Welcome to the digital edition of the May/June 2020 issue of CERN Courier.

This month’s issue looks at the latest progress in niobium-tin (Nb,Sn) accelerator magnets for high-energy exploration. Discovered to be a superconductor more than half a century ago, and already in widespread commercial use in MRI scanners and employed on a giant scale in the under-construction ITER fusion experiment, it is only recently that high-performance accelerator magnets made from Nb,Sn have been mastered. The first use of Nb,Sn conductor in particle physics will be the High-Luminosity LHC (HL-LHC), for which the first Nb,Sn dipole and quadrupole magnets have recently been tested successfully at CERN and in the US. As our cover feature describes, the demonstration of Nb,Sn in the HL-LHC also serves as a springboard to future hadron colliders, enabling physicists to reach significantly higher energies than are possible with present-generation niobium-titanium accelerator magnets. To this end, CERN and the US labs are achieving impressive results in driving up the performance of Nb,Sn conductor in various demonstrator magnets.

Sticking with accelerators, this issue also lays out the possible paths towards a high-energy muon collider – long considered a dream machine for precision and discovery, but devilishly difficult in its details. We also describe the rapid progress being made at synchrotron X-ray sources, arguably the most significant application of accelerator science in recent decades, towards understanding the molecular structure of the SARS-CoV-2 virus. The importance of accelerators for neutron science is a theme of the Viewpoint article, and, in addition to the Courier’s regular coverage of the news, conferences and reviews, this issue includes reports on how high-energy physicists are responding to the COVID-19 pandemic.

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IN THIS ISSUE

FEATuRES

BIOPHYSICS

Synchrotrons on the coronavirus frontline
The impressive progress being made by synchrotron X-ray facilities to solve the structure of SARS-CoV-2.

MAGNETS

Taming the superconductors of tomorrow
Accelerator magnets for the HL-LHC are also a springboard to future fundamental exploration.

ACCELERATORS

Sketching out a muon collider
Muon colliders are receiving renewed attention as a means to explore the energy frontier.

opINIoN

VIEWPOINT

Bridging Europe’s neutron gap
The recent closure of reactors means making the most of existing facilities, says Helmut Scholze.

REVIews

A unique exercise in scientific diplomacy

DEPARtmeNTS

FROM THE EDITOR

NEWS DIGEST

APPOINTMENTS & AWARDS

RECRUITMENT

BACKGROUND

High-energy ventilator
The particle physicists bringing detector expertise to the fight against coronavirus.

POLAR-2

What gamma-ray polarisation can tell us about astrophysics.

PeoPle

CAREERS

Opening doors with a particle-physics PhD
Transferable skills make particle-physics PhDs highly sought after by industry.

ENERGY FRONTIERS

Additional Higgs bosons elude ATLAS; First sight of top-quark mass running; ALICE extends quenching studies; New SMQO on the horizon.

FIELD NOTES

Circular colliders eye Higgs self-coupling; Quark Matter in Wuhan; Cosmologists meet quantum theorists; German–Armenian internship.

OBITUARIES


OBSERVATORY

From the editor

NEWS DIGEST

APPOINTMENTS & AWARDS

RECRUITMENT

BACKGROUND

CERN Courier • May/June 2020

FEARLESS

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Synchrotron X-ray facilities to solve the structure of SARS-CoV-2.
Accelerating science – and medicine

Two dipole magnets, currently hooked up to test rigs in CERN’s SIMA facility, are soon to make history. Scheduled to be lowered into the LHC tunnel later this year as part of the High-Luminosity LHC (HL-LHC), they will be the first operational accelerator magnets made from the superconducting compound niobium–tin (Nb3Sn). The 5.5 m-long magnets will be positioned at Point 5, where they will make space to allow the installation of a collimator to mop up off-trajectory particles. Without this assembly, the higher beam intensities at the HL-LHC potentially could cause quenches in the downstream dispersion-suppressor regions of the machine.

Next in line for testing are the powerful Nb3Sn quadrupole magnets that will sit on either side of CMS and ATLAS to reduce the proton beams to even smaller sizes than at present. The task is split between CERN, which is building eight 7.2 m-long quadrupoles, and Fermilab, Brookhaven and Berkeley in the US, which opted to build eight pairs of 4.2 m-long magnets. Following initial tests of the 11.5 dipole magnets at CERN last year, the first HL-LHC quadrupole magnet has recently been tested successfully at Brookhaven, sustaining a field gradient of around 150 T/m and reaching a peak field of 14.7 T at the conductor (p17).

As this month’s cover feature explains (p16), the demonstration run of Nb3Sn magnet technology for the HL-LHC is also a stepping stone to future hadron colliders. The LHC’s cutting-edge niobium–titanium accelerator magnets enabled physicists to reach the collision energies needed to discover the Higgs boson, but to explore nature at significantly higher energies a material that can provide higher fields is required. Nb3Sn is far from the only conductor that experts are confident is capable of sustaining such fields (up to 16 T) – the baseline field of the dipole magnets for the hadron–hadron mode of the proposed Future Circular Collider (FCC). The Nb3Sn programme is also relevant for a future lepton collider, featured on p12 of this issue.

CERN and the US labs are achieving impressive results in driving up the performance of Nb3Sn conductors in various demonstrator magnets. In 2018, a large-aperture dipole at CERN called FRESCA2 attained a record field of 14.6 T, while, earlier this year, CERN, in the framework of the FCC, achieved 16.4 T in the centre of a short “enhanced racetrack model coil”. In June 2019, a short “cos–theta” dipole magnet reached a bore field of 14.7 T at Fermilab. These and the recent HL–LHC milestones bode well for the future of the field.

COVID-19

In terms of scientific output, synchrotron X-ray sources are arguably the most significant application of accelerator science in recent decades, serving thousands of users across a vast range of topics – in particular molecular biology. In one of several reports in this issue relating to COVID-19, a team at the UK’s Diamond Light Source is rapidly uncovering the virus in recent decades, serving thousands of users across a vast range of topics – in particular molecular biology. In one of several reports in this issue relating to COVID-19, a team at the UK’s Diamond Light Source is rapidly uncovering the virus.
A superconducting quadrupole magnet for the high-luminosity LHC (HL-LHC) has been tested in the US, attaining a conductor peak field of 11.4 T – a record for a magneto-optical device. Designed in collaboration with Particle Accelerators to provide precise, high-speed actuation of beamline diagnostics. The 1.9 m-long, 190 mm-single-aperture device is based on the superconductor niobium-tin (Nb3Sn) and one of several quadrupoles being built by US labs and CERN for the HL-LHC, where they will reduce the size of the proton beams within the ATLAS and CMS experiments to produce a higher luminosity. The result follows successful tests carried out last year at CERN of the first accelerator-ready Nb3Sn dipole magnet, and the milestones are soon to be followed by tests of other 2.3 m and 4.2 m quadrupole magnets at CERN and the US.

Collaboration

“This copious harvest comes after significant recent R&D on niobium-tin superconducting magnet technology, and is the best answer to the question if HL-LHC is on time; it is,” says HL-LHC project leader Lucio Rossi of CERN. Speaking of the US quadrupole test, he concluded: “This full-length, accelerator-ready magnet performance record is a real textbook case for international collaboration: since the very beginning of the upgrade, the US labs and CERN teamed up and managed to have a common and very synergic R&D, particularly for the quadrupole magnet that is the cornerstone of the upgrade. This has resulted in substantial savings and improved output.”

The current LHC dipole magnets, which have been tested to a bore-field of 8.3 T and are currently operated at 7.7 T at 1.9 K for five hours. Eight longer quadrupole magnets are being produced by CERN. “We’ve demonstrated that this first quadrupole magnet behaves successfully and according to design, based on the multiyear development effort made possible by DOE [Department of Energy] investments in this new technology,” said Fermilab’s Giorgio Apollinari, head of the US Accelerator Upgrade Project in a Fermilab press release. “It’s a cutting-edge magnet,” added Kathleen Amm, Brookhaven’s representative for the project.

Dipole tests at CERN

In addition to stronger focusing magnets, the HL-LHC requires new dipole magnets positioned on either side of a collimator that corrects off-momentum protons in the high-intensity beam. To gain the required space in the magnetic lattice, Nb3Sn dipole magnets of shorter length and higher field than the current LHC dipole magnets are needed. In July 2019 the CERN magnet group successfully tested a full-length, 5.5 m, superconducting quadrupole magnet and achieved a nominal bore field of 11.4 T (corresponding to a conductor peak field of 11.8 T). CERN and the US labs are also achieving impressive results in driving the performance of Nb3Sn conductors to much higher fields, as would be needed for future hadron colliders beyond the LHC (see p14).

Before being judged fully operational and available for the HL-LHC, the US-based quadrupole magnets and the CERN-based dipole magnets must be connected in pairs. Each magnet in a pair has the same winding, and differs only in its mechanical interfaces and details of its electrical circuitry. Tests of the remaining halves of the quadrupole and dipole pairs were scheduled to take place in the US and at CERN this summer, with the dipole magnet pairs to be installed in the LHC tunnel by the end of the year. Given that the relevant laboratories are currently in teleworking mode due to COVID-19, this plan may have to be reviewed, says Rossi, who adds that this is now the high-priority discussion within the HL-LHC project.

High field

The unformed quadrupole magnet being prepared for use at Brookhaven National Laboratory.

This is a real textbook case for international collaboration in the accelerator domain.
Physicists develop stripped-down ventilator

As part of the global response to the COVID-19 pandemic, a team led by physicists at CERN has presented the design of a novel ventilator. The High Energy Ventilator (HEV) team has proposed a design that is simple and cheap to source and, although composed mostly of everyday objects by medical experts before it can enter use, in the interests of rapid development the HEV team has presented the design to generate feedback. The proposal is one of several recent and rapidly developing efforts launched by high-energy physicists to help combat COVID-19.

The HEV concept comprises electronics, a large air buffer container, a pressure regulator and several pressure and flow sensors. Embedded components – currently Arduino and Raspberry Pi – are being used to meet portability requirements. The HEV team noted that the functionality is comprehensive enough to provide long-term support to patients in the initial or recovery phases, freeing up high-end machines for the most intensive care patients. The HEV team outlined a simple touchscreen control that is intuitive to use for qualified medical personnel, even if they are not specialists in ventilator use, and it includes extensive monitoring and fail-safe mechanisms based on CERN’s long experience in this area, with online training being developed. The first phase of penetrometry, which was achieved at CERN on 27 March, demonstrated that the HEV principle is sound and enables the ventilator to operate within the required range of pressures and time. The support of clinicians and international organisations is now being harnessed for further prototyping and deployment stages. “This is a device that has patient safety as a major priority,” says HEV collaborator Themis Borrow of the University of Liverpool. “It is a aims to support patients at home and in the world, and in places that do not necessarily have state-of-the-art facilities.”

Complementary design

The HEV team further proposed another recent proposal initiated by physicists in the Global Workforce Collaboration. The Mechanical Ventilator Milano (MVM) is optimised to perform large-scale production in a short amount of time and at a limited cost, also relying on off-the-shelf components that are readily available. In contrast to HEV, which aims to control pressure by alternately filling and emptying a buffer, the MVM regulates the flow of the incoming mixture of oxygen and air via electrically controlled valves. The proposal stems from a cooperation of particle- and nuclear-physics laboratories and universities in Canada, Italy, the US, and Australia, with an initial goal to produce up to 100 units in each of the three countries while the interim certification process is ongoing, they hope.

The HEV team has presented its design to the MVM principle, but with emphasis on further reducing the number and specificity of components, another ventilator design called Project Open Air has been proposed by a team led by particle physicists at the Laboratory of Instrumentation and Experimental Physics of the University of Antwerp. All designs are evolving quickly and require further development before they can be deployed in hospitals. “It is difficult to conceive a project that involves so many parties and includes all the bells and whistles needed to get it into the hospital, but this is our firm goal,” says Collins. “If we can conceive of an experiment that is a functioning demonstrator, after two weeks we could have a working mechanical device and be now prototyping under clinical supervision. We find ourselves in a very unique position where there are many proposals on the market, but we don’t know which ones will in fact reach the hospitals, and which one that could be viable should be pursued.”

Further reading


Prototyping Ian Buytaert and Paolo Collinis with the HEV prototype in the LHCCVELO lab at CERN on 6 April.
Antimatter

**ALPHA sheds light on antihydrogen’s fine structure**

The ALPHA collaboration at CERN has reported the first measurements of fine-structure effects and the Lamb shift in antimatter atoms. The results, published in Nature in February, bring further scrutiny to our understanding of antimatter and ordinary matter, which, if found to behave differently, would challenge CPT symmetry and shake the foundations of the Standard Model.

