with the CERN-Slovak community.

Training tomorrow's accelerator scientists

More than 100 people attended an event organised by the European Scientific Institute (ESI), Archamps, on 15 February to mark the 25th anniversary of the Joint Universities Accelerator School (JUAS) and the fifth anniversary of its sister school, the European School of Instrumentation in Particle and Astroparticle Physics (ESIPAP). Among them were current and former students of both schools, as well as PhD and technical students from CERN who had participated in JUAS or ESIPAP in recent years.

ESI-Archamps

Frédérick Bordry, CERN director of accelerators and technology, marking the 25th edition of JUAS at ESI in February.

Overall, more than 1000 physicists and engineers have been trained at JUAS since it was founded. ESI president, Hans Hoffmann, stressed the need for international and interdisciplinary collaboration in order to tackle major societal challenges, and explained how this goal drives the ESI's thematic schools. Philippe Lebrun, former head of accelerator technologies at CERN and JUAS director since 2017, reiterated that JUAS exists to teach "the science and technology of accelerators, which are specific domains of physics and engineering in their own right, along with their latest developments, to the designers, builders and operators of tomorrow's machines".

These thoughts were echoed by ESIPAP director and a long-standing member of the ATLAS collaboration, Johann Collot. Citing the unprecedented international effort under way to reconcile microscopic physics and modern astronomy, he told students they were lucky to be able to focus their imaginations on such a noble task, "which stems from experimentation and whose conclusion will be revealed through experimentation". In concluding remarks, CERN director of accelerators and technology, Frédérick Bordry, affirmed the importance of JUAS and ESIPAP in preparing the next generation of particle-accelerator and detector scientists, and assured ESI of CERN's ongoing support.

Recruitment is already underway for the next editions of JUAS and ESIPAP, which will be held at ESI from January to March 2019. Both schools propose an innovative pedagogical approach, with an intensive mix of lectures, tutorials, seminars, group workshops, laboratory visits and practical sessions. They also include practical sessions at CERN and other internationally renowned facilities, such as the European Synchrotron Radiation Facility in Grenoble and Switzerland's Paul Scherrer Institut. Find out more at: esi-archamps.eu.

● *Bob Holland, ESI.*

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OBITUARIES

Jon Peter Berge 1935–2017

Jon Peter Berge, known as Peter to his friends and family, passed away on 14 November. He was born in Madison, Wisconsin, to Norwegian immigrant parents and his early years were marked by the Great Depression and World War II, which forced his family to move frequently. He went on to attend the University of California, Berkeley, where he obtained his BA in physics (1956), MA (1958) and his PhD (1964).

At Berkeley, he joined the group under Nobel Prize winner Luis Alvarez at the Lawrence Radiation Laboratory, where he participated on the development of the bubble chamber. While working there, he met his future wife, Louise Holstein. In 1967, Peter obtained a postdoctoral award to work with John Mulvey in Oxford, and three years later he accepted a position at CERN.

Peter Berge was a member of the CDF experiment at Fermilab.

In 1974 he took up a permanent position at Fermilab, where he worked on the CDF experiment. He was highly regarded for his skill in writing software used to control high-energy physics experiments, including that which led to the discovery of the top quark in 1995. He remained at the lab until his retirement in 2000.

Peter was an active fencer and competed in tournaments until the mid-1970s. He appreciated chess, good wine, fine dining, classical music and history. He was an astounding writer of endless postcards, including (post-office permitting) beer coasters. He had many lifelong friends and was known as a generous host.

● *His friends and colleagues.*

Daniel Boussard 1937–2018

The world of radio-frequency (RF) technology lost an outstanding inventor and leader when Daniel Boussard passed away on 6 January. Daniel made vast contributions to the design of RF systems for accelerating and controlling particle beams. He furthered our understanding in particle-beam dynamics and in the intricacies of controlling high-intensity beams. He was a technical innovator across low- and high-power electronics, right through to the sophisticated RF cavities required in the accelerators.

Daniel started at CERN in the late 1960s, working on the PS machine, but was soon recruited to design the beam control systems for the then new SPS accelerator. He made observations of the microwave signals disrupting the beams, putting forward his famous criterion for avoiding them. This started a programme that continues at CERN to this day to understand and control parasitic impedances, which drive beam instabilities, and to invent methods to counteract their effect. With increasing intensity in the SPS, formerly unobserved beam instabilities raised their heads. To deal with this, Daniel pioneered the use of new digital electronics, incorporating them in the one-turn feedback system that he invented to subdue the instabilities.

In the SPS, thoughts quickly turned towards using the machine for the P-PBAR project. Here the problem was to understand and control the noise sources inherent in the RF systems, which destroyed the circulating beams. Pinpointing the critical elements and finding solutions increased the lifetime of the beams from minutes to hundreds of hours.

E Jensen

Daniel Boussard in March 2012.

To accelerate leptons in the SPS for the new LEP accelerator required high RF voltages. Daniel dared to consider installing, for the first time, a superconducting cavity into an environment with high-intensity proton beams. While helping to accelerate the leptons to higher LEP injection energies, it was essential to make this cavity "invisible" to the high-intensity proton beams. He solved this by using sophisticated RF feedback techniques, and the SPS subsequently happily "multi-cycled" protons and leptons for the lifetime of LEP. In these areas, Daniel became an acknowledged leader in the world and his ideas are essential to all modern machines.

With his extensive knowledge of superconducting (SC) RF systems, Daniel was asked to lead the project to install the huge SC RF cavities required for the LEP energy upgrade. While the cavities themselves had to be technically robust, careful design of the electronics to control the voltage and cope with unexpected problems (such as ponderomotive oscillation instabilities) was essential. The experience and understanding gained from SC RF systems in the SPS and in LEP led to their selection for the LHC, and Daniel led the design and implementation of these highly successful accelerating elements.

The tutorials and lectures given by Daniel at CERN accelerator schools on beam loading, RF noise and Schottky diagnostics have become classical references, continuing to serve generations of scientists all over the world. He mastered the art of explaining complex issues in a simple manner.

As a leader, Daniel was kind, fair and highly esteemed, giving clear and carefully thought-out decisions. The remarkable person he was, he took good care of the people entrusted to him and gave honest credit to all those working with him. His natural authority derived from his human qualities and his undoubted technical expertise.

He greatly loved the mountains, going on long hikes both on foot and on skis. It is not surprising, knowing his CERN career, that in his retirement in the south of France Daniel built a guided solar-panel array and became mayor of his village, Valavoire.

● *His friends and colleagues.*

Violette Brisson 1934–2018

Violette Brisson, a highly respected member of the French particle-physics community who played a leading role in the discovery of neutral currents, passed away on 18 February at the age of 83. She led her long career at the Laboratoire Leprince-Ringuet (LLR) at École polytechnique, and the Laboratoire de l'Accélérateur Linéaire (LAL) in Orsay.

Violette joined the LLR in 1954 as a pioneering young woman in a domain then strongly dominated by male physicists. After a PhD devoted to measurements with cosmic rays, she was invited to work on the first hydrogen bubble-chamber experiment at Brookhaven's Alternating Gradient Synchrotron. On her return to France, she joined André Lagarrigue's heavy-liquid detector group. The highlight of the mid-1960s was the design and construction of Gargamelle, a giant bubble chamber to be located on the CERN PS neutrino and antineutrino beams. Violette's expertise from the US was a strong asset to the project. She took part in the design of the illumination system of the chamber and was responsible for the implementation at LLR of the special scanning and measurement devices needed to handle Gargamelle pictures. Her parallel participation in the stopped-kaon experiment X2 allowed her group to master modern computing techniques for photo analysis.

When Gargamelle started operation in 1971, the focus turned to the search for weak neutral current (NC) events predicted by the Glashow–Weinberg–Salam model. Violette played a leading role in the analysis of the leptonic channel, which turned out to be decisive: a single and by now famous leptonic event with negligible background, together with hadronic events, were the basis of the ground-breaking NC discovery published in 1973. (This saga and the associated controversy with the US competition were related with humour by Violette during CERN's 50th anniversary celebrations.) Afterwards, she became interested in nucleon structure functions in several experiments with Gargamelle and the Big European Bubble Chamber.

École polytechnique

Violette played important roles in the Gargamelle, H1 and VIRGO projects.