In 1957, physicist Willis Lamb and his colleagues observed an incredibly small shift in the n = 2 energy levels of hydrogen in vacuum. Under traditional physics theories of the day, namely the Dirac equation, these states should have the same energy and the Lamb shift shouldn’t exist. The discovery spurred the development of quantum electrodynamics (QED), which explains the discrepancy as being due to interactions between the atom’s constituents with vacuum-energy fluctuations, and won Lamb the Nobel Prize in Physics in 1959.

The ALPHA team creates antimatter atoms by binding antiprotons delivered by CERN’s Antiproton Decelerator (AD) with positrons. The antiprotons are then confined in a magnetic trap in a vacuum chamber, and illuminated with a laser to measure their spectral properties. This technique enables the measurement of known quantum effects such as the fine structure and the Lamb shift, which have now been measured in the antimatter atom for the first time. The ALPHA team previously used this approach to measure other quantum effects in antimatter, the most recent being a measurement of the Lyman–alpha (1S–2P) transition in 2018 (CERN Courier October 2018 p5).

In their new study, the ALPHA team determined the fine-structure splitting and the Lamb shift by inducing transitions between the lowest (n = 2) energy level of antimatter and the 1S and 2P levels, all in the absence of a magnetic field, and the resultant effect on the emission of quantum fluctuations associated with virtual photons.

The splitting of the n = 2 energy level of hydrogen is a separation between the 2P, and 2S, levels in the absence of a magnetic field, and is caused by the interaction between the electron’s spin and the orbital momentum. The classic Lamb shift is the splitting between the 2S, and 2P, levels, also in the absence of a magnetic field, and the resultant effect on the emission of quantum fluctuations associated with virtual photons.

In their new study, the ALPHA team determined the fine-structure splitting and the Lamb shift by inducing transitions between the lowest (n = 2) energy level of antimatter and the 1S and 2P levels, all in the absence of a magnetic field, and the resultant effect on the emission of quantum fluctuations associated with virtual photons.

The team chose a 1 T magnetic field. Using the value of the 

\[ \frac{\alpha}{\pi} = \frac{\pi}{2} \] 

where \( \alpha \) is the fine-structure constant, the team was able to induce the transitions of the fine-structure splitting and the Lamb shift. The results were found to be consistent with the theoretical predictions of the splittings in normal hydrogen, within the experimental uncertainties of 2% for the fine-structure splitting and 1% for the Lamb shift. “The work confirms that a key portion of QED holds up in both matter and antimatter, and probes aspects of antimatter interaction – such as the Lamb shift – that we have long looked forward to addressing,” says spokespersons Jorg Heidt.

The Lamb shift in ordinary hydrogen’s spectral structure that are now being followed with more than 30 years of effort by the low-energy antimatter community at CERN (CERN Courier March 2018 p9). The first antimatter atoms were observed at CERN’s LEAR facility in 1999, and, in 2002, the ATHENA and ATRAP collaborations produced cold (trappable) antimatter at the AD, opening the way to precision measurements of antimatter’s atomic spectra. In addition to spectral measurements, the charge-to-mass ratios for the proton and antiproton have been shown to agree to 69 parts per trillion by the BASE experiment, and the antiproton-to-electron mass ratio has been measured to agree with its proton counterpart to a level of 8 parts per billion by the ASACUSA experiment. The newly completed ELENA facility at the AD will increase the number of available antiprotons by up to two orders of magnitude. The ALPHA ALPHAn team is chilling large samples of antihydrogen using state-of-the-art laser cooling techniques. These techniques will transform antimatter studies and will allow unprecedentedly high-precision measurements of antimatter and antimatter, says Hangst.

Further reading

**CERN Courier** 2020 Nature 578 175

Flavour Physics

**Anomalies persist in B–meson decays**

The LHCb collaboration has confirmed previous hints of odd behaviour in the way B mesons decay into a K+ and a pair of muons, bringing fresh intrigue to the pattern of flavour anomalies that has emerged during the past few years. At a seminar an CERN on in March, Enrico Smith of RWTH Aachen University presented an updated analysis of the angular distributions of final hadrons and B decay final states. The results reveal a mild increase in overall tension with the Standard Model (SM) prediction, though, as more data are needed to confirm or rule out the effect.

The K+–K0 decay is a promising system for which to explore physics beyond the SM. A flavour-changing neutral current (FCNC) process that is forbidden in the SM, and that occurs naturally around once for every million B decays. The decay proceeds instead via operator–penguin processes, which are sensitive to the presence of new, heavy particles. Two new particles were seen in competing processes and could significantly change the B →K*+μ+μ− decay rate and the distribution of final state particles. Measuring angular distributions as a function of the invasion angle of the muon pair, Q2, and the mass squared of the muon pair, \( \Delta m^2 \), this has led physicists to speculate that these effects could be caused by the same new physics, with models involving leptoquarks or new gauge bosons in principle able to accommodate both sets of anomalous (CERN Courier May/June 2020 p315).

An update to B → μ+μ−, based on additional Run-2 data is hotly anticipated, and the collaboration is also planning to add data from the BABAR detector to its analysis. “We as a community have been eagerly waiting for this measurement and LHCb has not disappointed us,” says Zupan of the LHCb result, “The wait for the clear evidence of new physics continues.”

Further reading


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Gamma-ray polarisation sharpens multi-messenger astrophysics

Recent years have seen the dawn of multi-messenger astrophysics. Perhaps the most significant contributor to this new era was the 2017 detection of gravitational waves (GWs) in coincidence with a bright electromagnetic phenomenon, a gamma-ray burst (GRB). GWs consist of intense bursts of gamma rays which, for periods ranging from hundreds of milliseconds to hundreds of seconds, outshine any other object in the universe. Although the first such event was spotted back in 1967, and typically one GRB is detected every day, the underlying astrophysical processes responsible remain a mystery. The joint GW-electromagnetic detection answered several questions about the nature of GRBs, but many others remain.

recently, researchers made the first attempts to add gamma-ray polarisation into the mix. If successful, this could enable the next step forward within the multi-messenger field. So far, three photon parameters—arrival time, direction and energy—have been measured extensively for a range of different objects within astrophysics. Yet, despite the wealth of information it contains, the photon polarisation has been neglected. X-ray or gamma-ray fluxes emitted by charged particles within strong magnetic fields are highly polarised, while those emitted by thermal processes are typically unpolarised. Polarisation therefore allows researchers to easily identify the dominant emission mechanism for a particular source. GRBs are one such source, since a consensus on where the gamma rays actually originate from is still missing.

Difficult measurements

The reason that photon polarisation has not been measured in great detail is related to the difficulty of performing the measurements. To measure the polarisation of an incoming photon, details of the secondary products produced as it interacts in a detector need to be measured. With gamma rays, for example, the angle at which the gamma ray scatters in the detector is related to its polarisation vector. This means that, in addition to detecting the photons, researchers need to study its subsequent path. Such measurements are further complicated by the need to perform them above the atmosphere on satellites, which complicates the detector design significantly.

Recent progress has shown that, although challenging, polarisation measurements are possible. The most recent example came from the POLAR mission, a Swiss, Polish and Chinese experiment fully dedicated to measuring the polarisation of GRBs, which took data from September 2016 to April 2017. The team behind POLAR, which was launched to space in 2018 attached to a module for the China Space Station, recently published its first results. Though they indicate that the emission from GRBs is likely unpolarised, the story appears to be more complex.

The 2020s should see the start of a new type of astrophysics

Further reading

Neutron STAR measurements

The STAR collaboration at Brookhaven’s Relativistic Heavy-Ion Collider has measured the dipole moment of the neutron (nEDM), a possible sign of new physics beyond the Standard Model (SM). The team (Belle II et al., 2020) published the most sensitive measurement so far of the neutron EDM, reporting a limit of |d_n| < 3.2 × 10^{-26} e cm, by watching for shifts in the Larmor precession frequency of ultracold neutrons proportional to an applied electric field (Phys. Rev. Lett. 124, 031801). A nonzero nEDM would be evidence of the violation of time-reversal symmetry, therefore also suggesting the violation of CP (CP symmetry) holds. As the nEDM due to CP violation in the CKM matrix is estimated to be of the order of just so 10^{-26} e cm, the result places constraints on the hyperon–nucleon interaction and neutron–star interiors, where strange matter may be present: this is the energy that is released when a hypertriton comes into contact with a neutron. The result places new evidence for a mass difference between hypertritons and antihypertritons: a test of CP symmetry.

Kolkata cyclotron operational

More than three decades since the project began, external beam has been sighted at the Superconducting Cyclotron of the Variable Energy Cyclotron Centre in Kolkata – the only superconducting cyclotron in India, and one of only a handful in the world. The HELAC beam has been sighted at Michigan State University and Texas A&M University, the cyclotron will be used for nuclear physics and the treatment of ocular melanoma, a type of cancer that develops in cells that produce melanin. One of the largest cryogenic installations in Asia, the project builds on the legacy of noted astrophysicist Meghnad Saha, who masterminded the assembly of India’s first normal conducting cyclotron in Calcutta during the Second World War.

Neutrino search at VECC

Evidence for neutrino production at VECC will be a spectacular confirmation of the Standard Model (SM). The team has now used their global network of telescopes to image a jet produced by a supermassive black hole, the team (Birnhack et al., 2020) found the first strong evidence for the coupling g in the so-called 1-L, expansion of the SM. This model, wherein the Z’ couples only to muon and tau-lepton flavoured SM particles and the dark sector, thus also the potential to explain anomalies in (h→μμ) decays reported by LHCb (J. Fox et al., 2019) and the muon g-2 anomaly, claims the team (Phys. Rev. Lett. 124, 151801).

Black-hole sightings

The world took note last April when the Event Horizon Telescope collaboration published the first ever image of a black hole. The team has now used their global network of telescopes to image a jet produced by a supermassive black hole, the team (Birnhack et al., 2020) found the first strong evidence for the coupling g in the so-called 1-L, expansion of the SM. This model, wherein the Z’ couples only to muon and tau-lepton flavoured SM particles and the dark sector, thus also the potential to explain anomalies in (h→μμ) decays reported by LHCb (J. Fox et al., 2019) and the muon g-2 anomaly, claims the team (Phys. Rev. Lett. 124, 151801).
Prevent epidemic outbreaks with mathematical modeling and simulation.

Using math to analyze the spread of epidemic diseases is not a new concept. One of the first compartmental models of mathematical epidemiology dates back to 1960 and was presented by Daniel Bernoulli for studying the mortality rate of smallpox. Today, medical researchers and public health officials continue to use mathematical modeling and simulation to prevent and control epidemic outbreaks in the modern world. The COMSOL Multiphysics® software is used for simulating designs, devices, and processes in all fields of engineering, manufacturing, and scientific research. See how you can apply it to analyzing the spread of epidemic diseases.

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After the discovery of the long-sought Higgs boson at a mass of 125 GeV, a major question in particle physics is whether the electroweak symmetry breaking sector is indeed as simple as the one implemented in the Standard Model (SM), or whether there are additional Higgs bosons. Additional Higgs bosons would occur, for example, in the presence of a second Higgs field, as realised in two-Higgs-doublet models, among which is the well-known minimal super-symmetric extension of the SM (MSSM). The discovery of additional Higgs bosons could therefore be a gateway to new symmetries in nature.

ATLAS has recently released results of a search for heavy Higgs bosons decaying into a pair of tau leptons using the complete LHC Run 2 dataset (9.2 fb⁻¹) of 13 TeV proton-proton data. The new analysis provides a considerable increase in sensitivity to MSSM scenarios compared to previous results.

The MSSM features five Higgs bosons, among which, the observed Higgs boson can be the lightest one. The couplings of the heavy Higgs bosons to down-type leptons and quarks, such as the tau lepton and bottom quark, are enhanced for large values of tan β — the ratio of the vacuum expectation values of the two Higgs doublets, and one of the key parameters of the model. The heavy neutral Higgs bosons A (CP odd) and H (CP even) are produced mainly via gluon–gluon interactions or in association with bottom quarks. Their branching fractions to tau leptons can reach sizeable values across a large part of the model–parameter space, making this channel particularly sensitive to a wide range of MSSM scenarios.

The new ATLAS search requires the presence of two oppositely charged tau-lepton candidates, one of which is identified as a hadronic tau decay, and the other as either a hadronic or a leptonic decay. To profit from the enhancement of the production of signal events in association with bottom quarks at large tan β, the data set includes events with two top quarks, as well as events with two top quarks and a W or Z boson or Higgs boson (figure 1).

The data agree with the prediction assuming no additional Higgs bosons, despite a small, non-significant excess around a putative signal mass value of 400 GeV. The measurement places limits on the production cross section that can be translated into constraints on MSSM parameters. One realisation of the MSSM is the hMSSM scenario, in which the knowledge of the observed Higgs boson mass is used to reduce the number of parameters. The A/H search lower limit dominates over large parts of the parameter space (figure 2), but still leaves room for possible discoveries at masses above the top–anti-top quark production threshold. ATLAS continues to refine this and conduct further searches for heavy Higgs bosons in various final states.