In the early 1980s, when the electron–proton collider HERA entered the scene, Violette fully engaged with this new project. She played a major role in the French contribution to HERA and to one of its experiments, H1. She joined LAL in 1988 and was personally strongly involved in the construction of the H1 liquid-argon calorimeter, going into every detail of its design and not hesitating to spend months within the cryostat to install the complex cabling with the technical teams. Later on she worked on the HERA Fabry-Pérot polarimeter for the high-luminosity phase. HERA did not find the hoped-for quark substructures or leptoquarks, but delivered a wealth of textbook results that provides reference proton-structure measurements for the LHC and, together with LEP and the Tevatron, fully unveiled the mechanism of electroweak unification first hinted at by the Gargamelle discovery of neutral currents.

In the 1990s, though already well advanced in her career, Violette was bold enough to move to a completely new domain – the quest for gravitational waves – within the French–Italian VIRGO experiment. She again took on a major technical component of the detector, the 3 km-long vacuum chambers of the interferometer arms, taking care of the design of the complex ultra-high-vacuum system. This was a key ingredient to the success. It is comforting that, after many years of constant improvements of the interferometer, Violette was able to experience the first detection of a gravitational wave by VIRGO.

Beyond her talents as physicist, Violette had a deep sense of responsibility and outstanding organisational skills. She took on many collective duties, including assistant management of LLR for many years, the secretariat of the physics committee of the French Science Academy, French representation in international organisations such as IUPAP, and participation on conference committees. In 2003 she was nominated Chevalier de la Légion d'honneur.

Violette was not only a physicist: she was also a spouse, a mother and a faithful friend of many around the world, including a lot of colleagues. She led her life with passion, with a long and dense career crowned by two major discoveries. She will remain an inspiring model for all of us, and in particular to young female physicists.

● *Her friends and colleagues.*

Bookshelf

Compiled by Virginia Greco, CERN

The Standard Model in a Nutshell

By Dave Goldberg

Princeton University Press

This book is an excellent source for those interested in learning the basic features of the Standard Model (SM) of particle physics – also known as the Glashow–Weinberg–Salam (GSW) model – without many technical details. It is a remarkably accessible book that can be used for self learning by advanced undergraduates and beginning graduate students. All the basic building blocks are provided in a self-contained manner, so that the reader can acquire a good knowledge of quantum mechanics and electromagnetism before reaching the boundaries of the SM, which is the theory that best describes our knowledge of the fundamental interactions.

The topics that the book deals with include special relativity, basic quantum field theory and the action principle, continuous symmetries and Noether's theorem, as well as basic group theory – in particular, the groups needed in the SM: U(1), SU(2) and SU(3). It also covers the relativistic treatment of fermions through the Dirac equation, the quantisation of the electromagnetic field and a first look at the theory of gauge transformations in a familiar context. This is followed by a reasonable account of quantum electrodynamics (QED), the most accurate theory tested so far. The quantisation rules are reviewed with clarity and a number of useful and classic computations are presented to familiarise the reader with the technical details associated with the computation of decay rates, scattering amplitudes, phase-space volumes and propagators. The book also provides an elementary description of how to construct and compute Feynman rules and diagrams, which are later applied to electron–electron scattering and electron–positron annihilation, and how the latter relates to Compton or electron–photon scattering. This lays the basic computational tools to be used later in the sections about electroweak and strong interactions.

At this point, before starting a description of the SM per se, the author briefly describes the historical Fermi model and then presents the main actors. The reader is introduced to the lepton doublet (including the electron, the muon, the tau and their neutrinos), the weak charged and neutral currents, and the

vector bosons that carry the weak force (the Ws and the Z). This is followed by an analysis of electroweak unification and the introduction of the weak angle, indicating how the electromagnetic interaction sits inside the weak isospin and hypercharge. Then, the author deals with the quark doublets and the symmetry breaking pattern, using the Brout–Englert–Higgs mechanism, which gives mass to the vector bosons and permits the accommodation of masses for the quarks and leptons. We also learn about the Cabibbo–Kobayashi–Maskawa mixing matrix, neutrino oscillations, charge and parity (CP) violation, the solar neutrino problem, and so on. To conclude, the author presents the SU(3) gauge theory of the strong interactions and provides a description of some theories that go beyond the SM, as well as a short list of important open problems. All this is covered in just over 250 pages: a remarkable achievement. In addition, the book includes many interesting and useful computations.