Further reading

The new ATLAS search requires the presence of two oppositely charged tau-lepton candidates.
Control systems for Big Science, today

In the last decade, control system development has become an established engineering discipline and a core part of the systems that scientists had improved over years. This includes a variety of systems, such as large machines, typical for both experimental and theoretical research. Transitioning new systems or projects into operation often involves complex engineering tasks. It is common to think of the logistics of installation and error handling while also planning for testing and debugging. It usually makes the most sense to keep overall system responsibility in-house while outsourcing the control system implementation.

Standardisation is the key trend that has emerged in the last 10 years with ever more complex new scientific projects. Today, integration and decommissioning is the most prominent aspect of a control system project. Even though control system components are steadily becoming more standardised, they are also getting more complex and require more time and effort for integration. The main issues today are how will all the components fit into the main architecture, what will the interfaces be, and how shall the engineers address the requirements. Project managers, therefore, must make early choices regarding the main architecture and components and consider all control system development aspects if they want to avoid costly problems down the road.

In short, control system development is, with time, becoming an increasingly engineering discipline and less of a scientific one.

THE AUTHOR

Rok Šabjan is currently the Technical Director, ALICE, CERN. He leads the ALICE control system team and is a member of the ALICE management committee. He holds a PhD in physics and an executive MBA, with a specialisation in CERN's control system architecture and integration, project management and consulting. He has been active in the world of research and development in computer science, machine learning and artificial intelligence.


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First sight of the running of the top–quark mass

The coupling between quarks and gluons depends strongly on the invariance of the process. The same is true for the masses of the top quark. This effect — the so-called “running” — affects the strong coupling constant and the quark masses — is described by the renormalisation group equations (RGEs) of quantum chromodynamics (QCD). The experimental verification of the RGEs is both an important test of the validity of QCD and an indirect search for unknown physics, as physics beyond the Standard Model could modify the RGEs at scales probed by the Large Hadron Collider. The running of the strong coupling constant has been established at many experiments in the past, and, over the past 20 years, evidence for the running of the masses of the charm and bottom quarks was demonstrated using data from LEP, SLAC and HERA, though the running of the top–quark mass has proven elusive.

The CMS collaboration has now, for the first time, probed the running of the mass of the top–quark. The measurement was performed using proton–proton collision data collected between 2010 and 2018 and recorded by the CMS detector in 2016. The top–quark mass was determined as a function of the invariant mass of the top–quark–antiquark system (the energy scale of the process), by comparing the differential measurements of the system’s production cross section with theoretical predictions. In the vast majority of the cases, top–quark decays into a W boson and bottom quark. In this analysis, candidate events are selected in the final state where one W boson decays into an electron and a neutrino, and the other decays into a muon and a neutrino. The cross section was measured using a maximum-likelihood fit to multi-differential distributions of final–state observables, allowing the measurement to be significantly improved by comparison to standard methods (figure 1). The measured cross section was then used to extract the value of the top–quark mass as a function of the energy scale. The running was determined with respect to an arbitrary reference scale. The measured points are in good agreement with the one–loop solution of the RGEs, within ±1 standard deviation, and with a hypothetical no–running scenario is excluded at above 95% confidence level.

This novel result supports the validity of the RGEs up to a scale of the order of 1 TeV. Its precision is limited by systematic uncertainties related to experimental uncertainties and the expected performance of the top–quark production in the simulation. Further progress will not only require a significant effect in improving the calibration of the final-state objects, but also substantial theoretical developments.

Further reading

Cern Courier May/June 2020 (p.52).

Further reading

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Further reading

CERN Courier May/June 2020 (p.52).

Further reading
ENERGY FRONTIERS

The reference measurements in pp collisions (appropriately scaled) compared to four theoretical predictions.

Further reading


LHCb

New SMOG on the horizon

LHCb will soon become the first LHC experiment able to run simultaneously with two separate interaction regions. As part of the ongoing major upgrade of the LHCb detector, the new SMOG2 fixed-target system will be installed in long shutdown 2. SMOG2 will replace the previous System for Measuring the Over‑

eneral advantages, including the ability to measure the initial goal of calibrating luminosity

Further reading


Ultra-compact systems, typically one 19” rack / 100 kW (pulse)

Module Solid State architecture, compact modules (<10 kG)

Highly Maintainable with Hot Swap capability

Wall Plug efficiency competitive with tube technology (55% demonstrated)

MW power capability

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• Option to upgrade existing systems

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- Wall Plug efficiency competitive with tube technology (55% demonstrated)
- Highly robust to VSWR mismatch
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- MW power capability
Reports from events, conferences and meetings

**FCC Physics and Experiments Workshop**

**Circular colliders eye Higgs self-coupling**

Physics beyond the Standard Model must exist, to account for dark matter, the smallness of neutrino masses and the dominance of matter over antimatter in the universe; but we have no real clue of its energy scale. It is also widely recognised that new and more precise tools will be needed to be certain that the 125 GeV boson discovered in 2012 is indeed the particle postulated by Brout, Englert, Higgs and others to have modified the base potential of the whole universe, thanks to its coupling to itself, liberating energy for the masses of the W and Z bosons.

To tackle these big questions, and others, the Future Circular Collider (FCC) study, launched in 2014, proposed the construction of a new 100 km circular tunnel to first host a high-intensity frontier 90 to 365 GeV e+e− collider (FCC-ee), and then an energy-frontier (> 100 TeV) hadron collider, which could potentially also allow electron–hadron collisions. Potentially following the High-Luminosity LHC in the late 2030s, FCC-ee would provide $5 \times 10^{12}$ Z decays – over five orders of magnitude more than the full LEP era, followed by $10^8$ W pairs, $10^6$ Higgs bosons (ZH events) and $10^6$ top-quark pairs. In addition to providing the highest parton centre-of-mass energies foreseeable today (up to 40 TeV), FCC-hh would also produce more than $10^{13}$ top quarks and W bosons, and 50 billion Higgs bosons per experiment.

**Rising to the challenge**

Following the publication of the four-volume conceptual design report and submissions to the European strategy discussions, the third FCC Physics and Experiments Workshop was held at CERN from 13 to 17 January, gathering more than 250 participants for 115 presentations, and establishing a considerable programme of work for the coming years. Special emphasis was placed on the feasibility of theory calculations matching the experimental precision of FCC-ee. The theory community is rising to the challenge. For example, special emphasis was placed on the feasibility of theory calculations matching the experimental precision of FCC-ee. The theory community is rising to the challenge.

**Rhyming couplings**

Delegates at the FCC workshop in January explored effective field theories for high-mass new physics that decouples as $1/M^2$. This working diagram shows correlations (connection) and achievable precisions (water ring) for modified Higgs and electroweak couplings at candidate next-generation $e^+e^-$ colliders (arXiv:1907.04311). Many correlations vanish when hadron-collider results are added. (Credit: J de Blas et al.)
Physicists cannot refrain from investigating improvements

The latest edition of Colourful physics: The LHC and RHIC heavy ions dovetail in Wuhan

**Quark Matter 2019**

**Fundamental understanding** More than 150 participants discussed the latest results of the high-temperature programmes at the LHC and RHIC.

**LHC** and **RHIC** heavy ions dovetail in Wuhan

The latest conference on Ultrarelativistic Nucleus–Nucleus Collisions, also known as “Quark Matter”, took place in Wuhan, China, in November. More than 800 participants discussed the latest results of the heavy-ion programmes at the Large Hadron Collider and at Brookhaven’s Relativistic Heavy-Ion Collider (RHIC), as well as the most recent theoretical developments. The focus of these studies is the fundamental understanding of strongly interacting matter at extremes of temperature and density. In these conditions, which also characterise the possible subsequent hadrons, the quark–gluon plasma must be formed. Delegates discussed solutions for vertexing, tracking and calorimetry during a 2-pole run at FCC-ee, where data acquisition and trigger electronics would be confronted with visible 2 decays at 7 TeV, all of which would have to be recorded in full detail. A new subject was REdiS (Identification at energies and angles not accessible — a consequence of the strategy process, during which considerable interest was expressed in the flavour-physics programme at FCC-ee).

The January meeting showed that physicists cannot refrain from investigating improvements, in spite of the impressive statistics offered by the baseline design of FCC-ee. Increasing the number of interaction points from two to four is a promising way to nearly double the total detection of luminosity for extra-high power consumption, but construction costs and compatibility with a possible subsequent hadron collider must be determined. The conference discussed at the workshop aims to improve both luminosity (by a factor of 10) and energy reach (by improving FCC-ee into a 16 km energy-recovery linac). The cost, and how well this would actually work, are yet to be established. Finally, a tantalising possibility is to produce the Higgs boson directly in the s-channel: $ee \rightarrow H$, sitting exactly at the centre-of-mass energy equal to that of the Higgs boson. This would allow unique access to the tiny coupling of the Higgs boson to the electron. As the Higgs width ($\pm 2 MeV$ in the Standard Model) is more than 20 times smaller than the natural energy spread of the beam, this would require a beam manipulation called monochromatisation and a careful running procedure, which a task force was nominated to study.

The ability to precisely probe the self-coupling of the Higgs boson is the keystone of the FCC-physics programme. As a result, this self-interaction is the key to the electroweak phase transition, and could have important cosmological implications. Building on the solid foundation of precise and model-independent measurements of Higgs couplings at FCC-ee, FCC-ih would be able to access Hgg, Hgg, HZ and HWW couplings at sub-per-cent precision. Further study of double Higgs production at FCC-ih shows that a measurement of the Higgs self-coupling could be done at a statistical precision of a couple of percent with the full statistics, which is to say that after the first few years of running the precision will already have been reduced to below 10%. This is much faster than previously realised, and definitely confirmed the highlight of the workshop.

**Panagiotis Charitos** CERN and University of Patras

**Aleksi Kurkela** CERN and INFN Padova

**Andrea Dainese** INFN Padova, CERN and Stavanger University

**Andreas Drees** CERN

**Van Diest** INFN Padova

**Gianfranco Zuz款** INFN Padova

**Maria Blomquist** JU/Rike, CERN, INFN Padova, INFN Genova, INFN Bologna, INFN Roma, INFN Catania and INFN Padova

**Alain Blondel** EPHE Paris, CERN, INFN Genova and Panagiotis Charitos CERN.
Cosmologists confer with quantum theorists

The sixth Cosmology and the Quantum Vacuum conference attracted about 60 theoreticians to the Institute of Space Sciences in Barcelona from 5 to 7 March. This year the conference marked the 70th birthday of Spanish theorist Emilio Elizalde. He is a well known specialist in mathematical physics, field theory and gravity, with more than 300 publications and three monographs on the Casimir effect and zeta regularisation.

These meetings bring together researchers who study theoretical cosmology and various aspects of the quantum vacuum such as the Casimir effect. This effect manifests itself as an attractive force that appears between plates which are extremely close to each other. As it is related to the quantum vacuum, it is expected to be important in cosmology as well, giving a kind of effective induced cosmological constant.

Manuel Asorey (Zaragoza), Mike Bordag (Leipzig) and Aram Saharian (Erevan) discussed various aspects of the Casimir effect and zeta regularisation. Joseph Buchbinder gave a review of one-loop effective actions in supergravity theories. Conformal quantum gravity and quantum electrodynamics in de Sitter space were presented by Enrique Alvarez (Madrid) and Drazen (Erevan) (Brussels), respectively.

Joint German–Armenian internship in accelerator physics

Yerevan hosts early-career accelerator internship

The inaugural Joint German–Armenian internship in accelerator physics was held at the CANDLE Institute in Yerevan, Armenia, from 29 September to 1 October 2019. In this first round, 12 undergraduates of eight experimental stations recently submitted their applications to be considered for the internship.

Working together

German and Armenian undergraduates teamed up to tackle accelerator-physics experiments in Yerevan. The goal of the programme of week-long internships, which was supported by the German Federal Foreign Office, is to integrate accelerator physics and technology into undergraduate courses, and provide students with an early experience of international collaboration. It will make use of eight experimental stations recently set up to foster young academics learning accelerator technology in Armenia. CANDLE has proposed third-generation synchrotron-radiation facility in Armenia. As a first step towards its realisation, AREAL, an ultrashort laser-driven electron accelerator, has been constructed. The next steps are 5-band lasing acceleration up to 20–40 MeV and the generation of coherent and tunable X-rays in an undulator.
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Our product range includes:
- Metal sheathed mineral insulated cables, including thermocouple cable.
- Electric heaters
- Temperature measurement assemblies from 1.5K to 2300°C

Electric heaters

Our AerOrod electric heaters are offered in a wide range of sizes, styles and terminations. Among the list of benefits are:

- Flexibility
- Corrosion resistance
- High-watt density
- Long life in service
- Fast time response

We also manufacture cryogenic assemblies for temperatures down to 1.5K.

The assemblies that we manufacture are suitable for 1.5K to 2300°C and diameters of 0.08 mm to 26 mm.

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Temperature sensors can be manufactured to customers’ specific designs, or to our standard designs with a variation of cold end terminations and hot junctions, also including multipoint assemblies, Okazaki can also provide Hoskins 2300º in Type K and Type N, which are very accurate at a higher temperature compared to the standard cable.

Magnetic assemblies

Magnetic sensors in a fusion experiment. In the “configuration” column, m refers to the number of the sensors in the poloidal and toroidal direction, respectively, and e indicates the numbers of the sensors along poloidal or toroidal path, except for (progressive code for listed current).

<table>
<thead>
<tr>
<th>Type of sensor</th>
<th>Configuration</th>
<th>Physical property</th>
<th>Magnetic property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic probe</td>
<td>m=1, e=1 (Tiplate)</td>
<td>High frequency</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>Magnetic probe</td>
<td>m=1, e=1 (Tiplate)</td>
<td>Low frequency</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>Magnetic probe</td>
<td>m=1, e=1 (Tiplate)</td>
<td>Medium frequency</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>Magnetic probe</td>
<td>m=1, e=1 (Tiplate)</td>
<td>High frequency</td>
<td>Magnetic field</td>
</tr>
</tbody>
</table>

Mineral insulated cables (MI)

We manufacture a comprehensive range of metal-sheathed MI cables with an operating range from 1.5K to 2300°C. Both coax and triaxial cables can be supplied with hermetically sealed connectors such as BNC or SMA. Cables can be supplied with internal twisted conductors to avoid electrical noise. The cables are good for various adverse conditions and environments, including bake out, nuclear, UHV and Rogowski coils.

Electric heaters

Our AerOrod electric heaters are offered in a wide range of sizes, styles and terminations. Among the list of benefits are:

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- High-watt density
- Long life in service
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We also manufacture cryogenic assemblies for temperatures down to 1.5K.

The assemblies that we manufacture are suitable for 1.5K to 2300°C and diameters of 0.08 mm to 26 mm.

Unlocking the puzzle

The 3D structure of the main SARS-CoV-2 protease – an enzyme much smaller than the virus, which goes on to process the viral proteins that have been made, allowing the cell’s life cycle to continue. The organisation of alpha helices (coils) and beta sheets (arrows) is often referred to as the secondary structure of the protein, with the primary and tertiary structures being the amino-acid sequence and the 3D shape of the protein, respectively. (Credit: D Owen/Diamond Light Source.)

We will throw a chemical spanner in the works, blocking the virus’s ability to replicate and limiting the spread of the disease. Coronavirus is the family of viruses responsible for the common cold, MERS, SARS and others. Novel coronavirus, aka SARS-CoV-2, is the newly discovered type of coronavirus and COVID-19 is the disease that it causes.

Call to arms

On 26 January, Diamond’s life-sciences director, Dave Stuart, received a phone call from structural biologist Zhe Rao of ShanghaiTech University in China. Rao, along with his colleague Haitao Yang, had solved the structure of the main SARS-CoV-2 protease with a covalent inhibitor using the Shanghai Synchrotron Radiation Facility (SSRF) in China. Furthermore, they had made the solution freely and publicly available on the worldwide Protein Data Bank.
During the phone call, Rao informed Stuart that their work had been halted by a scheduled shutdown of the SSRF. The Diamond team rapidly mobilised. Since shipping biological samples from Shanghai at the height of the coronavirus in China was expected to be problematic, the team at Diamond ordered the synthetic gene. A synthetic gene can be generated provided the ordering of T, A, C and G nucleotides in the DNA sequence is known. That synthetic gene can be genetically engineered into a bacterium, in this case Escherichia coli, which reads the sequence and generates the coronavirus protease in large enough quantities for the researchers at Diamond to determine its structure and screen for potential inhibitors.

Eleven days later on 10 February, the synthetic gene arrived. At this point, Martin Walsh, Diamond’s deputy director of life sciences, and his team (consisting of Claire Strain-Damerell, Petra Luksic and David Owen) dropped everything. With the gene in hand, the group immediately set up experimental trials to try to generate protein crystals. In order to determine the atomic structure, they needed a crystal containing millions of proteins in an ordered grid-like structure. X-ray radiation bright enough for the rapid analysis of protein structures can only be produced by a synchrotron light source. The X-rays are directed and focused down a beamline onto a crystal and, as they pass through it, they diffract. From the diffraction pattern, researchers can work backwards to determine the 3D electron density maps and the structure of the protein. The result is a complex, curled ribbon-like structure with an intricate mess of twists and turns of the protein chain.

The Diamond team set up numerous trials trying to find the optimum conditions for crystallisation of the SARS-CoV-2 protease to occur. They modified the pH, the precipitating compounds, chemical composition, protein to solution ratio... every parameter they could vary, they did. Every day they would produce a few thousand trials, of which only a few hundred would produce crystals, and even fewer would produce crystals of sufficient quality. Within a few days of receiving the gene, the first crystals were being produced. They were paltry and thin crystals but large enough to be tested on one of Diamond’s macromolecular crystallography beamlines.

Watching the results come through, Diamond postdoc David Owen described it as the first moment of intense excitement. With crystals that appeared to be “flat like a car wind-shield,” he was dubious as to whether they would diffract at all. Nevertheless, the team placed the crystals in the beamline with a resignation that quickly turned into intense curiosity as the results started appearing before them. At that moment Owen remembers his doubts fading, as he thought, “this might just work!” And work it did. In fact, Owen recalls, “they diffracted beautifully.”

In addition to allowing the structure of tens of thousands of compounds, chemical composition, protein to solution ratio... each step they learn something new about the virus and how to target it.
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<table>
<thead>
<tr>
<th>NEW Best Cyclotrons</th>
<th>1–3 MeV</th>
<th>Deuterons for materials analysis (Patent Pending)</th>
</tr>
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<tbody>
<tr>
<td>1–150 MeV</td>
<td></td>
<td>For Proton Therapy (Patent Pending)</td>
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<tr>
<td>1–150 MeV</td>
<td></td>
<td>High current proton beams for neutron production and delivery (Patent Pending)</td>
</tr>
<tr>
<td>Best 15p Cyclotron</td>
<td>15 MeV</td>
<td>Proton only, capable of high current up to 1000 Micro Amps, for medical radioisotopes</td>
</tr>
<tr>
<td>Best 20u/25p Cyclotrons</td>
<td>20, 25–15 MeV</td>
<td>Proton only, capable of high current up to 1000 Micro Amps, for medical radioisotopes</td>
</tr>
<tr>
<td>Best 30u/35p Cyclotrons</td>
<td>30, 35–15 MeV</td>
<td>Proton only, capable of high current up to 1000 Micro Amps, for medical radioisotopes</td>
</tr>
<tr>
<td>Best 70p Cyclotron</td>
<td>70–35 MeV</td>
<td>Proton only, capable of high current up to 1000 Micro Amps, for medical radioisotopes</td>
</tr>
<tr>
<td>Best 150p Cyclotron</td>
<td>70–150 MeV</td>
<td>For all Medical Treatments including Benign and Malignant Tumors for Neurological, Eye, Head/Neck, Pediatric, Lung Cancers, Vascular/Cardiac/Stenosis/Ablation, etc. (Patent Pending)</td>
</tr>
</tbody>
</table>

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TAMING THE SUPERCONDUCTORS OF TOMORROW

The imminent deployment of accelerator magnets based on the superconductor Nb$_3$Sn for the high–luminosity LHC serves as a springboard to future accelerator magnets for fundamental exploration, writes Luca Bottura.

**The steady increase in the energy of colliders during the past 40 years, which has fuelled some of the greatest discoveries in particle physics, was possible thanks to progress in superconducting materials and accelerator magnets. The highest particle energies have been reached by proton–proton colliders, where beams of high–rigidity travelling on a piecewise circular trajectory require magnetic fields largely in excess of those that can be produced using resistive electromagnets. Starting from the Tevatron in 1983, through HERA in 1991, RHIC in 2000 and finally the LHC in 2008, all large–scale hadron colliders were built using superconducting magnets.**

Large superconducting magnets for detectors are just as important to high–energy physics experiments as beamline magnets are to particle accelerators. In fact, detector magnets are where superconductivity took its stronghold, right from the infancy of the technology in the 1960s, with major installations such as the large bubble–chamber solenoid at Argonne National Laboratory, followed by the giant BEBC solenoid at CERN, which held the record for the highest stored energy for many years. A long line of superconducting magnets has provided the magnetic fields for detectors of all large–scale high–energy physics colliders, with the most recent and largest realisation being the LHC experiments, CMS and ATLAS.

**Optimisation**

All past accelerator and detector magnets had one thing in common: they were built using composite Nb–Ti/Cu wires and cables. Nb–Ti is a ductile alloy with a critical field of 14.5 T and critical temperature of 9.2 K, made from almost equal parts of the two constituents. It was discovered to be superconducting in 1962 and its performance, quality and cost have been optimised over more than half a century of research, development and large–scale industrial production. Indeed, it is unlikely that the performance of the LHC dipole magnets, operated so far at 7 T, and expected to reach nominal conditions at 8.33 T, can be surpassed using the same superconducting material, or any foreseeable improvement of this alloy.

And yet, approved projects and studies for future circular machines are all calling for the development of superconducting magnets that produce fields beyond those produced for the LHC. These include the High–Luminosity LHC (HL–LHC), which is currently taking shape, and the Large Hadron Collider (LHC), in its final form it is brittle and cannot withstand large stress and strain without special precautions.

**The HL–LHC springboard**

To reach its main objective, to increase the levelled LHC luminosity of 10$^{34}$ cm$^{-2}$s$^{-1}$ in the interaction regions. These quadrupoles, currently being built and tested at CERN and Fermilab (see p7), are the main fruit of the 10–year US–DOE LHC Accelerator Research Program (US–LARP) – a joint venture between CERN, Brookhaven National Laboratory, Fermilab and Lawrence Berkeley National Laboratory. In addition, the increased beam intensity calls for collimators to be inserted in locations within the LHC “dispersion suppressor”, the portion of the accelerator where the regular magnet lattice is modified to ensure that off–momentum particles are centered in the interaction points. To gain the required space, standard arc dipoles will be substituted by dipoles of shorter length and higher field, approximately 11 T. As described earlier, such fields require the use of new materials. For the HL–LHC, the material of choice is the intermetallic compound of niobium and tin Nb$_3$Sn, which was discovered in 1954. Nb$_3$Sn has a critical field of about 37 T and a critical temperature of about 18 K, outperforming Nb–Ti by a factor of two. Though discovered before Nb–Ti, and exhibiting better performance, Nb$_3$Sn has not been used for accelerator magnets so far because in its final form it is brittle and cannot withstand large stress and strain without special precautions.

In fact, Nb$_3$Sn was one of the candidate materials considered for the LHC in the late 1980s and mid 1990s.
already at that time it was demonstrated that accelerator magnets could be built with Nb$_3$Sn, but it was also clear that the technology was complex, with a number of critical steps, and not ripe for large-scale production. A good 20 years of progress in basic material performance, cable development, magnet engineering and industrial process control was necessary to reach the present state, during which time the success of the production of Nb$_3$Sn for the ITER fusion experiment has given confidence in the credibility of this material for large-scale applications. As a result, magnet experts are now convinced that Nb$_3$Sn technology is sufficiently mature to satisfy the challenging field levels required by the HL-LHC.

**A difficult recipe**

The present manufacturing recipe for Nb$_3$Sn accelerator magnets consists of winding the magnet coil with glass-fibre insulated cables made of multi-filamentary wires that contain Nb and Sn precursors in a Ta matrix. In this form the cables can be handled and plastically deformed without breakage. The coils then undergo heat treatment, typically at a temperature of around 650 °C, during which the NbSn precursor elements react chemically and form the desired Nb$_3$Sn superconducting phase. At this stage, the reacted coil is extremely fragile and needs to be protected from any mechanical action. This is done by injecting a polymer, which fills the interstitial spaces among cables, and is subsequently cured to become a matrix of hardened plastic providing cohesion and support to the cables.