This work is a very welcome addition to the modern literature in particle physics and I certainly recommend it, in particular for self study. I hope, though, that in the second edition the correct Weinberg is portrayed on p184… an extremely hilarious blunder.

● *Luis Alvarez-Gaume, CERN and SUNY (New York, US)*

Technology Meets Research: 60 Years of CERN Technology, Selected Highlights

By Christian Fabjan, Thomas Taylor, Daniel Treille and Horst Wenninger (eds.)

World Scientific

This book, the 27th volume in the "Advanced Series on Directions in High Energy Physics", presents a robust and accessible summary of 60 years of technological development at CERN. Over this period, the foundations of today's understanding of matter, its fundamental constituents and the forces that govern its behaviour were laid and, piece by piece, the Standard Model of particle physics was established. All this was possible thanks to spectacular advances in the field of particle accelerators and detectors, which are the focus of this volume. Each of the 12 chapters is built using contributions from the physicists and engineers who played key roles in this great scientific endeavour.

After a brief historical introduction, the story starts with the Synchrocyclotron (SC), CERN's first accelerator, which allowed – among other things – innovative experiments on pion decay and a measurement of the anomalous magnetic dipole moment of the muon. While the SC was a development of techniques employed elsewhere, the Proton Synchroton (PS), the second accelerator constructed at CERN and now the cornerstone of the laboratory's accelerator complex, was built using the new and "disruptive" strong-focusing technique. Fast extraction from the PS combined with the van der Meer focussing horn were key to the success of a number of experiments with bubble chambers and, in particular, to the discovery of the weak neutral current using the large heavy-liquid bubble chamber Gargamelle.

The book goes on to present the technological developments that led to the discovery of the Higgs boson by the ATLAS and CMS collaborations at the LHC, and the study of heavy-quark physics as a means to understand the dynamics of flavour and the search for phenomena not described by the SM. The taut framework that the SM provides is evident in the concise reviews of the experimental programme of LEP: the exquisitely precise measurements of the properties of the W and Z bosons, as well as of the quarks and the leptons – made by the ALEPH, DELPHI, OPAL and L3 experiments – were used to demonstrate

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the internal consistency of the SM and to correctly predict the mass of the Higgs boson. An intriguing insight into the breadth of expertise required to deliver this programme is given by the discussion of the construction of the LEP/LHC tunnel, where the alignment requirements were such that the geodesy needed to account for local variations in the gravitational potential and measurements were verified by observations of the stars.

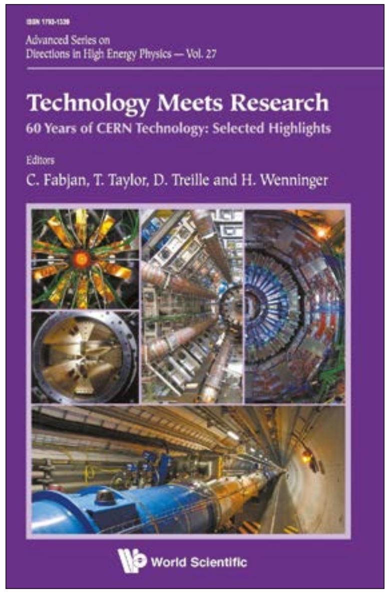
The rich scientific programme of the LHC and of LEP before it have their roots in the systematic development of the accelerator and detector techniques. The accelerator complex at CERN has grown out of the SC.

The book concisely presents the painstaking work required to deliver the PS, the Intersecting Storage Rings (ISR) and the Super Proton Synchrotron (SPS). Experimentation at these facilities established the quark-parton model and quantum chromodynamics (QCD), demonstrated the existence of charged and neutral weak currents, and pointed out weaknesses in our understanding of the structure of the nucleon and the nucleus. The building of the SPS was expedited by the decision to use single-function magnets that enabled a staged approach to its construction. The description of the technological innovations that were required to realise the SPS includes the need for a distributed, user-friendly control-and-monitoring system. A novel solution was adopted that exploited an early implementation of a local-area network and for which a new, interpretative programming language was developed.

The book also describes the introduction of the new isotope separation online technique, which allows highly unstable nuclei to be studied, and its evolution into research on nuclear matter in extreme conditions at ISOLDE and its upgrades. The study of heavy-ion collisions in fixed target experiments at the SPS collider and now in the ALICE experiment at the LHC, has its roots in the early nuclear-physics programme as well. The SC, and later the PS, were ideal tools to create the intense low-energy beams used to test fundamental symmetries, to search for rare decays of hadrons and leptons, and to measure the parameters of the SM.

I was struck by CERN's extraordinary pedigree of innovation

Reading this chronicle of CERN's outstanding record, I was struck by its extraordinary



pedigree of innovation in accelerator and detector technology. Among the many examples of groundbreaking innovation discussed in the book is the construction of the ISR which, by colliding beams head on, opened the path to today's energy frontier. The ISR programme created the conditions for pioneering developments such as the multi-wire proportional chamber, and the transition radiation detector as well as large-acceptance magnetic spectrometers for colliding-beam experiments. Many of the technologies that underpin the success of the proton–antiproton ($Sp\bar{p}S$) collider, LEP and the LHC, were innovations pioneered at the ISR. For example, the discovery of the W and Z bosons at the $Sp\bar{p}S$ relied on the demonstration of stochastic cooling and antiproton accumulation. The development of these techniques allowed CERN to establish its antiproton programme, which encompassed the search for new phenomena at the energy frontier, as well as the study of discrete symmetries using neutral kaons at CPLEAR and the detailed study of the properties of antimatter.

The volume includes contributions on the development of the computing, data-handling and networking systems necessary to maximise the scientific output of the accelerator and detector facilities. From the digitisation and handling of bubble- and spark-chamber images in the SC era, to the distributed processing possible on the worldwide LHC computing grid, the CERN community has always developed imaginative solutions to its data-processing needs.

The book concludes with thoughtful chapters that describe the impact on society of the technological innovations driven by the CERN programme, the science and art of managing large, technologically challenging and internationally collaborative projects, and a discussion of the R&D programme required to secure the next 60 years of discovery.

The contributions from leading scientists of the day collected in this relatively slim book document CERN's 60-year voyage of innovation and discovery, the repercussions of which vindicate the vision of those who drove the foundation of the laboratory – European in constitution, but global in impact. The spirit of inclusive collaboration, which was a key element of the original vision for the laboratory, together with the aim of technical innovation and scientific excellence, are reflected in each of the articles in this unique volume.

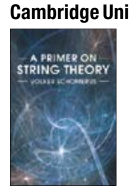
● *Kenneth Long, Imperial College, UK*

Books received

A Primer on String Theory

By Volker Schomerus

Cambridge University Press



This textbook aims to provide a concise introduction to string theory for undergraduate and graduate students. String theory was first proposed in the 1960s and has become one of the main candidates for a possible quantum theory of gravity. While going through alternate phases of highs and lows, it has influenced numerous areas of physics and mathematics, and many theoretical developments have sprung from it.

It was the intention of the author to include in the book just the fundamental concepts and tools of string theory, rather than to be exhaustive. As Schomerus states, there are already various textbooks available that cover this field in detail, from its roots to its most modern developments, but these might be dispersive and overwhelming for students approaching the topic for the first time.

The volume is composed of a brief historical introduction and two parts, each including various chapters. The first part is dedicated to the dynamics of strings moving in a flat Minkowski space. While these string theories do not describe nature, their study is helpful to understand many basic concepts and constructions, and to explore the relation between string theory and field theory on a two-dimensional "world".

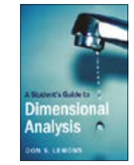
The second part deals with string theories for four-dimensional physics, which can be relevant to the description of our universe. In particular, the motion of superstrings on backgrounds in which some of the dimensions are curled up is studied (this phenomenon is called compactification). This part, in turn, includes three sections devoted to as many subtopics.

First, the author discusses conformal field theory, also dealing with the SU(2) Wess–Zumino–Novikov–Witten model. Then, he passes on to treat Calabi–Yau spaces and the associated string compactification. Finally, he focuses on string dualities, giving special emphasis to the AdS/CFT correspondence and its application to gauge theory.