The above process, though conceptually simple, has a number of technical difficulties that call for up–down–the line engineering and production control. To give some examples, the texture of the electrical insulation, consisting of a few tenths of mm of glass fibre, needs to be able to withstand the high-temperature heat-treatment step, but also retain dielectric and mechanical properties at liquid-helium temperatures some 10°C lower. The superconducting wire also changes its dimensions by a few percent, which is orders of magnitude larger than the dimensional accuracy requested for field quality and therefore must be predicted and accommodated for by appropriate magnet and cooling design. The finished coil, even if it is made solid by the polymer cast, still remains stress and strain sensitive. The level of stress that can be tolerated without breakage can be up to 150 MPa, to be compared to the electromagnetic stress of optimised magnets operating at 12 T that can reach levels in the range of 100 MPa. This does not mean leave headroom for engineering margins and manufacturing tolerances. Finally, protecting high-field magnets from quenches, with their large stored energy, requires that the protection system has a very fast reaction – three times faster than at the LHC – and excellent noise rejection to avoid false trips related to flux jumps in the large Nb$_3$Sn filaments.

**The next jump**

The CERN magnet group, in collaboration with the US–DOE laboratories participating in the LHC Accelerator Upgrade Project, is in the process of addressing these and other challenges, finding solutions suitable for a magnet production on the scale required for the HL–LHC. A total of six 11 T dipole coils (each about 6 m long) and 20 inner triplet quadrupoles (up to 7.5 m long) are in production at CERN and in the US, and the first magnets have been tested (see “Power couple” image above). And yet, it is clear that we are not ready to extrapolate such production on a much larger scale, i.e. to the thousands of magnets required for a possible future hadron collider such as FCC–hh. This is exactly why the HL–LHC is so critical for the development of high-field magnets for future accelerators: not only will it be the first demonstration of Nb$_3$Sn magnets in operation, steering and colliding beams, but by building it on a scale that can be managed at the laboratory level we have a unique opportunity to identify all the areas of necessary development, and the open technology issues, to allow the next jump. Beyond its prime physics objective, the HL–LHC is therefore the springboard to the future of high-field accelerator magnets.

**Climb to higher peak fields**

For future circular colliders, the target dipole field has been set at 16 T for FCC–hh, allowing proton–proton collisions at an energy of 100 TeV, while China’s proposed pp collider (SppC) aims at a 12 T dipole field, to be followed by a 20 T field. Are these field levels realistic? And based on which technology? Looking at the dipole fields produced by Nb$_3$Sn development magnets during the past 40 years (figure 1), fields up to 16 T have been achieved in R&D demonstrators, suggesting that the FCC target can be reached. In 2008 “FRESCA3” – a large-aperture (100 mm) dipole developed over the past decade through a collaboration between CERN and CEAC-Saclay in the framework of the European Union project EuCARD – attained a record field of 14.7 T at 1.9 K (13.9 T at 4.5 K). Another very recent result, obtained in June 2019, is the successful test at Fermilab by the US Magnet Development Programme (MDP) of a “cos-theta” dipole with an aperture of 60 mm called MD5PCT (see “Cos-theta 1” image above), which reached a field of 14.1 T at 4.5 K (CERN COURIER September/October 2019 p7). In February this year, the CERN magnet group set a new Nb$_3$Sn record with an enhanced racetrack model coil eRMC, developed in the framework of the FCC study. The setup, which consists of two racetrack coils assembled without mid-plane gap (see “Racetrack demo” image on p9), produced a 16.3 T central field at 1.9 K and a 16.7 T peak field on the coil, which is the highest ever reached for a magnet of this configuration. The magnet was also tested at 4.5 K and reached a field of about 16.7 T (see p7). These results send a positive signal for the feasibility of next-generation hadron colliders. A field of 16 T seems to be the upper limit that can be reached with a Nb$_3$Sn magnet. Indeed, though the conductor performance can be improved, as demonstrated by recent results obtained at the National High Magnetic Field Laboratory (NHMFL), Ohio State University and Fermilab within the scope of the US–MDP, this is the point at which the material itself will run out of steam.

As for any other superconductor, the critical current density drops as the temperature 1000 °C lower. The superconducting wire also changes its dimensions by a few percent, which is orders of magnitude larger than the dimensional accuracy requested for field quality and therefore must be predicted and accommodated for by appropriate magnet and cooling design. The finished coil, even if it is made solid by the polymer cast, still remains stress and strain sensitive. The level of stress that can be tolerated without breakage can be up to 150 MPa, to be compared to the electromagnetic stress of optimised magnets operating at 12 T that can reach levels in the range of 100 MPa. This does not mean leave headroom for engineering margins and manufacturing tolerances. Finally, protecting high-field magnets from quenches, with their large stored energy, requires that the protection system has a very fast reaction – three times faster than at the LHC – and excellent noise rejection to avoid false trips related to flux jumps in the large Nb$_3$Sn filaments.

**The HL–LHC is the springboard to the future of high-field accelerator magnets**

The high-field magnets currently under construction have a peak field of 11 T, which is not far from the 14.1 T achieved at Fermilab. As for the HL–LHC, the required peak field is some 16 T. It is clear that we are not yet ready to extrapolate such production on a much larger scale, i.e. to the thousands of magnets required for a possible future hadron collider such as FCC–hh. This is exactly why the HL–LHC is so critical for the development of high-field magnets for future accelerators: not only will it be the first demonstration of Nb$_3$Sn magnets in operation, steering and colliding beams, but by building it on a scale that can be managed at the laboratory level we have a unique opportunity to identify all the areas of necessary development, and the open technology issues, to allow the next jump. Beyond its prime physics objective, the HL–LHC is therefore the springboard to the future of high-field accelerator magnets.

**Magnet experts are now convinced that Nb$_3$Sn technology is sufficiently mature to satisfy the challenging field levels required by the HL–LHC**

Hence, the HL–LHC is the springboard to the future of high-field accelerator magnets.
The potential of high-temperature superconductivity to make a quantum leap is enormous. As the limit of Nb3Sn comes into view, we see history repeating itself: the only way to push beyond it to higher fields will be to resort to new materials. Since Nb3Sn is technically the low-temperature superconductor (LTS) with the highest performance, this will require a shift to high-temperature superconductors.

High-temperature superconductivity (HTS), discovered in 1986, is of great relevance in the quest for high fields. When operated at low temperature (the same liquid-helium range as LTS), HTS materials have exceedingly large critical fields in the range of 10 T and above. Yet, only recently has the material and magnet engineering reached the point where HTS materials can generate magnetic fields in excess of LTS ones. The first user applications coming to fruition are ultra-high-field MRI magnets, as recently delivered by Bruker Biospin, and the intense magnetic fields required by materials science, for example the 32 T all-superconducting user facility built at NHMFL.

As for their application in accelerator magnets, the potential of HTS to make a quantum leap is enormous. But it is also clear that the tough challenges that needed to be solved for Nb3Sn will escalate to a formidable level in HTS accelerator magnets. The magnetic force scales with the square of the field produced by the magnet, and for HTS the problem will no longer be whether the material can carry the super-currents, but rather how to manage stresses approaching structural material limits. Stored energy has the same square–dependence on the field, and quench detection and protection in large HTS magnets is still a spectacular challenge. In fact, HTS magnet engineering will probably differ so much from the LTS paradigm that it is fair to say that we do not yet know whether we have identified all the issues that need to be solved. HTS is the most exciting class of material to work with; the new world for brave explorers. But it is still too early to count on practical applications, not least because the production cost for this rather complex class of ceramic materials is about two orders of magnitude higher than that of good-old Nb–Ti.

It is thus logical to expect the near future to be based mainly on Nb3Sn. With the first demonstration to come imminently in the LHC, we need to consolidate the technology and bring it to the maturity necessary on a large-scale production. This may take place in steps – exploring 12 T territory first, while seeking the solutions to the challenges of ultimate Nb3Sn performance towards 16 T – and could take as long as a decade. For China’s 9 T, iron-based HTS has been suggested as a route to 20 T dipoles. This technology study is interesting from the point of view of the material, but the magnet technology for iron-based superconductors is still rather far away. Meanwhile, nurtured by novel ideas and innovative solutions, HTS could grow from the present state of a material of great potential to its first applications. The LHC already uses HTS tapes (based on Bi-2223) for the superconducting part of the current leads. The HL-LHC will go further, by pioneering the use of MgB2, to transport the large currents required to power the new magnets over considerable distances (thereby shielding power converters and making maintenance much easier). The grand challenges posed by HTS will likely require a revolution rather than an evolution of magnet technology, and significant technology advancement leading to large-scale application in accelerators can only be imagined on the 25-year horizon.

Road to the future
There are two important messages to retain from this rather simplified perspective on high-field magnets for accelerators. Firstly, given the long lead times of this technology, and even in times of uncertainty, it is important to maintain a healthy and ambitious programme so that the next step in technology is at hand when critical decisions on the accelerators of the future are due. The second message is that with such long development cycles and very specific technology, it is not realistic to rely on the private sector to advance and sustain the specific demands of HEP. In fact, the business model of high-energy physics is very peculiar, involving long investment times followed by short production bursts, and not sustainable by present industry standards. So, without taking the place of industry, it is crucial to secure critical know-how and infrastructure within the field to meet development needs and ensure the long-term future of our accelerators, present and to come.

Floating into the process measurement technology
The model BGN/BGF flow metres of KOBOLO Messring GmbH from Hofheim, which function in accordance with the float measuring principle, make dependable flow measurement of liquids and gases even in difficult application cases possible. The robust all-metal devices can also be used for metering and monitoring various media in addition to flow measurement. Various measuring ranges, from 0.5 l/h to 130,000 l/h, offer an enormous application spectrum, even in high-pressure and high-temperature areas. The current measurement value is transferred to the clearly legible display by means of magnets without contact and without a risk of disconnection.

Due to its special design with a measuring ring and conical float, a guide rod for the float can be omitted, which has tremendous advantages; the float has almost no friction loss and the danger of contamination in the internal measurement space is greatly reduced. A linear characteristic curve also results from the optimised form of the float.

In addition to the usual vertical type of installation (flow from the bottom to the top), the measuring device, model BGF, offers the possibility of horizontal installation or vertical flow from top to bottom. The devices can be optionally equipped with a spring stop and an attenuation. This buffers pressure spikes and prevents indicator flutter.

Various transducers are available for the evaluation of the measurement results. In addition to the 4–20 mA output signal, NAMUR-contacts and HART protocol, as well as Profield PA can be selected. There is also a design with a counter.

As to the potential of high-temperature superconductivity, the question of whether or not the business model will be sustainable is the real issue. Without economic incentives, the business model is not sustainable by present industry standards.
A high-energy muon collider is receiving renewed attention as a possible frontier-exploration machine. Daniel Schulte, Nadia Pastrone and Ken Long describe the possible paths ahead.

High-energy particle colliders have proved to be indispensable tools in the investigation of the nature of the fundamental forces. The LHC, at which the discovery of the Higgs boson was made in 2012, is a prime recent example. Several major projects have been proposed to push our understanding of the universe once the LHC reaches the end of its operations in the late 2030s. These have been the focus of discussions for the soon-to-conclude update of the European strategy for particle physics. An electron–positron Higgs factory that allows precision measurements of the Higgs boson’s couplings and the Higgs potential seems to have garnered consensus as the best machine for the near future. The question is: what type will it be?

Today, mature options for electron–positron colliders exist: the Future Circular Collider (FCC-ee) and the Compact Linear Collider (CLIC) proposals at CERN; the International Linear Collider (ILC) in Japan; and the Circular Electron–
The unique potential of a multi-TeV muon collider deserves a strong commitment to fully demonstrate its feasibility.

Positron Collider (CEPC) in China. FCC-ee offers very high luminosity at the required centre-of-mass energies. However, the maximum energy that can be reached is limited by the emission of synchrotron radiation in the collider ring, and corresponds to a centre-of-mass energy of 365 GeV for a 100-km-circumference machine. Linear colliders accelerate particles without the emission of synchrotron radiation, and hence can reach higher energies. The ILC would initially operate at 250 GeV, extendable to 1 TeV, while the highest energy proposal, CLIC, has been designed to reach 3 TeV. However, there are two crucial challenges that must be overcome to go to higher energies with a linear machine: first, the beam has to be accelerated to full energy in a single pass through the main linac; and, second, it can only be used once in a single collision. At higher energies, the linac has to be longer (around 50 km) for a 1 TeV ILC and 2 TeV CLIC, and is therefore more costly, while the single collision of the beam also limits the luminosity that can be achieved for a reasonable power consumption.

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An ingenious solution to overcome these issues is to replace the electrons and positrons with muons and anti-muons. In a muon collider, fundamental particles that are not constituents of ordinary matter would collide for the first time. Being 200 times heavier than the electron, the muon emits about two billion times less synchrotron radiation. Rings can therefore be used to accelerate muon beams efficiently and to bring them into collision repeatedly. Also, more than one experiment can be served simultaneously to increase the amount of data collected. Provided the technology can be mastered, it appears possible to reach a ratio of luminosity to beam power that increases with energy. The catch is that muons live on average for 2.2 μs, which leads to a reduction in the number of muon collisions induced by about an order of magnitude before they enter the storage ring. One therefore has to be rather quick in producing, accelerating and colliding the muons; this rapid handling provides the main challenges of such a project.