A Student's Guide to Dimensional Analysis

By Don S Lemons

Cambridge University Press



Dimensional analysis is a mathematical technique that allows one to deduce the relationship between different physical quantities from the dimensions of the variables involved in the system under study. It provides a method to simplify – when possible – the resolution of complex physical problems.

This short book provides an introduction to dimensional analysis, covering its history, methods and formalisation, and shows its application to a number of physics and engineering problems. As the author explains, the foundation principle of dimensional analysis is essentially a more precise version of the well known rule against "adding apples and oranges"; nevertheless, the successful application of this technique requires physical intuition and some experience. Most of the time it does not lead to the solution of the problem, but it can provide important hints about the direction to take, constraints on the relationship between physical variables and constants, or a confirmation of the correctness of calculations.

After a chapter covering the basics of the method and some historical notions about it, the book offers application examples of dimensional analysis in several areas: mechanics, hydrodynamics, thermal physics, electrodynamics and quantum physics. Through the solution of these real problems, the author shows the possibilities and limitations of this technique. In the final chapter, dimensional analysis is used to take a few steps in the direction of uncovering the dimensional structure of the universe.

Aimed primarily at physics and engineering students in their first university courses, it can also be useful to experienced students and professionals. Being concise and providing problems with solutions at the end of each chapter, the book is ideal for self study.

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The Department of Physics and Astronomy in the Faculty of Mathematics and Natural Sciences of the University of Bonn invites applications for a

Professorship (W2 Tenure Track W3)
for Experimental Physics
Strong Interaction Physics

at the Helmholtz-Institut für Strahlen- und Kernphysik.

Hadron physics together with elementary particle physics is one of the main research areas of the Physics Department of the university. The experimental groups conduct research at the local accelerator ELSA as well as at external laboratories with the experiments PANDA at FAIR, ALICE, COMPASS and ATLAS at CERN, and Belle/Belle2 at KEK.

The research focus of the professorship is expected to be in the field of exotic states of the strong interaction and should extend and strengthen the existing research activities in the area of meson and/or baryon spectroscopy. Possible research topics are: the spectroscopy of hadrons with heavy quarks, exotic quark configurations or gluonic degrees of freedom. Candidates should have an outstanding research profile in developing and building detector systems as well as in data analysis.

The candidate is expected to contribute significantly to the new "Research and Technology Centre Detector Physics" (FTD) at the University of Bonn. Participation in new collaborative research projects is desired as well as a collaboration with the CRC 110 "Symmetries and the Emergence of Structure in QCD".

Teaching at the usual level for such a professorship is required.

The conditions of employment are according to *§ 36 Hochschulgesetz NRW.*

The University of Bonn is committed to diversity and equal opportunity. It is certified as a family-friendly university and has a dual career program. It aims to increase the proportion of women in areas where women are under-represented and to promote their careers in particular. It therefore urges women with relevant qualifications to apply. Applications will be handled in accordance with the *Landesgleichstellungsgesetz* (State Equality Act). Applications from suitable individuals with a certified serious disability and those of equal status are particularly welcome.

Applicants are invited to send the usual documents electronically (curriculum vitae, summary of research interests, list of publications, copies of all university certificates) by **July 1st, 2018** to the Chairperson of the Department of Physics and Astronomy: fachgruppe@physik-astro.uni-bonn.de.

UNIVERSITÄT BONN

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The Department of Physics and Astronomy in the Faculty of Mathematics and Natural Sciences of the University of Bonn invites applications for a

Professorship (W2) for Experimental Physics
Particle Physics

at the Physikalisches Institut.

Particle Physics is one of the three main research areas of the Department of Physics and Astronomy at the University of Bonn. The experimental particle physics groups are engaged in research at external accelerators with the experiments Belle/Belle II in Japan, ATLAS, ALICE and COMPASS at CERN, PANDA at FAIR as well as experiments at the university's own accelerator ELSA. The department wants to strengthen its research in experimental particle physics, in particular in the area of B-meson physics. Candidates should have experience in experiments with B mesons and be interested in making strong contributions to the research program of the Belle II experiment at the SuperKEKB B-factory in Japan. Possible areas of research at Belle II include precision measurements of fundamental parameters of the Standard Model, semileptonic and rare decays, CP violation, and indirect searches for new phenomena in B decays. An active participation in coordinated research activities would be very welcome.

Successful candidates should be able to teach experimental physics in its full breadth and have an outstanding track record in data analysis and development and construction of experiments at particle accelerators. The candidate is expected to contribute significantly to the new "Research and Technology Centre Detector Physics" (FTD) at the University of Bonn

The conditions of employment are according to *§ 36 Hochschulgesetz NRW.*

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Applicants are invited to send the usual documents electronically (curriculum vitae, summary of research interests, list of publications, copies of all university certificates) by **June 15th, 2018** to the Chairperson of the Department of Physics and Astronomy: fachgruppe@physik-astro.uni-bonn.de

CERN Courier Archive: 1975

A look back to CERN Courier vol. 15, May 1975, compiled by Peggie Rimmer

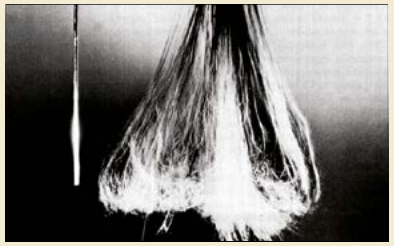
Superconducting magnets

A post-Frascati review

Argonne

A coil of the huge superconducting magnet built at Argonne for the 12 ft bubble chamber, a pioneering application of superconductivity.

AERE Harwell



Nb_3Sn multi-filamentary conductors promise much higher fields and better temperature stability than NbTi. The wire on the left contains filaments that are revealed when the bronze matrix is etched away.

The Fifth International Conference on Magnet Technology was held from 21–25 April in Rome, having relocated from the Frascati Laboratory because of increasing attendance. Interest focused on the use of superconducting magnets in high-energy physics, where extreme requirements push the technology further than elsewhere.

Bubble chambers and spectrometers need high fields over large volumes. Pioneering work was done at the Argonne Laboratory where [in 1968] they built a magnet to give a 2 T field in the 12 ft bubble chamber. Another leader was the Omega spectrometer magnet at CERN, with a 1.8 T field in a 1.5 m aperture, achieved in 1973. High field, small volume magnets are required for detecting particles such as hyperons that live for around 10^{-10}s, to manoeuvre them after production to observe their interactions. At CERN, a very compact hyperon beam region was achieved with two short superconducting quadrupoles. Polarized proton targets also require high fields in small volumes to line up the proton spins while allowing the particles to emerge over as wide a range of angles as possible. The first to operate was at the late-lamented Cambridge Electron Accelerator in 1968.

The interest in pulsed magnets is higher peak fields, which would allow synchrotron energies to increase without increasing the machine size. The Fermilab proton synchrotron hopes to reach 500 GeV with 2.25 T fields from the conventional magnets around its 2 km diameter ring. If 4.5 T superconducting magnets could be used, the energy could reach 1 TeV in the same ring; magnets for such an "Energy Doubler" are under development.

Other applications were more prominent than at previous magnet conferences. This was particularly true of fusion research where recent advances coupled with the world energy crisis have refired the desire to bring thermonuclear fusion reactions under control. Magnets for medical applications also drew a good deal of attention with various "medical beam lines" being developed at accelerators.

Practically all the magnets reported use niobium-titanium [NbTi] superconductor. However, NbTi does not retain its superconductivity much beyond current densities of 0.8 kA/mm or temperatures higher than about 5 K. Other materials offer higher field operation and temperature transitions. Niobium-tin [Nb_3Sn] can tolerate current densities of about 2 kA/mm, retaining superconductivity up to a temperature of 18 K. It is more difficult and expensive to work since it is very brittle, but during the past year Harwell/ Rutherford has made solenoids using filamentary Nb_3Sn superconductor. But even after niobium-tin is mastered, there will still be challenges facing superconducting specialists.

● Compiled from texts on pp147–154.

Around CERN

Protecting the environment around CERN

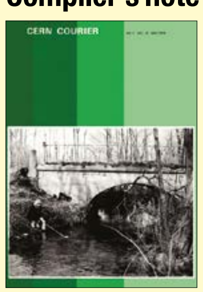
CERN 185.4.75

During the past year, samples of air, water, etc, have been taken around the CERN 400 GeV proton synchrotron site [SPS] to confirm that machine operation will not affect the environment from the point of view of radiation [see the cover thumbnail below].