Precision and discovery

The development of a muon collider is not as advanced as the other lepton–collider options that were submitted to the European strategy process. Therefore the unique potential of a multi-TeV muon collider deserves a strong commitment to fully demonstrate its feasibility. Extensive studies have been submitted to the strategy update show that a muon collider in the multi-TeV energy range would be competitive both as a precision and as a discovery machine, and that a full effort by the community could demonstrate that a muon collider operating at a few TeV can be ready on a time scale of about 20 years. While the full physics capabilities at high energies remain to be quantified, and provided the beam energy and detector resolutions at a muon collider can be maintained at the parts-per-mille level, the number of Higgs bosons produced would allow the Higgs’ couplings to fermions and bosons to be measured with extraordinary precision. A muon collider operating at lower energies, such as those for the proposed FCC-ee (250–365 GeV) or stage-one CLIC (380 GeV) machines, has not been studied in detail since the beam-induced background will be harsher and careful optimisation of machine parameters would be required to reach the needed luminosity. Moreover, a muon collider generating a centre-of-mass energy of 10 TeV or more and with a luminosity of the order of 10^{35} cm^{-2} s^{-1} would allow a direct measurement of the trilinear and quadra-linear self-couplings of the Higgs boson, enabling a precise determination of the shape of the Higgs potential. While the precision on Higgs measurements achievable at muon colliders is not yet sufficiently evaluated to perform a comparison to other future colliders, theorists have recently shown that a muon collider is competitive in measuring the trilinear Higgs coupling and that it could allow a determination of the quartic self-coupling that is significantly better than what is currently considered attainable at other future colliders. Owing to the muon’s greater mass, the coupling of the muon to the Higgs boson is enhanced by a factor of about 10^5 compared to the electron–Higgs coupling. To exploit this, previous studies have also investigated a muon collider operating at a centre-of-mass energy of 10–100 GeV (the Higgs pole) to measure the Higgs–boson line–shape. The specifications for a such a machine are demanding as it requires knowledge of the beam–energy spread at the level of a few parts in 10^{7}.

Half a century of ideas

The idea of a muon collider was first introduced 50 years ago and formally developed by Alexander Skrinsky and David Neuffer until the Muon Collider Collaboration became a formal entity in 1997, with more than 100 physicists from 20 institutions in the US and a few more from Russia, Japan and Europe. Brookhaven’s Bob Palmer was a key figure in driving the concept forward, leading the outline of a “complete scheme” for a muon collider in 1997. Exploratory work towards a muon collider and neutrino factory was also carried out at CERN around the turn of the millennium. It was only when the Muon Accelerator Program (MAP), directed by Mark Palmer of Brookhaven, was formally approved in 2011 in the US, that a systematic effort started to develop and demonstrate the concepts and critical technologies required to produce, capture, condensation, accelerate and store intense beams of muons for a muon collider on the Fermilab site. Although MAP was wound down in 2012, it generated a reservoir of expertise and enthusiasm that the current international effort can build on. It was only when the Muon Accelerator Program was formally approved in 2011 in the US that a systematic effort started to develop and demonstrate the concepts and critical technologies required to produce, capture, condensation, accelerate and store intense beams of muons for a muon collider on the Fermilab site. Although MAP was wound down in 2012, it generated a reservoir of expertise and enthusiasm that the current international effort can build on.

The alternative approach to a muon collider, proposed in 2013 by Mario Antonelli of INFN–LNF and Pantaleo Raimondi of the ESRF, avoids a specific cooling apparatus. Instead, the Low Emissivity Muon Accelerator (LEMLA) scheme would send 45 GeV positrons into a target where they collide with electrons to produce muon pairs with a very small phase space (the energy and the electron and positron–mass frame are small, so little transverse momentum can be generated). The challenge with LEMLA is that the probability for a positron to produce a muon pair is exceedingly low, requiring an unprecedented positron–beam current and inducing a high stress in the target system. The muon beams would be cooled in a chain of low-Z absorbers in which they lose energy by ionising the matter, reducing their phase space volume, the lost energy would then be replaced by acceleration. This is so far the only concept that can achieve cooling within the timeframe of the muon lifetime. The beams would be accelerated in a sequence of linacs and rings, and injected at full energy into the collider ring. A fully integrated conceptual design for the MAP concept remains to be developed.

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Muons that pass through MICE are seen to migrate from high to low phase space, with an enhancement of the number at low amplitudes providing evidence of ionisation cooling. The effect in a single absorber is stronger for higher initial-emittance beams (3 mm) than for lower and intermediate configurations (4 and 6 mm). The results are shown for beams with a momentum of 140 MeV.

bunches as possible before they are accelerated and collider in a fashion similar to the proton-driven scheme of MAP. The low emittance of the LEMMA beams potentially to fit into the same magnet apertures. Another possibility is to use a fast-ramping synchrotron: when the beam is injected at low energy it is kept on its orbit by operating the bending magnets at low field. The beam is then accelerated and the strength of the bends is increased accordingly until the beam can be extracted into the collider. It is very challenging to ramp superconducting magnets at the required speed, however. Normal-conducting magnets can do better, but their magnetic field is limited. As a consequence, the accelerator ring has to be larger than the collider ring, which can use superconducting magnets at full strength without the need to ramp them. Systems that combine static magnets (mainly photons, electrons and neutrons) may be produced when muons decay also help to improve the robustness of the bends against lead to a quench (whereby the magnet suddenly loses its magnetic field, and also from the machine elements. Their type, flux and characteristics therefore strongly depend on the machine lattice and machine elements. Their type, flux and characteristics thus must be studied in detail since it strongly depends on the beam energy at the collision point and on the design of the interaction region. The background particles reaching the detector are mainly produced by the interactions between the decay products of the muon beams and the machine elements. Their type, flux and characteristics that ionisation cooling occurs with a liquid-hydrogen or lithium-hydride absorber in place. Data from the experiment were found to be well described by a Granić-based simulation, validating the designs of ionisation cooling channels for an eventual muon collider. The most important step towards a muon collider would be to design and build a cooling module combining the cavities with the magnets and absorbers, and to achieve that the energy. This effort could profit from tests at Fermilab of accelerating cavities that can operate in a very high magnetic field, and also from the excellent knowledge of the beam composition and the quality of the beam crossing, due to the different paths taken by the beam–induced background and the muons, new-generation Δη silicon sensors that allow exploitation of the time distribution will be needed to remove a very high occupancy in the first layers of the tracking system, which impacts the detector performance. Since the arrival time in each sub-detector is asynchronous with respect to the beam crossing, due to the different paths taken by the beam–induced background and the muons, new-generation Δη silicon sensors that allow exploitation of the time distribution will be needed to remove a significant fraction of the background hits.

Collider ring

The collider ring itself is another challenging aspect of a muon collider. Since the charge of the injected beams decreases over time due to the random decays of muons, superconducting magnets with the highest possible field need to be minimised to the ring circumference and thus maximise the average number of collisions. A larger muon energy makes it harder to bend the beam and thus requires a larger ring circumference. Fortunately, the lifetime of the muon also increases with its energy, which fully compensates for this effect. Dipole magnets with a field of 10 T would allow the muons to survive about 2000 turns. Such magnets are about 12 m long, which are about 20% more powerful than those in the LHC, could be built from niobium-tin (Nb3Sn) as used in the new-generation for the precise measurement of neutrino-scattering and the search for sterile neutrinos – can provide the ideal test-bed for the technologies required to deliver a muon collider. A collision of muons of energy 1 TeV in the LHC, could be built from niobium-tin (Nb3Sn) as used in the new-generation for the precise measurement of neutrino-scattering and the search for sterile neutrinos – can provide the ideal test-bed for the technologies required to deliver a muon collider.

Material can be placed, or designs where the magnets have no superconductor in the plane of the beam. Future magnets based on high-temperature superconductors could also help to improve the robustness of the bends against this problem since they can tolerate a higher heat load. Other systems necessary for a muon collider are only seemingly more conventional. That being the case for the beam to the collision energy is a prime example. It has to ramp the beam energy in a period of milliseconds or less, which means the beam has to circulate at very different energies through the same magnets. Several solutions are being explored. One, featuring a so-called fixed–field alternating–gradient ring, uses a complicated system of magnets that enables particles at a wider than normal range of energies to fly on different orbits that are close enough to allow the beams to catch up. Another possibility is to use a fast-ramping synchrotron: when the beam is injected at low energy it is kept on its orbit by operating the bending magnets at low field. The beam is then accelerated and the strength of the bends is increased accordingly until the beam can be extracted into the collider. It is very challenging to ramp superconducting magnets at the required speed, however. Normal-conducting magnets can do better, but their magnetic field is limited. As a consequence, the accelerator ring has to be larger than the collider ring, which can use superconducting magnets at full strength without the need to ramp them. Systems that combine static magnets (mainly photons, electrons and neutrons) may be produced when muons decay also help to improve the robustness of the bends against lead to a quench (whereby the magnet suddenly loses its magnetic field, and also from the machine elements. Their type, flux and characteristics therefore strongly depend on the machine lattice and machine elements. Their type, flux and characteristics thus must be studied in detail since it strongly depends on the beam energy at the collision point and on the design of the interaction region. The background particles reaching the detector are mainly produced by the interactions between the decay products of the muon beams and the machine elements. Their type, flux and characteristics thus must be studied in detail since it strongly depends on the beam energy at the collision point and on the design of the interaction region. The background particles reaching the detector are mainly produced by the interactions between the decay products of the muon beams and the machine elements. Their type, flux and characteristics thus must be studied in detail since it strongly depends on the beam energy at the collision point and on the design of the interaction region. The background particles reaching the detector are mainly produced by the interactions between the decay products of the muon beams and the machine elements. Their type, flux and characteristics thus must be studied in detail since it strongly depends on the beam energy at the collision point and on the design of the interaction region. The background particles reaching the detector are mainly produced by the interactions between the decay products of the muon beams and the machine elements. Their type, flux and characteristics thus must be studied in detail since it strongly depends on the beam energy at the collision point and on the design of the interaction region. The background particles reaching the detector are mainly produced by the interactions between the decay products of the muon beams and the machine elements. Their type, flux and characteristics thus must be studied in detail since it strongly depends on the beam energy at the collision point and on the design of the interaction region. The background particles reaching the detector are mainly produced by the interactions between the decay products of the muon beams and the machine elements. Their type, flux and characteristics thus must be studied in detail since it strongly depends on the beam energy at the collision point and on the design of the interaction region.
Muons-based facilities have the potential to provide lepton–anti-lepton collisions at centre-of-mass energies in excess of 3 TeV and to revolutionise the production of neutrino beams. Where could such a facility be built? A 14 TeV muon collider in the 27 km-circumference LHC tunnel has recently been discussed, while another option is to use the LHC tunnel to accelerate the muons and construct a new, smaller tunnel for the actual collider. Such a facility is estimated to provide a physics reach comparable to a 100 TeV circular hadron collider, such as the proposed Future Circular Collider, FCC-hh. A LEMMA-like positron driver scheme with a potentially lower neutrino radiation could possibly extend this energy range still further. Fermilab, too, has long been considered a potential site for a muon collider, and it has been demonstrated that the footprint of a muon facility is small enough to fit in the existing Fermilab or CERN sites. However, the realistic performance and feasibility of such a machine would have to be confirmed by a detailed feasibility study identifying the required R&D to address its specific issues, especially the compatibility of existing facilities with muon decays. 

Minimising off-site neutrino radiation is one of the main challenges to the design and civil-engineering aspects of a high-energy muon collider because, while the interference of the neutrino flux pointing to Earth’s surface is spread out, it is one of the promising solutions to alleviate the problem, although it requires further studies.

A muon collider would be a unique lepton–collider facility at the high-energy frontier. Today, muon–collider concepts are not as mature as those for FCC-ee, CLIC, ILC or CEPC. It is now important that a programme is established to prove the feasibility of the muon collider, address the key remaining technical challenges, and provide a conceptual design that is affordable and has an acceptable power consumption. The promises for the very high-energy lepton frontier suggests that this opportunity should not be missed. 

Further reading


Further reading

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It is also important to begin strategic discussions that aim beyond 2030

OPINION

VIEWPOINT

Bridging Europe’s neutron gap

The recent closure of reactors means making the most of existing facilities while preparing accelerator-based sources, says Helmut Schober.

In increasing its focus towards averting environmental disaster and maintaining economic competitiveness, both the European Union and national governments are looking towards green technologies, such as materials for sustainable energy production and storage. Such ambitions rely on our ability to innovate – powered by Europe’s highly developed academic network and research infrastructures.

Europe is home to world-leading neutron facilities that each year are used by more than 5000 researchers across all fields of science. Studies range from the dynamics of lithium-ion batteries, to developing medicines against viral diseases, in addition to fundamental studies such as measurements of the neutron electric-dipole moment. Neutron science holds enormous potential at every stage of innovation, from basic research through to commercialisation, with at least 10% of publications globally attributed to European researchers. Yet, just as the demand for neutron science is growing, access to facilities is being challenged.

Three of Europe’s neutron facilities closed in 2019: BER II in Berlin, Orphée in Paris, and JEEP outside Oslo. The rationale is specific to each case. There are lifespan considerations due to financial resources, but also political considerations when it comes to nuclear installations. The potentially negative consequences of these closures must be carefully managed to ensure expertise is maintained and communities are not left stranded. This constitutes a real challenge for the remaining facilities. Sharing the load via strategic collaboration is indispensable, and is the motivation behind the recently created League of advanced European Neutron Sources (LENS).

We must also ensure that the remaining facilities – which include the FRM II in Munich, the Institut Laue-Langevin (ILL) in France, ISIS in the UK and the SINQ facility in Switzerland – are fully exploited. These facilities have been upgraded in recent years, but their long-term viability must be secured. This is not to be underestimated. For example, 20% of the ILL’s budget relies on the contributions of 10 scientific members that must be renegotiated every five years. The nest is provided by the ILL’s three associate countries (France, Germany and the UK). The loss of one of its major scientific members, even only partially, would severely threaten the ILL’s upgrade capacity.

Accelerator sources

The European Spallation Source (ESS) under construction in Sweden, which was conceived more than 20 years ago, must become a fully operating neutron facility at the earliest possible date. This was initially foreseen for 2019, now scheduled for 2023. Europe must ask itself why the ESS, or FAIR in Germany, takes so long. After all, neutron-science pioneers built the original ILL in just over four years, though admittedly at a time of less regulatory pressure. We must regain agility. The Chinese Spallation Neutron Source has just reached its design goal of 100 kW, and the Spallation Neutron Source (CANS) in Oak Ridge, Tennessee, is actively pursuing plans for a second target station.

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It is also important to begin strategic discussions that aim beyond 2030, including the need for powerful new national sources that will complement the ESS. Continuous (reactor) neutron sources must be part of this because many applications, such as the production of neutron-rich isotopes for medical purposes, require the highest time-averaged neutron flux. Such a strategy, which is currently under way in the US, and Europe should soon follow suit.

Despite last year’s reactor closures, Europe is well prepared for the next decade thanks to the continuous modernisation of existing sources and investment in the ESS. The value of neutron science will be judged on its contribution to solving society’s problems, and I am convinced that European research will rise to the challenge and carve a route to a greener future through world-leading neutron science.
The International Thermonuclear Experimental Reactor – now simply ITER – is a unique exercise in scientific diplomacy, and a politically driven project. It is also the largest international collaboration, and a milestone in the technological history of mankind. These, I would say, are the main conclusions of Michel Claessens’ new book ITER: The Giant Fusion Reactor – Bringing a Sun to Earth. He unfolds a fascinating story that crosses more than 40 years of the history of nuclear fusion in a simple, but not simplistic, way that is accessible to anyone with a will to stick to facts without prejudice. The full range of opinions on ITER’s controversial benefits and detriments are exposed and discussed in a fair way, and the author never hides his personal connection to the project as its head of communications for many years.

Why don’t we more resolutely pursue a technology that could contribute to the production of carbon-free energy? ITER’s path has been plagued by rivalries between strong personalities, and difficult technical and political decisions, though, in retrospect, few domains of science and technology have received such strong and continuous support from governments and agencies. Claessens’ book begins by discussing the need for fusion among other energy sources – he avoids selling fusion as the “unique and final solution to energy problems” – and quickly brings us to the heart of a key problem that humanity is facing today. Traveling through history, the author shows that when politicians take decisions of high inspiration, as at the famous-failed summit between presidents Reagan and Gorbachev in Geneva in November 1985, where the idea for a collaborative project to develop fusion energy for peaceful purposes was born, they change the course of history – for the better! The book then goes through the difficulties of setting up a complex project animated by a political agenda (fusion was on the agenda of political summits between the US and the former USSR since the Cold War) without a large laboratory backing it up. Progress with ITER was made more difficult by a complex system of in-kind contributions that were not optimised for cost or technical success, but for political “return” to each member state of ITER (Europe, China, Japan, Russia, South Korea, the US, and most recently India). Claessens’ examples are striking, and he doesn’t skirt around the inevitable hot questions: what is the real cost of ITER? Will it even be finished given its multiple delays? How much of these extra costs and delays are due to the complex and politically oriented governance structures established by the partners? The answers are clear, honestly reported, and quantitative, though the author makes it clear that the numbers should be taken cum grano salis. Assessing the cost of a project where 90% of the components are in-kind contributions, with each partner having its own accounting structures, and in certain cases no desire to reveal the real cost, is a doubtful enterprise. However, we can say with some certainty that ITER is taking twice as long and likely costing more than double what was initially planned – and as the author says on more than one occasion, further delays will likely entail additional costs. By comparison, the LHC needed roughly an additional 25% in both budget and time compared to what was initially planned.

Price tag
Waste initial cost estimate for ITER simply too low, perhaps to help the project get approved, or would a better management, with a different governance structure, have performed better? Significantly, I have not seen a single needed deputy person who should not strongly express that ITER is a textbook case of bad management organisation, though in my opinion, the book does not do justice to the energetic action of the current director-general, Bernard Bigot. His directive has been a turning point in ITER’s construction, and has set the project back on track in a moment of real crisis when many scientists and managers expected the project to fail. A key question surfaces in the book: is the price tag important? ITER’s cost is peanuts compared to the European Union’s budget, for example, and the cost is not significant by comparison to the promise that it delivers: carbon-free energy in large quantities, at an afford-
Particle and nuclear physics

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Opening doors with a particle-physics PhD

Transferable skills in communication, teamwork and computing make particle-physics PhDs highly sought after by industry.

Alexandra Martín Sánchez began her studies in particle physics at the University of Salamanca, Spain, in 2003, during which she had an internship at the University of Paris-Sud at Orsay working in the LHCb collaboration. This prompted her to take a master’s degree in particle physics, followed by a PhD at Laboratoire de l’Accélérateur Linéaire (LAL) in Orsay. She worked on CP violation in B$\rightarrow$$\psi$$\phi$ decays and hadronic trigger performance with the LHCb detector, and the subject fascinated her. She recalls with emotion witnessing the announcement of the Higgs boson discovery in July 2012 from Melbourne, Australia, where the (ICHP) conference was being held and where she was presenting her work. “Despite the distance, the atmosphere was super-charged with excitement!”

Yet, one year later, Alexandra decided to leave the field. Why? “[There were possibilities to do a postdoc in Marseille for LHCb, or elsewhere for other experiments, but I had already changed countries once and had created strong links in Paris,” she explains. “I loved working in research at CERN, and if it had been easier to continue in this way I would have, but getting a permanent position is particularly hard nowadays and you need to do several postdocs, often switching countries.”

After submitting her thesis, she consulted the careers office at Orsay to discuss her options. But it was word-of-mouth and friends who had already made the transition from research to industry that were the biggest help. After attending an IT careers fair in Paris in 2013, she was offered a job with French firm Bertin Technologies, who were looking for skills in scientific computing, in particular to offer consulting services for large groups including French energy giant EDF. Reckoning that this first step into industry could open the door to a large company, she took the plunge.

“Bertin Technologies had recruited me without having a clear idea regarding the profile of a particle-physics researcher, but they were immediately very satisfied with the way I worked. My recruiters were surprised to see me at ease in all aspects of the job, whether it was coding, functioning in teams or collaborating with other services.”

Moving on

After one year with the firm, Alexandra was recruited by EDF R&D, just as she had hoped for. Initially joining as a research engineer, five years later she is now project manager of open-source software called SALOME and leads a team of seven people. SALOME is used for industrial studies that need physical simulations, making it possible to model EDF’s operation of facilities and means of production, such as nuclear power plants or hydroelectric dams. “Computer science is the same as at CERN, even if it is applied to different data. Programming is also done in Python and C++. The code used is also that generated by researchers, that is to say, more or less ‘industrial’ and easily found my way around, as we share the same development work habits. At CERN we work on software developed by CERN, and at EDF on software developed by EDF. In both cases it is also teamwork. The principles remain the same,” she explains.

“Large groups like EDF are of course fatty hierarchical companies, but CERN is also very large and very hierarchical. One can feel protected by such structures. On the other hand, they have a cumbersome administrative side, which means that things do not necessarily move as quickly as we would like. What I miss, however, is the international aspect of the collaborations. Today I’m thinking of staying at EDF because I’m happy there. The career paths are varied and the company motivates its engineers to change jobs every four or five years, unless they wish to become specialists in their fields.”

The biggest lesson is that the skills she had learned during the process of obtaining a PhD in an environment like CERN are extremely transferable. “During my recruitment interviews, I highlighted my programming experience, my ability to communicate and present my work, and especially my ability to complete a thesis project over several years,” she says. “My advice to alumni looking for a job is to make the most of this PhD experience. Both sides of the job are of interest to recruiters: the technical part but also the communication and collaboration skills with researchers and engineers from all over the world. This makes a real difference from candidates coming from an engineering school: the thesis is a real professional experience.”

Interview by Laure Esteveny, CERN.
Russi receives Wideröe Prize
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Appointments and awards

**National Order of the Lion**
Panpa Diagne Syène, first director of the library at Alimoune Dior University of Bamby, Senegal, was included in the country’s National Order of the Lion with the grade of knight at a ceremony held in Dakar on 24 February, for her services to the nation. Diagne Syène has a long relationship with CERN. She participated in the CERN–UNESCO School on Digital Libraries in 2011, was a visiting librarian in CERN’s scientific information service for six months in 2015, and is a member of the scientific committee organising the biannual CERN–UNESCO Workshop on Innovations in Scholarly Communication.

**First Stephen Hawking Fellows**
In recognition of Stephen Hawking’s contributions to science and its popularisation, UK Research and Innovation (UKRI) has announced the first nine Stephen Hawking Fellows. Each fellowship provides up to four years’ funding and supports fellows with training in public engagement. Danai Antonopoulou (University of Southampton) will focus on gravitational waves and the early universe, and aim to inspire others via public-engagement activities on the history of the universe. Rebecca Nealon (University of Warwick) will focus on the formation of protoplanetary discs, and use numerical simulations in public talks and outreach activities.

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[Image of a scientist with a head of a particle and text]
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Very deep knowledge of photonic and accelerator technology and very good knowledge in laser technology

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Further development of tools for detailed characterization of the electron beam phase space. Perform accurate modeling and numerical simulations of electron beam measurements using calculating software tools. Develop and test software packages for automation and optimization of electron beam measurements: job offer APPO005/2020

Further developments of tools for detailed characterization of the electron beam phase space.

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For further information please contact Dr. Frank Stephan, +49-33762 77-338, f.stephan@desy.de

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For further information please contact Prof. Dr. Anke-Susanne Müller, email: dekanat@physik.kit.edu.

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Remembering a visionary physicist

Alvin Tollestrup 1924–2020

Alvin Tollestrup, who passed away on 9 February at the age of 95, was a visionary. I joined his group at Caltech in 1960. Alvin had helped build Caltech’s electron synchrotron, the highest energy photon-producing accelerator at the time. But he thought more exciting physics could be performed elsewhere, and managed to get approval to run an experiment at Berkeley’s promising new high-energy beam facility, the Bevatron.

The Bevatron was designed and built to find the antiproton, and sure enough Segré and Chamberlain found it as soon as the machine was turned on, earning them a Nobel Prize. Alvin also didn’t get the recognition he deserved. His intuition for electronics was a gift from the gods. In the 1950s, when the giants of the day were trying to understand the origin of parity violation, his knowledge of photomultipliers led him to show me how to analyse and judge the measurements of others. This was essential in making sense of the many “discoveries” of hadrons in the early 1960s. Without his influence, I never would have built the Tevatron, was completed in 1983. Alvin went on to convert it to a proton–antiproton collider in 1987, which led, within a decade, to the discovery of the top quark. Alvin was the primary spokesperson for the CDF collaboration from 1980 to 1992, and his critical contributions to the Tevatron were recognised in 1989 with a US National Medal of Technology and Innovation.