This photograph was taken in the "Lion stream", which crosses the Laboratory II site. The stream has to be temporarily rerouted for work on the beam-line to the North Experimental Area. The Franco-Swiss fishing Union was alerted and cleared 700 m of the stream of its population – a haul of 366 trout. The trout were stunned by an electrical fishing rod (a 350 V, 4 A device) and transported to safety further downstream.

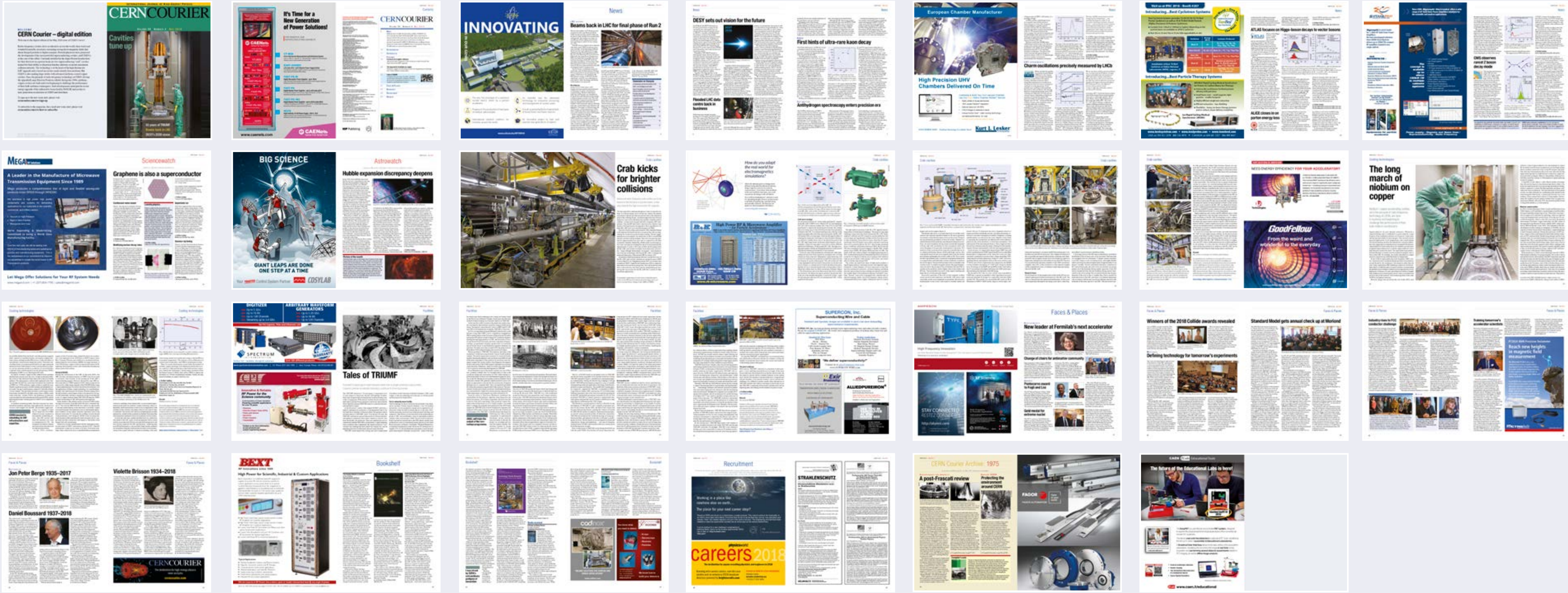
● Compiled from texts on pp146 and 160.

Compiler's note



The use of magnets and particle accelerators in medicine is now widespread, and Fermilab did indeed upgrade the Main Ring to become the Tevatron, where the top quark was discovered in 1995. However, endeavours to generate power from nuclear fusion have been less successful, owing to horrendous engineering and technological difficulties in creating and confining the resulting plasma for longer than a few seconds. Collaborative research continues and the first plasma in the 35-nation ITER tokamak in the south of France, using Nb_3Sn superconductor technology, is foreseen for 2025.

The first operation of the high-luminosity LHC is also foreseen for 2025. It too will use Nb_3Sn superconducting magnets to achieve the necessary increase in performance over the present NbTi-based LHC magnets.



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