Virtuosity with modesty

The virtuosity required to create new accelerators sometimes exceeds what is necessary to run the resulting Nobel-prize-winning experiments. Alvin once told me that the Bevatron’s director, Ed Lofgren, never got the recognition he deserved. The Bevatron was designed and built to find the antiproton, and sure enough Segré and Chamberlain found it as soon as the machine was turned on, earning them a Nobel Prize. Alvin also didn’t get the recognition he deserved. His modesty only exacerbated the problem.

There were some things I could never learn from Alvin. His intuition for electronics was beyond my grasp, a gift from the gods. In the 1950s, when the giants of the day were trying to understand the origin of parity violation, his knowledge of photomultipliers led him to show me how to analyse and judge the measurements of others. This was essential in making sense of the many “discoveries” of hadrons in the early 1960s. Without his influence, I never would have built the Tevatron, was completed in 1983. Alvin went on to convert it to a proton–antiproton collider in 1987, which led, within a decade, to the discovery of the top quark. Alvin was the primary spokesperson for the CDF collaboration from 1980 to 1992, and his critical contributions to the Tevatron were recognised in 1989 with a US National Medal of Technology and Innovation.

Virtuosity with modesty

The virtuosity required to create new accelerators sometimes exceeds what is necessary to run the resulting Nobel-prize-winning experiments. Alvin once told me that the Bevatron’s director, Ed Lofgren, never got the recognition he deserved. The Bevatron was designed and built to find the antiproton, and sure enough Segré and Chamberlain found it as soon as the machine was turned on, earning them a Nobel Prize. Alvin also didn’t get the recognition he deserved. His modesty only exacerbated the problem.

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A passion for the elementary and cosmic-ray physics

Marcello Cresti, a leading researcher in cosmic-ray and elementary-particle physics, former director of the University of Padua, and grand officer of the Italian Republic, passed away in Padua on 2 January, aged 91.

Born in (to quote) Crespi, graduated at the Scuola Normale Superiore in Pisa in 1950, and in 1951 moved to the Padua Physics Institute directed by Antonio Rostagni. Working until 1953 at the high-altitude cosmic-ray observatory on the slopes of the Marmolada mountain and developed and used a setup including two Wilson chambers in a magnetic field. In 1972 he was at the Max Planck Institute for Physics in Göttingen, directed by Werner Heisenberg, and developed a technique for reconstructing events that used one of the first electronic computers. The following year he moved to the University of California Radiation Laboratory at Berkeley. In the group of Luis Alvarez, which was leading the development of hydrogen bubble chambers. Here he discovered parity violation at Berkeley, in the group of Luis Alvarez, which was leading the development of hydrogen bubble chambers. He designed and built the first electrostatic separator for bubble-chamber detectors. In 1965 he moved to the CERN theoretical physics department from 1957 until her retirement in 1995, passed away peacefully on 13 February, shortly before her 95th birthday. She was the great-granddaughter of Peter Carl Fabergé, jeweller to the 19th-century Russian Imperial Family. Born to illustrious parents in Geneva, she trained in design and worked in the family business for a few years. Then, in 1957, teams of CERN theorists from Copenhagen and Geneva were merged into, on the Meyrin site, what is now called the theoretical physics department. The new group needed a secretary, and Tania’s personality and talent for languages (she eventually mastered seven) won her the job. She went on to become a pillar of theoretical physics at CERN for decades, as the group grew and evolved, and the secretariat expanded. There were department leaders and so Directors-General while she was at CERN. During this time she welcomed thousands of visitors to the theory groups and was an asset to the environment in CERN. With her robust sense of humour and colourful character that nobody could ever forget, she was able to maintain the delicate balance of forces at CERN, setting the friendly tone that has long been a hallmark of the theoretical secretariat. Tania was a talented artist and an auteur, whose theatrical appearances in many theory Christmas pantomimes were highly appreciated. Owned the lab, for many years, Tania helped administer physics schools on the Adriatic coast of what was then Yugoslavia. Her home in Venice became a second home for Russians working at CERN. She often held open houses, not only for theorists, but also for many others in the wider CERN community, in particular legendary parties marking the Russian Orthodox Easter and her name days. Following her retirement, Tania embraced a new calling. She treated the globe for many years, connecting with flâneur members of the Fabergé clan, preserving the family heritage, protecting its name, and writing several books of reference about her great-grandfather’s work. Her spirit lives on.

Tania Fabergé in her realm.

Marcello Cresti at the Max Planck Institute for Physic at Göttingen in 1955 with the “G” – one of the first automatic calculators. and analysis of bubble-chamber film. Relevant results were obtained on antiproton annihilations and meson resonances. In 1976/1978 Marcello created a low-energy antiproton beam with excellent monochromaticity and collimation at CERN, and measured the antineutrino mass with, is what is still today, the best precision. Beginning in 1976 he also contributed to the European Hybrid Spectrometer at CERN’s SPS, where his group made one of the electromagnetic calorimeters and a wire chamber. In the late 1980s he joined the DELPHI experiment at LEP, with his group leading the construction of the end-cap electromagnetic calorimeters. Full professor at Padua since 1995, Marcello was the dean of the science faculty from 1994 to 1996, and rector of his university from 1994 to 1987. From 1971 to 1973 he chaired the CERN Track Chamber Committee, responsible for bubble-chamber physics. During the final part of his career Marcello returned to his first love, cosmic rays. From 1989, with his group in Padua and a group from Pisa, he designed and carried out an experiment – CLUB – aimed at the detection of high-energy cosmic gamma rays, this started the Italian astroparticle activity at the Roque de los Muchachos observatory in the Canary Island of La Palma. He retired in 2000. Marcello is survived by three daughters, Diana, Lucia and Paola. Two leading research groups in Padua continue his activities, respectively, on accelerator (LHC) and cosmic-ray physics. His students and friends remember his enthusiastic, fascinating and generous way of teaching, and his witty and funny conversation.

His friends and students.

A CERN institution of force and nature

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Marie-Noëlle Fontaine, Perrine Verrin and John Ellis CERN. A life dedicated to science and solidarity

Robert Klapisch, a former director of research at CERN, passed away on 21 March. Robert was a tireless worker, not only passionate about the field of fundamental physics, covering both nuclear and particle physics. He was eager to hear about innovative developments in any scientific field. He was always progressing through science. Once a goal had been set, he pulled out all the stops to achieve it, following a well-defined path, supported by the courage of his convictions, an infectious enthusiasm and tenacity every turn. The many facets of his personality made Robert an endearing friend and a highly appreciated colleague. Open-minded, supporters of others, committed, loyal and with an irresistible joie de vivre, was a fine example of a human being.

Robert was born on 26 December 1933 in Cachan, France. After studying at the École supérieure de physique et de chimie industrielle ESPCI in Paris, he went straight on to join the CTNS in 1956. At the Radium Institute he became proficient in mass spectrometry and precision isopic separation under the supervision of his mentor, René Bernas. Later, Robert became the director of CSSNM Centre de spectrométrie nucléaire et de spectrométrie de masse. This centre became the innovative centre of excellence producing many applications for mass and nuclear spectrometry.

Pioneering spirit

Together with his team, Robert carried out pioneering research using “online” mass spectrometry on accelerator beams, notably at CERN’s Proton Synchrotron (PS) and then at LEP/LE. At this brand-new online isotope separator, the team came out the first ever laser spectroscopy, which, when combined with mass spectrometry, enabled unprecedented studies of exotic short-lived nuclei. This work allowed them to make significant advances in the fields of nuclear and particle physics. This work allowed them to make significant advances in the fields of nuclear and particle physics.

After returning to France, Robert participated in the group led by Rubbia that was carrying out research into an innovative approach to the production of nuclear energy and the processing of nuclear waste through transmutation. More recently, he lent his support to initiatives on the transport of electrical energy by superconducting cables.

In 2000, Robert launched the “Sharing Knowledge” series of conferences, which brought together numerous scientific experts from around the Mediterranean. These conferences, the last of which took place at CERN in 2009, covered many subjects, from the digital divide to satisfying humankind’s basic needs (water, energy, food). They were always a resounding success. To ensure the lasting impact of these conferences, in 2006 Robert created the “Sharing Knowledge Foundation”, which he directed for 15 years, working towards encouraging sustainability in countries around the world and protecting the daily transfers and developing scientific knowledge. Thanks to the efforts of the foundation, and of Robert himself, students from Morocco and Palestine were able to participate in CERN’s technical and doctoral student programmes. These students are now assistant professors back in their own countries and are ideal ambassadors for CERN’s culture of international collaboration. In addition, with a view to creating a friendly space for discussions at SESAME, the international centre for synchrotron-light experimentation in the Middle East, Robert convinced the foundation to finance a cafeteria there.

Humanism and solidarity

As well as being an exceptional scientist, Robert knew how to enjoy life. He was fond of a good celebration, and a fan of fine food and wine, in particular Burgundy wine, of which he was a great connoisseur. Many of us had the pleasure of tasting rare vintages with him during animated discussions on science, politics or society in general. Robert was a generous man and his door was always wide open. He was also an expert in many cultural domains: literature, art, theatre and cinema. The best way to pay tribute to him is to continue to promote his ideals of humanism and solidarity.

Our thoughts are with his family, particularly his three children, Coline, Cédric and Marianne. His friends and colleagues at CERN and CNRS.

Robert Klapisch carried out pioneering research using online mass spectrometry and also worked to encourage sustainable development.
Notes and observations from the high-energy physics community

From the archive: May 1980

Grand unification...

Recent successes of the electroweak theory have made theorists confident enough to tackle ‘grand unifications’ of strong interactions with the electroweak force. One prediction is that protons can decay with a lifetime of some $10^{33}$ years. This means that a man (sic!) would have to live for more than a century before he could say that there was a good chance that just one of the protons in his body had disintegrated.

The apparent absence of magnetic monopoles when the equations of electromagnetism are symmetric with respect to electric and magnetic charge has long intrigued physicists. The ‘grand unification’ theory argues for the existence of such monopoles, heavier even than the bosons held responsible for proton decay, much heavier than a bacterium! If such superheavy monopoles were produced in the extreme temperatures of the Big Bang, they should still be around.

Compiled from text on pp114–115 of CERN Courier May 1980.

Compiler’s note

40 years on and neither proton decay nor real magnetic monopoles have been observed. Monopoles are rather like zero-length pieces of string, more easily imagined (by theorists?) than described (for experimentalists?), making it difficult to know what to look for. As for proton decay, with a half-life of some $10^{33}$ years there would be about one event per week, with a fairly distinctive signature, in a tank containing 1000 tonnes of water. Easy to describe, challenging to implement. The principal problem is cosmic and geological background, so the tank must be buried a kilometre or two deep in Earth’s bedrock and covered in veto counters. Nonetheless, although tricky, searches for these two elusive phenomena continue, so watch this space, or rather watch this journal.

The approximate number of scientific observations in the Hubble MAST data archive, released by NASA to celebrate the 30th year in orbit of the Hubble Space Telescope

550,000

Media corner

“The scientific case for the future of experiments in particle physics – accelerator-based or not – is strong. Scientific merit aside, convincing politicians and the public that it’s worth the investment might be harder... However, a utilitarian argument that emphasises the innovation, skills and technology that come out of a healthy infrastructure for particle physics is compelling.”

From an editorial in Nature Physics (6 April) devoted to the European strategy for particle physics (Nat. Phys. 16 156).

“The increase [in the brilliance of light sources] by a factor of about ten from the mid 1960s to the present gives the average doubling time of about eight months – three times as fast as for transistors and six times as fast as the luminosity of colliders.”

Vladimir Shiltsev writing in the April issue of Physics Today about advances in accelerator physics.

“Weisberg’s paper is a bit of lightning in the dark. All of a sudden a whole field is suddenly working again on these problems.”


“We analysed simulated data of Higgs experiments with the aim of identifying the most suitable quantum machine-learning algorithm for the selection of events of interest.”

Panagiotis Barkoutsos of IBM Research quoted in Physics World (5 April) on a collaboration between IBM and CERN opalp to explore quantum computing in high-energy physics.

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Cosmic Hunter is a new educational tool through which CAEN wants to inspire young students and guide them towards the analysis and comprehension of cosmic rays. Cosmic Hunter SiPM based, is composed of one detection - coincidence unit together with two plastic scintillating tiles. A third tile is available on request. Muons detections, flux estimation, shower detection and more are allowed thanks to a flexible system geometry.

Experiments
- Cosmic Muons detection
- Coincidence (single, double and triple)
- Zenit angle dependence
- Cosmic Shower Detection

Ascent commemorates cosmic-ray pioneers
At the 42nd international balloon festival in Château-d'Oex, Hans Peter Beck (University of Bern and Fribourg) ascended on January 25th with some of his students up to 4000m in a hot-air balloon, commemorating the historic flight of Albert Gockel from 1909 (with modern equipment using CAEN Cosmic Hunter), measuring cosmic rays.